Hydrology and Earth System Sciences, 1(3), 399–407 (1997) © EGS

Hydrology & Earth System Sciences

A consideration of rainfall, runoff and losses at Plynlimon in the context of long term hydrological variability in the UK and maritime Western Europe

S. Green and T.J. Marsh

Institute of Hydrology, Wallingford, UK

Abstract

Important questions concerning the resilience of current water management strategies have been raised by the recent volatility of climatic conditions across large parts of western Europe. The last decade, overall, has been exceptionally warm and there have been very large spatial and temporal variations in rainfall, river flows and aquifer recharge rates. Examination of historical rainfall and runoff records for parts of maritime western Europe confirms that there is no close modern parallel to the conditions experienced recently. Some—but far from complete—consistency with a number of favoured climate change scenarios may be recognised.

Analyses of recent trends in lengthy rainfall and runoff series for the UK demonstrate significant regional differences and provide conflicting signals especially in relation to trends in catchment losses. Difficulties in reconciling the results from different areas may reflect both real hydroclimatological differences between catchments and variations in the precision of hydrometric time series—uncertainties in the assessment of areal precipitation in upland areas in particular. The dense monitoring networks at Plynlimon together with a rigorous data quality control programme underpins the value of the hydrometric datasets as important benchmarks against which to assess the significance of the very unusual patterns of rainfall and runoff which have characterised the recent past.

This paper places the rainfall, runoff and losses data for Plynlimon in the perspective provided by a number of long hydrometric records for maritime western Europe. The representativeness of the Plynlimon base period is considered with particular reference to both the historical stability which typifies the great majority of European hydrometric time series and the recent extension in the recorded range of accumulated rainfall and runoff totals which has been identified in some regions (e.g. western Scotland and Norway). Particular attention is directed to changes in seasonal rainfall and runoff patterns and the recent increases in evaporative demands. Some of the implications for the overall water balance and for water resource management are considered.

Introduction

Research in the Plynlimon experimental catchments has substantially improved the understanding of upland hydrological processes and the hydrological implications of land use change (Kirby *et al.*, 1991). Dense monitoring networks, often utilising innovative sensing and recording techniques, have provided a wealth of hydrometeorological data to underpin a wide range of fundamental and applied studies. As importantly, the associated point and areal hydrometric datasets have established a set of reliable benchmarks against which to assess the hydrological effect of contemporary and future climatic conditions. Such baseline datasets assume a particular importance at a time when there is a priority need to quantify the impact of global warming on rainfall patterns and the associated hydrological responses.

The UK, together with other parts of western Europe, has experienced very unusual climatic conditions over much of the recent past—especially in the last decade (Institute of Hydrology/British Geological Survey, 1996, Green *et al.*, 1996). These have underlined Britain's vulnerability to hitherto rare weather patterns and focussed attention on many of the issues at the heart of hydrological science and its practical application. However, the interactions between the unusual spatial distribution and seasonal partitioning of rainfall, a decreased contribution from snowfall and generally high evaporative demands, can have complex hydrological implications. Partly as a consequence, national hydrometric monitoring programmes can produce conflicting signals regarding the overall impact of the recent climate patterns on catchment water balances and, by extension, the appropriateness of existing water management practices and procedures. Hydrological knowledge acquired during the Plynlimon research programme provides the means of reconciling many of the conflicting signals but, in common with the great majority of catchments monitored in western Europe, the Plynlimon areal rainfall and runoff records are mostly less than 35 years in length. To capitalise fully on the hydrometric data collected as part of this major experimental programme, they must be placed in the spatial and temporal context of the hydrological variability captured by monitoring programmes extending over the last 150 years or more.

RAINFALL—A LONG TERM PERSPECTIVE

Most lengthy rainfall series in western Europe are characterised by a lack of any significant long term trend (Jones and Conway, 1996, Green *et al.*, 1996). Perturbations about the mean can, however, be substantial and persistent (Thomsen, 1993); this is especially true of the Celtic regions where the preferred tracks of Atlantic frontal systems, over a run of seasons up to a few decades, can be very influential. As a consequence, the apparent significance of any perceived trends can be influenced heavily by the timespan over which a time series is examined. Records commencing during a dry phase (e.g. in the 1940s in England) may show a convincing upward trend which, when considered alongside the variability captured in records of 100 years or more, proves to be only a noteworthy departure from a relatively stable long term mean.

Figure 1 illustrates 5-year running means of annual rainfall totals for six index sites in western Europe; the locations are shown in Fig. 8. The 138-year series for Rhayader in central Wales is particularly helpful in providing a historical context in which to place the 1954–96 rainfall series for the Severn catchment at Plynlimon (also shown in Fig. 1). Each of the long rainfall series displays broadly similar characteristics with little or no overall trend until around 1970. Thereafter, and especially in the period to the mid-1990s, a very notable increase in rainfall occurs at Fort William and Bergen; this is consistent with increases in precipitation reported for Iceland (Jonsson, 1994), the Norwegian Arctic islands (Hanssen-Bauer and Forland, 1994) and the Faroes (Frich, 1994). Placing this wet-phase in a wider climatological context, Hurrel (1995) and Wilby *et al.* (1997) note its correspondence with exceptionally high values for the North Atlantic Oscillation, a quasi-periodic fluctuation in pressure gradients across the North Atlantic.

The post-1970 increase in rainfall at Rhayader is notable in the context of data covering the twentieth century but less outstanding than the recent precipitation at Fort William where five of the ten wettest years on record cluster in the post-1986 period. For Scotland as a whole, rainfall over the 16 years up to 1995 was around 18% greater than the preceding average (Anon. 1995); notwithstanding the effect of anomalies in the national rainfall series (Smith, 1995), the recent increased rainfall represents the largest sustained anomaly in a series from 1757. In the more southerly sites featured in Fig. 1, seasonal rainfall in

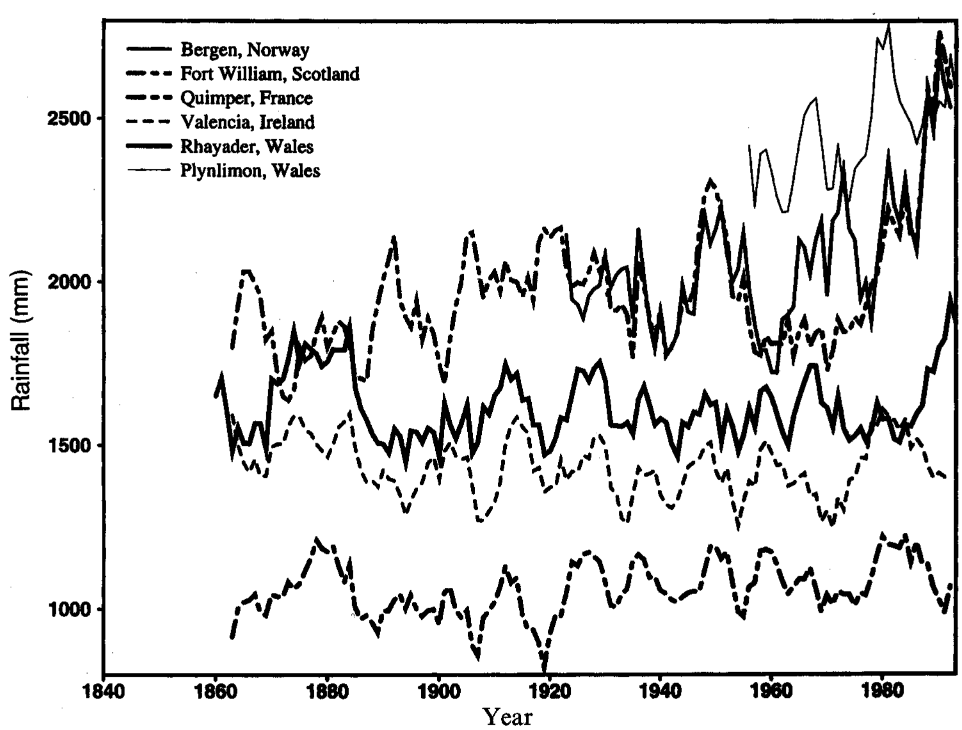

Fig. 1. *5-year running mean of annual rainfall totals for selected raingauges.*

the recent past has been very variable but no significant departure from the long stability in mean rainfall is yet evident. Similar conclusions have been reported for analyses of long precipitation series for more continental locations; Heino (1994), for example, demonstrates long term stability in precipitation for Finland.

The tendency for underestimation where snow constitutes a significant component of precipitation (Merscherskaya *et al.*, 1995) could be a factor in the apparent rise in annual precipitation for the more northerly sites featured in Fig. 1. At these locations, snow was a substantially lower proportion of total precipitation in the 1990s than 30 years ago; for the Moel Cynnedd climate station at Plynlimon, the average number of days with lying snow during each of the last ten years is 16 compared with 28 for the preceding record. However, snow has always contributed a relatively minor proportion of overall precipitation at Bergen and Fort William, both low-lying coastal sites, so the time series are indicative of a real increase in rainfall over the 1970–95 period. This conclusion is supported by evidence from stream gauging stations in the same area; runoff totals increased similarly within the same timeframe. Although below average precipitation in the early 1960s accentuates the recent trend, the 1980–95 wet phase is notable in the context of the full rainfall series; for example, accumulated rainfall totals over 12–48 months are greater than any registered prior to 1980.

The unusual nature of rainfall, especially in the Scottish Highlands over the post-1970 period is emphasised by Fig. 2 which illustrates the 10-year running mean of the ratio of annual rainfall totals at Fort William and Kew (London). Figure 2 testifies to a strengthening of the north-west/south-east rainfall gradient across Great Britain which has no modern parallel. The broad similarity with the corresponding ratio for Bergen and Copenhagen (also shown in Fig. 2) suggests a common synoptic backcloth. Most of the recent increase in the ratio is attributable to a greater wetness in the north and west rather than any significant decline in rainfall in the eastern lowlands. Examination of the ratio for Rhayader and Pode Hole (in the east Midlands, Kington, 1988) demonstrates that the ratio has covered a wide range over the last 35 years, but there has been no comparably steep increase in the west-to-east rainfall gradient across central Britain—this has important regional water transfer implications.

The unusual spatial pattern in rainfall over the recent past has been accompanied by notable changes in the distribution of rainfall throughout the year. On average, rainfall in north-western Europe is fairly evenly distributed through the year with a tendency towards an autumn maximum in the more maritime west; summers tend to be drier to the south and east. Since the mid-1980s particularly, many areas have witnessed a more distinct partitioning of rainfall between the winter and summer half years. For England and Wales as a whole, this tendency towards a higher proportion of annual rainfall falling in the winter is especially notable if the periods November-March (winter) and May-September (summer) are used; this seasonal division broadly separates the infill and drawdown periods for many gravity fed reservoir systems and major ground-

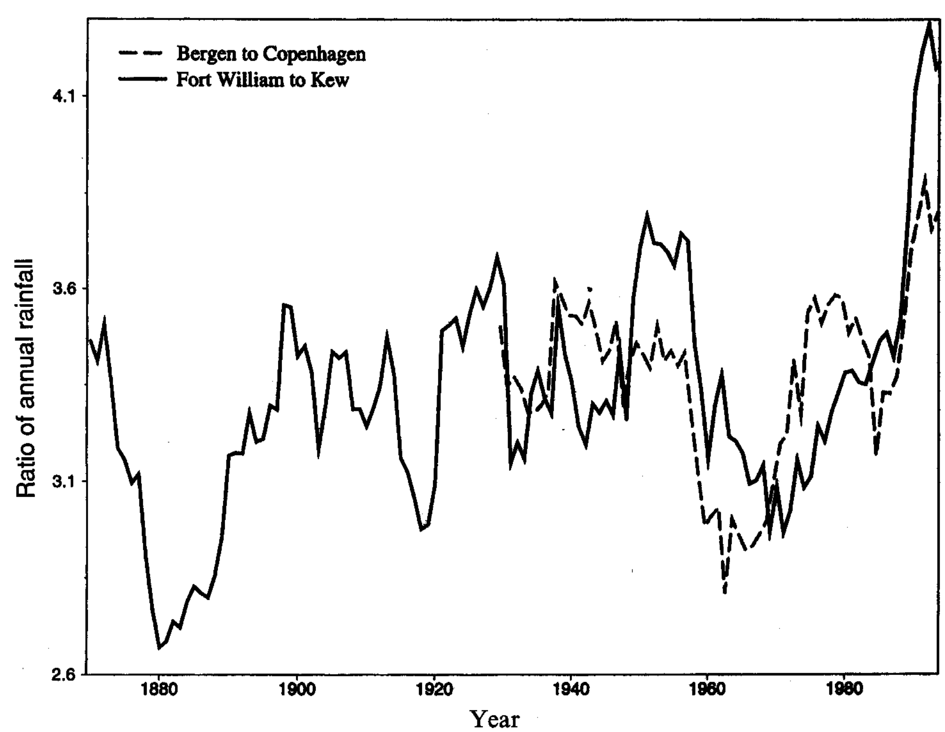

Fig. 2. *10-year running mean of the ratio of annual rainfall totals.*

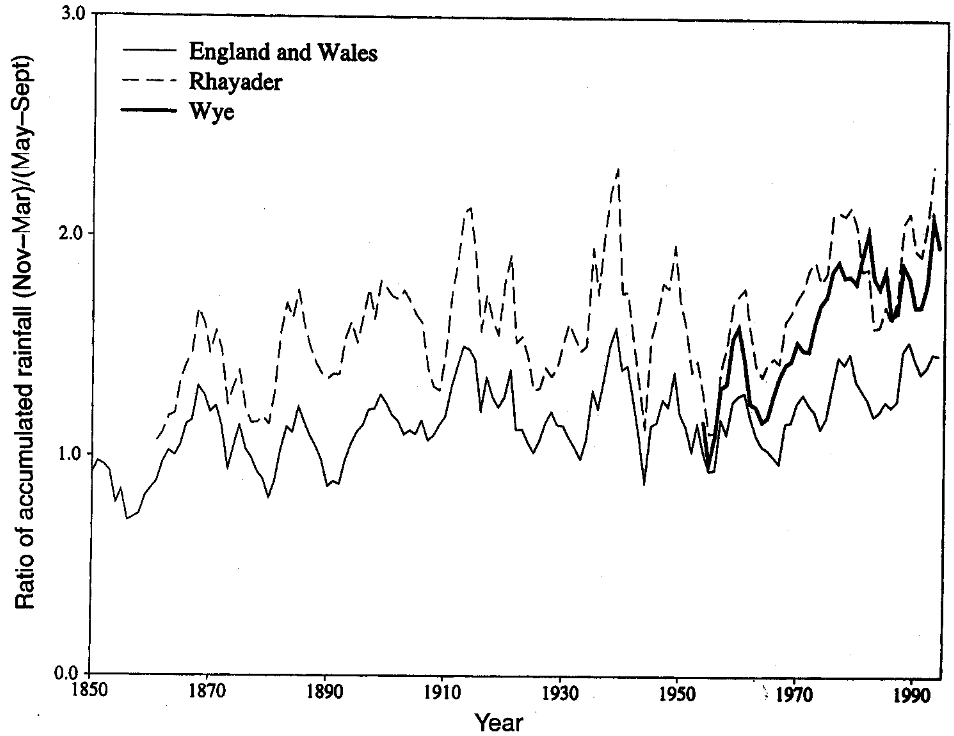

Fig. 3. *Ratio of winter 5-month rainfall (Nov.–Mar.) to summer 5-month rainfall (May–Sep.).*

water storages. Figure 3 plots the ratio of November-March rainfall to that of the ensuing May-September. The unrepresentative nature of the raingauge network—especially the sparsity of raingauges in Wales, and above 200 metres, prior to 1850 (Symons, 1870), limits the value of the early data but the there is no precedent for the persistence of the increasing trend over the 30 years from the mid-1960s. For central Wales, the running mean of the winter/summer ratio at Rhayader provides a useful historical context within which to assess the significance of the very notable rise in the ratio for the Wye catchment (Plynlimon) over the period from the early 1950s. Both series have, however, been close to the period-of-record maxima over much of the last 15 years. Similar tendencies towards a more seasonally distinct rainfall regime have been found in Brittany and Norway (Green *et al.*, 1996).

EVAPORATION AND SOIL MOISTURE

Increased overall rainfall and/or a higher proportion of the annual precipitation falling in the winter (when evaporative losses are modest), would be expected to increase overall runoff and generally bring benefits for water resources. However, the recent past has also been typified by consistently high temperatures—the last 10 years, taken together, are the warmest of any 10-year sequences in the Central England Temperature (CET) series which begins in 1659 (Manley, 1974). The exceptional nature of summers over the last 25 years is evident from Fig. 4 which

(a) Winter (Oct–Mar)
(b) Summer (Apr–Sep)

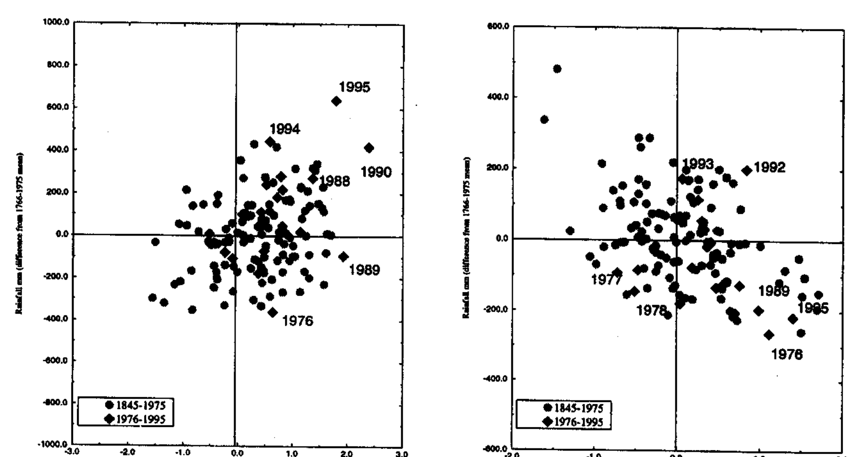

Fig. 4. *Rhayader rainfall and Central England Temperature anomalies 1858–1995.*

illustrates winter and summer temperature and rainfall anomalies for Rhayader and the CET series. The clustering of recent summer half-years in the warm/dry quadrant is clearly evident. Also of significance is the mildness of recent winters and the large variation in October-March rainfall totals. Similar plots for Fort William highlight a preponderance of mild, wet winters in the last 30 years whereas for England and Wales as a whole, the clustering of hot, dry summers is even more marked (Marsh, 1997).

Abnormally high temperatures over the last decade have contributed to exceptional evaporative demands, appreciably higher than those typifying the 1960s (Burt and Shahgedanova, in press, Marsh and Sanderson, 1996). In the more maritime western regions of Britain, potential evaporation losses have been unusually high and, in several recent years (e.g. 1990 and 1995), soil moisture deficits during the summer have been of sufficient magnitude to inhibit transpiration and cause actual evaporation totals to fall appreciably short of the potential value. Table 1 shows the number of months, in 5-yearly blocks, for which soil moisture deficits (computed using MORECS, Thomson, 1981) for two 40 × 40 km squares in central Wales exceeded 60 mm. The increase over 35 years is consistent with an assumption that evaporation during recent summers may be inhibited even at altitudes above 250 metres. In the eastern lowlands of England, where water resources are vulnerable to relatively small changes in net evaporation, the hot and dry conditions have commonly resulted in parched summer soils and substantial soil moisture deficits persisting into the early winter. As a consequence, the aquifer recharge season has often been much reduced, producing conditions were more typical of parts of the North European Plain.

Evidence for net changes in overall regional water balances over the last 30 years is currently limited and the hydrological signals emerging from national hydrometric networks can be ambiguous. In Wales, an influential examination of catchment losses (rainfall–runoff) 20 years ago (Jack, 1977) confirmed the Wye catchment as typical of Welsh headwaters (with little afforestation). Unfortunately, less water balance information from reservoired catchments is now readily available and losses over the post-1975 period for individual catchments can depart markedly from the relative stability indicated by the losses for the Wye catchment, see Fig. 5. Reservoir storage and catchment transfers are not significant factors in the water balances for the catchments shown but minor abstractions and returns may result in modest import or export of water to or from individual catchments. More influential is likely to be uncertainties in the runoff measurements due to the hydrometric performance of the gauging station or imprecision in the catchment rainfall assessments due largely to the unrepresentative nature of the individual gauge sites and difficulties in deriving accurate areal totals—especially in periods when snowfall is significant; such circumstances can combine to produce occasional negative annual losses. The presence of a substantial number of strategically important gravity-fed reservoirs in the western uplands of Britain emphasises the continuing need to monitor and interpret the net effect of changing evaporative demands and transpiration rates at the catchment scale. This in turn underlines the importance of the unique capability represented by the Plynlimon programme.

Table 1. Number of months for which MORECS soil moisture deficit exceeds 60 mm

Years	North Powys	Central Powys
1962–1966	6	5
1967–1971	3	9
1972–1976	11	9
1977–1981	5	5
1982–1986	10	7
1987–1991	13	11
1992–1996	14	10

RUNOFF

In contrast to raingauge networks which were well established in many areas 150 years ago, most flow measurement stations in western Europe have been commissioned since 1960; the average length of flow record is typically around 20–25 years (WMO, 1994). Work undertaken with a number of long term runoff series (Robson *et al.*, 1998, Marsh, 1996) indicates that river flow monitoring over this period is very unlikely to have captured the full range of runoff variability—leaving aside any consideration of the impact of climate change. This, together with the lack of homogeneity which typifies many long term runoff datasets, determines that any apparent trends over the recent past need to be treated with caution. In much of western Europe, the increasingly pervasive impact of water management on river flows and groundwater levels implies that many apparent trends in runoff or recharge rates are due to anthropogenic effects or artifacts in the time series. Changes in monitoring site and/or measuring technique, a feature of many long hydrometric records, can introduce systematic errors or step changes even in well maintained and strategically important datasets (Littlewood and Marsh, 1996). For these reasons, the understanding of hydrological processes and the development of improved water management strategies relies heavily on the minority of, mostly small, catchments where consistently high hydrometric standards are maintained and disturbance to the runoff (or recharge) regime is very limited.

Notwithstanding the limitations of data quality and representativeness of individual time series, most lengthy runoff series in western Europe exhibit a long term stability in the their mean flow, albeit with significant short-term temporal variations. Figure 6 illustrates 5-year

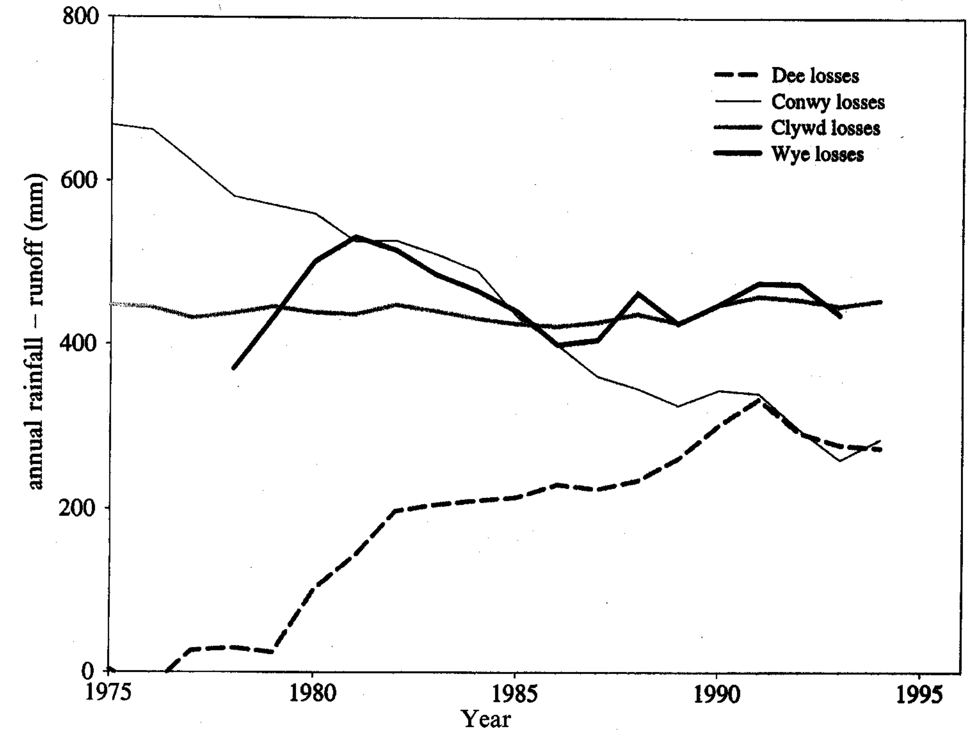

Fig. 5. *5-year running mean of losses (rainfall–runoff) from catchments in North and central Wales.*

running mean runoff totals for four time series extending back into the nineteenth century; the corresponding trace for the River Wye at Cefn Brwyn is superimposed. Runoff from the River Bulken in Norway since the mid-1970s is seen to have increased sharply with accumulated runoff totals over the recent past being significantly greater than any previously recorded. A marked tendency towards increased runoff over the 20 years to 1995 is also evident for many rivers draining from the Scottish Highlands (Black, 1996). This abundant runoff has been associated

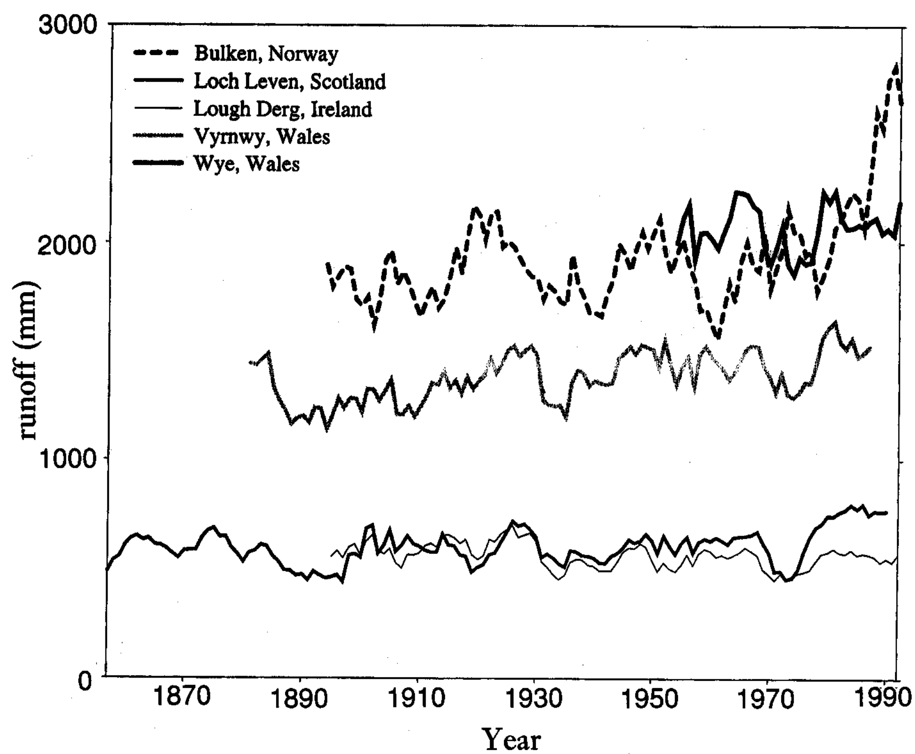

Fig. 6. *5-year running mean of annual runoff totals.*

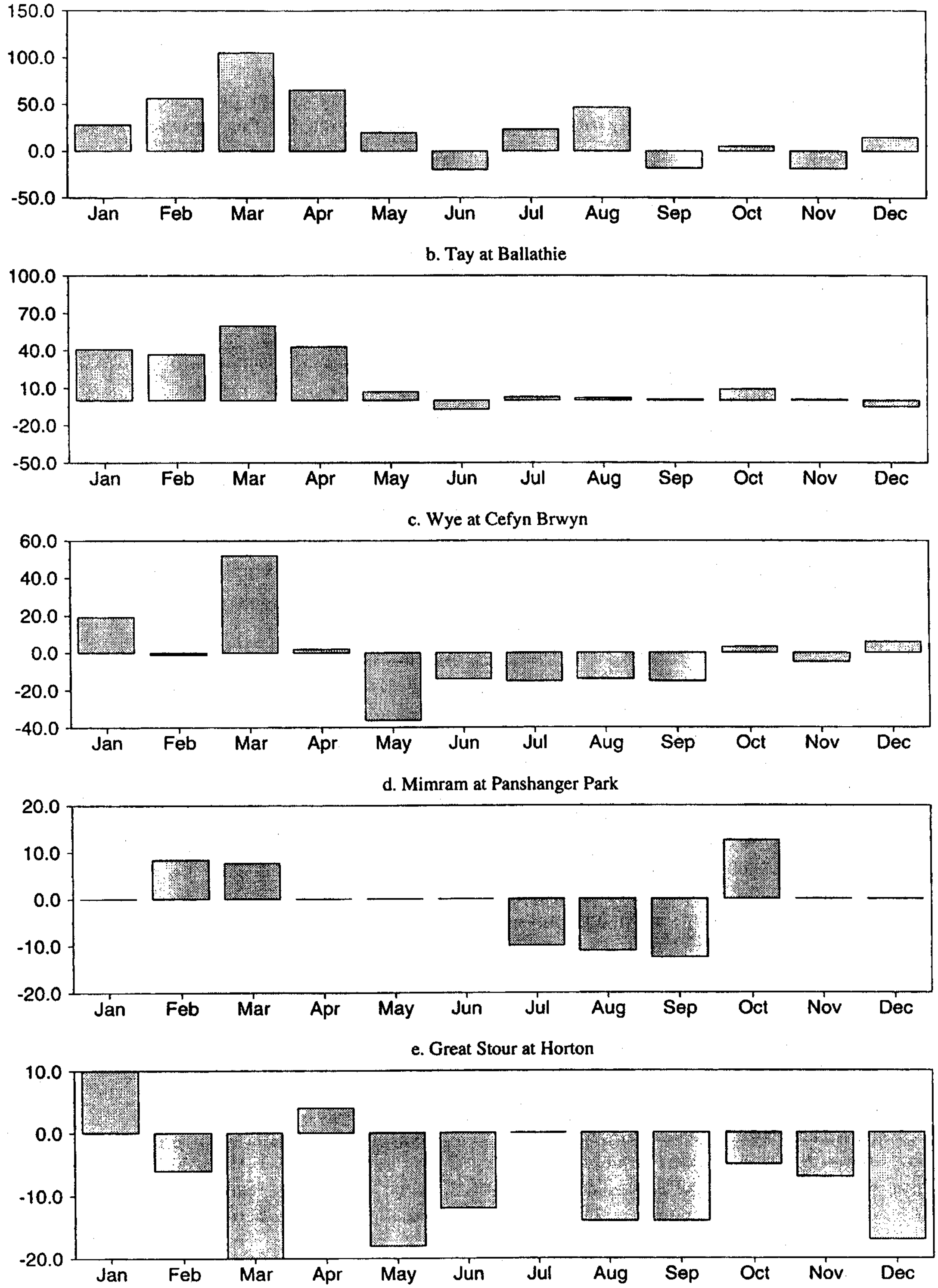

Fig. 7. *Percentage change in monthly runoff for the 1986–1995 period compared to the previous record*

with a sequence of notable flood events (Black and Bennet, 1995) prompting suggestions that the return period of extreme events may be decreasing. Away from the maritime north-west of Europe, however, this tendency is very muted, and insignificant in, for example, south-west Ireland or Brittany. Runoff data for the 1960–96 period at Cefn Brwyn are consistent with this lack of recent overall trend.

As with rainfall, runoff patterns have shown enhanced seasonal contrasts in many west European catchments over the last decade. Catchment geology has, however, moderated the effect of enhanced seasonal rainfall contrasts in some regions. Increased winter rainfall over the English lowlands, northern France and Denmark has produced a lagged runoff response in permeable catchments. Many Chalk streams, including the River Mimram to the north of London, have reported enhanced early summer flow rates in some years, notwithstanding the very modest summer rainfall; this was particularly evident during the extensive droughts of 1990 and 1995 (Institute of Hydrology/British Geological Survey, 1996).

In more responsive river systems draining the steeper, impermeable catchments of north-western Europe, an accentuated seasonality is a feature of runoff patterns over the last 20 years. Figure 7 illustrates changes in monthly average runoff over the 1986–95 period relative to the preceding average. The Scottish rivers (Tay and Falloch which both drain from the Scottish Highlands) exhibit substantially increased winter runoff with little change over the summer months. By contrast, monthly flows in the Great Stour (in Kent) are considerably below the pre-1986 average for most months of the year. The Wye at Cefn Brwyn, with characteristic grassland terrain, shows enhanced seasonal contrasts with particularly large departures from the preceding average in the spring. On the basis of this small sample, the Wye catchment appears to be transitional in both a geographical and hydrological sense. Departures from the monthly average over relatively short timespans are to be expected given the normal variation in runoff through time. However, those illustrated assume a greater significance in the light of their consistency with most favoured climate change scenarios (Arnell and Reynard, 1996)—and should provide valuable insights into conditions which may occur with a greater frequency in the future.

Conclusion

Water management in Europe, as elsewhere, is underpinned by a long term stability in rainfall, runoff and aquifer recharge patterns. There is increasing, but not yet decisive, evidence that this stability may not continue into the future; recent hydrological conditions in parts of western Europe have extended the range of recorded variability in rates of runoff and aquifer recharge. Given the strong evidence of global warming and the expectation that this will impact on flow regimes and water resources, it can no longer be assumed that such exceptional hydrological conditions represent simply another perturbation about the long term average. The uncertainty associated with predictions based on Global Circulation Models, particularly their limited spatial resolution, implies that climate change scenarios will achieve full public and political credibility only when they can demonstrate a consistency, through time, with the hydrological consequences captured by contemporary hydrometric monitoring programmes. Plynlimon has a continuing and crucial role both in reconciling the evolving theories relating to climate change impacts with observational groundtruth and in further extending hydrological knowledge to help establish a firm foundation for the development of improved water management strategies.

Acknowledgement

An investigation of this type would not have been possible without the active cooperation of many organisations and individuals involved in the acquisition, processing and dissemination of hydrometric data. There has never been a greater need to maintain the integrity and continuity of such datasets, nor has it ever been harder to ensure their continuity with time. To all those concerned, the authors wish to express their gratitude.

The MORECS data featured in the paper were provided by the Meteorological Office and the Climate Research Unit (University of East Anglia) was the source of the recent Central England Temperature data.

The authors are grateful to Frank Law and John Gash for their helpful comments on a draft of this paper.

References

Institute of Hydrology/British Geological Survey. 1996. *1995 Yearbook. Hydrological data UK series.* Institute of Hydrology, Wallingford, UK, pp 5–33.

Arnell, N.W. and Reynard, N.S. 1996. The effect of climate change due to global warming on river flows in Great Britain. *J. Hydrol.* **183**, 397–424.

Black, A.R. and Bennet, A.M. 1995. Regional flooding in Strathclyde, December 1994. In: *1994 Yearbook, Hydrological data UK series.* Institute of Hydrology, Wallingford, UK, pp 29–36.

Black, A.R. 1996. Major flooding and increased flood frequency in Scotland since 1988. *Phys. Chem. Earth*, **20**, No. 5–6, pp 463–468.

Burt, T.P and Shahgdenova, M. 1998. A historical record of evaporation losses since 1815 calculated using long-term observations from the Radcliffe Meteorological Station, Oxford, England. *J. Hydrol.* (In press).

Frich, P. 1994. Precipitation trends in the North Atlantic European region. *Climate Variations in Europe* (Ed: Heino, R.), Academy of Finland, Publication 3/94 196–200.

Green, S., Sanderson, F.J. and Marsh, T.J. 1996. Evidence for recent Instability in rainfall and runoff patterns in the Celtic regions of Western Europe. *Hydrologie dans les pays celtique.* Proc. 1st InterCeltic Colloquium, INSA, Rennes, July 1996, 73–84.

Hanssen-Bauer, I. and Forland, E. 1994. Homogenising of long Norwegian precipitation series. *J. Climate.* **7**, 1001–1013.

Heino, R. 1994. *Climate in Finland during the period of meteorological observations.* Finnish Meteorological Institute contributions, No 12. 209pp.

Hurrel, J.W. 1995. Decadal Trends in the North Atlantic Oscillation: Regional Temperatures and Precipitation. *Science*, **269**, Aug. 1995, 676–678.

Jack, W.L.1977. Annual catchment losses—a practical method. *J. Instn. Wat. Engrs. Scient.* **31**, 280–284.