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The long-term water balance (1972–2004) of upland forestry and grassland at Plynlimon, mid-Wales

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Abstract

This paper reviews research into the hydrological impacts of UK upland forestry and updates the water balance of the Plynlimon research catchments for the period 1972–2004. Comparison of this network of densely instrumented coniferous forest and grassland catchments builds upon previously reported differences in annual evaporation of the two land uses and, most crucially, provides evidence of systematic, age-related, variations in forest evaporation losses over a managed plantation forest cycle. In comparison with the grassland catchment, the additional water use of the 70% forested catchment fell from 250 to 150 mm yr^{-1} because of increasing forest age; this is equivalent to a decline from 370 mm to 210 mm extra evaporation from a complete forest cover. At present, with up to half of the forest area felled or only recently replanted, the difference in evaporation between the forest and grass catchments is negligible. Knowledge of the period of maximum tree water use may be critically important for the future management of multi-use forests. This is also being investigated by micro-meteorological measurements at the scale of the forest stand using eddy covariance, in conjunction with the long-term catchment monitoring.

Keywords: catchments, forest hydrology, Plynlimon, water balance

Introduction

The Plynlimon catchments in mid-Wales are the UK's best-known research basins and have served as an open-air laboratory for research into hydrological processes and land-use change for nearly 35 years. This paper reviews the long-term water balance results since they were last updated to 1995 (Hudson *et al.*, 1997). Since then, the period of observations following the start of forest felling and subsequent replanting and regrowth has nearly doubled, providing new insights into this important phase of the managed forest cycle.

The findings of the Plynlimon catchments that upland forests evaporate more water than grass have been widely published (Newson, 1985; Kirby *et al.*, 1991; Hudson *et al.*, 1997) and presented in evidence to UK Government committees concerned with future forest planning and water resources (Walsh, 1980; Calder, 1996). The research findings have also been incorporated into UK forest management guidelines for both state and private forestry (Forestry Commission, 2004).

This paper summarises the catchment results to assess the impact of the commercial forest felling in the catchments since the 1980s and the effects of forest age and regrowth. This paper deals principally with long-term catchment water balances. The published water balance values have varied over time as the length of the data sets has been extended and as the figures themselves have been refined and reworked. Previously published water balances have included annual catchment evaporation (P–Q) of 435 mm for the moorland Wye and 716 mm for the 70% forested Severn (for 1970–75, Clarke and Newson, 1978) and 491 mm for the Wye and 632 mm for the Severn (for 1972–85, Hudson *et al.*, 1997). Small-scale process studies into evaporation losses found annual losses from *complete* forest cover of ~900 mm (Calder, 1976).

Background

In the first half of the 20th Century, catchment studies in Continental Europe and in the USA indicated that forestry could reduce total streamflow relative to grassland (Engler, 1919; Bates and Henry, 1928; Keller, 1988; Swank and Crossley, 1988). At first, scientists and engineers in Britain assumed that these findings were not relevant to UK conditions due to physical differences, particularly in climate. It was argued, for example, that many of the study areas were drier than the UK uplands and consequently any higher water use of the forests could be attributed to the greater rooting depth of trees. Most British forests are in upland areas where the soils are often peaty and remain wet in all but the most exceptional droughts. Under such conditions it was argued that it would make "very little difference" to streamflow yield whether the area was all forest or all grass (Schofield, 1948). In addition, some of the early catchment experiments were not well designed, making it difficult to extrapolate their results to other areas and this led to a great deal of criticism of early catchment research (Ackermann, 1966). For example, since it is far easier and quicker to cut down an existing forest than to grow a mature forest in a non-forested area, most experiments then (as now) dealt with water balances before and after the *felling* of a forest. There are relatively few studies of the effects of *afforestation* (Robinson, 1998). In a global review of the effects of forest on streamflow (Bosch and Hewlett, 1982), over 80% of the studies cited were concerned with deforestation. It is, however, essential for the proper interpretation and evaluation of forest clearance studies to distinguish clearly between the effects of logging and the land cover change itself. Many of the observed effects (at least in the short-term) may owe more to soil compaction and the construction of logging roads than to the presence or absence of the forest biomass. Furthermore, newly deforested grassland will still have a forest soil.

The impetus for catchment research into the effects of forestry on water yield in Britain originated largely in the work of Frank Law, a water engineer in NW England (Law, 1956, 1957). He had read the accumulating evidence from overseas studies and was concerned about the potential impact upon water yield of the increasing forest cover in the 'gathering grounds' of his reservoirs. There was already considerable evidence that net precipitation reaching the ground beneath a forest could be much less than the rain in open ground, but it was unclear whether the water intercepted and held on the tree branches and leaves represented a real increase in evaporation or was balanced by an equivalent reduction in transpiration. The recognised authority on evaporation, Dr Howard L Penman, declared that "whilst energy was being used to get rid of intercepted water, the same energy could not be used to get rid of transpired water" (Penman, 1963). Law established a 450 m^2 forest lysimeter and found that the forest water use (rainfall minus outflow) was 50% greater than the calculated Penman (1948) potential evaporation for short grass.

Because of this and other land-use change concerns, the UK Government established an *Interdepartmental Scientific Working Group on Hydrological Research.* In 1961 its Committee on Hydrological Research recommended that a full time research unit should be set up to pursue the study of the yield of catchment areas, especially in relation to land use. This research unit, initially called the *Hydrological Research Unit (HRU)* was later to become the internationally famous *Institute of Hydrology (IH),* under its founder Director Dr Jim McCulloch. Its most significant and influential catchment study is the paired catchment comparison on the flanks of Plynlimon in mid-Wales. This study has provided source material for over 300 science publications and research theses (Kirby *et. al.*, 1997), although not even Dr McCulloch foresaw that degree of success and longevity when he wrote in the June 1965 HRU report to the Natural Environment Research Council (NERC) that Plynlimon was to be "a relatively short-term study of the hydrological difference between two valleys, one dominated by grass and the other by trees".

In the light of the earlier criticisms that catchment studies could demonstrate hydrological responses to land-use changes but failed to explain the mechanisms responsible or to permit extrapolation to other catchments, great care was taken to embed process studies within the Plynlimon catchment framework. Such an approach, using process studies to support the results observed from the basins as a whole, had been pioneered in a series of catchment studies in East Africa in the 1950s and 1960s (Edwards and Blackie, 1981). Without a knowledge and understanding of the processes taking place, the results of catchment studies are difficult or impossible to extrapolate elsewhere; the observations and conclusions are really applicable only to situations where the same combination of processes is operating (McCulloch and Robinson, 1993).

Despite new process studies (Rutter, 1967; Rutter *et al.,* 1971) which indicated the importance of wet canopy evaporation ('interception'), at the time when the Plynlimon catchments were established, the traditional arguments about forest evaporation differences being attributed to rooting depth rather than canopy effects were still deeply entrenched. It was claimed that the Plynlimon climate was too wet to show up evaporation differences between forest and grassland (Derbyshire, 1972). In fact, the opposite is true; due to its wet and windy climate Plynlimon has some of the highest forest evaporation losses recorded anywhere in the world (Shuttleworth and Calder, 1979; Roberts *et al*., 2005).

STUDY SITE

The Plynlimon catchments (4°45′W, 52°28′N) lie in the Cambrian Mountains of mid-Wales about 100 km north of Cardiff and 25 km inland from Aberystwyth (Fig. 1). They comprise the headwaters of the Rivers Severn (~70% forested with conifer plantations) and the Wye (grassland used for sheep pasture). The topography of the catchments is characterised by rolling hills (~350–650 m AOD) and the climate is wet, with precipitation up to 2500 mm yr^{-1}. The planting of conifers in the Severn catchment began in the late 1930s as part of the larger Hafren Forest and, by the mid-1960s, nearly 70% of the catchment was under plantations managed by the Forestry Commission. The main tree species are Sitka spruce (*Picea sitchensis*), Lodgepole Pine (*Pinus contorta*) and Norway Spruce (*Picea abies*). Tree harvesting commenced in 1983 and by 2000 half of the forest had been felled (Robinson and Dupeyrat, 2005). The underlying geology comprises slates, mudstones and sandstones of the Ordovician and Silurian Periods of the Early Palaeozoic and are generally classified as impervious with only limited groundwater (Kirby *et al.*, 1991). Soils are derived from the upper fractured zone of regolith and glacial deposits together with peats (Bell, 2005). Estimates of the catchment storages have indicated that soil moisture and these shallow groundwater stores may each amount to 120 mm, totalling 10% of the average annual precipitation (Hudson, 1988; Kirby *et al.*, 1991). The magnitude of these stores in a watertight upland catchment that is classified as having negligible permeability (EA, 1999) has important implications for the sustainability of low flows and for water chemistry (Neal *et al.*, 1997). Water storage in the regolith and its transmission downslope within a shallow fissured system is the subject of recent research (Haria and Shand, 2004). General aspects of catchment water quality have been described elsewhere (Reynolds *et al.*, 1989; Neal, 2005).

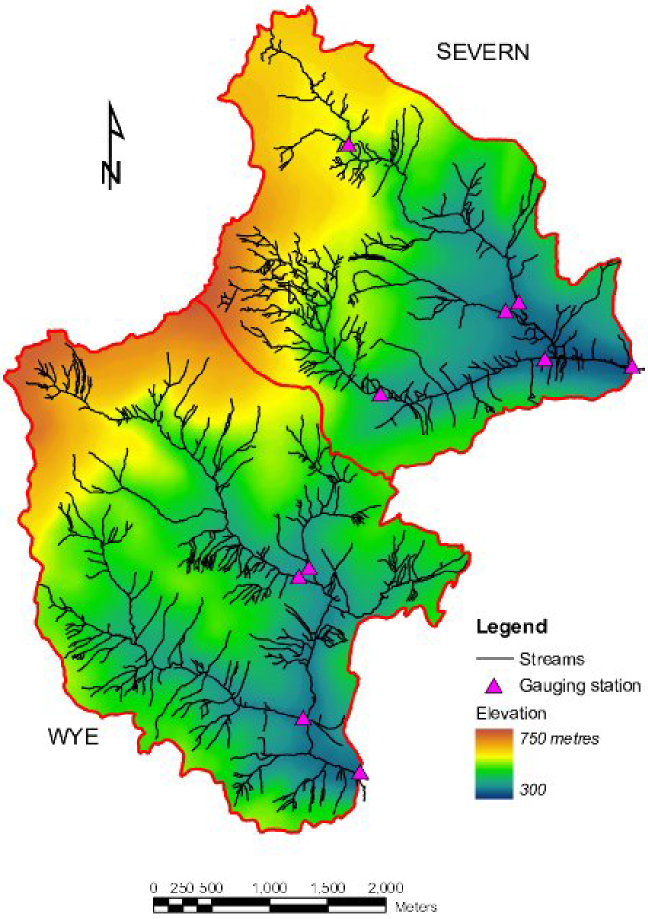

Fig. 1. *Plynlimon catchments showing the Severn and its tributaries (from North to South – Hafren, Tanllwyth and Hore) and the Wye (Nant Iago, Gwy and Cyff).*

Spatial data including topography, stream networks, soils and vegetation (with details of forest planting and harvesting areas and dates) have been put onto a GIS (Brandt *et al.*, 2004) and further catchment information and data are also available on the Plynlimon website (www.ceh.ac.uk) including a comprehensive list of publications based on the catchment research.

PRECIPITATION

Review of the rainfall database

The installation of a network of 48 monthly-read storage raingauges was completed in 1971. In the grassland Wye, precipitation was estimated from 21 ground level gauges while in the Severn, the measurements were made from a combination of 11 canopy gauges in the forest areas and 7 ground level gauges in the unplanted parts of the catchment. During severe snow periods, information was provided by 9 UK standard height (30.5 cm or 12 inch) raingauges situated close to roads in or just outside the catchments. Standard height gauges were also used in place of some of the canopy gauges after forest felling. Scaling up to catchment precipitation was performed using the Thiessen polygon method. In addition to the storage gauges, sub-daily (hourly or less) data are available from between 4 and 6 tipping bucket raingauges (depending on the time period).

In 1999, to lower the costs and the labour involved, the number of storage gauges was reduced from 48 to 21. The network now comprises 9 ground level gauges in the Wye and 12 gauges in the Severn (8 canopy and 4 ground level raingauges). Nevertheless, the reduced density of raingauges (1 per 0.92 km^2) is still 65-times the UK average of 1 per 60 km^2 (WMO, 1995). As a consequence of this change, to ensure the homogeneity of the rainfall record, it was necessary to recalculate the areal rainfall for all the catchments and sub-catchments, and to assess the influence upon the catchment rainfall estimates.

The impact of this reduction can be estimated by comparing the monthly rainfall estimates for the full and reduced catchment networks before 1999 (Fig. 2). Overall, the removal of more than half the storage gauges had little impact on the figures since there was a high degree of 'redundancy' in the original network. For example, all of the raingauges in the Wye catchment had a correlation >0.96 with the Thiessen catchment areal rainfall, and 66% of the gauge pairs had inter-correlations >0.97.

The criteria for removing or retaining gauges included consideration of:

(a) Proximity to other gauges with similar catches,
(b) Reliability, e.g. missing data and ease of access in bad weather,
(c) Overall spatial and altitudinal distribution.

The reduced density of raingauges in the catchments is now 1 per 96 ha for the Wye and 1 per 67 ha for the Severn catchment. The network reduction caused only a slight change in the computed rainfall inputs to the individual catchments. Table 1 shows that the new estimates are in good agreement with the former values. The linear correlations were high for both main catchments and all their sub-catchments. Using the new network, the estimated areal precipitation for the Wye was reduced by 1.3%, and for the Severn by 2.8%. For the sub-catchments the largest changes were +4.9% for the Gwy sub-catchment and –3.1% for the Hore. The average absolute magnitude of the difference was 2.4% (about 60 mm yr^{-1}) which is similar to the uncertainty in the catch of individual raingauges (Kirby *et al.*, 1991). Accordingly, to ensure complete homogeneity over the whole period of record, all the catchment precipitation values in this paper were calculated using the reduced gauge network, adjusted to be equivalent to the full network, by

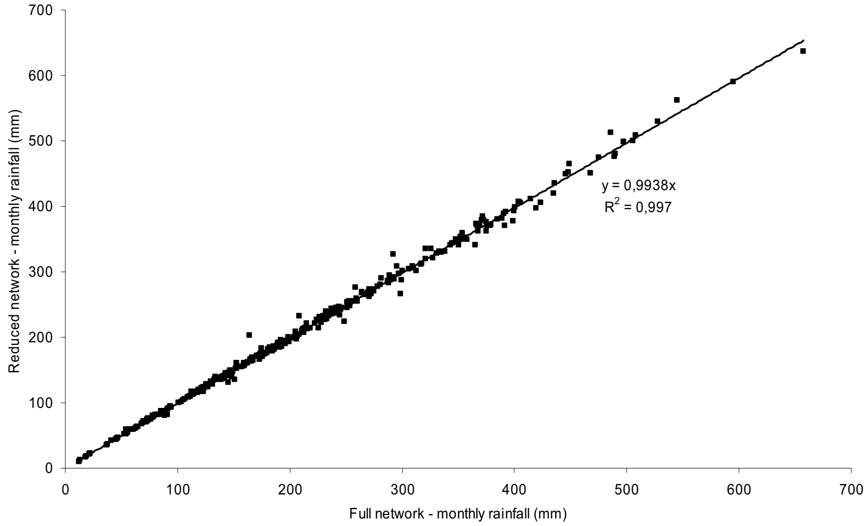

Fig. 2. *Comparison of mean monthly precipitation (pre-1999) for the full network (48 gauges) and the reduced network (21 gauges).*

Table 1. Impact of the reduction in the number of raingauges on the monthly catchment rainfall estimates for the two main catchments (bold) and their sub-catchments (RN : reduced gauge network ; FN : full network).

Catchment	*Area (ha)*	*No. RN gauges*	*R²*	*RN = α FN* α	*(std error)*
Wye	1055	11	0.995	0.987	(0.0016)
Gwy	398	8	0.979	1.049	(0.0052)
Cyff	313	5	0.979	1.009	(0.0051)
Severn	870	13	0.996	0.972	(0.0016)
Hore	308	9	0.984	0.969	(0.0044)
Hafren	367	9	0.973	1.013	(0.0064)
Tanllwyth	89	5	0.983	0.970	(0.0046)

applying the α factors in Table 1.

Missing values from the individual gauge records, for example due to leaking gauges, drifting snow or damage by animals, were infilled using an iterative method whereby each gap is infilled using the ratio of the long-term total of that gauge to the network mean (Hudson *et al*., 1997). An exceptional gap occurred when Foot and Mouth Disease restrictions prevented access to most sites in February and March 2001. The individual raingauge records for those months were infilled using the long-term ratios of their catches to those of the recording raingauges.

In conjunction with this reappraisal of the raingauge network totals, a detailed field study confirmed that the catches of canopy level gauges over forest gave consistent results and were in good agreement with nearby ground level gauges (Robinson *et al*., 2004).

Analysis of rain over space and time

The mean annual catchment precipitation (1972–2004) amounted to approximately 2600 mm and 2555 mm for the Wye and Severn respectively (Table 2).

Table 2. Mean annual precipitation P, streamflow Q, and actual evaporation (P-Q) (mm) for the main catchments (bold) and their sub-catchments (1972-2004)

Catchment	*Precipitation*	*Streamflow*	*Evaporation*
Wye	2599	2111	488
Gwy	2499	2244	255
Cyff	2510	2106	404
Severn	2553	1987	566
Hore	2571	1985	586
Hafren	2483	1987	496
Tanllwyth	2604	2238	366

The spatial distribution of annual precipitation in both catchments increases with altitude, as it does in most upland areas in Britain. The annual values are similar in the Severn and in the Wye for the highest altitude raingauges (above 550 m) but, at lower elevations (below ~450 m), the relationship is poorer and the Wye is generally wetter than the Severn for the same altitude (Fig. 3). The annual rainfall gradient of ~1.7 mm m^{-1} is somewhat lower than that reported by Brunsdon *et al.* (2001) for a much less densely distributed national gauge network with few gauges above an altitude of 200 m. In addition, due to the prevailing south-westerly winds, the annual rainfall distribution also varies according to the aspect (Kirby *et al*., 1991; Hudson *et al.*, 1997). On south-west facing slopes, there is an upwind 'rain shadow' effect and on the north-east of major interfluves, there is a leeward 'fallout' effect. These processes were also reported in the Balquhidder catchments in Scotland (Blackie *et al*., 1986) where the altitude range of the topography is much greater than that at Plynlimon.

The annual precipitation totals show a weak increase over time in both the Wye and the Severn (Fig. 4). Even though not statistically significant, this trend has also been observed elsewhere in northern and western Europe (Green and Marsh, 1997; Frich, 1994). An increase in precipitation since the early 1970s has been linked to exceptionally high values of the North Atlantic Oscillation (Hurrell, 1995; Wilby *et al*., 1997); alternatively, it could reflect the marked decrease in the contribution of snowfall in recent years and the well-known underestimation of snow by conventional raingauges (Green and Marsh, 1997). Manual measurements of daily snow-water equivalent at Plynlimon, however, indicate this was not a major factor in the precipitation trends. The ratio of winter precipitation (October to March) to the annual water year total (October to September) also showed no evidence of a change in the seasonal distribution of annual

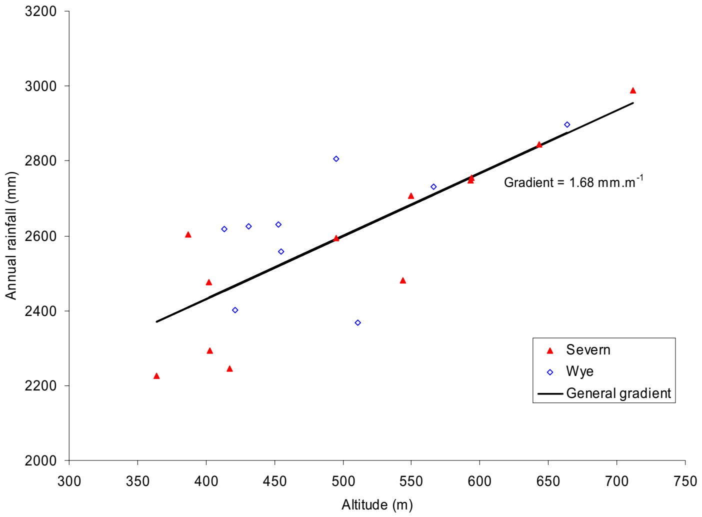

Fig. 3. *Relationship between mean annual precipitation (1972–2004) and raingauge altitude in the Plynlimon catchments.*

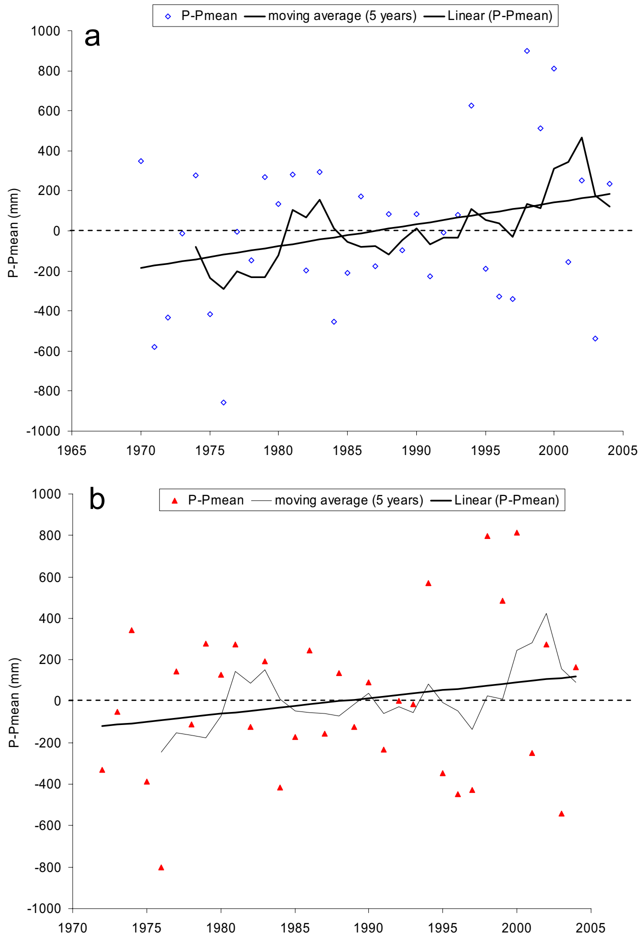

Fig. 4. *Increasing trend of annual precipitation in (a) the Wye and (b) the Severn*

precipitation in the Plynlimon catchments. The observed trend of annual precipitation was somewhat steeper in the Wye (an increase of ~4 mm yr^{-1} relative to the Severn), indicating that changes occurred in precipitation patterns over the Plynlimon range (Fig. 5).

Splitting the data into three decades: 1970s, 1980s and 1990s, indicated that all raingauges showed an increase in catch over the successive decades. The 1970s were relatively dry at Plynlimon, as elsewhere in the UK, and the 1990s were wetter. Rainfall: altitude relations for individual decades generally showed an upward shift at all altitudes but, notably, the lower altitude gauges in the Wye showed a particular increase during the 1990s.

STREAMFLOW

Changes in the network

Streamflow gauges have been operated since the early 1970s. The gauging stations for the two main catchments were completed in 1968 (Wye) and 1971 (Severn) respectively. Eight additional sites were subsequently gauged on the three major tributaries of each main catchment (Fig. 1). These have specially designed steep stream flumes to cope with the fast flowing waters and high sediment loads (Harrison and Owen, 1967; Herbertson, 1972). The stage-discharge ratings for the flow gauges were checked by multiple depth current metering and dilution gauging. Five sub-catchment gauges were built in the early 1970s (Cyff, Gwy, Hore, Nant Iago and Tanllwyth), the Hafren flume was completed in 1976 and the Upper Hore was instrumented in 1985 to act as an experimental control while the forest was clear- felled in the downstream part of the Hore catchment. The gauge on the Nant Iago was

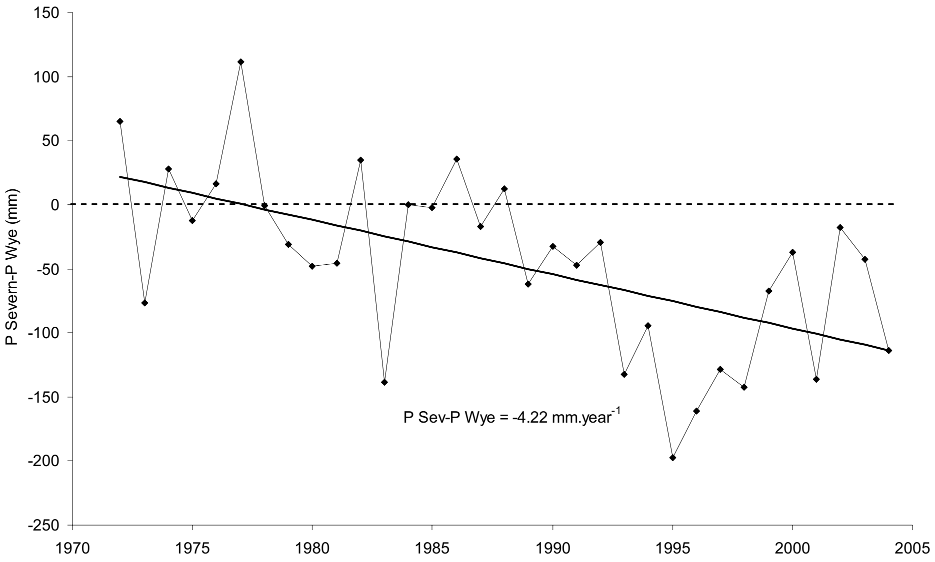

Fig. 5. *Time series of the annual precipitation differences between the Severn and Wye*

discontinued in June 1999. In autumn 2004, a new flume was completed to monitor the unforested headwaters of the Hafren.

Analysis of streamflow over space and time

The mean annual streamflow over the common data period 1972–2004 was 2111 mm in the Wye and 1987 mm in the Severn (Table 2). Within the Wye basin, the Cyff sub-catchment's long-term averaged streamflow is similar to that of the main catchment; by contrast, flows in the Gwy sub-catchment were >100 mm higher (1970–2004, Fig. 6a). Kirby *et al*. (1991) noted that, compared with the Wye catchment overall, the Gwy had a greater specific flow and the adjacent Nant Iago had a lower flow. This was attributed to the uncertainty surrounding the delineation of the boundary between the two sub-basins. A lateral error of just 110 m along their common boundary would result in an underestimation of the Gwy area by 6% and would be enough to yield a similar flow depth as in the Wye and the Cyff. Such an error is quite realistic considering the smoothness of the relief over the 2 km length of the common watershed. As expected from the trend of increasing rainfall, cumulative values plotted as a function of time (Fig. 6b) show a flow increase over time.

In the Severn, a similar pattern of annual flow over time is observed for the main catchment and the Hafren and Hore sub-catchments (Fig. 7a). The flow in the Upper Hore is usually higher, consistent with its greater rainfall. The stream flows in the Tanllwyth sub-catchment, appear significantly higher than those recorded elsewhere and this behaviour

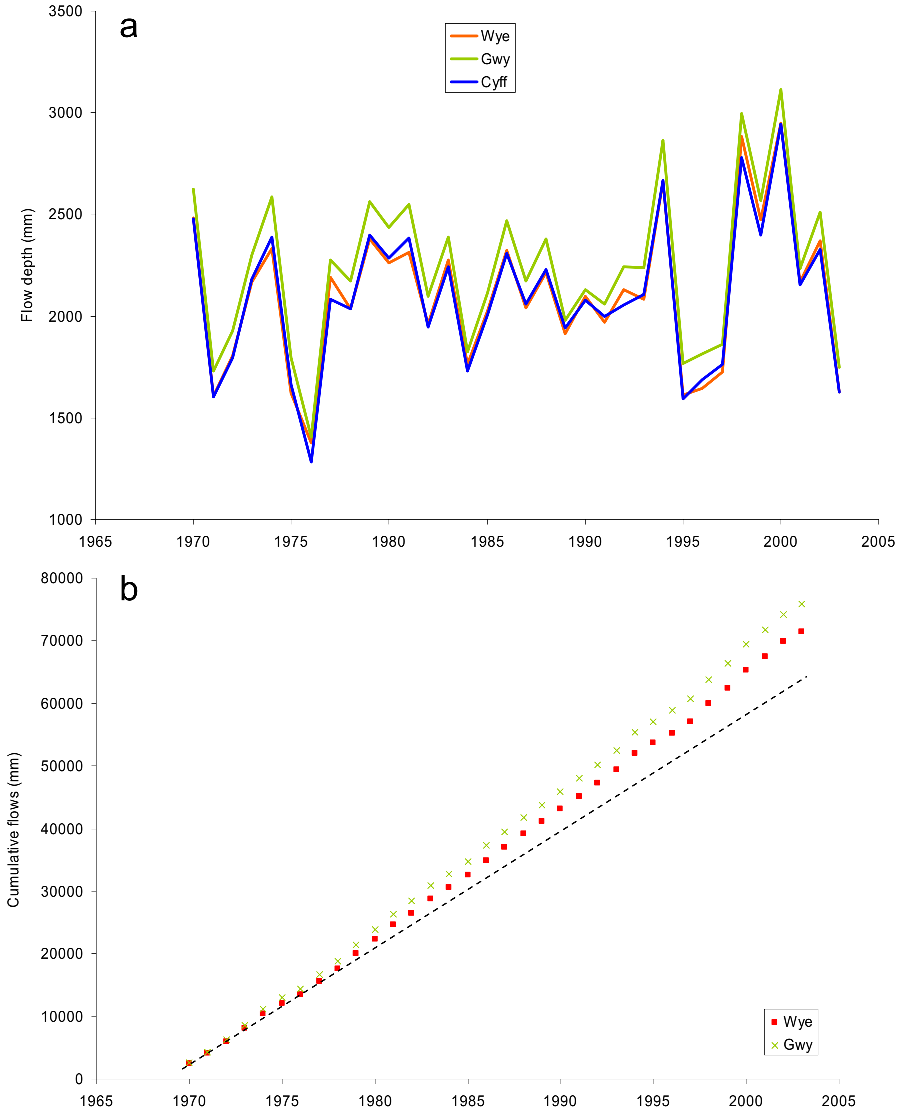

Fig. 6. *(a) Time series of annual flows for the Wye and its sub-basins, (b) Cumulative annual flows for the Wye and the Gwy.*

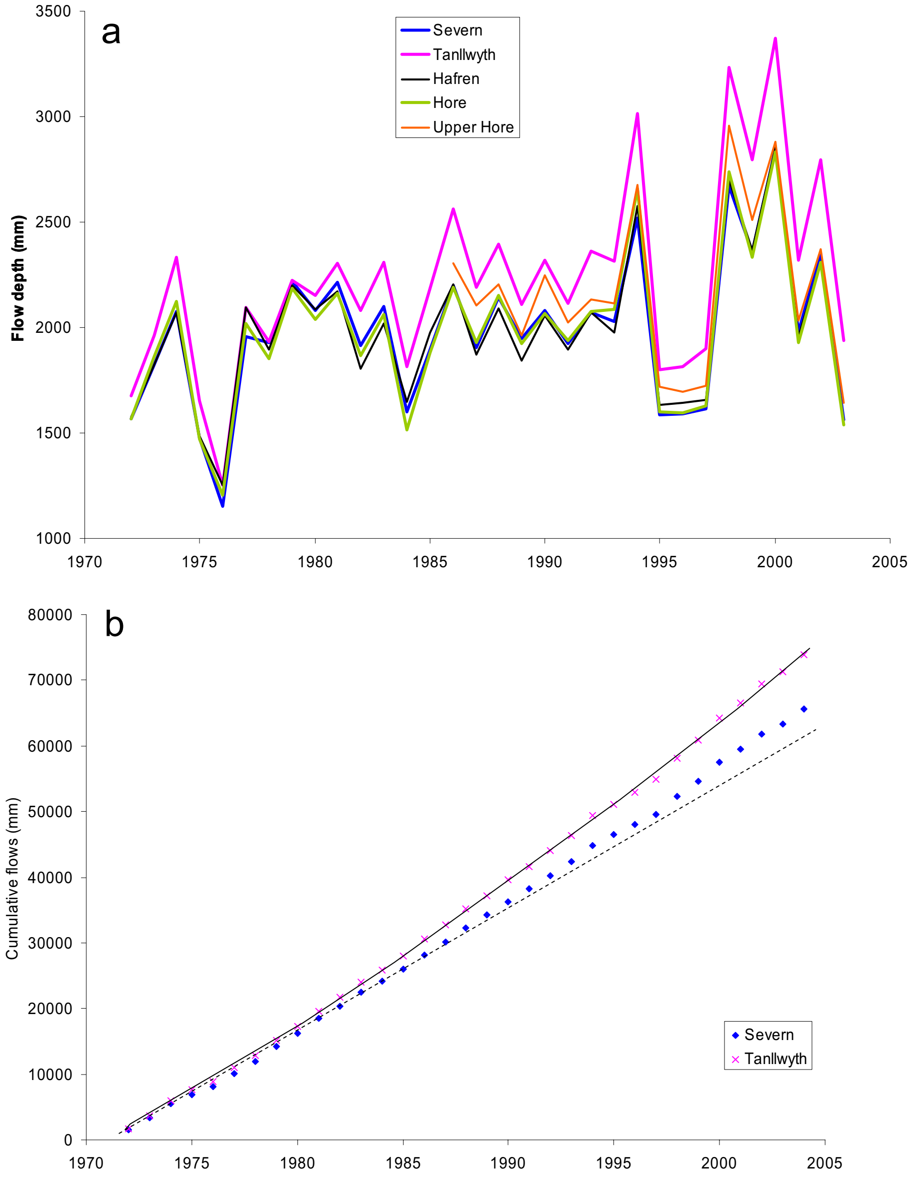

Fig. 7. *(a) Time series of annual flows for the Severn and its sub-basins,, (b) Cumulative annual flows for the Severn and the Tanllwyth.*

cannot be warranted by a higher precipitation. Figure 7b reveals that, from the early-1980s, the flow of the Tanllwyth has increased steadily relative to the main catchment and the other sub-catchments. Initially, this was interpreted as a consequence of the felling which commenced at about this time in the sub-catchment but the streamflow has continued to increase and the actual evaporation (P–Q) has now declined to an unreasonably low value. This water balance discrepancy cannot be attributed to an erroneous rainfall estimate since the values are consistent with gauges in the rest of the Severn catchment. Nor is it due to any leakage of surface or subsurface water from outside the catchment since it is enclosed between the Hore and Hafren, neither of which shows any corresponding reduction in flow. Although hydrogeological and hydrochemical investigations in the Tanllwyth subcatchment have shown an active shallow groundwater fracture flow system (Neal *et al*., 1997), any such increase in flow would have affected the regime in the Hore or the Hafren. In the absence of any chemical, isotopic or hydrological evidence for any contribution to the streamflow from deep groundwater (the origin of which would have to be outside the Plynlimon catchment), the decline in P–Q seems most likely to be due to some subtle deterioration of the flow measurements with time. Hence, pending the findings of detailed checks on the gauging structure, flows from the Tanllwyth have been excluded from further discussion.

EVAPORATION

Estimation of potential evaporation

Estimates of Penman potential evaporation provide a useful baseline against which to compare evaporation losses. In 1973, four automatic weather stations (AWS) were installed over grass, two in each of the Severn and Wye catchments; one at low altitude (~350 m AOD) and the other at higher altitude (~500 m AOD). Each AWS was equipped with sensors recording net and solar radiation, wet and dry bulb temperature, wind speed and direction, as well as a 0.5 mm tipping bucket raingauge. Errors in these variables will affect the Penman evaporation estimates. Thorough procedures of quality control and data infilling were set up from the start of the measurements, to ensure that the values are reliable. There were also two long-term daily-read manual meteorological stations — one in the lower Tanllwyth catchment and the other 5 km outside the catchments at Dolydd. These were used to produce meteorological estimates of potential evaporative demand and provided a long-term mean annual grass potential evaporation of about 400 mm (Crane and Hudson, 1997).

The processes of evaporation at Plynlimon

Extensive studies of the micro-climate at Plynlimon were carried out in the 1970s following the work undertaken by the Institute of Hydrology into the evaporation processes in Thetford forest, East Anglia (Stewart and Thom, 1973). Results from Plynlimon and elsewhere have confirmed that a forest can evaporate more water from its surface than would be possible from radiant energy alone. In addition to the energy available from direct solar radiation, the deep band of turbulence above the forest canopy provides advected heat which evaporates rainwater intercepted on the vegetation (Gash and Stewart, 1977; Stewart, 1977). As a consequence, in areas where the canopy is wet for most of the year, as at Plynlimon (~220 rain days per year), the interception loss is expected to be the largest component of the total evaporation. Special attention was given to the intercepted water, involving experimental studies (Calder, 1976; Gash *et al*., 1980) as well as model development (Calder, 1977; Gash, 1979). Measurements at a forest lysimeter in the Hore catchment (Calder, 1976) found actual evaporation was double that of grass (about 900 mm compared with 400 mm). Transpiration rates from forest and grassland were similar and only half of the magnitude of the interception (Kirby *et al*., 1991). Two-thirds of the total loss was due to interception from wet canopies. The Penman potential evaporation model is inappropriate for woodlands since transpiration and intercepted evaporation occur at such different rates for forests that they must be modelled separately. The implication of these findings is that upland forests may evaporate water at a greater rate than is suggested by the Penman model – a result with vitally important implications for water users downstream.

WATER BALANCE RESULTS

Changes over time

The mean annual catchment water losses (precipitation minus streamflow) for 1972–2004 amount to 488 mm and 566 mm in the Wye and in the Severn respectively (Table 2). Annual values show no clear trend over time for the Wye or its sub-catchments (Fig. 8). A higher variability apparent from the early 1990s onwards is attributed largely

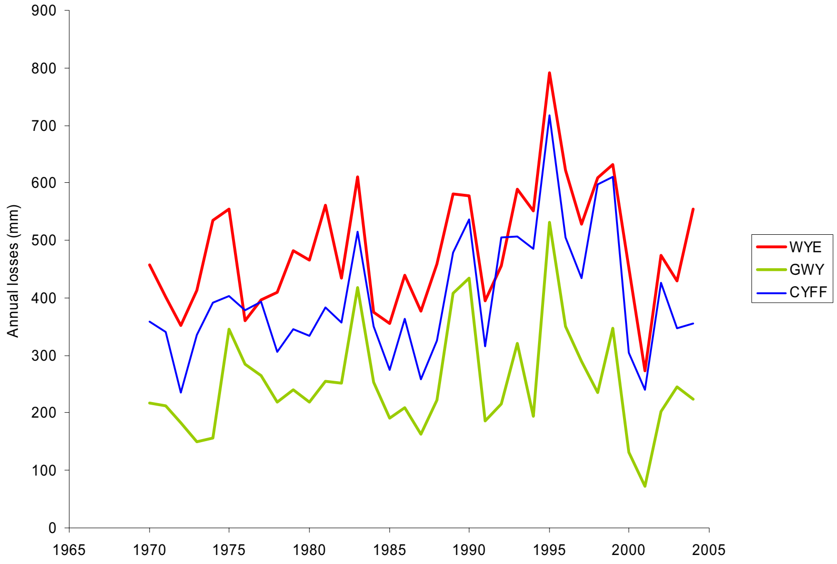

Fig. 8. *Time series of the annual water losses (P – Q) in the Wye and its sub-catchments.*

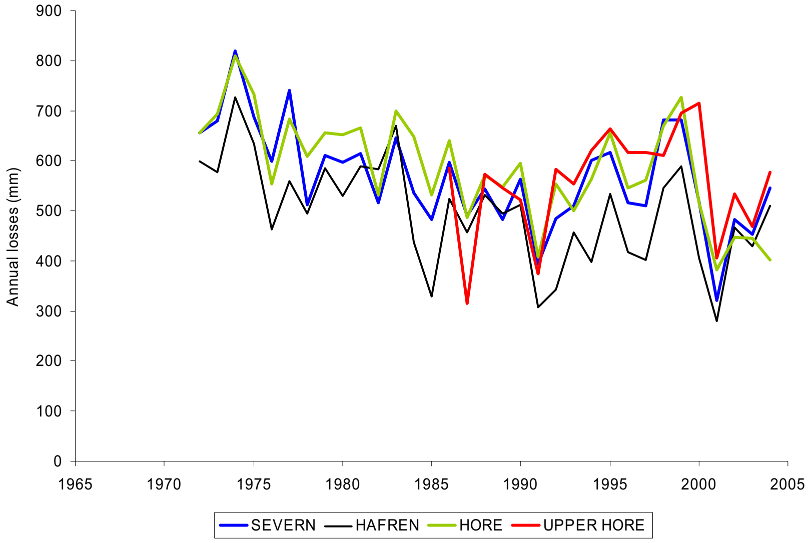

Fig. 9. *Time series of the annual water losses (P – Q) in the Severn and its sub-catchments.*

to two extreme years 1995 and 2001. The low water losses in the Gwy subcatchment can be explained by the probable 6% overestimation of the runoff depth because of the inexact position of the watershed discussed earlier; this amounts to ~100 mm yr^{-1} underestimation of evaporation. In contrast, in the Severn catchment, there was a clear decrease in evaporation over time (Fig. 9). In the main catchment and all the sub-catchments, the actual evaporation declined steadily from the beginning of the observation period, i.e. before the start of the forest felling, until the early 1990s. Over this period the annual evaporation decreased by around 200 mm.

From the early 1990s, evaporation rose in both the Severn and the Wye catchments, indicating a general climatic effect. Figure 10 shows the difference in actual evaporation between the Severn and the Wye. To reduce annual storage effects the difference between the two-year moving averages of P–Q for each catchment is shown. In the period 1972–82, before the tree felling, the mean actual evaporation (P–Q) for the Severn catchment was about 170 mm higher than

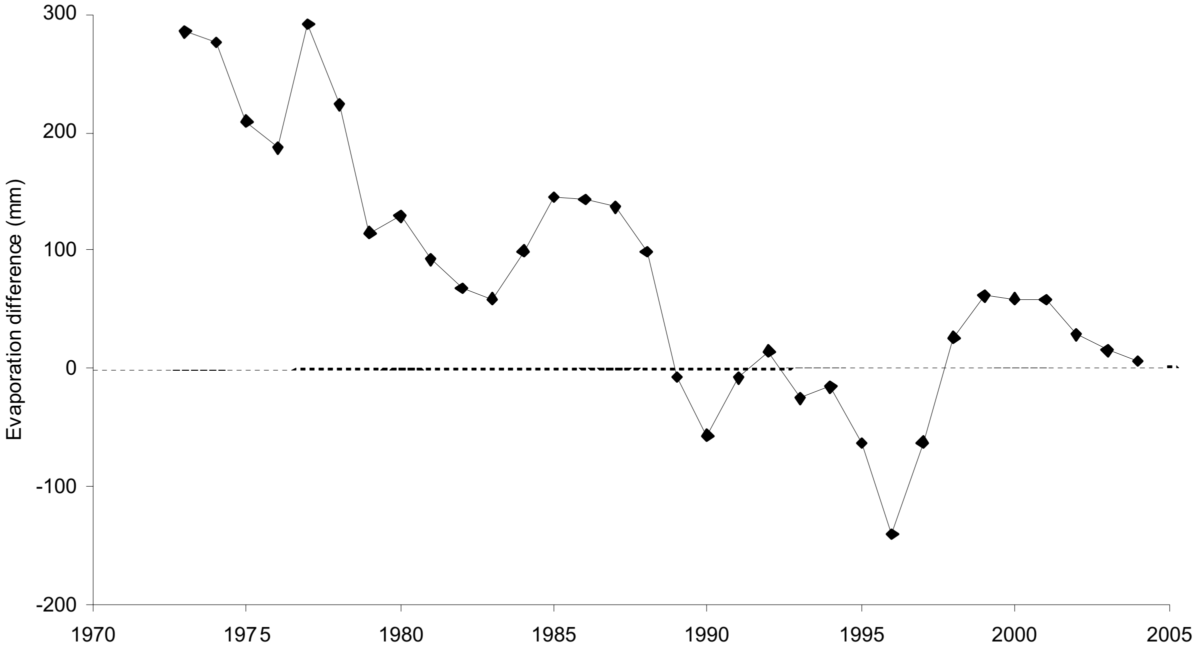

Fig. 10. *Time series of the difference of annual P–Q between Severn and Wye.*

that for the Wye, which is equivalent to nearly a 10% reduction in streamflow. There was a reduction in the 'excess' evaporation (Severn minus Wye) from 250 mm to 150 mm yr^{-1} prior to the felling. In recent years the actual evaporation (P–Q) is similar for the two catchments, which in not unexpected given that by 2000 about half of the forest (~35% of the Severn catchment) had been felled and most of that area has either no trees or they are younger than five years.

In the early years of the study (1972–1976), the Severn losses averaged 688 mm against 443 mm in the Wye (+ 60%). For the succeeding years (1977–82) up to the commencement of felling, the corresponding figures were 598 and 458 mm (Table 3). If these pre-felling figures are corrected to allow for the unforested area (~32%) by assuming that the unforested part of the Severn evaporates at the same rate as the Wye, then the annual water loss (1972–1976) from a 100% forest covered catchment forest would

Table 3. Wye and Severn catchments annual water balances (mm)

	WYE			SEVERN		
	P	*Q*	*P–Q*	*P*	*Q*	*P–Q*
1972	2157	1805	352	2222	1567	655
1973	2580	2168	412	2503	1823	680
1974	2867	2333	534	2895	2076	819
1975	2176	1622	554	2164	1476	688
1976	1735	1375	360	1751	1152	599
1977	2586	2190	396	2697	1957	740
1978	2443	2034	409	2442	1931	512
1979	2861	2378	483	2830	2220	610
1980	2727	2261	466	2679	2083	596
1981	2874	2312	562	2829	2214	615
1982	2396	1961	434	2431	1915	516
1983	2885	2275	610	2747	2101	646
1984	2138	1764	375	2138	1602	536
1985	2381	2026	355	2379	1897	482
1986	2764	2325	440	2800	2202	597
1987	2415	2038	377	2398	1907	491
1988	2675	2215	459	2687	2144	543
1989	2493	1912	581	2431	1948	483
1990	2675	2097	578	2642	2080	563
1991	2366	1971	395	2319	1924	395
1992	2584	2128	456	2555	2070	485
1993	2673	2084	589	2540	2030	510
1994	3216	2664	552	3121	2521	600
1995	2402	1610	792	2204	1588	617
1996	2265	1644	621	2104	1588	516
1997	2253	1725	529	2124	1615	509
1998	3492	2883	609	3350	2669	681
1999	3106	2475	631	3039	2356	682
2000	3402	2949	452	3365	2846	519
2001	2438	2165	273	2302	1980	322
2002	2845	2371	474	2828	2346	482
2003	2056	1626	429	2013	1561	452
2004	2829	2274	555	2715	2170	545
Mean 1972–76	2303	1860	443	2307	1619	688
Mean 1977–82	2648	2190	458	2651	2053	598
Mean 1983–94	2605	2125	480	2563	2035	528
Mean 1995–04	2709	2172	537	2604	2072	533

be 810 m. This would represent an 18% reduction in flow compared to grassland. This is about 1.8 times the grassland evaporation, which is close to the factor of 2 deduced from a natural lysimeter with 35-year old trees and a Penman estimate of evaporation from short grass (Calder, 1976). In the following period (1977–82) the estimated evaporation from a complete forest cover was 667 mm, which is ~1.5 times the grass evaporation.

This apparent 140 mm yr^{-1} reduction in evaporation from a closed forest canopy without human intervention is noteworthy, and beyond measurement uncertainties. Although botanists have long been aware of age-related changes in woody plants (Bond, 2000), until relatively recently few land-use studies dealt with the relation between tree age and evaporation rate. In one of the first studies, Langford (1976) found that wildfire of old growth Mountain ash (*Eucalyptus regnans*) in south-east Australia reduced annual streamflow. Subsequently, Jayasuriya *et al*. (1993) reported that annual water use of the forest was 200 mm lower for a 230-year old stand than for a 50 year-old stand. They attributed this to a decrease in the sapwood area and hence in transpiration with increasing stand age. It is probable that the primary driver for changes in sapwood cross-sectional area is fluctuations in the Leaf Area Index and Haydon *et al.,* (1996) confirmed that, in those catchments, interception losses also reduced with age. Elsewhere, work on Norway spruce (Pices *abies*) in Southern Germany (Köstner *et al.*, 2002) and Ponderosa pine (*Pinus ponderosa*) in Oregon (Ryan *et al.*, 2000) have shown that increasing tree age results in changes in tree physiology, leading to reductions in photosynthesis and canopy conductance. Delzon and Lousteau (2005) have shown a similar age-related decline in the transpiration for Maritime pine (*Pinus pinaster*) in south-western France. In their study, 10-year old trees were found to transpire 508 mm yr^{-1} against 144 mm for the 54-year old trees. This was due to a decrease in stomatal conductance in taller trees and a significant reduction in the Leaf Area Index (38%), which, of course, would also have consequences for the interception processes. Catchment studies in South Africa of pine and eucalypt plantations have found that water yields decline initially due to the rapid plant growth, but then start to recover to pre-afforestation levels as they mature (Scott, 2005).

The *current annual increment* (CAI) of timber volume is widely used as a measure of forest growth in managed forests. Forestry Commission data for UK forests (Hamilton and Christie, 1971) indicate that CAI for the tree species and yield classes at Plynlimon would peak at about 35 years of age and then decline. This is similar to the forest age at the start of the Plynlimon study. In the early years of the Plynlimon study in the 1970s the evaporation from the ~30-year old forest may have been at its maximum; it then reduced over time up to the felling at about 40–50 years of age. Elsewhere in upland Britain, a 10-year study of interception losses of Sitka spruce at the Coalburn catchment in N England (tree ages ~20 → 30 years) found interception losses were stable over the period (Robinson, 2004), at a time when the catchment evaporation (P–Q) was increasing. This suggests that the increase in evaporation over that forest age range is due to transpiration rates increasing to their peak. Annual precipitation at Coalburn is only half of that at Plynlimon and so transpiration would be a relatively larger component of the total evaporation. As the trees at Coalburn are currently of an age similar to those at the start of the Plynlimon catchment study, the future water balance of that catchment will provide a valuable contrast with the wetter climate at Plynlimon.

The effects of timber harvesting on the flow regimes at Plynlimon were studied by Robinson and Dupeyrat (2005) by using the Wye catchment streamflow as a ‘control’ to remove any effects of climate variability. They showed that baseflows in particular were higher after the felling commenced and so there was a relatively modest increase in annual flows in the Severn catchment and its sub-catchments. The impact was most pronounced when a large area was cut in a single year; the pattern of flow increased, and subsequently declined, over about a decade. The overall effect was to decrease the annual water loss for a few years and to augment low flows, but there was no detectable change in flood peaks.

There was a general decrease in forest evaporation until the mid-1990s, with partial recoveries in the mid-1980s and late 1990s coinciding with periods of large-scale felling and regrowth. In some years, the catchment evaporation of the Severn was less than that of the Wye. This result is very important because it means that a simplistic comparison of paired forest and grassland catchments could have reached very different conclusions regarding the question “Do trees use more water than grass?”, depending upon the time period (i.e. tree age) considered. In the early years of the Plynlimon study, forest evaporation losses were much higher than those from short vegetation, a result which was supported by the contemporaneous process studies. Subsequently, the picture has become much less clear owing to the balancing effects of tree felling, tree ageing and the rising transpiration rate of young trees. If the observations at Plynlimon had started a decade later then a very different conclusion regarding the water use of forests might perhaps have been reached! This highlights and emphasises the value of long-term monitoring together with process studies.

Uncertainty on P and Q and implications for the water balance

The Plynlimon study has produced not only evidence of forest and grassland differences, and felling effects, but also non-stationarity in closed canopy forest evaporation — a time when many authors take the conventional view that a forest has reached an equilibrium state. The variation in such evaporation losses over time is important to water resource managers. The estimation of actual evaporation from a catchment water balance is probably one of the best techniques as it produces a full catchment-scale value from independent variables. Nevertheless, the water balance method has a basic limitation in that the evaporation is calculated as the difference between two much larger numbers – at Plynlimon grass evaporation accounts for only 20% and forest evaporation ~40% of the annual precipitation.

Errors in the estimate of catchment evaporation arise from uncertainties in the measurement of areal rainfall (gauge catch and spatial distribution) of ~5% and flow ~2.5% (Kirby *et al*., 1991). The combined standard uncertainty (ISO, 1995) of the actual evaporation is at least $\sqrt{(5^2 + 2.5^2)}$ %, ~5.6% (or 30 mm in an annual loss of 550 mm). This gives 95% confidence limits of ± 61 mm for the annual actual evaporation.

Another source of uncertainty in the annual water balance method is that year-to-year storage variations within the catchments have not been taken into account. Long-term soil moisture monitoring indicated that soil moisture storage capacity may amount to 120 mm (Hudson, 1988). Running catchment water balances (Kirby *et al.*, 1991) found that 'geological' storage (groundwater) proved to be of similar magnitude. The total potential water storage capacity of about 250 mm thus amounts to about 10% of the mean annual rainfall. However, between calendar year ends, the mean actual storage variation is under 1% of the annual precipitation, and can be ignored for long-term water balance purposes (Hudson, 1988).

Discussion — another method to measure actual evaporation

Due to the uncertainties in the water balance approach, it is difficult to make a precise analysis of the relation between changes in the land use and forest hydrology. Recent technical and numerical advances make it possible to consider a direct and continuous measurement of actual evaporation based on the energy balance. Hence, sonic anemometers were set up at Plynlimon to obtain independent estimates of the actual evaporation from different vegetative covers. By measuring net radiation and sensible heat flux, the latent heat (i.e. actual evaporation rate) is then derived from the energy budget (Berbigier *et al*., 1996; Moncrieff *et al*., 1997; Gash *et al*., 1999). This method can provide areal estimates of scale 4 ha and, from land cover information, these can then be scaled up to the entire catchment.

Two sonic anemometers (Solent R3, Gill Instrument, Lymington, UK) were set up in the Plynlimon catchments in 2000 (Severn) and 2002 (Wye). Sensitivity tests of their performance showed that the instruments were accurate and reliable. The main objective is to confirm previous results obtained from the water balance (consistency of the actual evaporation estimates and forest felling impact) and from detailed process investigations (estimation of the interception/transpiration partition and comparison with earlier plot scale experiments, derivation of the canopy resistance, g_c for the dry periods and calibration of the Penman-Monteith model). Measurements over forest blocks of different ages will help to investigate the age-related decline in water use which has been detected previously only from the water balance. It is then expected to quantify, with greater accuracy, the impact on the water use of the stand and to identify the relative importance of transpiration and interception in the observed decrease in evaporation from the catchment.

A first investigation has been carried out at the forest site, to determine the relevance of the sonic anemometer for the study of wet canopy evaporation (van der Tol *et al*., 2003). The results showed that the average wet canopy evaporation measured with the Solent was consistent with a previously estimated Penman-Monteith value (0.12 mm h^{-1} and 0.13 mm h^{-1} respectively; Gash *et al*., 1980). The eddy correlation technique was also used to estimate the aerodynamic resistance, g_a and, hence, to show that wind direction-dependent differences in surface roughness caused g_a to vary significantly. Over rough vegetation surfaces, particularly forest canopies, it is necessary to correct for the effects of turbulence (Van der Molen, 2004) and this work is under way for the forest site.

At the grassland site, the Solent evaporation was very similar to the Penman grass estimate in 2004 (Fig. 11). This was a wet year (2829 mm against an average of 2599 mm); in the previous, drier year (2003, P=2056 mm) the Solent evaporation was 95% of the Penman evaporation, possibly as a result of soil water deficits, but still within the error limits of the method.

An extensive use of these new techniques is expected to provide a long-term database of the actual forest evaporation.

Conclusions

The updated long-term water balance results for the

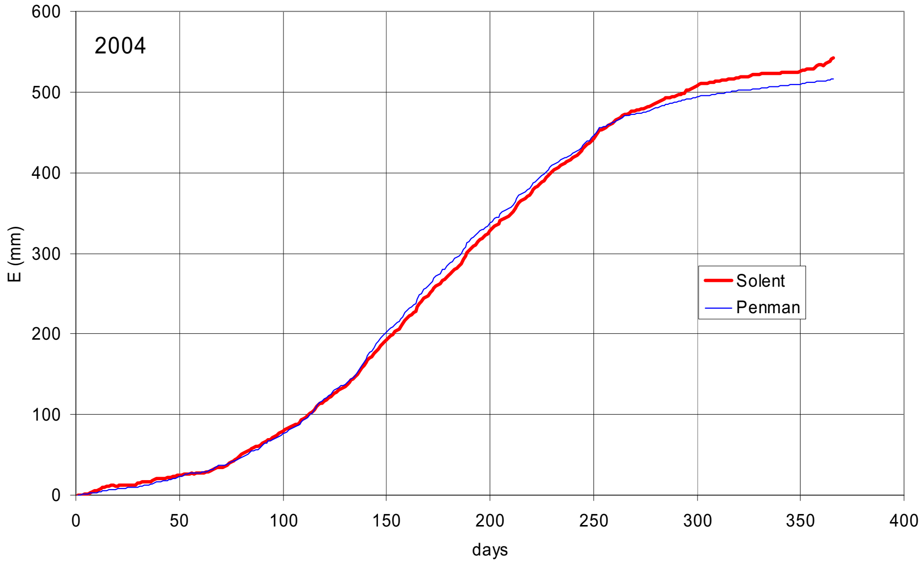

Fig. 11. *Comparison between actual evaporation at the grassland site (Solent sonic anemometer) and the Penman potential evaporation for 2004.*

Plynlimon catchments confirm the results reported previously; evaporation losses from forests are greater than those from grassland. That water use by a mature forest cover in wet upland areas exceeds that from grassland is now generally accepted, together with its implications for water resources. Due to its particular climatic conditions (with the canopy wet for much of the year) forest evaporation losses in the Plynlimon area can be double those from grass. However, the longer time series of data presented here shows important changes in the water balance over the forest cycle (Fig. 12). As expected, felling of the forest results in an increase in flows and reduced evaporation losses, but what was less expected was the fact that the evaporation losses were reducing *before* the felling. The most likely explanation is that this was due to ageing of the trees, and there is a growing body of evidence that evaporation depends on forest age. With any even-aged crop, it is unwise to look at just short time periods since their behaviour may well differ from a heterogeneous vegetation cover that is in a state of balance.

The rainfall time series analysis has shown an increase in

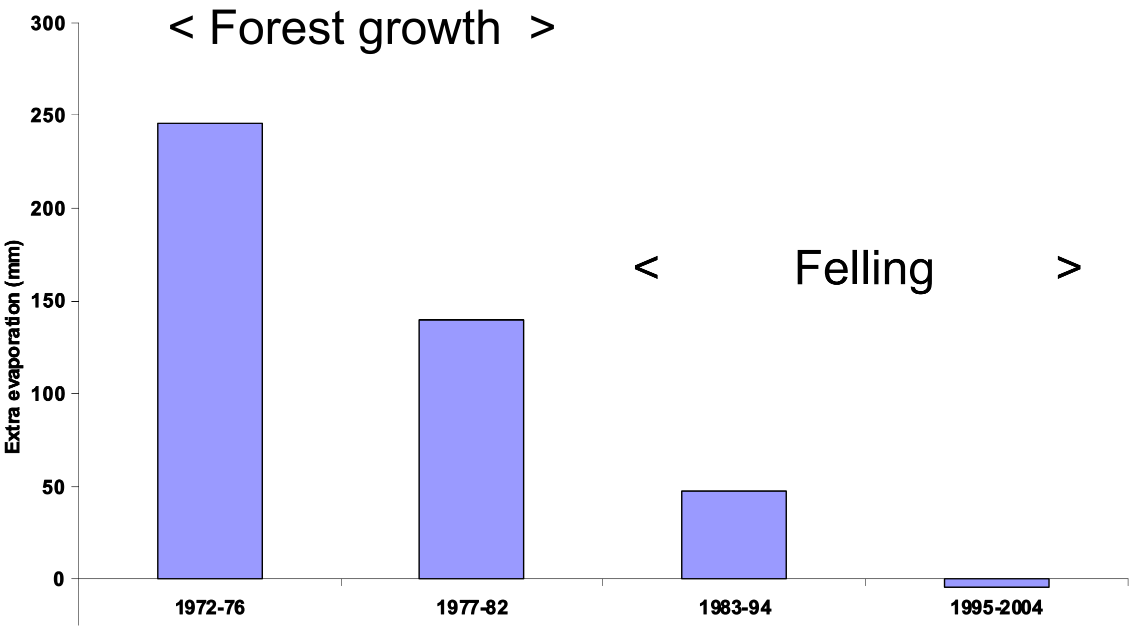

Fig. 12. *Simplified pattern of changing forest water use (relative to grassland) for the Severn and Wye catchments.*

precipitation at Plynlimon that has been described in other parts of UK and is attributed to global climate change/variability (Green and Marsh, 1997). These results emphasise the need to maintain a high quality level of hydrological monitoring to detect, study and eventually model long-term, slow, subtle and complex environmental changes including land cover and management.

In a large and heterogeneous catchment with a range of forest ages and some felled areas, the question remains whether this will result in a net increase or a decrease in streamflow in the future. Continuation of the catchment monitoring at Plynlimon, where the Forestry Commission's Design Plans for the Hafren Forest include the permanent opening up of some of the forested area, should shed further light on this aspect of water use.

A new research approach based on micro-meteorological measurements to establish the energy balance offers the potential to supplement the traditional catchment water balance technique. It can also be used for smaller areas of a few hectares within a catchment to look at spatial variations in evaporation — for example with altitude and in areas of different forest age.

The evidence of changes in forest evaporation over time from apparently closed canopy and 'monotonous' conifer plantations means that whilst the question "*Do* forests use more water than grass?" can be answered broadly in the affirmative, it has been replaced by the new question — "*When* do they use more water?". Critically for the present research, the issue now becomes one of forest age and structure.

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