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The impact of the growth of new plantation forestry on evaporation and streamflow in the Llanbrynmair catchments

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Abstract

Annual water balances (1983–1995) for the Cwm and Delyn catchments at Llanbrynmair Moor in mid-Wales have been used to quantify the hydrological effects of the land use change in the Cwm from moorland to forestry. Initially, the actual evaporation (precipitation minus streamflow) of the Cwm catchment declined rapidly relative to the Delyn, due to the disruption of the vegetation by ploughing the ground in preparation for planting the trees. It then increased, more quickly than expected, to greater levels than for the original moorland since in the early stages of forest growth a dense understorey of dwarf shrubs contributed to both interception and transpiration.

Introduction

Research carried out since the 1950s has indicated that widespread afforestation in upland Britain may lead to an increase in evaporation, a consequent decrease in streamflow and changes in the time distribution of these fluxes. This has important implications in water gathering grounds intended for water supply, river regulation and hydro-electric power generation; afforestation will affect the ability of upland streams to sustain their present unique and diverse ecological characteristics. The potential hydrological effects of afforestation have hitherto been inferred largely from studies carried out in paired mature forested and moorland headwater catchments; many have incorporated process studies to explain the observed changes. Other studies have used the hydrological effects of clear-felling to represent the afforestation process in reverse (Bosch & Hewlett, 1982). The Institute of Hydrology's experiments at Plynlimon in mid-Wales (Kirby *et al.*, 1991) and at Balquhidder in Central Scotland (Johnson, 1995), probably the best known in Britain, have used the 'paired catchment' approach to provide a realistic comparison of integrated rainfall and flow volumes from 'stable' well-established forest and moorland areas.

Studying catchments undergoing a land use change, such as forest planting, entails the longer term approach of monitoring a catchment through an actual land use change from its original vegetation to forestry while a similar but stable land use catchment acts as a control. This is the best way of separating the hydrological effects of the land use change from those caused by climatic variability. The Coalburn catchment experiment, in an upland area of northern England, was one of the first of this type in Britain (Robinson, 1986). Since 1966, it has yielded vital information on the effects of ground preparation and afforestation on evaporation and runoff, especially flood flows and low flows, in a predominantly deep peat catchment where the vegetation is dominated by *Molinia spp.* (Robinson *et al.*, 1998). Owing to the naturally-diverse characteristics of UK catchments, in terms of geology, morphology, soils, climate, indigenous vegetation, tree growth rates and, perhaps most importantly, forest management, the results from a single catchment can never be universally applicable, so that further evidence from other regions is required.

The Cwm catchment at Llanbrynmair in mid-Wales has been monitored since 1982 as an example of a catchment undergoing a land use change broadly similar to that at Coalburn; however, there are features that contrast with and others that complement the deeper ploughing and drainage methods used at Coalburn. The Cwm has undergone a wide range of different management practices such as screef planting[1], contour ploughing and downslope ploughing associated with arterial drainage. Data are also

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[1] Screef planting is a minimum disturbance technique for planting trees, which entails removal of a single turf, planting of the sapling and replacement of the turf, usually accompanied by a remedial dressing of PK fertiliser.

available, since 1990, from nested subcatchments within the experimental catchment. Future assessments of changes in the Cwm could help to separate the effects of the different management practices operating within the catchment.

The aim of this present phase of the study is to determine what proportion of the observed changes in actual evaporation from the Cwm (defined as P − Q, the long term difference between integrated precipitation (P) and streamflow (Q)) over the initial afforestation period can be attributed to climate variability and/or change, and how much is due to the concurrent land use change. Such an analysis relies on the availability of data from a control catchment, the Delyn, to characterise the underlying climatic effects. The analysis of differences between catchments is essential where there is any possibility of systematic errors in the estimates of the water balance fluxes. At Llanbrynmair, as with most catchment studies, these could occur in point rainfall, in spatial weighting of rainfall, in the delineation of catchment areas, in calibrations of flow structures and in unmeasured storage changes. For paired catchments, it is assumed that such systematic errors will affect both catchments equally, and will not therefore discredit conclusions drawn from the relative changes in response over time or models developed to predict the behaviour of one catchment from the other. This paper concentrates on the catchment scale changes in water balances over the early growth phase of the young forest, and attempts to explain these changes in terms of catchment characteristics and variations in forest management practices, as well as variations in the factors that control forest evaporation. It also aims to identify how quickly after planting a forest evaporation effect becomes apparent, and thus aims to contribute eventually to a complete hydrological description of the plantation forest cycle.

Study Areas

The Llanbrynmair catchments and their surrounding area, Fig. 1, are described in detail by Roberts *et al.* (1986) and Hudson *et al.* (1997a). Details of the Coalburn experiment, with which comparison is made, are given by Robinson (1986) and Robinson *et al.* (1998). The Llanbrynmair Study, in central Wales, consists of the Cwm experimental catchment (2.89 km^2) and the Delyn control catchment (1.19 km^2) both of which drain off Llanbrynmair Moor into the Afon Dyfi system.

In 1983, amid environmental controversy over the future of Llanbrynmair Moor, 42% of the Cwm catchment was planted, mainly on the interfluve areas. This was followed by a second swathe of planting comprising, in 1984 mainly screef planting on the steep valley sides, in 1985 contour ploughing in the valley bottom and in 1986 further conventional ploughing and planting on the interfluve areas. When planting was complete, 87% of the catchment was under predominantly Sitka spruce (*Picea sitchensis*) forest and 76% had been ploughed and drained, providing an ideal site for a study of the multi-faceted hydrological and hydrochemical impacts of initial afforestation. Nature conservation pressure, combined with difficulties of planting some wet areas and the need to protect important water source areas, persuaded the forest planners to leave some riparian areas unplanted, to experiment with contour ploughing in the valley bottom to prevent soil erosion and improve stream water quality (Emmett *et al.*, 1991) and in other susceptible areas of the catchment to minimise drainage works. Wherever practical, drainage channels were left discontinuous to prevent the rapid concentration of flow that causes soil erosion, and to minimise the effect of drainage on catchment flow response.

The afforestation of the Cwm is a good example of the environmentally-sensitive approach adopted by modern forestry practitioners, as the development was generally carried out using techniques and safeguards now recommended by the latest guidelines (Forestry Commission, 1993). At the catchment scale, the hydrological effects result from an integration of all three types of planting.

Instrumentation Networks and Data Collection

Instruments were first installed on the catchments in 1982, and their deployment and characteristics are described by Roberts *et al.* (1986) and Hudson *et al.* (1997b). The networks were designed primarily to measure those components of the water balance required for calculation of hydrochemical fluxes Emmett *et al.*, 1991), but have also proved to be accurate and precise enough for hydrometric measurement and hydrological analysis.

RAINFALL

Point rainfall is measured using ground level storage gauges at three sites in the Cwm, read fortnightly, and two in the Delyn read at 2–3 monthly intervals. To obtain catchment rainfall values, the catches from each of these gauges are weighted according to the areas they represent in each catchment in terms of topography, altitude and regional climatic gradients.

This is relatively easy in the Cwm because the spatial variation in rainfall is small, and the catch of none of the three gauges differs by more than 6% from either of the others. There is no significant correlation with any of the usual controlling variables—altitude, slope, aspect or longitude—so the arithmetic mean catch of the three Cwm gauges gives as good an estimate of catchment rainfall as any more complicated combination. In addition, the excellent long term relationships between the gauges in the Cwm (Table 1), can be used to infill missing data and to aid network consistency by extending records in time. For infilling, the relationships have been chosen firstly accord-

Table 1. Rainfall (fortnightly totals in mm) interrelationships for gauges in the Cwm and Delyn. These are used to infill missing data and to extend data series at particular sites after problem periods have been eliminated.

Dependent Gauge	Independent Gauge	Intercept	Slope	r^2	Degs. of Freedom
Llanbrynmair Moor	Cwm Weir	1.5221	1.0253	0.989	207
Cwm North End	Cwm Weir	1.7002	1.0569	0.986	114
Cwm Weir	Llanbrynmair Moor	–1.5468	0.9790	0.989	205
Delyn Middle	Delyn Upper	–6.3230	1.0402	0.992	38
Delyn Upper	Delyn Middle	7.8033	0.9535	0.992	38

ing to data availability (Cwm North End raingauge for example was not installed until 1987) with subsequent choices made in descending order of r^2 value.

The estimation of precipitation into the Delyn catchment is more complicated than the Cwm. The catchment is long and narrow, so raingauge siting has been confined to a profile along the catchment axis, and also to mid-altitude; this was due to problems of physical access in the upper part of the catchment and the lack of a suitable raingauge site in the lower part. Fortunately, the daily-read standard gauge at Pentre Celyn Farm is sited near the catchment outlet and can represent the lower part of the catchment. The gauge also gives index daily rainfall against which the integrated storage in the ground level gauges in both the Delyn and Cwm can be time-distributed for various accounting periods to suit the water balance framework or for subsequent modelling purposes.

The upper Delyn precipitation can be represented by the gauges at Cwm North End and/or Llanbrynmair Moor. The mean annual catch at Cwm North End (2120 mm) is considerably higher than either the Delyn middle gauge (1524 mm) or the upper gauge (1500 mm). The relationship between catch and altitude in the Delyn appears to be complex, and there are insufficient gauges to determine its functional form, indicating that a limited gauge network is not ideal for accounting for all the factors affecting rainfall distribution. This makes it difficult to define an obvious rainfall weighting model for the catchment (Fig. 1). Initial values of P – Q calculated using just the two Delyn gauges plus that at Pentre Celyn were negative in some years; this indicates that rainfall is seriously underestimated. most probably on the interfluves of the Delyn. Indeed, sensible P – Q figures can be obtained only by inferring that rainfall over the upper parts of the catchment is similar to that falling on the Cwm. The estimate of mean annual catchment rainfall (1780 mm) has therefore been calculated as the weighted value (using the mean hypsometric altitude (or elevation, E) of the quadratic relationship with altitude, where:

$$P_{DELYN} = 3201.9 - 12.01\,E + 0.0203\,E^2 \text{ [mm]}$$
$$r^2 = 0.947$$

This relationship and the hypsometric distribution of proportional area (A) are both shown in Fig. 1. Annual catchment rainfall is then calculated as the annual mean of the four contributing gauges multiplied by the ratio 0.937, which represents the long term ratio (1982–1995) of the altitude-weighted and arithmetic means. Clearly, the uncertainties of curve-fitting will always mean that estimates of absolute rainfall into the Delyn are much less reliable than those for the Cwm; however, as the main aim of the study is to assess the changes over time in evaporation and flow resulting from the land use change, any associated change in differences between the catchments will still represent a valid measure of land use impact.

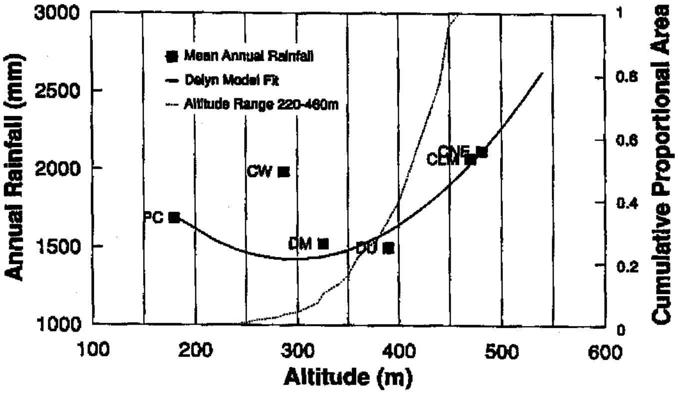

Fig. 1. *The relationship between precipitation and altitude in the Cwm and Delyn catchments, in conjunction with the area-altitude distribution used to weight point rainfall, which together form the basis of a spatial model to calculate mean areal precipitation into the Delyn. This uses the gauges CLM (Cwm Llanbrynmair Moor), CNE (Cwm North End), DU (Delyn Upper), DM (Delyn Middle) and PC (Pentre Celyn).*

None of the storage gauges has a complete record from 1982–1995, although the gaps are not serious and the Cwm Weir gauge is the most complete. Time series plots of the magnitude of the relative catch between gauges (Fig. 2) highlight certain problems, including a period between early 1989 and March 1992 when excessive shelter of the Llanbrynmair

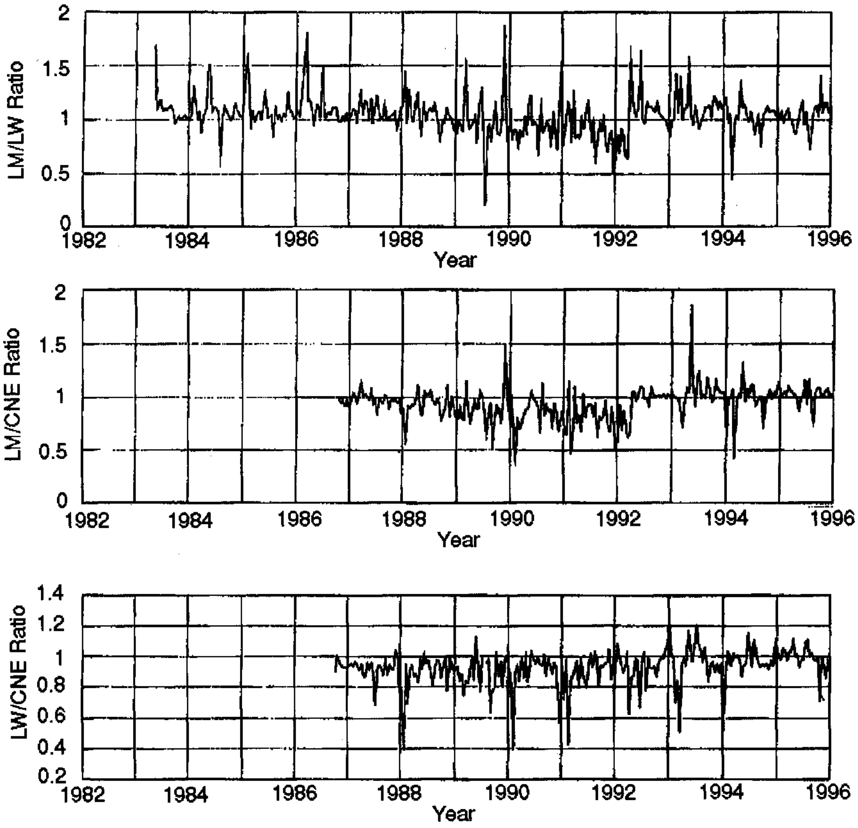

Fig. 2. *Comparative time series of gauge catches used to identify periods of poor gauge performance (LM = Llanbrynmair Moor, LW = Cwm weir, CNE = Cwm North End).*

Moor gauge by growing trees caused an obvious undercatch, and there was a similar problem with Cwm North End gauge during 1994 and 1995. Data from these periods and during snow were left out of the regression analysis used to establish inter-site relationships. The strong non-snow relationships between network gauges thus derived (Table 1) can be used with confidence to infill data suspected as being inadequate for any reason other than snow.

Snow presents the main measurement problem in upland catchments. Because the standard Met. Office snow procedures are followed, the manual, daily reading of Pentre Celyn standard gauge gives sensible data at such times. In the event, the disruption caused by snow at Llanbrynmair over the study period has been mild. Catches including heavy snow can be identified easily as significant deviations from the strong non-snow relationships with Pentre Celyn, especially where these coincide with positive values in the daily record of snow days and lying snow kept for the Moel Cynnedd climate station at Plynlimon. Snow is more frequent at Plynlimon, so this provides a suitably harsh threshold for rejecting suspect data. When snow is the cause of observed deviations, ground level data are replaced using the equations given in Table 2. This method was developed originally at Plynlimon (Hudson *et al.*, 1997*b*) and has also been used in the Balquhidder catchments in central Scotland (Johnson *et al.*, 1990) where snow is more common and creates greater problems.

FLOW MEASUREMENTS

A triangular-profile, broad-crested weir (Crump, 1952) was constructed to measure flow from the Cwm catchment and a compound 90°V- and rectangular notch to perform the same function for the Delyn catchment. A continuous record (a prerequisite for water balance analysis) has been ensured through judicious infilling of gaps in the data, using the strong relationships derived between the main flow gauges in each catchment for a period of concurrent data immediately before and after each break in the record. Examples are shown in Table 3.

Problems with infilling are greatest when both Cwm and Delyn gauges malfunction simultaneously, a situation that was particularly prevalent in 1988 due to the introduction of new data logging systems. The approach to infilling adopted in this situation, which rarely involves more than a few weeks data in an average year, was to use the relationships of both gauges to the quarter-hourly data from the Cyff subcatchment of the Upper Wye at Plynlimon. Although the Cwm and Delyn catchments are further from

Table 2. Relationships between network gauge totals (in mm) and Pentre Celyn daily gauge, used to hindcast data series and (especially) to replace data affected by snow.

Dependent Gauge	Independent Gauge	Intercept	Slope	r^2	Degs. of Freedom
Cwm Catchment					
Llanbrynmair Moor	Pentre Celyn	4.2246	1.1702	0.955	208
Cwm North End	Pentre Celyn	3.1693	1.2021	0.954	114
Cwm Weir	Pentre Celyn	1.5671	1.1583	0.966	278
Delyn Catchment					
Delyn Middle	Pentre Celyn	8.1624	0.8850	0.993	38
Delyn Upper	Pentre Celyn	15.6840	0.8434	0.984	38

Table 3. Examples of linear relationships between flow data (mm 15-min^{-1}) from the gauging structures, used for infilling missing flow data.

Dependent Gauge	Independent Gauge	Intercept	Slope	r^2	Period used
Cwm	Delyn	0	0.66	0.75	8/95
Cwm	Cyff	0.65	0.668	0.84	12/87–1/88
Delyn	Cwm	0.01	0.97	0.91	12/93
Delyn	Cyff	1.02	0.64	0.86	12/87–1/88

the Cyff than from, for instance, the gauge on the same river system at Dyfi Bridge, and are not therefore subject to exactly the same weather patterns, they are nevertheless more similar to the Cyff in terms of size, morphology, soils, vegetation and altitude range, and probably also in terms of rainfall regime and integrated catchment response.

One remaining uncertainty in flow measurement is the effect on the calibration of the Cwm structure of sediment build-up in the weir stilling pool, one of the inevitable consequences of disturbance during the land use change (Leeks & Roberts, 1987). To achieve absolute consistency of flow measurement over the study period, periodic adjustments should be made to the rating of the Crump weir. However, it has been difficult to reconstruct the sediment accretion history of the structure in a sufficiently quantitative way to justify a variable calibration approach. The effect of sediment in a Crump weir is to reduce the effective weir height, P(m), and thus to reduce the cross sectional area of flow, A(m^2) for any given stage (the upstream water depth above weir crest level, h(m)). Area is defined as $A = (h + P)b$, where b(m) is the weir width. At any given stage, a change in the parameter P clearly changes the flow velocity, V(m sec^{-1}), estimated from the standard weir equation (BSI, 1981):

$$V = 0.633 \sqrt{g}\, H^{1.5} / (h+P)$$

where, H (m) is the total head over the weir and represents the sum of the potential and kinetic heads and g is the acceleration due to gravity (9.81 m sec^{-2}). The effect of introducing a variable rating would be a slight reduction in the estimates of flow in the Cwm; however, the discrepancy is intermittent and pronounced only at very high flows. Overall, the error is considered too small to warrant changes being made for the sake of an annual water balance analysis, but might be considered before an analysis of flood peaks is undertaken.

The compound sharp-crested weir of the type used in the Delyn is a reliable structure with a well-known rating when flow is solely in the V-section. However, the calibration becomes complicated once flow enters the superimposed rectangular notch. The Barnes (1916) formula, shown below in the specific form for the Delyn which has a rectangular weir crest width of 4.264 m, is used to allow for the interaction of the component weirs:

$$Q = 1.34739\,(h_v^{2.48} - h_r^{2.48}) + 6.03988\, h_r^{1.49}\,(21/(21+h_r))^{0.11}$$

where h_r and h_v are respectively the water depths (m) over the rectangular crest and V-notch invert. In practice, the flow is in the rectangular section for only a small proportion of the time, and only transient flows occur between V-full condition ($h_v = 0.381$ m; $h_r = 0$) and the design lower head limit for the rectangular section ($h_r = 0.07$ m). Thus, the calibration can be interpolated with some confidence over this range; above the lower limit, the errors introduced by using the V-section outside the recommended range, $h_v > 0.381$ (BSI, 1981), will be insignificant relative to total flow.

ATMOSPHERIC DEMAND FOR MOISTURE

Before the observed changes in the water balance can be extrapolated to other areas, it is necessary to understand the change in evaporation in terms of the atmospheric demand and the availability of water. P – Q values from the experimental and control catchments are compared in Table 4 to Penman's (1948; 1949) independent estimate of potential evaporation for short grass, E_t, which represents a ground cover that will be found at most meteorological sites, even those situated in forest clearings.

Unfortunately, apart from a short period at the beginning of the experiment there has been no manual or automatic weather station (AWS) at Llanbrynmair from which it would be possible to calculate E_t directly (Hudson *et al.*, 1996). However, E_t estimates are available from the manually-read daily climate measurements at Moel Cynnedd in the nearby Plynlimon catchments (Kirby *et al.*, 1991). Manual daily data may miss some of the important diurnal variation in temperature or humidity, but E_t provides a continuous and reliable index and takes advantage of integrated radiation values from the AWSs, data that have recently benefitted from extensive quality control (Crane & Hudson, 1997).

Using the network of Plynlimon AWS data, it has been possible to adjust the Moel Cynnedd manual E_t values to allow for the higher atmospheric demand for moisture indicated by stations on the open hillsides than is evident from the meteorological data collected in the forest clearing at Moel Cynnedd. Crane & Hudson (1997) observed a 31% greater E_t for the average of the two AWS sites in the grassland Wye catchment. It is apparent from this that the absolute magnitude of E_t can vary markedly across a small area, a finding in line with measurements in the Balquhidder catchments in the central Highlands of Scotland (Blackie & Simpson, 1993), where an increase in E_t with altitude was found, contrary to accepted wisdom at the time. It is possible, therefore, that the Cwm and Delyn experience very different values of potential evaporation, which also suggests that these contiguous catchments need not necessarily exhibit similar values of actual evaporation (P – Q). This spatial variation in E_t is indicative of the extent to which meteorological conditions can vary rapidly over short distances in areas of rough topography. Variability may be even greater than is indicated by the climate data, as most meteorological sites and AWSs are located to conform with exposure criteria imposed by the Met. Office, and may not sample the more extreme local weather conditions that exist in open catchments. The E_t will be dependent on site factors such as:

- exposure to solar radiation, (controlled by frequency of cloud cover and physical obstructions such as horizon declination, or encroaching vegetation that is often a feature of forest clearing sites);
- temperature, (which may vary rapidly though not always consistently with altitude, so that low altitude sites will generally give measurements that are greater than the true catchment mean);
- humidity, (the measurement of which depends on temperature and also on ventilation, indexed by wind speed that generally increases with altitude);
- ground cover, (which controls the energy balance via albedo and net long wave radiation); snow frequency can also have an important impact on the energy balance and this also increases with altitude.

It has proved difficult enough to estimate mean catchment potential evaporation (PE) in the Plynlimon catchments

Table 4. Annual water balances (mm) for the Llanbrynmair catchments and independent estimates of evaporative demand.

Year	Cwm				Delyn			Plyn E_t	
	P	Q	D	P–Q+D	P	Q	P–Q	Man	Corr
1983	2339	1748	55	*646*	1907	1534	*373*	394	516
1984	1827	1308		*519*	1446	1153	*293*	425	557
1985	1954	1439	26	*541*	1565	1326	*240*	366	479
1986	2244	1660	18	*601*	1775	1400	*375*	354	464
1987	1869	1578		*269*	1571	1408	*163*	366	479
1988	2161	1483		*362*	1787	1442	*346*	357	468
1989	1816	1318		*498*	1472	1157	*315*	431	565
1990	2187	1677		*511*	1755	1534	*221*	425	557
1991	1950	1515		*435*	1590	1260	*330*	367	481
1992	2112	1532		*580*	1652	1484	*168*	381	499
1993	1986	1453		*533*	1637	1411	*226*	382	514
1994	2599	2037		*562*	2109	1908	*201*	371	486
1995	1720	1146		*574*	1422	1122	*299*	436	571
Mean	2059	1530		*510*	1668	1395	*273*	389	510

where the measurements have been taken at a low altitude, sheltered site, let alone to extrapolate the Plynlimon estimates to Llanbrynmair some 20 km away. However, the Moel Cynnedd estimate is the only adequate reference index of PE available to which actual evaporation can be related to form the basis of explanatory functions and predictive models.

Catchment Evaporation from Annual Water Balances

The time series for the Llanbrynmair catchments of annual precipitation (P), streamflow (Q) and the actual evaporation (AE) estimate from the water balance:

$$AE = P - Q + D - \Delta S$$

where D is a flow correction for catchment dewatering following forest plough drainage (dewatering by transpiration is implicit in the AE estimate), and a positive value of ΔS is the increase in catchment storage over the calendar year accounting period, are shown in Fig. 3 and Table 4. Differences in the water balances of the experimental and control catchments for the period 1983–1995 have been used as a measure of the effects of the land use change on water resources.

Clearly some of the year-to-year variability in P – Q for both catchments is caused by neglecting ΔS but, unfortunately, no direct measurements of storage are available to rectify this situation. However, provided these unmeasured storage changes are similar in each catchment, comparisons between adjacent catchments and the relationships derived should not be compromised. It is inevitable that, over a number of years, ΔS approaches insignificance, so that individual year-to-year variability can be removed by adopting a moving average of annual P – Q as the estimate of actual evaporation. Figure 4 shows a 3-yr moving average which may actually overcompensate for storage changes. The result is a P – Q estimate that is more conservative from year-to-year (Roberts, 1983) and one that is not influenced unduly by annual fluctuations in rainfall or streamflow; this represents the classic situation of a moorland catchment where transpiration is the dominant form of evaporation.

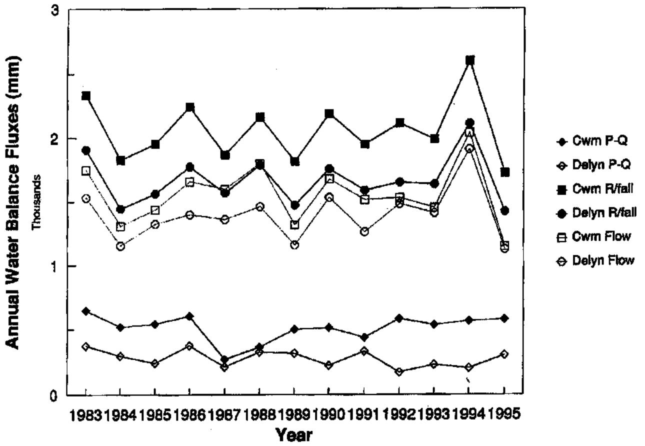

Fig. 3. *Time series of annual P, Q and P – Q in the Cwm and Delyn catchments.*

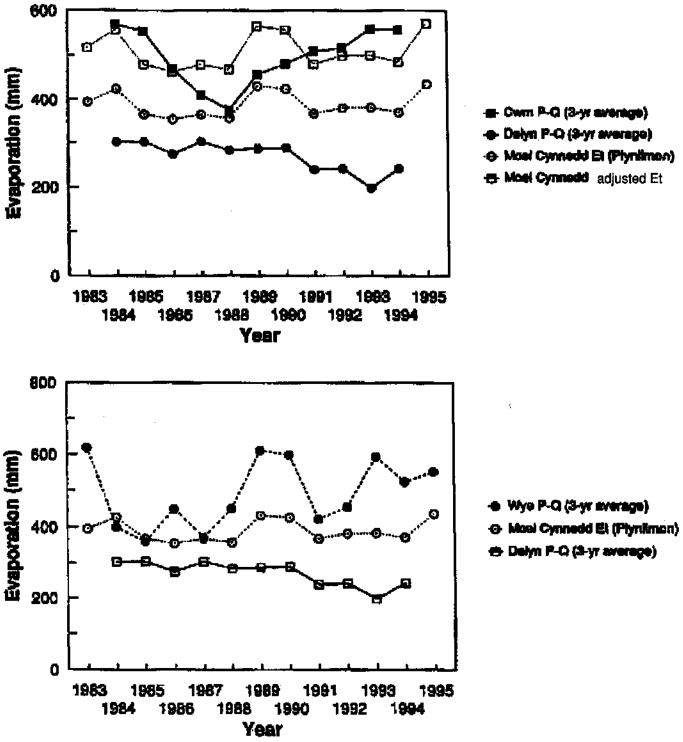

Fig. 4. *P – Q estimates for the Cwm and Delyn after storage effects have been removed by using the 3-yr moving averages, compared with the grassland evaporation in the Wye catchment at Plynlimon, and the E_t values, actual and adjusted, from the Moel Cynnedd met. site.*

The Cwm water balance must also take into account the fact that the catchment has been subjected to a disruptive land use change, ploughing and draining prior to planting of the trees; this affects the storage of water in the soils and shallow groundwater. This is bound to introduce further uncertainties to the water balance flux estimates in some years. An allowance for dewatering, which is effectively an increase in discharge (and a decrease in P – Q) not caused by an actual reduction in evaporation, has therefore been made during and after each ploughing phase. The dewatering effect, shown in Table 4, has been estimated using existing information on the average depth and width of drains cut (0.6 m deep by 0.525 m wide), the average drain spacing gleaned from aerial photos and ground measurement (4.75 m), the areas of drainage carried out in particular years (42% in 1983, 20% in 1985 and 14% in 1986), the likely permanent change in peat water content in an area completely drained, estimated at

130 mm (from Hudson & Roberts, 1982), and the length of time taken for the dewatering to cease. According to Hudson & Roberts (1982), this can take up to 2 years but, for the present analysis it is assumed to have had an effect only in the year when drainage took place.

For comparison with the water balance estimates, the annual Penman E_t estimate from the Moel Cynnedd meteorological station at Plynlimon is also shown in Fig. 4 and Table 4, along with an adjusted version of E_t which takes into account the higher values gained on the open hillside from the two AWSs in the Wye (Crane & Hudson, 1997c). In Fig. 4, the $P - Q$ values from the grassland Wye catchment at Plynlimon are included for comparison.

CATCHMENT EVAPORATION RATES

The most striking aspect of the water balance analysis is the large difference in absolute $P - Q$ values for the Cwm and Delyn at the start of the study, at a time when some 42% of the Cwm had recently been ploughed and planted, but when the indigenous vegetation was still dominant. Average annual $P - Q$ in the Cwm for the first four years, 1983–1986, was 577 mm, considerably higher than Plynlimon E_t at 385 mm (a $(P - Q)/E_t$ ratio of 1.50) but not much higher than adjusted E_t of 504 mm which gives a more realistic ratio of only 1.14. An actual evaporation loss $(P - Q)$ that is 14% greater than the estimated short grass Penman potential rate is comparable to the 9% value observed at the moorland Coalburn catchment prior to its afforestation (Robinson *et al.*, 1998), and it is close to the ratio of 1.18 found in the moorland Monachyle catchment at Balquhidder (Blackie, 1993), a catchment with a similar vegetation mix to the Cwm.

One explanation for the apparently large difference in the actual evaporation losses in the Cwm and Delyn is the difference in the indigenous vegetation and its management. The Delyn catchment is mainly under acidic grassland species (*Festuca ovina*, *Nardus stricta* and *Agrostis tenuis*) and they are kept short by sheep grazing. The Cwm has been managed largely as grouse moorland, and is dominated (Woods, 1978) by a mixture of dwarf shrubs such as heather (*Calluna vulgaris*) and bilberry (*Vaccinium myrtilus*), rank herbal vegetation such as ungrazed grasses (*Molinia caerulae, Nardus stricta, Festuca ovina and Agrostis tenuis*) and some areas of bracken (*Pteridium aquilinum*) on the lower slopes. Evaporation from such intermediate-height vegetation often includes a considerable amount of interception (Hall & Harding, 1993), which will offset any shortfall in transpiration from the potential rate. Transpiration restriction will occur only rarely in this high rainfall catchment (average 2060 mm), because conditions of soil moisture stress will be infrequent. Soil temperatures (Emmett *et al.*, 1991) are generally high enough to indicate that transpiration rates will not be constrained by temperature and the length of the growing season (Wright & Harding, 1993), although there may be a slight reduction in transpiration when the canopy is wet (Calder & Newson, 1979).

Evaporation from the Delyn on the other hand, with $P - Q$ at 320 mm for the first four years, amounts to only 83% of the Plynlimon E_t for the same period (or 63% of adjusted E_t), a proportion that is more characteristic of high-altitude, water-stressed grassland in colder climates (Wright & Harding, 1993) than of average conditions for mixed moorland/grazed grassland in Wales (Hudson & Gilman, 1993). Possible explanations for the low $P - Q$ values in the Delyn are that:

- computed rain for the Delyn catchment underestimates catchment rainfall,
- the low evaporation values in the Delyn are real and caused by shortfalls in both transpiration and interception from regional potential values. This could result from a combination of intensive grazing in the catchment producing a short crop, low annual rainfall and thin soils combining to cause water supply limitations during drier summers, the high mean altitude of the catchment and shelter afforded by the orientation of the catchment encouraging low temperatures, short growing seasons and low E_t within the catchment.

When considered in these terms, the initial differences in $P - Q$ between the two catchments may be physically realistic and therefore unrelated to inaccurate estimation of Delyn rainfall.

CHANGES IN THE WATER BALANCE OVER TIME

The water balance of a catchment can change over time for a number of reasons. Climate is normally the main control, as it affects the amount, type and time distribution of precipitation, and also the atmospheric conditions that dictate the evaporation rates from the crop both as transpiration and interception. Superimposed on this climatic control are the effects of land use changes over the same period, changes in vegetation being of particular importance.

To assess the hydrological effects of the land use change in the Cwm, ideally it should be possible to define, quantify and explain, preferably in physical terms but at the very least statistically, the evaporation in both catchments over the initial 4-year control period and for the Delyn over the whole study period; then it should be possible to use the Delyn $P - Q$ data to predict what would have happened in the Cwm in the absence of a vegetation change.

Climatic Control of Annual $P - Q$ in the Delyn

The absence of process studies within the Cwm, and the relatively short series of detailed climate data specific to Llanbrynmair, make it difficult to develop physically meaningful relationships, either between the catchments or with environmental controls. Development of new evaporation models or use of existing ones to complement the annual water balance approach should become a possibility in future when longer series of AWS climate data become available, (Monteith, 1965; Rutter *et al.*, 1971; Gash & Morton, 1978; Hall & Harding, 1993; Calder & Newson, 1979). A combined meteorological and within-year water balance approach could also be taken in which catchment storage changes are inferred from internal soil moisture (Calder *et al.*, 1983) and groundwater accounting procedures (Hudson, 1988).

The variation of the annual Cwm and Delyn P – Q values over the study period can be described in terms of the Plynlimon climatic regime. Attempts to relate Delyn P – Q to Penman E_t have not been successful in terms of deriving strong predictive relationships. Although the *absolute levels* of P – Q must be dependent at least partly on atmospheric demand, the year-to-year *variation* in P – Q is not simply related to the same variation in E_t. Penman E_t fluctuates but averages out at a roughly constant level over the study period. In contrast, even allowing for year-to-year fluctuations, the Delyn P – Q declines significantly (Figs. 3 & 4).

Comparison with results from the grassland Wye catchment at Plynlimon (Fig. 4) does not help to unravel the problem. The Wye P – Q is more variable and shows a slight increase as part of a longer term cycle (Hudson *et al.*, 1997b), while over the same period the Delyn clearly decreases. This may simply reflect the uncertainties in the estimation of precipitation inputs to the Delyn, although there is no evidence to suggest an underlying downward trend in the precipitation data, or it may be that the Llanbrynmair and Plynlimon evaporation regimes are not that similar, in which case the Plynlimon E_t may not be the ideal index for explaining variability in Delyn P – Q. Provided the Delyn data are correct, the cause of this decline may turn out to be the underlying control on evaporation rates in the Delyn but, until the cause is identified, a simple ratio or regression model is all that can be used to predict Cwm evaporation levels and provide the baseline from which the effects of the land use change can be quantified.

Extension of Moorland Evaporation rates for the Cwm, 1987–1995

The model to predict the Cwm evaporation rates in the absence of afforestation must take into account the apparent decline in atmospheric demand as indexed by the Delyn P – Q. The decline is unlikely to be due to reducing interception, because this is believed to be low in the Delyn in any case, and is most likely due to the imposition of as yet unidentified controls on transpiration forcing rates lower than predicted by E_t.

A regression model of the relative behaviour of the Cwm and Delyn has been derived for the initial 4-year period of the study, 1983–1986. It was then assumed that these relationships would have held in the absence of the land use change for comparisons in subsequent years. This baseline period includes the plough drainage of significant areas of the catchment and the years 1983, 1985 and 1986 have been 'corrected' for catchment soil de-watering. In the absence of any direct measurements, it was assumed that any reductions in transpiration and interception due to the disturbance of the indigenous vegetation would have had a minimal effect on the evaporative response of the Cwm. The pre-land use change relationship between the annual P – Q for the two catchments was fitted, both with and without the adjustment term for catchment dewatering:

a) Excluding dewatering:

$$(P - Q)_{CWM} = 363.5 + 0.5886\,(P - Q)_{DELYN}$$
$$r^2 = 0.907$$

b) Including dewatering:

$$(P - Q)_{CWM} = 343.9 + 0.7274\,(P - Q)_{DELYN}$$
$$r^2 = 0.687$$

The strength of the relationship including D is, ironically, a lower r^2 than without the dewatering adjustment. This probably illustrates the inherent instability in a relationship derived from only four data pairs; the slope of the regression line in a) may only be as significant as it is by chance. However, both represent stronger relationships than can be derived with any alternative control data, including the Wye P – Q or the Plynlimon E_t.

THE EFFECTS OF INITIAL AFFORESTATION ON EVAPORATION AND STREAMFLOW

A cumulative plot of the rainfall equivalent of streamflow from the two catchments (Fig. 5) indicates a divergence up to 4 years after the first trees were planted. This initial difference in flow between the catchments is not surprising considering the large differences in catchment rainfall inputs, in spite of the counterbalancing effect of the higher

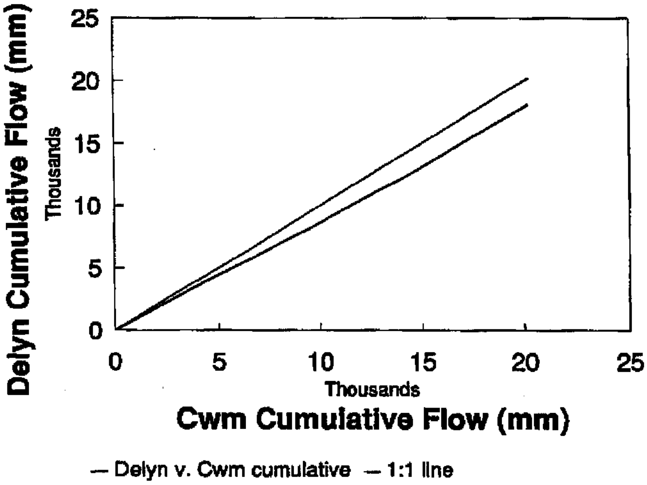

Fig. 5. *Relative changes in cumulative streamflow (rainfall depth equivalent) in the Cwm and Delyn, 1983–1995, associated with the ploughing and the growth of the new forest.*

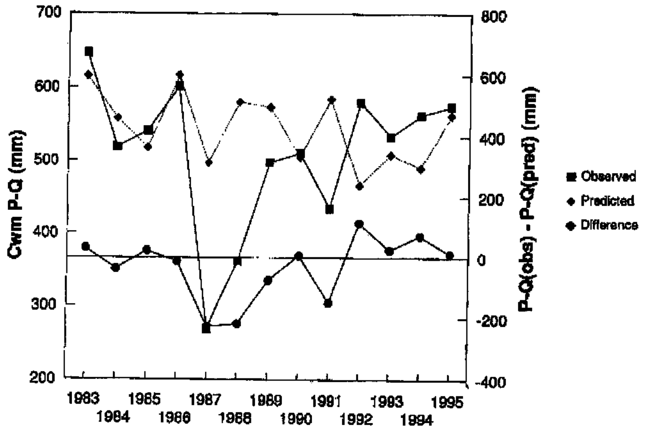

Fig. 6. *Model prediction of annual evaporation from the Cwm, using the pre-forest relationship between the Cwm and Delyn, in comparison with observed P – Q in the Cwm.*

evaporation losses from the Cwm. After the initial control period, the rate of divergence in flow is increased by a combination of the de-watering of the catchment and the eventual reduction in evaporation in the Cwm due to severe damage done to the indigenous vegetation during the ploughing. This leads to a period of very low evaporation in the Cwm, between 1987 and 1989. It is not until 1990 that the cumulative streamflow stops diverging, as evaporation in the Cwm once more attains the annual rate predicted from the evaporation model (Fig. 6). In 1991, there appears to be an aberration as Cwm P – Q reduces once more, a problem as yet unexplained that will require further investigation. In spite of this anomaly, from 1992 onwards, the evaporation in the Cwm is continuously, although variably, higher than predicted, which suggests that a new evaporation regime is established, at the latest after 9 years, and possibly as rapidly as 7 years after the initial planting. The importance of running a controlled experiment is clear from the fact that the increase in evaporation from the Cwm, the 'land use effect', only becomes evident in relation to the declining evaporation in the Delyn. Without the control data, absolute values of P – Q for the Cwm were reduced for a few years, but over the study period climbed back only to initial levels.

The rapid re-attainment of pre-ploughing evaporation rates is due to re-establishment of the initial transpiration rates as the ploughed areas recolonise, and to increased interception from the combined canopy of immature trees and the rank herbal and shrub understorey. In plantation forests, growth of shrubbery is no longer constrained by sheep grazing, so unless other management measures are taken, an aerodynamically rough canopy will develop quickly; when manifest as high canopy water storage and low aerodynamic resistance to vapour transfer, this encourages high rates of interception (Calder, 1977). The profuse understorey checked the tree growth in certain areas of the Cwm through competition for limited soil nitrogen (Tilhill Ltd., *pers. comm.*). This warranted an application of NPK fertiliser in 1990, which allowed the trees to grow and eventually to outcompete the heather and bilberry understorey. The existing mixed canopy was effectively replaced with one of similar height and roughness, albeit with a more conventional forest structure.

The changes in the Cwm to a new evaporation regime appear to have happened more quickly than those observed at Coalburn. Robinson *et al.* (1998) identified a significant reduction in streamflow starting some 15–20 years after planting, a considerably longer delay than the 7–9 years seen in the Cwm. The difference in response supports a regional approach to studying the hydrology of forest plantations, and can be accounted for by site differences including:

- At Coalburn the tree growth has been slower than in the milder conditions of mid-Wales. A severe frost occurred soon after planting at Coalburn that may have checked the growth of Sitka Spruce for some years; some small areas of forest had to be replanted. The fact that growing conditions are better at Llanbrynmair in spite of the higher average altitude of the Cwm is highlighted by Emmett *et al.* (1991), who identified a number of years in the late 1980s where growing seasons, as defined by a threshold soil temperature of 6°C, lasted throughout the year.
- Annual rainfall at Coalburn is 40% lower, at 1350 mm, compared to the average of 2060 mm recorded in the Cwm, which indicates that the developing canopy at Coalburn stays drier for longer periods, and may be less prone to interception losses which will be the main cause of changes in evaporation from pre-afforestation levels (Calder & Newson, 1979). The planted area at Coalburn of 90% is very similar to that at Llanbrynmair (87%) and so cannot account for the observed differences.
- The indigenous vegetation at Coalburn, dominated by *Molinia spp.*, did not respond to reduced grazing in the same way as the dwarf shrub communities, dominated by heather (*Calluna vulgaris*) and bilberry (*Vaccinium myrtilus*), did in the Cwm. There was no development of an intermediate height canopy at Coalburn under the young trees.

After 14 years under trees in parts of the Cwm, and as the environmentally-critical canopy closure phase approached (Hudson *et al.*, 1996), the land use effect in the 87% tree-covered catchment amounted to an increase in evaporation for the period 1992–1995. This increase averaged 56 mm yr^{-1} including the dewatering adjustment D, and 67 mm yr^{-1} excluding D with the highest annual difference in P – Q recorded of 114 mm and 118 mm respectively in 1993. This is still some way short of the peak difference of 232 mm identified at Plynlimon, between the forested Severn catchment adjusted to 100% cover and the moorland Wye control (Hudson *et al.*, 1997b). The importance of these combined results to the future cooperation between forestry and water resource interests in upland catchments demonstrates the case that the monitoring should continue at Llanbrynmair and Coalburn to establish, in addition to the time taken for these forest effects to show, the regional differences in the maximum forest evaporation effect, and also the effect of forestry and forest management on the time distribution of extreme flows. The primary reason for setting up the Llanbrynmair catchments should not be forgotten either, as it is also important to establish how the hydrological impacts of land use change to forestry also control the hydrochemical response of these catchments.

Conclusions

The change in land use from traditional, managed moorland to plantation forestry involves important short and long term changes in the processes that convert rainfall to streamflow. These result not just from the change in vegetation canopy, but also from the soil and vegetation disruption that accompanies the planting of exotic coniferous species in upland catchments.

Over the initial 4-yr period, which approximates the pre-afforestation conditions, streamflow from the Cwm experimental catchment was greater than from the Delyn control catchment because the higher average annual rainfall in the Cwm was not completely offset by its higher evaporation rates. The Cwm evaporation is characteristically much greater than the Delyn, due to inherently higher interception rates from the dwarf shrub vegetation communities that have been encouraged to grow by cessation of grazing, and also by the favourable climatic conditions. In addition, transpiration in the Cwm is higher than in the Delyn, as the Cwm is more favourably exposed in terms of the factors that control evaporation; it has a low radiation horizon, deeper soils, more efficient ventilation, and a lower average altitude giving higher average temperatures. As a result, initial evaporation values at 577 mm yr^{-1} are 14% higher than the adjusted E_t values measured at the Plynlimon meteorological site at Moel Cynnedd (504 mm yr^{-1}). Delyn evaporation on the other hand was 37% below E_t, showing rates that, as a proportion of E_t, are more akin to high altitude grass in the Scottish Highlands. This suggests that in the Delyn there are severe restrictions on both the energy budget and aerodynamic components of potential evaporation.

There was a more marked divergence in cumulative catchment streamflow after the initial 4-year control period, due partly to dewatering after drainage and ploughing, but mainly to the inevitable reduction in evaporation from the heavily disturbed vegetation. However, 7 years after the first areas were planted, the deviation in streamflow stops, indicating that annual evaporation rates from the Cwm catchment have returned to or even exceeded pre-disturbance levels. This is probably due to the recovery of both interception and transpiration rates resulting from re-establishment of an intermediate height canopy of heather, bilberry and other dwarf shrubs among the young trees.

In recent years, evaporation from the Cwm has continued to increase relative to the Delyn as the new trees start to establish their full canopy. Canopy closure had not been reached by 1995, but already the $P - Q$ from the Cwm was estimated to be, on average, 56–67 mm yr^{-1} higher than predicted in the absence of the land use change. One word of caution is that the increase in $P - Q$ in the Cwm is only obvious as a difference from the Delyn evaporation, which declined over the study period. The Delyn figures contradict the results from Plynlimon, where both actual evaporation ($P - Q$) from the Wye catchment and potential evaporation (E_t) at Moel Cynnedd in the Severn increased slightly over the 1983–1995 period. When compared to the Plynlimon potential evaporation records, the recovery of evaporation to pre-forestry rates in the Cwm can still be seen, but the start of a 'forest effect' is not obvious.

The increase in evaporation ($P - Q$) of the new forest in the Cwm catchment occurred much more quickly than that at Coalburn, a parallel study being carried out in the colder and drier climate of the northern Pennines. The onset of increased evaporation has occurred after 9 years in the Cwm compared to about 20 years at Coalburn, due partly to differences in the climate and tree growth rates, but also to the different characteristics of the indigenous vegetation and its management. The rough canopy that developed at Llanbrynmair, an association of rank vegetation and small trees, combined with the higher annual rainfall, encouraged an early resumption of high interception rates. In those parts of the catchment drained by contour ploughing, transpiration rates may have been maintained by healthy soil moisture reserves resulting from efficient infiltration. The high interception rates have continued as the forest canopy has grown to outcompete the indigenous vegetation, encouraged by judicious applications of nitrogen fertiliser. The contrast with Coalburn lies in the fact that vegetation there was dominated by wet moor grasses such as *Molinia spp.* that never develop the efficient interception characteristics of intermediate-height canopies.

In terms of water resources, it appears that there will be large regional differences in the time it takes after ploughing and afforestation for a reduction in annual streamflow to become significant. It is as yet too early to say, either at Llanbrynmair or Coalburn, whether peak rates of evaporation will rise to the levels recorded for mature forest at Plynlimon and elsewhere. However, where large scale ground disturbance is associated with forest planting, there will always be a period where streamflow resources increase due to suppression of the original vegetation and mining of catchment storage. Continuation of monitoring in these catchments is essential, not only to establish the maximum evaporation rates and to assess the changes in extreme flows, but also as part of hydrochemical and ecological studies, where it is becoming clear that changes in nutrient cycling, acidification status and stream biology are all heavily dependent on changes in hydrological pathways and water fluxes.

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