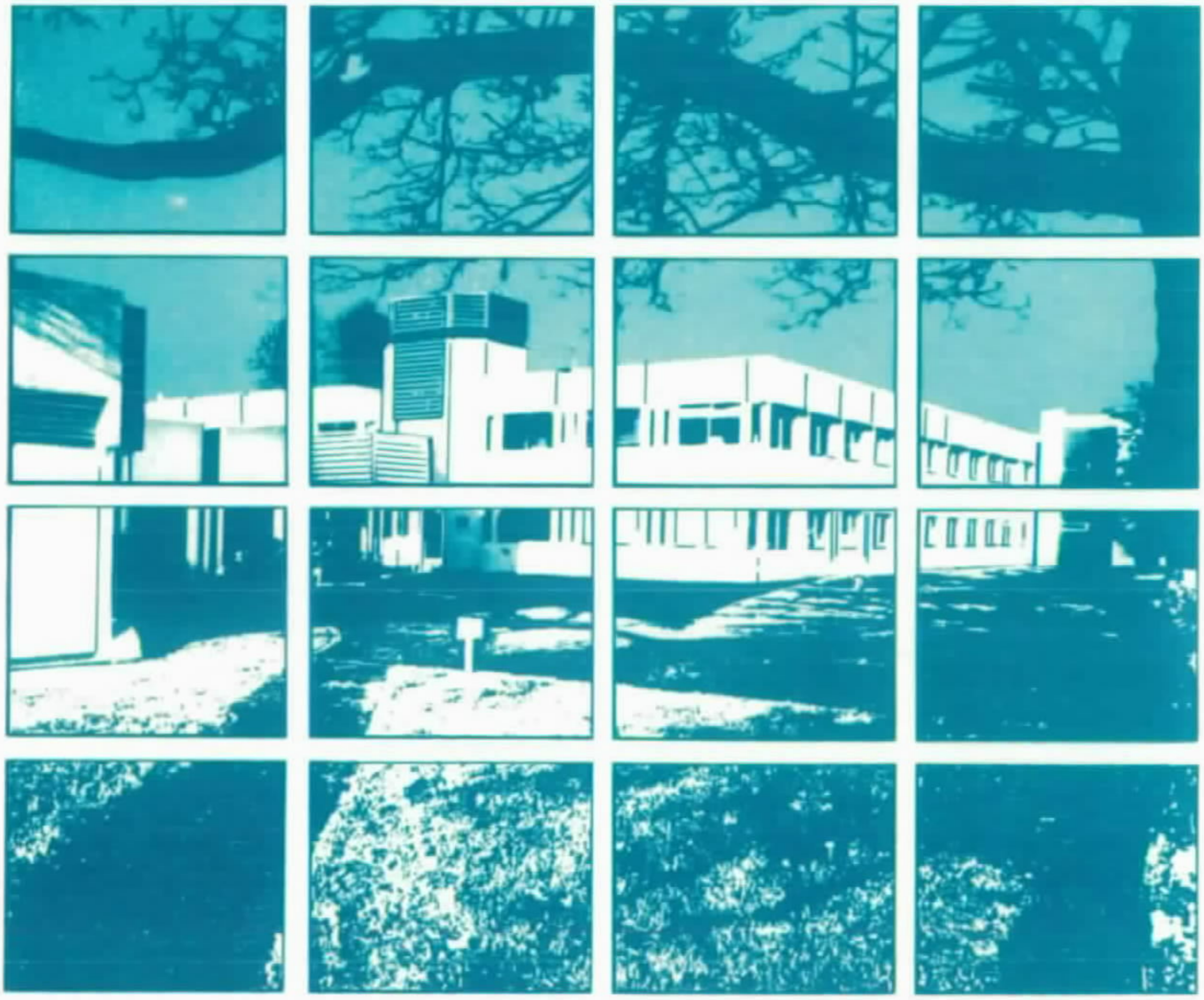
Institute of Hydrology

Report No. 109

Plynlimon research: The first two decades



Natural Environment Research Council

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Plynlimon research: The first two decades

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Foreword

More than twenty years ago the Hydrological Research Unit, the fledgling Institute of Hydrology, based in the Thames Valley, launched an ambitious project on the eastern slopes of Plynlimon in the uplands of Wales. The original aim of the Plynlimon catchment experiment was to collect data which could resolve the question of the water use of conifer forests. It has subsequently developed into a multi-disciplinary project which has underpinned hydrological research within IH up to the present day and has an important role for the future.

The Plynlimon instrument network has always combined the best elements of traditional manual observation and state-of-the-art technology, and the experimental catchments have provided an outdoor laboratory for the exposure of new instruments and techniques to severe field conditions. Plynlimon has been the testing ground for instruments such as the automatic weather stations and data loggers that are fundamental to the Institute's field operations. The catchment data set from Plynlimon is unique in the UK, possibly in the world, and has served as a foundation and an inspiration for the development of whole families of hydrological models which have gone on to have wide application in the UK and overseas. The Institute's considerable scientific reputation in accounting for and modelling changes in the quality of natural waters is based in part on a detailed understanding of the processes of runoff generation within the Plynlimon catchments, and is supported by a painstaking programme of sampling made possible by the Institute's presence at Plynlimon.

The field office, set up on the outskirts of the Hafren forest to provide simple working space for the tiny field staff of the project, has grown into a more versatile station, with laboratory accommodation, computer facilities and a small staff with a wide range of expertise. The station has external contacts with universities and other institutes, and is host to a stream of visitors from the UK and abroad. Research on the scale of the Plynlimon project has required a long-term commitment of the Institute's resources: this commitment has been fully justified, in that the implications of the project extend far beyond the problems of water use in the British uplands. For instance, the Plynlimon catchment experiment has recently formed an important component of the network of north west European catchment studies adopted by the FREND project.

As with all good scientific experiments, Plynlimon has always yielded a rich crop of new questions as well as answers to old ones, and this tradition looks set to continue into the future. It is pertinent at this stage, therefore, to pay tribute to the foresight of the Institute's first Director, Dr J.S.G. McCulloch, in establishing this pair of representative catchments. Without his courage in making such a massive commitment of resources in the early days of the Institute, we should now be much poorer scientifically. The Plynlimon experiment provides a framework for the consideration of the water resources and water quality implications of large-scale afforestation, and it is now making its contribution to the debate on the effects of acid precipitation. The background of detailed measurements of catchment yield and climatic variables puts Plynlimon into an excellent position for the investigation of the complex interactions between 'natural' fluctuations of climate and the local effects of global warming. The combination of careful measurements carried out in the long term and imaginative scientific interpretation will continue to add considerably to our understanding of the natural world.

W. B. Wilkinson
Director, Institute of Hydrology

Preface

In the course of a long-term scientific experiment, there is a continuous process of reassessment and revision. As the results come in, it is possible to make amendments to the instrument network, and to incorporate new or additional instrumentation as it becomes available. Over the duration of the Plynlimon experiment, the technology of microelectronics has made dramatic progress, and the labour-intensive instrumentation installed at the start of the study has largely been replaced by solid-state devices, freeing staff for the more interpretive aspects of the project. As a stage in the review of the Plynlimon project, it was decided to assemble the data from the experiment, including both the catchment data and the results of process studies and water quality studies undertaken at Plynlimon, in an internal report that could form the basis for planning future changes in the direction of work at Plynlimon.

The preparation of that report was a valuable exercise that has been instrumental in the shaping of the Plynlimon station as it now exists. It was felt that the report, with some modification, could be of interest to a more general readership. Thus the long process leading to this document began.

The Plynlimon report has many authors and draws on the expertise of many sections of the Institute of Hydrology, at Plynlimon and at Wallingford. Research of the scale and duration of the Plynlimon project relies on the collaboration of several different groups. The consequent involvement of many different staff over the years has had the advantage of bringing new dimensions, new insights and new talents to bear. It also makes it difficult to decide upon the right time to draw conclusions as there is always the tantalising possibility that a little more data will add a new dimension. In presenting this report, therefore, it has been decided to focus on the Plynlimon results as they stood at the end of 1985, but also to incorporate some of the more recent, exciting developments. A fuller scientific account of the Plynlimon results is to be found in the many journal papers, books and other publications, most of them referred to in this report.

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A generation of students from Luton College of Higher Education

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Chapter 1
The British uplands and the Plynlimon study

Marked contrasts in geology, physiography, climate and economic activity occur over comparatively short distances within Great Britain. The oldest and hardest rocks, the highest land, the coldest, wettest and windiest climate occur in the north and west, but the majority of the population lives in the south and east where the physical conditions are kinder and where most of the major organs of political and economic decision-making are located. The combination of low population density and high precipitation in the uplands is the basis of their importance for water supply. Pastoral farming, forestry, sporadic mineral extraction and recreation are the major economic activities of these regions, which, when they take place on water catchments, can have effects on water quantity and quality that lead to a conflict of interests. The objective of the Plynlimon experiment is to understand the relationship between land use and water yield so that these conflicts may be resolved.

Physical diversity is the chief characteristic of the British uplands and efforts to bring about a better economic balance between upland and lowland Britain have generally been made against a background of inadequate information. As an example, 20% of the total surface of Britain is land over an altitude of 300 m (Harrison, 1974) but only 4% of the country's climate stations were located in these upland areas at the outset of the project.

The Plynlimon study is based upon the collection of a wide range of geographical and hydrological data, ranging from climatic averages to records of sediment output. However, the main aim of the study was and is to compare the hydrological behaviour of grassland and forest and to determine the processes that control this behaviour. Although studies of the hydrological effects of different land uses were an early stage in the development of scientific hydrology in other parts of Europe and in North America, it was largely through the work of a water engineer, Frank Law, that this topic was introduced to Britain. It was his study of Stocks Reservoir on the headwaters of the River Ribble (Law, 1955; 1956) which first sought to answer for British conditions the question, "Do trees use more water than grass?"

Since mid-Victorian times, and the realisation that water pollution brought about disease and death, a large part of the British lowland urban population has looked to the uplands for an abundant supply of clean water, supplied relatively cheaply by gravity. The Victorian reservoir in upland Britain has a very characteristic appearance: an impressive masonry dam, backed by a tree-ringed lake, with grazed moorland comprising the remainder of the catchment. Occasionally both lake and catchment perimeter were fenced or walled, in the interests of keeping the water pure by preventing trespass. Any debate about the characteristics of the catchment influencing the water supply centred on the prevention of disease, especially after a typhoid outbreak arose from a lowland supply reservoir (Ministry of Health, 1948).

Whilst the warmer periods of the post-glacial era had encouraged the spread of deciduous woodland over much of the British uplands, climatic deterioration, industrial exploitation and successive waves of settlement have been responsible for the loss of most of the deciduous trees. Even in the remnants of forests, timber extraction continued without replacement, so that in the 1914-1918 war Britain experienced a timber shortage when the colonial produce normally imported by sea was blockaded. To secure supplies for the future, the Forestry Commission was established in 1919 to carry out re-afforestation. The Commission chose the uplands for the largest areas of planting because land there was relatively cheap, and planted conifers for their rapid growth characteristics.

The uplands present a hostile environment for agriculture, and with competition from imports and lack of financial investment, upland pastoral farmers between the wars were frequently close to bankruptcy. The food shortages of the 1939-1945 war prompted the introduction of government protection for, and investment in, farming (Beresford, 1975), a policy of particular benefit to upland farmers. This policy continued to benefit upland farming and it experienced a further fillip from 1972 onwards when the EEC Common Agricultural Policy was applied. Indeed, upland agriculture became so much more attractive that land prices rose and the acquisition of land for forestry, although also government-financed, declined (Mather,1978).

When Frank Law performed his experiments, he was concerned that plantation forestry was replacing moorland on his catchments. His results showed that the conifers caused extra losses of water owing to interception by the canopy and evaporation of the intercepted water. He stated quite firmly that water was a more economically justifiable harvest from upland areas than either livestock or trees, and that afforestation led to significant costs in replacing lost water resources.

Law's experiments were on relatively small plots of land, calling into question the validity of extrapolating them to the drainage basin scale and the use of the results to back up economic arguments. The hydrological effects of afforestation demanded research on a larger scale and it was to this problem that the newly-formed Institute of Hydrology addressed its efforts in the first instance. Subsequently, the Institute's research has covered most other aspects of man's interaction with the hydrological cycle.

The Institute's main approach to studying the effects of afforestation on the hydrological cycle has been the instrumentation and operation of a pair of research catchments. The catchments selected for study were the headwaters of the Rivers Wye (grassland) and the Severn (mature conifer forest) on an upland massif (Plynlimon) in central Wales (Figure 1). The Plynlimon catchments have been used to investigate other hydrological problems concerned with the effects of land-use on the flood hydrograph, for example on drought flows and on aspects of water quality. The site is also used by university researchers and other agencies because of the extensive data set now available. Results from this experiment have been applied to the whole of upland Britain.

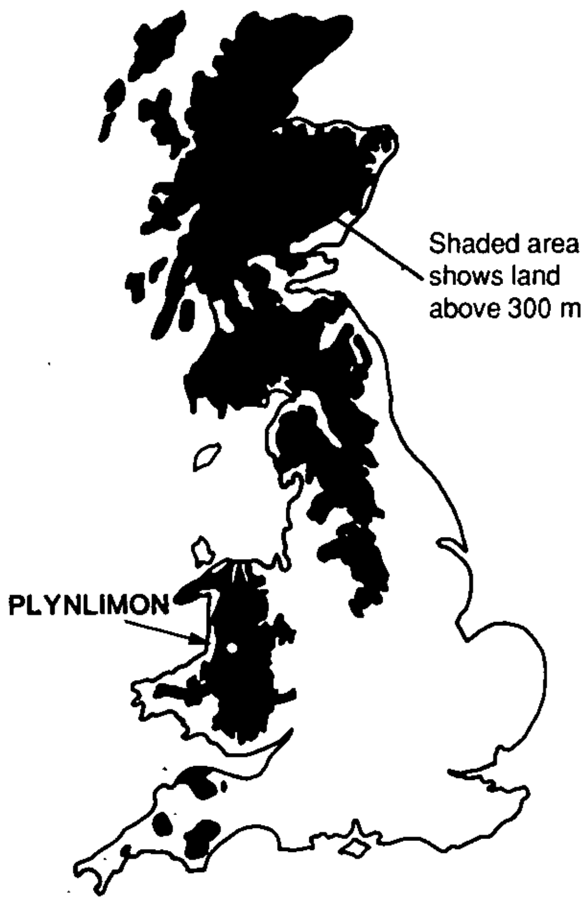


Figure 1a. Location of the Plynlimon research catchments

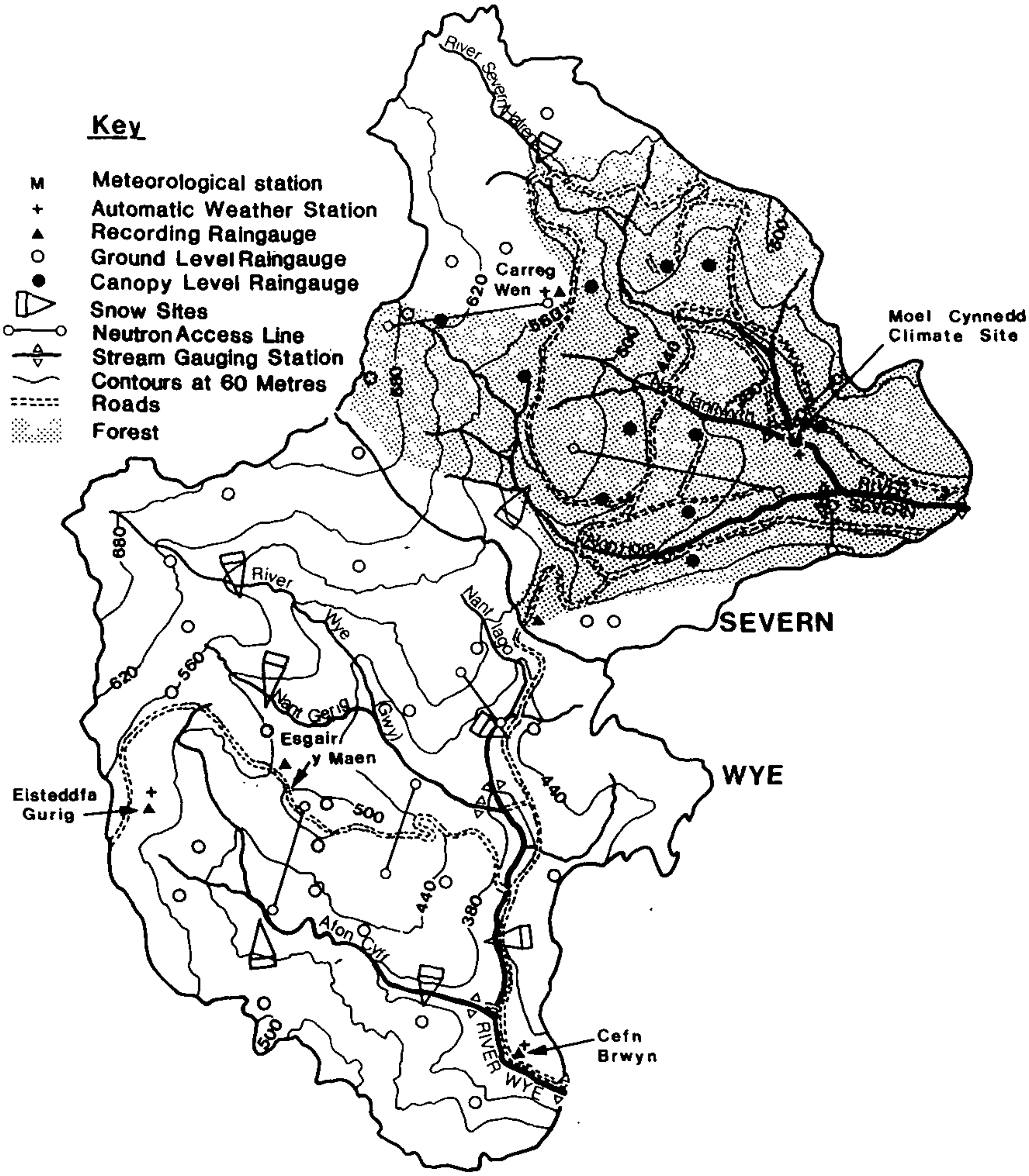


Figure 1b. The Plynlimon research catchments, showing the Rivers Severn and Wye and their tributaries and the main measuring networks.

1.1 The catchment approach to studies of land and water interaction

The catchment* is the fundamental unit for most hydrological research. The water budget of a catchment can be partitioned into simple terms, with no surface or subsurface inflow, and all lateral outflow can be concentrated to flow through a single measuring structure.

During the International Hydrological Decade 1965-1974, two main types of research catchment were specified: representative and experimental. The former were instrumented to collect measurements of all or most of the components of the water balance to typify certain climatic, physiographic or land-use zones. The latter, by definition, required, in addition, a specific experimental investigation such as changing the land use during the period of investigation. The Plynlimon study incorporates both types of catchment.

The basis of the Plynlimon experiment is a 'twin catchment'approach, in which two catchments are selected to be similar in all respects except land use. As the experiment has gone on, it has been possible to monitor changes caused by land-use practices in a catchment whose hydrological processes are now understood after years of study.

A major decision in catchment research *(i.e. a defined area where input, output and storage changes are measured)* is the choice of size of catchment. There has to be a compromise between the necessity to obtain results relevant to large areas and the needs of the measuring systems, which are more precise (for a realistic level of expenditure) over small areas. Where land use or land management is concerned, good experimental design demands that a large proportion of the area of the catchment is covered by a single land-use unit, whether of vegetation type or management practice. Of 252 catchment studies listed by Da Costa and Jacquet (1965), only 18 were as large as 20 km^2 (the total area of the Plynlimon catchments is 19.25 km^2). The Plynlimon catchments are thus among the largest of their type. Even at such small scales, however, it is unlikely that each individual catchment area will be a single runoff unit. Consequently, attention is given to identifying the smaller units which build up the research catchment.

Scale problems are inherent in a synthetic approach, since many of the processes of hydrology are themselves dependent on area or channel length (e.g. rainfall intensity, routing). A compromise is inevitable: measurement of the water balance characteristics of each runoff domain within a small catchment, especially if statistically rigorous in experimental design, would be prohibitively expensive. Consequently most catchment studies adopt a general network coverage. This reduces both experimental control and the applicability of the results, even to larger areas of the same catchment.

Environmental variables cannot be controlled in a long-term study and changes may occur with time. To give full account of environmental changes and the effect of gradual changes in land use, many more variables may need to be measured than would be the case in a fully controlled experiment. The occurrence of climatic extremes must be provided for in the design of instruments, and the instruments and their layout must be kept under review so that the measurement programme remains effective under changing circumstances.

** The term "catchment" is used in this report, although "basin" is in more common international usage and "watershed" is employed in the United States of America.*

1.2 The Plynlimon study: a short history

There were four major criticisms of Law's study at Stocks Reservoir (Law, 1956, 1957). One was that the plantation where the forest lysimeter was located was so small that edge effects might account for the results obtained. The second was that the lysimeter leaked (Chard, 1985). The third was that the results from a small plot in one part of Britain did not necessarily apply to the whole of the British uplands. Finally, there was the paradox that the extra evaporation demanded by Law's results required extra energy but there was no obvious source for this extra energy. Hence enhanced evaporation should not occur at Stocks Reservoir, nor at any of the other sites where the results seemed to show that trees used more water than grass. These and other criticisms of Law's studies have been re-examined in the light of a recent appraisal of Stocks Reservoir results (Calder, Newson and Walsh, 1982) which found them to be almost identical to those from similar, previous studies. It was felt, therefore, that a catchment experiment would overcome some of the difficulties inherent in Law's lysimetric method.

In the ensuing search for suitable catchments there was a need to select one with extensive mature forest cover in a region representative of "reservoir country". Because of the urgency of the study, a truly experimental approach, i.e. long-term observation starting at the afforestation stage, was ruled out: coniferous plantations in the British uplands take at least 25 years to mature to the first thinning stage. Instead in 1967 a representative pair of catchments was chosen, the Upper Wye being occupied by a fairly traditional sheep farm (Plate 1, top), while its immediate neighbour to the north, the Severn, was entirely owned by the Forestry Commission and approximately 70% afforested (Plate 1, bottom). Initially a ten-year study was proposed. However, the forest (Hafren Forest) was first planted in the 1930s, and parts of it were likely to reach maturity in the 1980s or 1990s. This made it possible to plan to investigate the effects of felling and timber harvesting during the study. The early stages of afforestation have subsequently been covered by work on the Institute's experimental catchments at Llanbrynmair, mid-Wales and at Coalburn in Cumbria.

Instrumentation began in 1968 with the peak of effort occurring ten years after the project was initiated. This length of time was necessary because of the logistics of the experiment, the need for long-term data and the development of special instrumentation.

1.3 The physical background

The general physiography of the Wye and Severn catchments is similar: one would expect almost identical basins from the fact that the rivers flow from adjacent portions of the same upland massif. This massif is composed of Lower Palaeozoic rocks (Ordovician slates and Silurian mudstones); it marks the crest of the Teifi anticline (Bowen, 1977). The landscape bears a considerable imprint of Quaternary glaciation and periglaciation. Newson (1976a) gives a detailed historical account of the geomorphological development of the Wye and Severn; only the present-day morphology is described here.

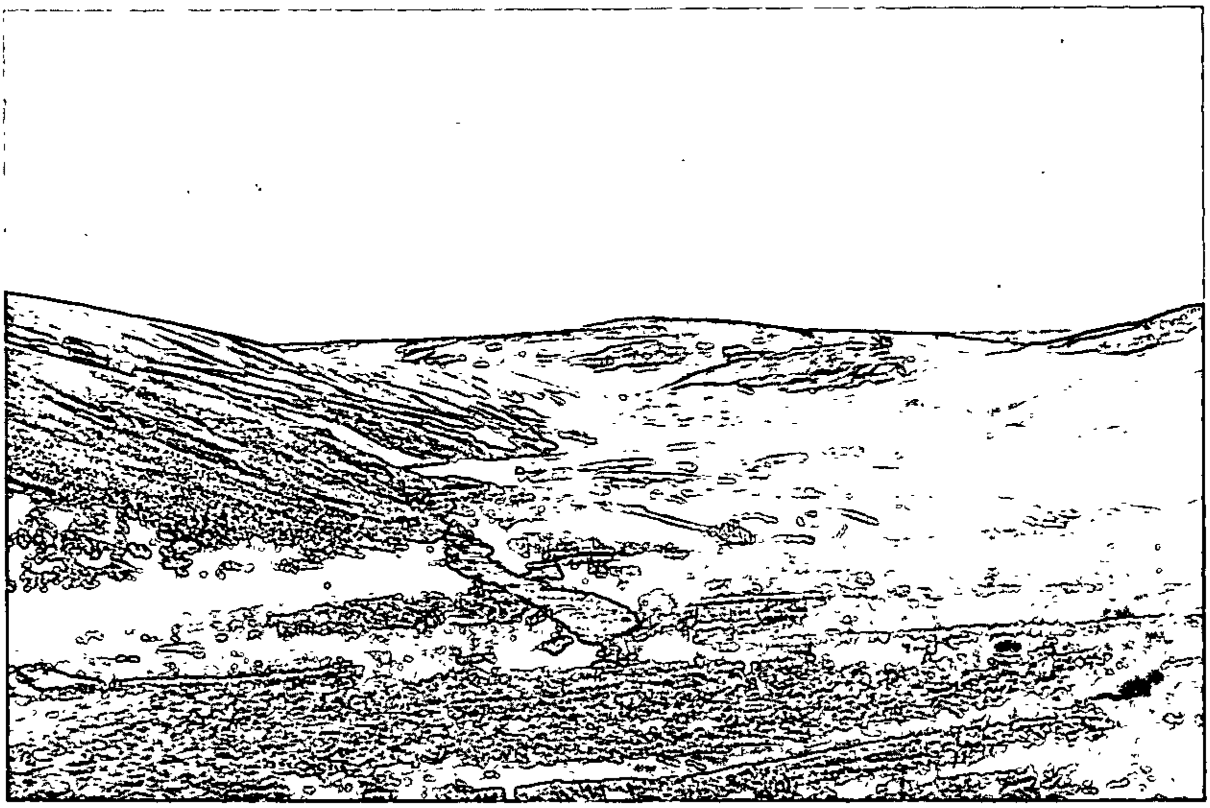


PLATE 1 Views of the Wye catchment (top) and the Severn catchment (bottom)

Physiography

The landscape of Plynlimon is dominated by rolling hills dissected by steep valleys. The altitudinal range is from 319 m ODN in the Severn and 341 m in the Wye up to 738 m. In terms of slopes, the Severn is locally steeper than the Wye catchment. Both catchments have limited development of valley flat areas associated with short alluvial reaches. Most reaches are confined within valley side slopes.

Most streams are flowing over bed rock, sometimes with a shallow covering of river sediments. The long-profiles for each of the main channels are shown in Figure 2. The irregularities in the profiles are typical of British upland channels. The steps often coincide with resistant bands of rock. Such rock controls are apparent in both catchments. With regard to the catchment surface, overland slope angles are illustrated in Figure 3. Although there are slope angles greater than 25° which are

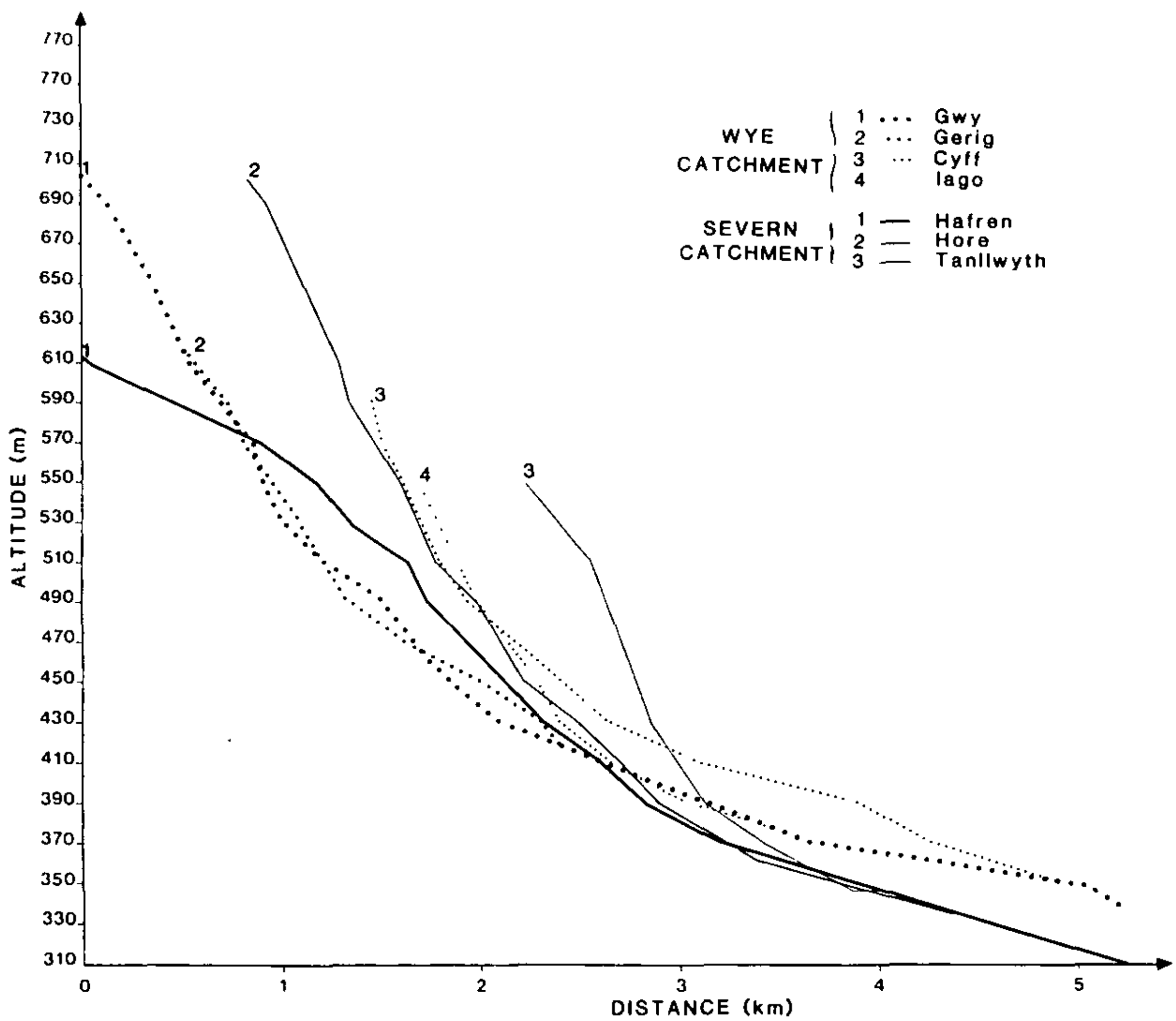


Figure 2. Long-profile of Severn (solid lines) and Wye (dashed lines) channels. (From Huntings 1:5000 survey via program STREAMSLOPES.)

local to the lower parts of the Wye catchment, the vast majority of slopes in both catchments are in the range 0° to 15°.

The major differences between the two catchments concern the degree to which the extensive Tertiary plateaux of Plynlimon (Brown, 1960; Rodda, 1970a) are crossed by their tributary streams, and the different directions the mainstreams follow to the coast - the Severn taking the more circuitous route (Figure 3).

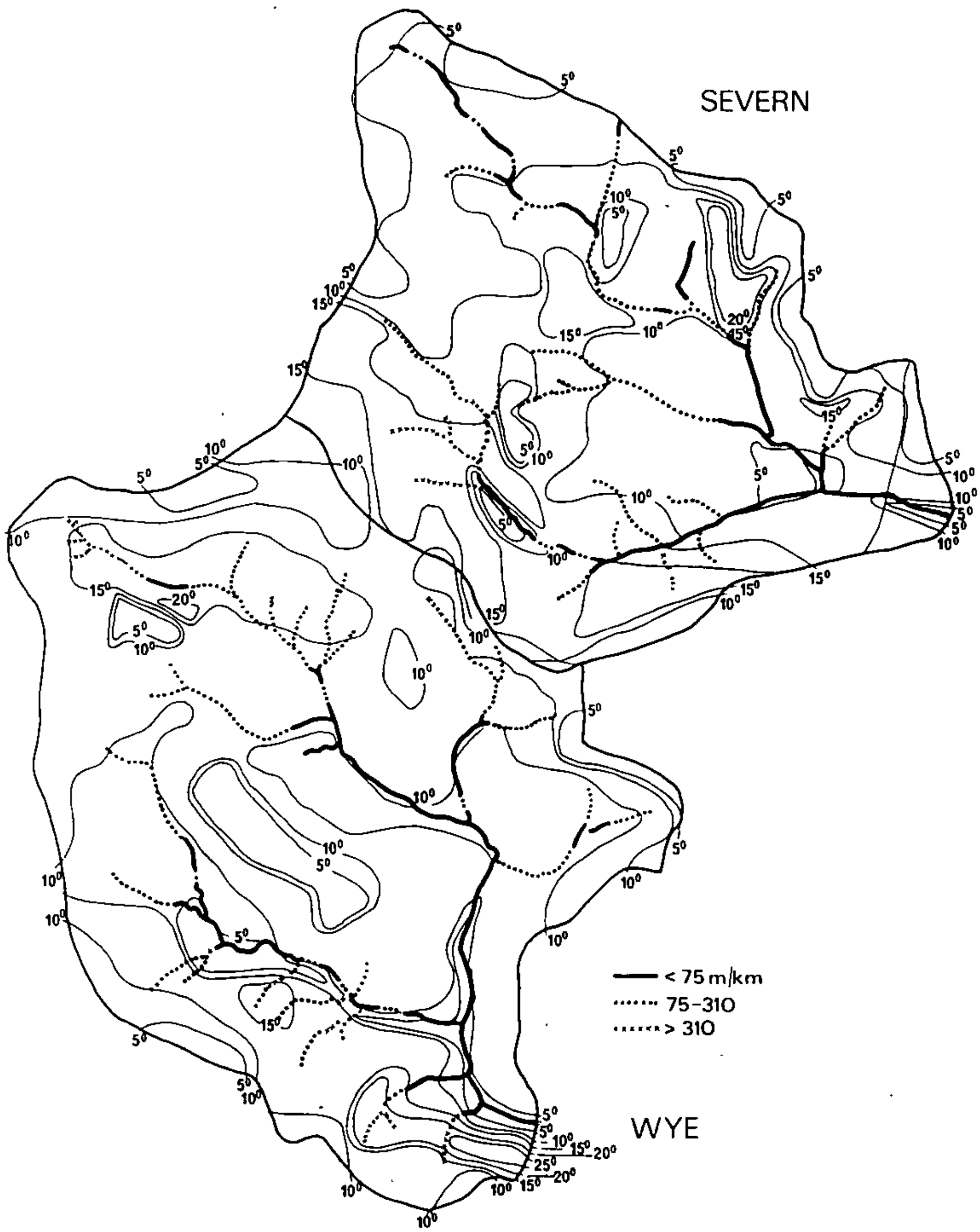


Figure 3. Overland slopes and channel gradients, Plynlimon catchments

TABLE 1: Morphometric analysis of the Plynlimon catchments

	WYE	SEVERN
Area	10.55 km^2 *	8.70 km^2 *
% forest	1.20%	67.50% +
Strahler order	4	4
Drainage density	2.04 km km^{-2}	2.40 km km^{-2}
Stream frequency	2.88	3.60
Outline shape (K)	1.36	1.37
(S1085) Main channel slope	36.3 m km^{-1}	67.0 m km^{-1}
Main channel length	7.32 km	4.58 km
Bifurcation ratio	1.54	1.67

** "True areas" (1/cos slope) are Severn: 8.924, Wye: 10.823 km^2*
+ roads, channels, 'rides' and other non-tree areas are included here.
For futher explanation of the terms used in this table, see Flood Studies Report (NERC, 1975).

Soils

Two separate surveys of the soils of the experimental catchments have been carried out by the Soil Survey of England and Wales, one by C. C. Rudeforth in 1967 and the other by R. Hartnup in 1988. The survey by Rudeforth is illustrated in Figure 4. The generalised pattern is of parent materials which are similar throughout the catchments (Palaeozoic grits, mudstones and shales, or drifts composed of them) and therefore soil differentiation is mainly dependent on drainage. Thus the impeded drainage of the plateaux and wider interfluves have led to the accumulation of organic deposits - blanket peat - whilst the more freely draining slope soils are podzolized.

In the valley bottoms, drainage is also impeded and there occurs a complex of peat and gleyed mineral soils, the balance of which at any site is the result of local topography. The main soils of this sequence are shown in Plate 2. Whilst the two catchments are almost identical in soil types, the lower parts of steeper slopes in the Wye are mantled by a free-draining brown earth; steeper slopes in the Severn have skeletal soils or patchy podzols.

The Wye also has small areas covered by the spoil from lead/zinc mines (Jones, 1922; Bick, 1977). These mines were explored before instrumentation of the catchments, both to ensure that they did not conduct water across catchment boundaries and also to establish the water-bearing characteristics of the strata. Geological evidence is that these are watertight catchments: in areas where the soil/drift cover is thin, there is clear evidence of shallow percolation into coarse drift or fractured bedrock aquifers which influence low flow.

However, the topographic boundary with neighbouring catchments is clear, and, with steeply-dipping non-porous strata on the east side of a major anticlinal axis (the Plynlimon dome), there is no reason to suspect major catchment leakage. In retrospect, the study has shown the Wye to have a very similar water balance to that of neighbouring upland catchments in Wales (e.g. Risbridger and Godfrey, 1985; see also Ward, 1981 for a national review).

As well as being important in assessing the representativeness and comparability of the catchments, soils mapping has a major potential for extrapolation of the results of research on (for example) runoff processes or nutrient removal. However, in Britain, progess in mapping the country at a similar scale of detail to that available for Plynlimon has been very slow. Consequently vegetation mapping has been investigated (Newson, 1976b) and shows that the plant

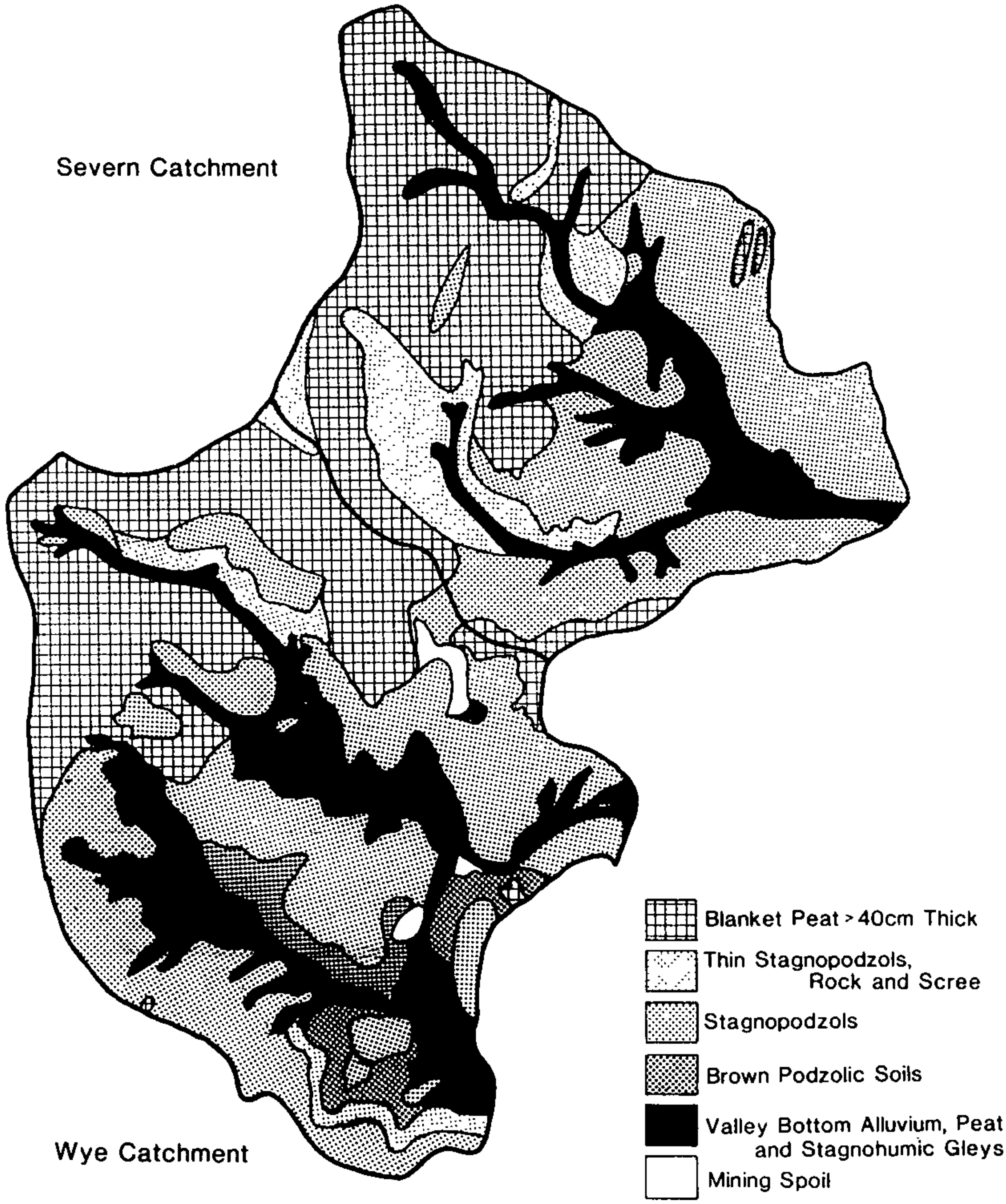


Figure 4. Generalised soils map, Plynlimon catchments

communities of the Wye and of the unforested parts of the Severn are sufficiently unaltered by pastoral farming (except in a historical sense) to be satisfactory indicators of soil moisture status. Indicator species have been identified but nevertheless the simplest sub-division resembles that for soils: heaths on the peaty plateau, grasslands on the free-draining slopes and mires in the valley bottoms.

PLATE 2 The simple catenary sequence of soil types at Plynlimon: (a) Blanket peat, (b) Podzol, (c) Gley

Vegetation

Even before the intervention of large-scale forestry and grassland improvement, the vegetation of Plynlimon consisted of 'semi-natural' communities, dominated by those species which could tolerate close cropping by animals. The slopes have been grazed by ponies and sheep since the Middle Ages. The Nature Conservancy Council has recognised the importance of the resulting habitat: it has recently designated the higher slopes in the Plynlimon catchments as part of a Site of Special Scientific Interest (SSSI).

Three main communities may be recognised: heath, acidic grassland and mire. The heath is dominated by two species of cottongrass, *Eriophorum vaginatum* and *E. angustifolium*, in association with the bilberry *Vaccinium myrtillus*, the heather or ling *Calluna vulgaris* and the matgrass *Nardus stricta*. Eroded blanket mire has reverted to heathland and the cottongrass *E. angustifolium* is a coloniser of bare peat areas in the heavily eroded upper Severn. By far the largest area of the Wye catchment under semi-natural vegetation consists of acidic grassland dominated by two species, the matgrass *Nardus stricta* and sheep's fescue *Festuca ovina*. These characterise the long, well-drained slopes with podzol soils. Other mixed communities with sheep's fescue include arctic alpine species near the summit of Plynlimon.

Although there is some surviving blanket mire on the flatter interfluves, most true mires are located in the valley bottom, extending upslope along the lines of rush flushes. These mesotrophic mires are dominated by the purple moorgrass *Molinia caerulea* and by the soft rush *Juncus effusus*. The moorgrass produces a characteristic tussock structure; it produces dry litter and is often burned to promote new shoots for grazing. The Wye catchment is 98.8% grassland, while in the Severn forestry is dominant, covering 67.5% of the catchment.

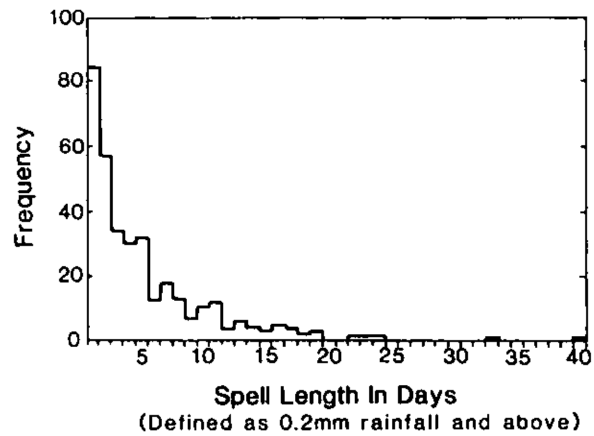
1.4 The climate of Plynlimon

The characterisation of the climate of an experimental catchment and its surrounding area is an integral part of any hydrological investigation, facilitating the eventual application of the results to an area that the experimental catchment is designed to represent.

It is known from previous work on the relation between climate and evaporation, particularly that of Penman (1948), that such variables as temperature, humidity deficit, wind speed, solar and net radiation and soil moisture deficit are of major importance. The climate regime also controls the nature of the indigenous vegetation and dictates the success - or otherwise - of the exotic species (e.g. ryegrass and Sitka spruce) being planted to increase productivity and to make better economic use of the land. Rainfall depth, intensity, duration and frequency also define the amount of water available for evaporation and the rate at which rainfall is transformed into runoff.

It was realised at an early stage in the experiment that meteorological conditions would vary markedly across the catchments A network of eight automatic weather stations was set up on four sites (duplicated stations giving increased reliability) with other stations set up at various times to accompany particular process studies. In extreme conditions, sophisticated instrumentation is always the first to fail, and for this reason a manual climate station, run to Meteorological Office specification, has been operating at Moel Cynnedd (altitute 358 m) in the Hafren Forest since the experiment began. The existence of at least one traditional climate station which could be tied into a national network has been an essential part of the study; it has provided continuity and provides a basis for interpreting the catchment results in the context of other upland areas.

At this stage in the report, the salient features of the Plynlimon climate are described in relation to the climate of the British uplands as a whole: for a general review see Taylor (1976) or, for Wales alone, Howe (1957). Newson (1976) pointed to a marked autumn/winter rainfall maximum: 60% of the total falls between October and March. November, December and January together account for nearly 40%



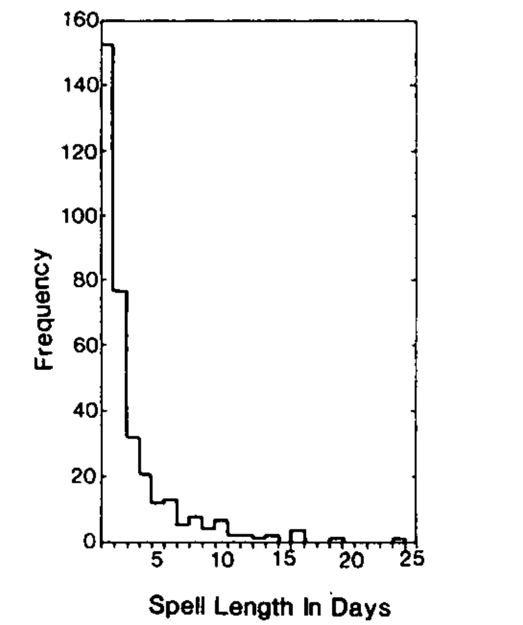


Figure 5. Frequency plots of wet and dry spells of days, Moel Cynnedd, Plynlimon

of the total, and the average number of wet winter days is 120 (two-thirds of winter days record precipitation). There were 137 days between 1 September 1974 and 31 January 1975 when rain occurred. The frequencies of wet and dry spells, which have a clear bearing on interception, soil pipe formation and many other aspects of the study, are shown in Figure 5. Nearly 75% of rainfall occurs from the westerly synoptic type (Lamb, 1972), 10% from a cyclonic circulation, and the showery northwesterly type is the only other principal contributor.

Cold front waves and warm sector orographic rainfall are responsible for most heavy rainfall. Studies of the nature of orographic rainfall in England and Wales (Browning and Hill, 1981) have shown that it is the enhancement of storm rainfall intensity from under 2 mmh^{-1} at the coast to between 4 and 10 mmh^{-1} over hills which is the principal orographic effect. It is the result of rainfall from upper level "seeder" clouds passing through "feeder" clouds which cloak the hills and mountains. By combining radar and raingauge estimates, the pattern of enhancement has been mapped for airstreams giving different wind directions and speeds. Over Plynlimon, enhancement is between 2 and 4 mmh^{-1} with winds from a west-south-westerly direction; the other major wind direction producing such an enhancement is a south-south-westerly (if of sufficient strength). The contribution of snow to the annual precipitation total is highly variable but averages only 5% by volume.

Newson (1985) contains details of analysis of the records from the Moel Cynnedd climatological station, including mean monthly temperature over the whole period, soil temperatures and wind-run over short periods. Although Plynlimon is not a site with a major snow problem, low temperatures, strong winds and wet, cool soils dominate the year, leaving a short growing season in which ground frost still affects valley sites by night. Gilman (1980) provides data which indicate low soil temperatures at Plynlimon; Green, Harding and Oliver (1984) suggest further cooling of the soil under a forest cover.

Mean annual temperature at Moel Cynnedd fluctuated by 0.7°C. The mean annual maximum daily temperature ranges between 10.5 and 11.6°C and the minimum from 2.9 to 3.7°C, giving annual averages of 11.0 ±0.1°C and 3.4 ±0.1°C respectively and a mean annual temperature of 7.2°C. The range of mean monthly temperatures for Moel Cynnedd is 11.4 degrees, which is midway between the maritime station with a small annual range, such as Valentia on the south-west coast of Ireland with 8.6 deg C, and more 'continental' type stations illustrated by a range of 13.7 deg C at Heathrow, west London. The highest maximum recorded in a ten-year period between 1968 and 1977 was 29.1°C on 3 July 1976 and the lowest minimum was -14.4°C on 31 January 1972. Since the analysis of the ten-year averages, the extremely cold winter of 1981-82 produced lower minimum air temperatures at the site, namely -14.6°C on 13 December 1981 and -16.4°C on 15 January 1982.

The frequency of frost is high at Moel Cynnedd; however, its situation in an area of rough grassland in the floor of an otherwise forested basin should be borne in mind. Grass minima below 0°C normally occur in every month of the year; the only exception in ten years of records was July 1974. In February 1968 and 1969, and in December 1976, there was a ground frost on every night of the month. The annual mean number of days of ground frost is 162 ±4 days.

Similarly, air frost is very frequent, averaging 98 ±4 days a year, and it has been recorded in every month of the year. The implications for plant growth are considerable. The greatest numbers of air frosts occurring in one month within the ten years were 25 each in February 1968 and March 1969 and 24 in December 1976. The monthly mean number of days with air frost again emphasises the late start of spring: March has the most of any month, namely 17, while April still has an average of 13 (one more than January). In Figure 6, the mean monthly air maxima and minima show the slow rise of spring temperatures and the shortness of the growing season, broadly defined as the period when the temperature is below 6°C.

The rigours of the upland climate are especially relevant to the extensive development which upland plateau country has undergone since the war, principally for forestry and farming. Both foresters and farmers have found that it is expensive to counter climatic problems, especially wetness. Windblow affects a sizeable proportion of mature conifer plantations and leaching of expensive fertiliser leads to rapid reversion of improved pasture, unless nutrient levels are topped up at further expense. These problems of climate are mainly advantageous for water harvesting, the third major land use, as high rainfall and low evaporation rates ensure a plentiful supply of water. The reduction of evaporation rates to far less than potential as a result of temperature restrictions on growth is discussed in later chapters. The disadvantages are the leaching and sediment transport and deposition which can cause water quality changes detrimental to the management of the rivers and reservoirs of the uplands.

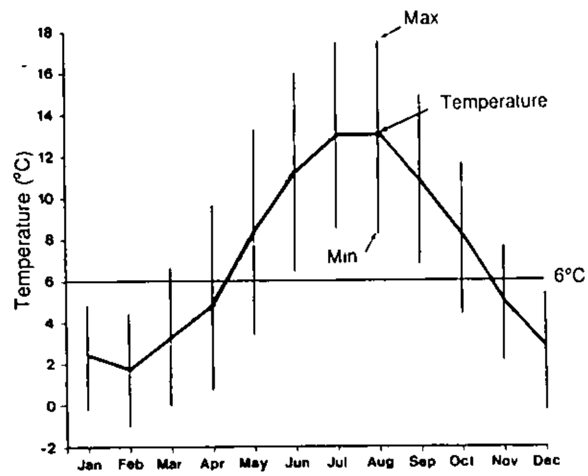


Figure 6. Fifteen-year temperature means, Moel Cynnedd, Plynlimon. The top of each bar represents the mean monthly maximum air temperature and the base the mean monthly minimum. The mean monthly temperatures are joined by the curve.

1.5 Farming and forestry on the catchments

The Wye catchment comprises part of the 2200 hectare estate (5000 acres) of Mr Simon Bennett-Evans, a farmer specialising in the rearing of Welsh Mountain sheep. Around 4000 ewes graze the pasture and lambs are sold in late summer for fattening elsewhere. Replacement ewe lambs are kept on lower pastures and have access to concentrated feed and shelter at night. Hill-pastured ewes are fed with bought-in hay and feed-blocks between Christmas and the late spring lambing. Welsh Black cattle are kept for beef to balance the selective grazing of sheep and to aid fertiliser input to improved pastures. Of the improvement techniques available, the farm was early to experiment with drainage, ploughing, liming, slagging and re-seeding with ryegrass and clover. Sir George Stapledon, the great promoter of upland pasture improvement and founder of the Welsh Plant Breeding Station, writing in 1933, says, "With the Caterpillar tractor you can plough the open hill all right – we have in fact ploughed nearly 100 acres on the foothills of Plynlimon thanks to the lion-hearted endeavours of my friend Captain Bennett-Evans".

None of the catchment has been tile-drained; thus the pasture is atypical of land affected by the enormous post-war spread of tile drainage and plastic drains in Mid-Wales. The Cyff and other valley-bottom bogs were drained in the 1950s by Cuthbertson plough but the ditches have not been maintained as they were considered a danger to sheep. Burning of the valley bottom bogs and *Molinia*-clad slopes was formerly an annual practice, before pasture improvement.

Originally, the Severn catchment was rough pasture for sheep grazing, but the depressed state of farming in the late 1920s and 1930s and low land prices led to government purchase. The planting of conifers which then commenced in the Severn catchment (Figure 7) began in the Hore subcatchment, mainly on the right bank where Norway Spruce (*Picea abies*) were planted in 1937/1938. Most of these early sites were hand-dug for turf planting and fairly sparsely drained (again by hand) because of their naturally well-drained situation. Two later plantings in the Hore were of Sitka Spruce and Lodgepole Pine (*Pinus contorta*) in 1958 and in 1960.

The 1940s saw the introduction of tractor ploughing. A major planting of Sitka Spruce was carried out in 1942 in the lowest, left bank area of the Severn (although Norway Spruce was planted in some areas). At the same time mixed Norway and Sitka spruce were planted on the left bank in the Hafren subcatchment. Sitka spruce and Scots pine (*Pinus sylvestris*) strip plantations divide this part of the catchment into a mosaic. The next major phase of planting did not take place until 1948. Further mosaic planting occurred on the left bank of the upper Hafren, mainly of pure Sitka and pure Norway, but also of Japanese Larch (*Larix kaempferi*) with Lodgepole pine mixed here and there. The years 1949 and 1950 saw the large expanse in the middle of the Severn basin planted with Sitka Spruce, by then proven as the most successful coniferous species except in the most difficult locations.

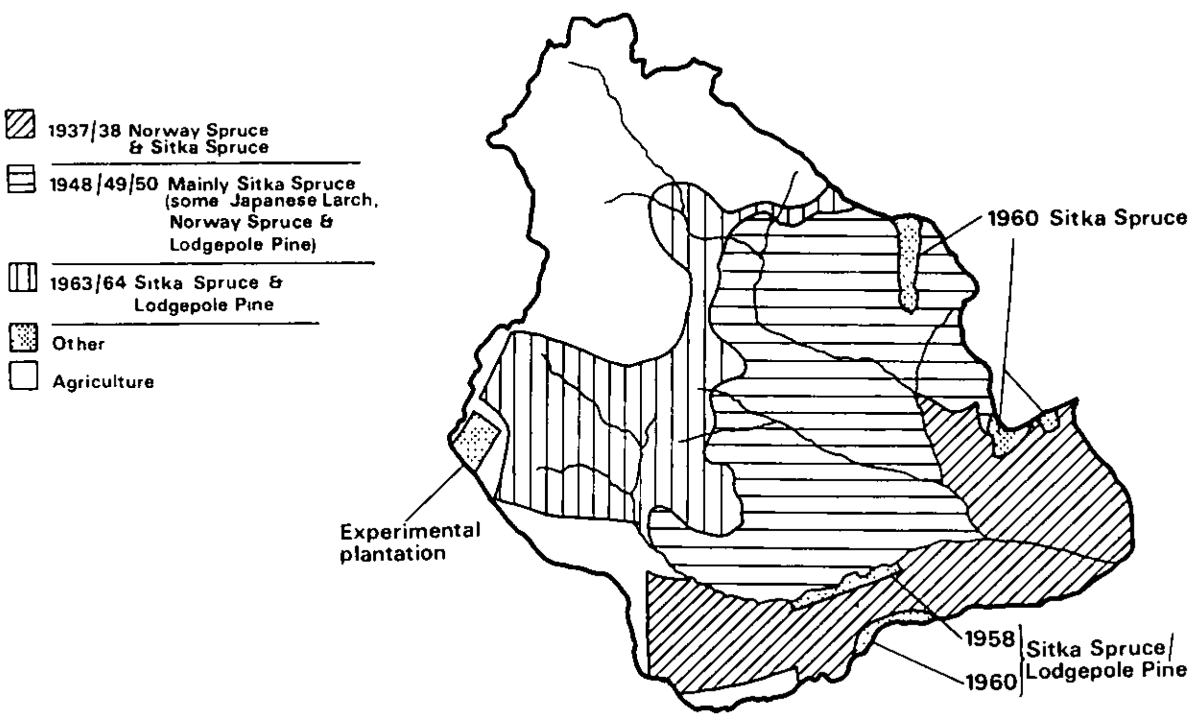


Figure 7. The progress of afforestation in the Severn catchment.

Improvements in drainage machinery allowed larger areas to be drained and planted and it was to even more severe locations that planting turned in 1963 and 1964. For example, in the Upper Hore there is an experimental plantation near the summit of Plynlimon (741 m) at one of the highest altitudes ever tackled by the Forestry Commission. Lodgepole pine also became a feature of planting in the Upper Hafren areas in 1964.

Ploughing, followed by planting on the inverted turf of the ridge, has proved to be a successful procedure in these severe areas, although exposure is considered to be the major reason for the poor performance of the higher plantations. The growth rate of Hafren Forest as a whole was boosted by aerial applications of potash (200 kg ha^{-1}) and phosphate (375 kg ha^{-1}) from September to November 1974, but some problem areas are seriously "in check" or "unusable" because of thin soils, exposure, poor nutrition or boggy ground conditions.

Thinning a commercial conifer crop has been taken for granted until recently as part of production forestry, but the practice has had detrimental effects on the remaining trees in those parts of the country with a windthrow hazard (Hamilton, 1980). For this reason, the practice has been modified, especially in regions of moderate hazard, including Plynlimon. However, damage has already occurred within the Severn catchment, and by 1984 up to 7% of the area of the subcatchments of the Severn had been clear-felled as a result of windthrow.

Chapter 2
Quantifying catchment water balances

Virtually all hydrological studies depend to a large extent on the continuity or water balance equation; this enables assessment of a water flux into or out of a system when other inputs and outputs are known. To assess evaporative losses from catchments the water balance equation is arranged thus:

$$AE = P - Q - \Delta S - \Delta G$$

where AE = actual evaporation
P = precipitation input
Q = streamflow output
ΔS = change in soil moisture storage (positive)
ΔG = change in groundwater storage (positive)

The equation assumes that, in spite of movements of water into and out of soil moisture, drift and solid geology, ultimately no water flows from the catchment other than through the flow gauging structure.

The water balance variables can be accumulated over any period to suit the time increment of evaporation required. For periods of one year or more, the change in storage within the catchment becomes insignificant compared to the magnitude of the main variables and the equation effectively reduces to:

$$AE = P - Q$$

For accurate assessment of evaporation over time increments of less than one year – or if ground conditions differ at the start and end of a year – then changes in storage have to be assessed; the shorter the time interval required the more significant becomes the precision of the estimate of storage.

In addition to quantifying the differences in evaporation between the Plynlimon catchments, a major aim was to explain the differences. By their nature, small scale plot studies reveal more about the processes involved in the translation of rainfall to runoff, and the studies performed at Plynlimon are explained more fully in Chapter 4. However, to be of more general use, the processes have to be integrated on a catchment scale.

One aim of the catchment study, therefore, was to quantify separately interception, i.e. the direct evaporation of free water on the vegetation canopy, and biological transpiration, using a combination of catchment and canopy water balances.

When the study started, satisfactory methods for establishing the areal mean precipitation, net rainfall, streamflow and storage changes were either unavailable, untried or untested. The first stage of the experiment was devoted to refining instrument and networks so that they could be used with confidence to achieve the required objectives. The techniques and methods described here represent the culmination of the gradual development of reliable instrument networks, operating procedures and data processing techniques.

2.1 Input assessment

Water is input to catchments in all its phases: liquid in the form of rainfall, solid in the form of snow or hail, and gaseous, in the form of condensation on vegetation or snow packs, for example. Of these, rainfall and snow are the most important volumetrically, although the importance of the input of latent energy during condensation to snowmelt and the deposition of pollutants in cloud droplets during occult precipitation are both discussed in the respective contexts in later chapters.

2.1.1 Rainfall

At the outset of the experiment, little was known about the true variability of precipitation in the Plynlimon area. Isohyets had been derived by the Meteorological Office for the period 1916-1950 for the former Water Resources Board (Figure 8), but – as over much of Britain – the network consisted mainly of low altitude gauges.

Altitudinal extrapolation was one means of predicting high altitude rainfall but was based on dense networks of gauges in other areas that were not necessarily relevant to the specific conditions in mid-Wales. With honourable exceptions, gauges had often been located for the convenience of observers.

Although many reservoir catchments in upland Britain contained extensive rain-gauge networks at the time the Plynlimon study commenced, few advances had been recorded in the methods of designing those networks. The major influence was no doubt

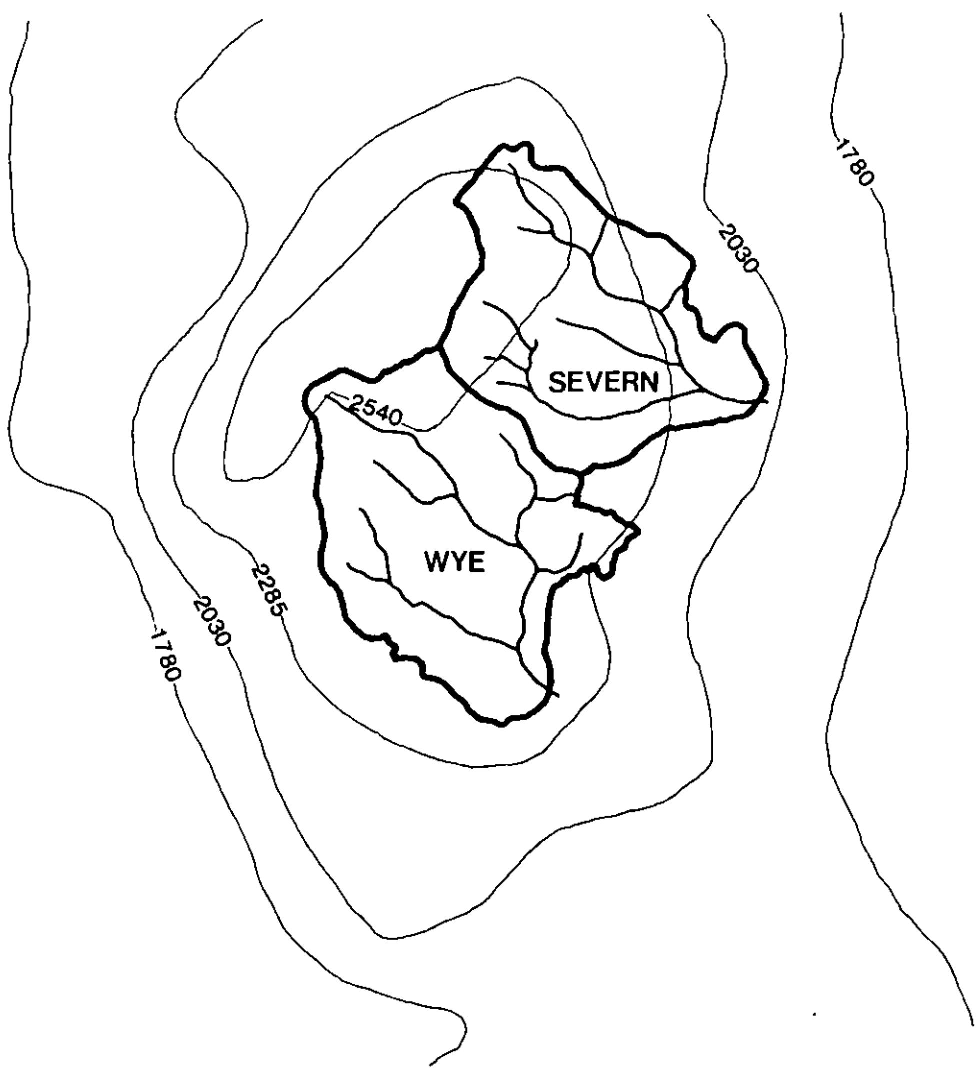


Figure 8 1916-1950 mean annual rainfall (from Water Resources Board 1:250 000 scale maps) the Report of the Joint Committee to Consider Methods of Determining the General Rainfall of any Area (Smith *et al.*, 1937). This was exemplified in water balance papers for the Elan (Risbridger and Godfrey, 1954), Derwent (Thompson and Saxton, 1963) and Alwen valleys (Lewis, 1957).

In previous work to the west of Plynlimon in the Rheiddol catchment (Howe and Rodda, 1960; Rodda, 1962), relationships had been established between rainfall amounts and altitude and other gauge site characteristics. These ideas were applied to the design of the Plynlimon network by the domain approach. Attention had also been given to the problem of gauge exposure, with one series of experiments resulting in the development of the turf wall (Huddleston, 1933). Further experiments on raingauge performance (Rodda, 1967a; Rodda, 1967b) had demonstrated that a ground-level raingauge provided a 'more nearly true' measurement of rainfall. It was appropriate that the domain approach and the ground level raingauge were combined in the Plynlimon network.

Network design

The raingauge network was established by siting gauges on a stratified random sampling basis. Domains were parts of the catchment defined by discrete combinations of classes of altitude, slope and aspect. These classes are shown in Figure 9 alongside a domain map constructed from the 1:5000 map of each catchment: this had been commissioned in 1967 from Hunting Surveys.

Each altitude class has an interval of 99m on the Wye and 104 m on the Severn. Slope was determined from calculation of the vertical separation in each square of a 0.25 km grid drawn over the map, followed by the construction of isopleths at 10° intervals to show slope distribution. Aspect was mapped by delineating areas of approximately uniform direction of ground slope, using the minor watersheds and stream courses as boundaries. The domain map (Figure 9) consists of 38 different altitude-slope-aspect combinations out of a possible 48. These are not necessarily circumscribed by a single boundary but are distributed as a series of domains over the catchment, which when combined form a single domain class. The map shows 275 such domains.

One raingauge was installed at a randomly selected location in each domain which contributed more than 2% of the total area of each catchment. Other domains were gauged where there would have been obvious gaps in the network, for example where a particular class of altitude, slope or aspect would have contained no gauge or a catchment would have been under-represented. A particular problem involved slope class 3 in the Wye, which initially contained no gauge and caused considerable statistical difficulties during domain analysis. This was rectified with the installation of a gauge in the Lower Wye A32 domain in December 1973.

Installation of the raingauges began in November 1969, but records before April 1971 are incomplete because of the consistent failure of gauges specially designed to record daily totals over a 32-day period. These 32-day gauges were eventually replaced by gauges which accumulate the total rainfall over a period. The storage gauges were supplemented by a smaller network of recording gauges with which it was intended to distribute the catches of the storage gauges using the ratios of their period catches. The completed storage network, established by April 1971, consists of 39 monthly-read period gauges, 18 on the Severn and 21 on the Wye. Those in the grassland Wye and the unforested part of the Severn (7 gauge sites) are set in pits, with their orifices at ground level in the same plane as the slope, and surrounded by a grid 1.33 m^2 to prevent

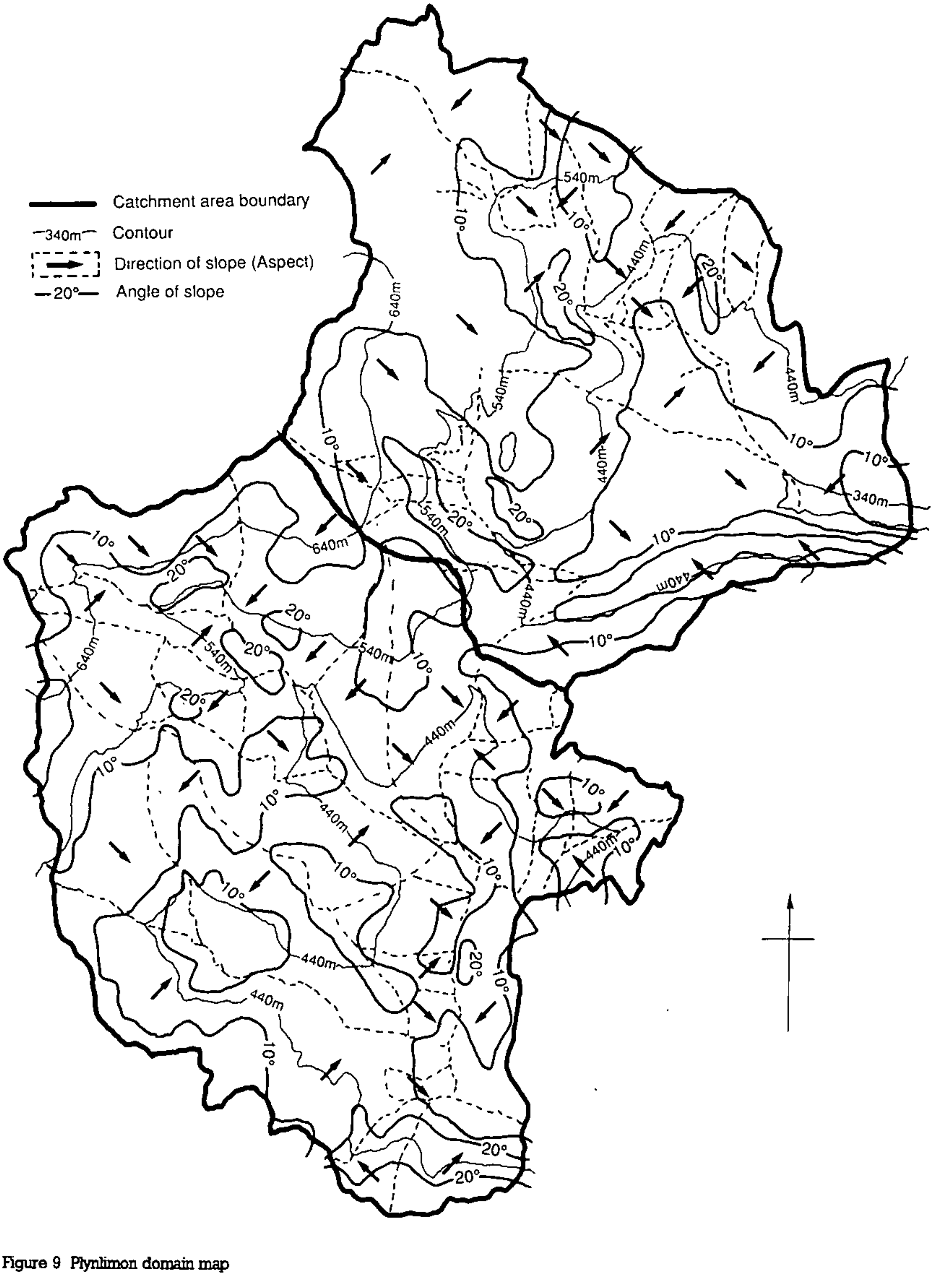


Figure 9 Plynlimon domain map

splash (Plate 3) and to simulate the aerodynamic roughness of the surrounding vegetation. More recently a 1.22 m² grid has been used to increase the strength of the grid and to enable the supporting base to be made from standard ply sheets. The gauges in the forested Severn have their funnels mounted on masts at mean canopy level or above: their funnels are all horizontal.

The raingauge used at the ground-level sites is the standard storage gauge (Octapent). The forest gauges are funnel gauges which were supported initially by scaffold pipe connected by polyethylene tubing to a collector at the bottom. Later these gauges were mounted on proprietary triangular-section masts, with their funnels set above the general canopy level (Plate 4).
Both ground-level and canopy gauges are known to give erroneous catches during snow; the ground-level gauge pit tends to fill up and encourage a drift across the funnel, exaggerating the precipitation total after a thaw; this is due to the conical flow lines of meltwater in the pack overlying the funnel.

PLATE 3 Ground-level raingauge in slope class 3 (>20°)

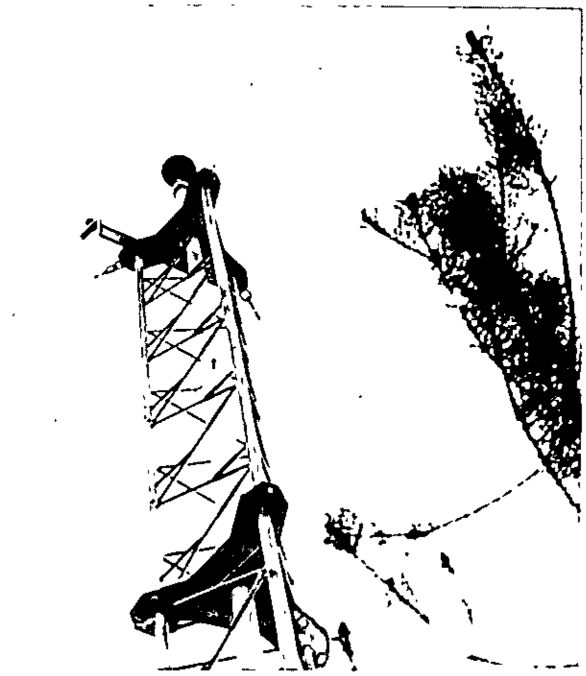


PLATE 4 Canopy-level raingauge

The small canopy-level funnel undercatches snow because of its limited capacity.

Raingauge performance
A first priority of Rodda's early work on the ground-level raingaguge was the setting up of a number of sites equipped with both standard and ground-level gauges to enable comparison of their catches in areas of varying exposure. The initial analysis was hampered by the short run of data. More recently, the results from their network of sites across Britain have been analysed (Rodda and Smith, 1986; Rodda *et al.*, 1986).

Within the Plynlimon catchments the ground-level gauge has been found to catch between 2% and 16% more than the standard gauge, the value depending on the exposure of the site (Table 2). There are many components of exposure, and quantification of their effects on raingauge performance is complicated. Wind tunnel tests carried out at Southampton University (Robinson and Rodda, 1969) identified windspeed at the gauge orifice as the main controlling variable and this has been

TABLE 2: Comparative annual catches by ground-level and other raingauge configurations at three sites

Year	Dolydd			Moel Cynnedd			Carreg Wen				
	GL	STD	%	GL	STD	%	GL	STD	%	TW	%
1971	-	-	-	-	-	-	2322	1968	85	2164	93
1972	1776	1760	99	2142	2110	98	2574	2219	86	2390	93
1973	1853	1795	97	2398	2332	97	2926	2495	85	2774	95
1974	2301	2236	97	2759	2734	99	3303	2840	86	3116	94
1975	1587	1561	98	2014	2001	99	2543	2113	83	2356	93
1976	1360	1322	97	1653	1645	99	2052	1723	84	1879	92
1977	2020	1998	99	2596	2540	98	3121	2665	85	2875	92
1978	1869	1839	98	2313	2264	98	3088	2414	78	2755	89
1979	2153	2092	97	-	-	-	2214	1801	81	2008	91
1980	2020	1977	98	-	-	-	2537	2146	85	2361	93
1981	1983	1943	98	-	-	-	2721	2289	84	2527	93
1982	1713	1692	99	-	-	-	3088	2419	78	2806	91
1983	2210	2130	96	-	-	-	3355	2683	80	3122	93
1984	1744	1712	98	-	-	-	2559	2047	80	2333	91
1985	2200	2143	97	-	-	-	2801	2187	78	2531	90
TOTALS	26788	26200	98	15875	15626	98	41210	33994	82	37991	92

Dolydd: altitude, 297m, sheltered site. O.S. grid reference SN874905
Moel Cynnedd: altitude 358m, Meteorological Office approved site. O.S. grid reference SN843877
Carreg Wen: altitude 576m, over-exposed site. O.S. grid reference SN 829885
GL = ground level
STD = standard
TW = turf wall
% = catch as a percentage of ground-level catch.

confirmed and quantified by Rodda and Smith (1986) in their field trials. Ground-level gauges are not essential everywhere in the British uplands. However, their relative independence of site problems makes them an indispensable component of a domain-based network in which gauges are randomly located rather than restricted to sites chosen to suit the standard gauge.

When using combinations of different types of gauges as a single network, it is important that there is no systematic variation in their performances. To compare the catch by canopy-level and ground-level gauges, Newson and Clarke (1976) used statistical methods to test the hypothesis that catches by ground-level and canopy-level gauges do not differ, except for random variation. The statistical method used involved isolation of the deviations from the catchment mean caused by altitude, aspect and slope and then quantified the extra differences between gauges caused by the level at which they were set, either at ground or canopy level (see Table 3). This was necessary because the two subnetworks were not evenly distributed across the catchments, with most of the ground-level gauges at high altitude and most of the canopy-level gauges at low altitude.

In 13 of the 24 months analysed, ground-level gauges caught more than the overall mean; in the remaining 11 months they caught less. On average, over all 24 months, ground-level gauges caught 2.8 mm more than the monthly mean (174.4 mm) and the canopy-level gauges caught 1.8 mm less. The level constants showed significant ($P<0.05$) departures from zero in only three of the 24 months (February and March 1972, February 1973). All three were months when snow fell at Moel Cynnedd.

If means are taken over all months when snow fell, gauges at ground level caught 7.3 mm more precipitation over a month

TABLE 3: Parameters l_1, l_2 representing the difference between ground-level and canopy-level raingauge catch, April 1971 - March 1973

	Mean,all gauges (mm)	Ground level (l_1)	Canopy level (l_2)	Snow days Moel Cynnedd
Apr. 1971	71.2	+0.8	-0.5	0
May 1971	75.2	+2.1	-1.3	0
June 1971	192.4	+2.4	-1.6	0
July 1971	71.1	+1.2	-0.7	0
Aug. 1971	217.8	-1.3	+0.8	0
Sept.1971	89.7	+1.5	-1.0	0
Oct. 1971	211.2	+6.9	-4.4	0
Nov. 1971	307.9	+8.9	-5.7	7
Dec. 1971	127.9	-0.6	+0.4	3
Jan. 1972	227.6	+10.1	-6.4	8
Feb. 1972	145.9	+18.6*	-11.8*	6
Mar. 1972	213.2	+21.1*	-13.4*	3
Apr. 1972	301.2	+18.8	-12.0	0
May 1972	145.8	-6.5	+4.1	0
June 1972	198.1	-15.9	+10.0	0
July 1972	141.0	-6.4	+4.1	0
Aug. 1972	123.8	-5.0	+3.2	0
Sept.1972	62.0	-2.4	+1.5	0
Oct. 1972	81.1	-1.6	+1.0	0
Nov. 1972	328.5	-3.5	+2.2	1
Dec. 1972	254.8	-5.5	+3.5	1
Jan. 1973	176.4	+5.7	-3.6	4
Feb. 1973	283.4	+26.7*	-17.0*	9
Mar. 1973	138.6	-8.4	+5.4	1
Overall mean	174.4	+2.8	-1.8	
Mean, months when snow fell	110.4(10)	+7.3	-4.6	
Mean, months when no snow fell	141.5(14)	-0.4	+0.2	

* *denotes statistical significance ($P<0.05$)*

than the mean for all gauges, and those at canopy level about 4.6 mm less. Differences between ground-level and canopy-level gauges were much less evident in snow-free months, when, on average, ground-level gauges caught about 0.4 mm less and canopy-level gauges about 0.2 mm more than the mean for all gauges.

Spatial distribution over the catchments
The statistical difficulties in determining the precision and accuracy of the estimate of mean areal precipitation obtained from a given raingauge network are considerable.

A simple means of doing this is the superposition of a second network of raingauges on the catchment to examine the differences in mean areal estimates given by the two networks. Accordingly, a replicate network of eight gauges was set up for a short period within the Cyff subcatchment in the Wye and another network of six gauges in the Hafren subcatchment in the Severn. The gauges were distributed according to domain theory using different random sites from the existing gauges. The gauges used were Rimco tipping bucket recording gauges with, in the Cyff, funnel extensions that could be tailored to the ground slope, and, in the Hafren, horizontal canopy-level funnels.

The areal means given by the two networks in the Cyff subcatchment did not differ significantly ($P<0.05$): the total catch for the 5-month period January-May 1975 differed by only 3%. This was in spite of a relatively large difference in April 1975, which may have been caused by heavier than normal rainfall: tipping buckets are susceptible to undercatch at high flow rates because of the large volume of flow not recorded during the tip. Moreover, the bucket mechanism has to be calibrated accurately to record the correct volume. The conclusions for the networks in the Hafren subcatchment are similar, with no significant difference between totals for the Rimco type and those for storage gauge networks.

Despite the fact that much of the spatial variability of rainfall is associated with altitude, a regression relationship of the average annual catch by the Wye and Severn ground-level networks against altitude shows considerable scatter. The relationship is significant ($P<0.01$), but the fact that only 59% of the total variance is accounted for by altitude indicates that other factors are involved. A multiple regression was fitted to independent variables including altitude, slope, aspect and two indices of exposure. The exposure indices could not be derived for the forest at canopy level, so the analysis was initially restricted to the ground-level gauges. The inclusion of these variables was designed to investigate the effect of local site factors on patterns of rain distribution in hilly terrain.

For the multiple regression, altitude remains the most important variable in explaining the rainfall pattern, at least at ground level, although slope is important. The analysis was repeated, including the neighbouring canopy-level network in the forested lower Severn.

The residuals from the enlarged altitude regression are mapped in Figure 10. A clear and fairly consistent pattern emerges: positive residuals to the northeast of prominent interfluves (particularly the right banks of the Cyff, Hore and Severn) and negative residuals on the longer southwest facing slopes (left banks of the Cyff, Wye and Severn). A positive residual indicates that a regression equation based on altitude and slope underestimates the precipitation, i.e. there is a local 'fallout' effect. On slopes exposed to the prevailing south-westerly winds there is a 'rain shadow' effect. The effect is one of macrotopography: the local aspect values determined for the domain theory of raingauge locations appear to be less significant than the larger-scale landform. Evidence supporting this windward 'rain shadow' and leeward 'fallout' effect is emerging from the

Institute's Balquhidder catchments (Blackie *et al.*, 1986), where the topography has greater amplitude than at Plynlimon.

Variations in annual precipitation between catchments and between subcatchments

It is important to discover whether there are any consistent differences between the precipitation totals for the subcatchments in the Wye (the Nant Iago, Gwy and Cyff), or between the Severn subcatchments (the Hore, Hafren and Tanllwyth) as well as between the totals for the Wye and Severn catchments as a whole. Analysis of variance tests carried out for the Wye subcatchments indicate that there are no systematic differences in the patterns of rainfall that are

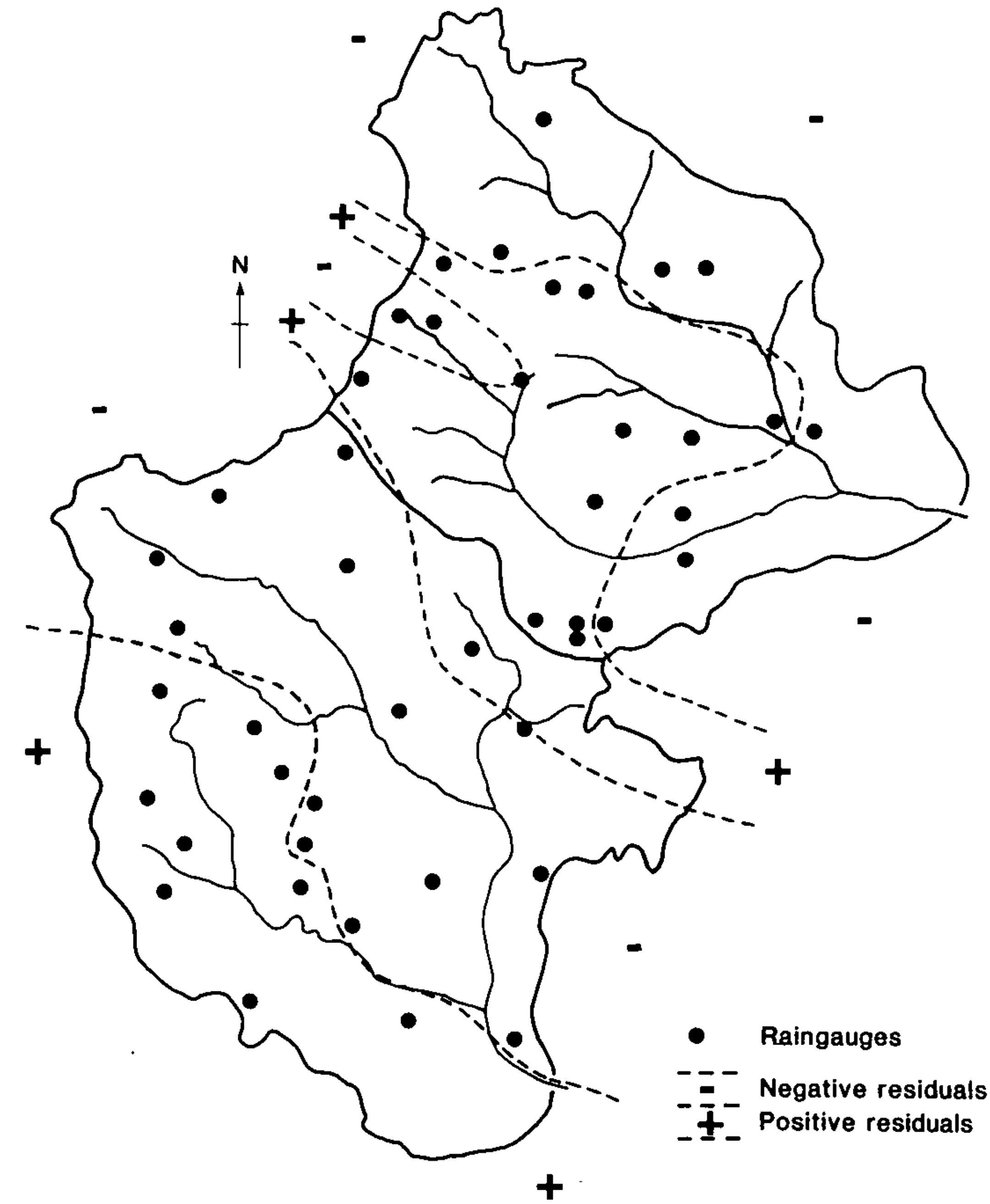


Figure 10 The residuals from a regression of all gauges, mean annual rainfall against altitude. Residuals are in mm.

significant although the Gwy has the highest rainfall, presumably as a direct result of its higher mean altitude. Differences between the subcatchments in the Severn are similarly insignificant and do not appear to be related to altitude. Overall, for the period 1972-1980, the Severn received 32 mm more precipitation on average, an insignificant amount considering the mean annual totals of 2414 mm for the Wye and 2446 mm for the Severn.

Rainfall recorders
For the purposes of rainfall/runoff modelling and investigation of the flood hydrograph, the monthly rainfall totals measured by the network of storage gauges at ground and canopy level are not on a short enough time interval. At first thought, it would seem feasible to install networks in which all gauges are capable of recording rainfall down to hours, or fractions of hours. However, the difficulty and expense associated with operating continous rainfall recorders in adverse conditions precludes the use of large networks. A small network of recording gauges was employed, each used to distribute the catch of a larger number of monthly storage gauges down to hourly intervals. In the case of recording gauge malfunction, values from nearby recording gauges can be substituted.

The recorder employed initially was the modified Dines tilting siphon gauge, shown in Plate 5 (Met. Office, 1969). This produces a record on a roll of chart lasting four weeks. Further modifications to the instrument were necessary to prevent frost damage to the delicate float chamber and siphon mechanisms, as described by Rodda (1963).

Steps were also necessary to frost-proof the Rimco tipping-bucket rain recorder (Plate 6) which replaced the Dines gauges in 1980. At first, this gauge was linked to a modification of the multi-channel Microdata logger, being used for river level and automatic weather station data, which allowed single channel

PLATE 5 A Dines tilting siphon recording raingauge in use at Plynlimon

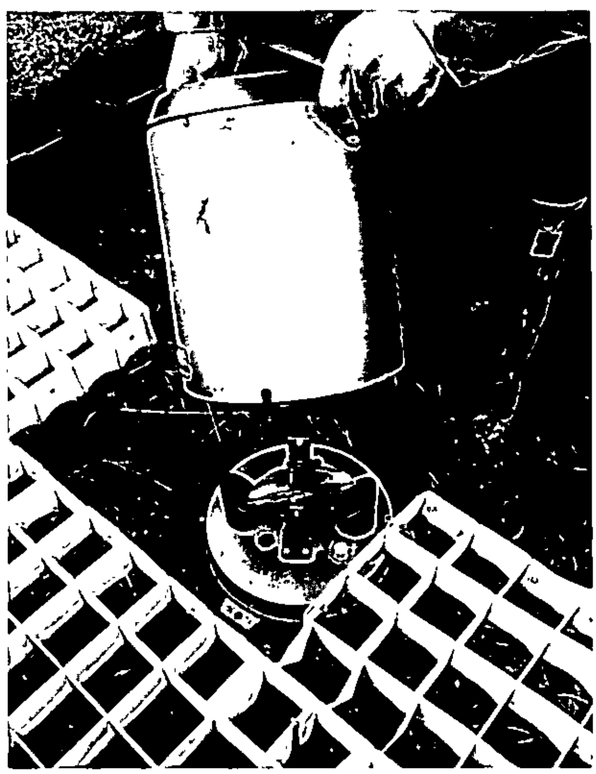


PLATE 6 A Rimco tipping-bucket raingauge

recording of rainfall. More recently the Rimco gauge has been coupled with a solid-state event recorder (Turner and Brundson, 1978).

Analysis of variance on 11 storms distributed throughout the period from April 1971 to March 1973, using only the Dines records from both catchments, indicates that 12 recorders would be required to estimate mean areal hourly rainfall over both catchments to within 20% of its true value, and about 49 would be required to estimate it within 10%. When it is considered that all 39 storage gauges are employed in the estimation of hourly catchment rainfall, rather than just the six recording gauges, then the total volume of individual storm rainfall is probably being estimated to within 10% of the true value, though the distribution of hourly rainfall with each storm may be subject to larger errors.

2.1.2 Snow

Newson (1976) described the rainfall climatology of the Moel Cynnedd climatological site in the Severn catchment. She confirmed the view of Oliver (1958) that, with only 37 days with falling snow per year, snow plays a less significant role in the precipitation input to the Welsh uplands than might be expected. The short duration of snow periods arises from the dominance of warm fronts or occlusions in producing snowfall in this part of Britain (Lowndes, 1971). Indeed, many of the difficulties of snow measurement in the United Kingdom result from its ephemeral nature: lying snow does not form a regular feature of the winter landscape. Snow makes a larger impact on the water balance of upland catchments in Wales by its disruption of conventional instrumentation designed primarily to measure rainfall than by its total volume input.

The difficulties of measuring snow can be summarised as follows:

- Mobility around the catchments is severely restricted;
- The snow is more uneven when lying than when falling;
- It is redistributed when lying;
- It accumulates, evaporates and melts over short time periods, often before measurement is possible;
- Two variables – depth and density – have to be measured to estimate volume input.

Depth and water equivalent of lying snow

No provision was made initially in the Plynlimon catchments for snow measurement, other than in the observations made at Moel Cynnedd and at Dolydd, a Met. Office snow site in the Clywedog catchment. However, the persistent snow cover of February and early March 1969 revealed the inadequacy of ground level and canopy level raingauges during snowy periods (Plate 7).

PLATE 7 Ground-level raingauge affected by drifting snow

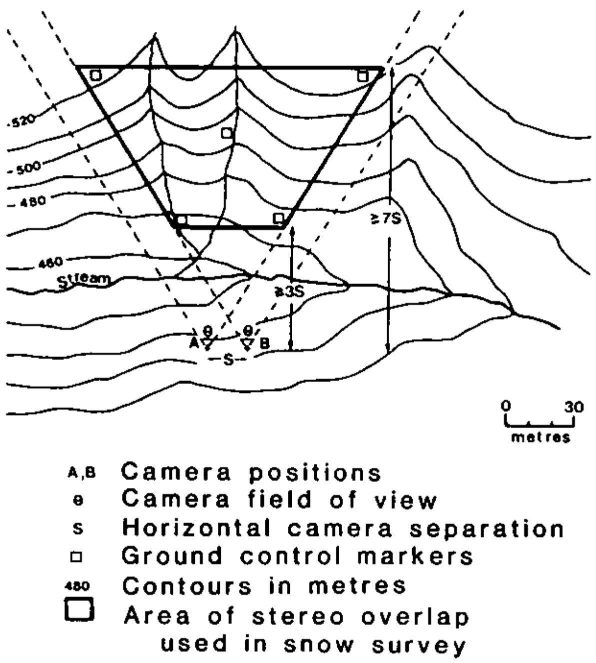


Figure 11 Generalised plan of photogrammetric snow measurement site

In November 1974, a system using terrestrial photogrammetry was installed at four sites on slopes to measure areal snow depth (Figure 11; Blyth *et al.*, 1973; Blyth and Painter, 1974). This system was designed not solely to contribute to monthly precipitation totals but also to test its feasibility for use in snowmelt hydrograph modelling. As a back-up to this method, more extensive coring and weighing was carried out to establish water equivalents, while development work was carried out on weighing snow pillows to enable them to operate continuously on slopes.

Use of domains for snow measurement

Ironically, the first years of an intensified approach to snow measurement were characterised by mild winters and few problems arose from drifting snow. One result was that no method from the growing list of snow techniques, for instance the melt gauge (Hudson, 1977) was tested fully until 1976/77. During that winter an extended survey of depths and densities was tested, using rainfall domain theory to guide sampling by coring and weighing, in an attempt to refine further the measurement of winter water balances.

At first it was hoped that correction figures for raingauge totals could be obtained by basing simple coring and weighing surveys during snow on rainfall domains. To bring the snow survey into line with rainfall data collection, a two-level sampling programme was inaugurated. Domain criteria were used to choose sampling sites (41 in all, compared with 39 in the raingauge network), since it seemed likely that on the Plynlimon catchment scale, altitude, aspect and slope would constitute the controls on snow depth.

The second level of sampling required the choice of sampling points within domains. Since any particular domain has a small altitude range and approximately constant slope and aspect, the main control on variation of snow depth becomes the microtopography, at least in the Wye and in the unforested Upper Severn catchment. Two stakes were therefore erected to define a sampling line for depths and densities along a line of maximum topographical variation, the distance between the stakes depending upon the wavelength of the microtopography, fixed so that an approximately equal number of the 25 depths and 15 densities would occur on positive and negative topographic features. In the forested parts of the Severn the distribution of trees and clearings obviously affects the distribution of snowfall inputs at ground level. However, the wider roads and road junctions have been found to collect fairly uniform snow cover and the sampling network therefore includes a number of such sites.

Statistical analysis of the first water equivalent results from the network, combining errors of estimation of depth and density, suggests that, for an event without drifting, 150 data points would be adequate to assess catchment inputs with comparable error (5%) to the existing raingauge network during snow-free months. The number of points required rises to over 500 for a snowfall event accompanied by extensive drifting.

Catchment inputs during snow events

The techniques described, whilst feasible theoretically, proved problematical in practice. Stereo photogrammetry was impossible during the prevailing poor light conditions, and without the continuous records of standing water equivalent that would have been available from a successful snow pillow it became pointless, because the slopes had to be visited for density measurements in any case. It was concluded that snow inputs were best estimated as the snow was falling, before wind distribution introduced an extra order of magnitude or variability, or before evaporation and melting reduced the measured input volume.

The gauges chosen for network deployment were demonstrably unsuitable for snow input estimation. However, the Meteorological Office standard gauge, set at 30 cm above ground level, was designed specifically to enable a reasonable accumulation of snow without overtopping. In the Hafren Forest, there exist enough clearings which provide an even and representative accumulation of snow while providing aerodynamic shelter for the standard gauge. Seven gauges, operated by IH for the Severn Trent Water Authority, have been in existence since the experiment started. Two further gauges were added to cover an obvious altitude gap and the whole network was carefully 'gardened' and the gauge contents melted periodically to prevent overtopping.

Using this small network of standard gauges is not as statistically rigorous a technique as sampling by domain theory. However, the main advantage is that only one type of gauge is required to cope with both rain and snow. There is no absolute standard against which to test the network, and yet the close agreement between altitudinal regressions of canopy, ground level and standard networks during rain-only periods can be used as a justification. During mixed precipitation, the regression line for the standard gauges lies midway between those for the ground level, which overcatch, and those for the canopy level, which undercatch. This departure can be used on an index of 'snow months' when areal estimates from the standard gauge network are used as catchment inputs. As the long-term mean inputs for the Severn and the Wye are so close, inputs to the Wye are assumed equal to those in the Severn during snow periods.

2.2 Catchment outputs

2.2.1 Streamflow measurement

To demonstrate differences in the runoff regimes of the two catchments, it is essential to measure flow to high degrees of accuracy and precision. It was recognised that this fundamental element in the Plynlimon study was very exacting, particularly when flows were estimated to range over more than three orders of magnitude, gradients were steep, Froude numbers high and flows supercritical. An additional problem was the large volume of sediment load carried by the streams, particularly those draining forested catchments.

The main principles underlying flow gauging revolve around the estimation of flow velocity in a channel of fixed and known dimensions, from which discharge can be calculated as the product of velocity and cross-sectional area. In such channels, flow velocity is related to flow depth, and accurate estimation of depth above a flow control is essential. In streams where kinetic forces dominate gravitational forces, i.e. where Froude numbers exceed unity, it is impossible to estimate flow depth accurately. The design of fixed flow gauging structures is therefore aimed at reducing Froude numbers to less than 0.5 to ensure stable water surfaces and to minimise afflux, the rise in water level for a given rise in discharge. In conventional structures the problem also arises that reduction of Froude numbers is only possible with a reduction in velocity, which decreases the sediment-carrying capacity of the stream and causes sediment deposition and changes in cross-sectional area.

When the study started, two structures had already been in existence for a number of years: a compound Crump weir on the Wye at Cefn Brwyn in use since 1951 and a sharp crested weir on the Severn since 1953. On the advice of the Hydraulics Research Station the Crump weir (Crump, 1952) was modified (by improving the cutoff walls for the centre section and the intake to the recorder well) to form the main gauging station at the outlet from the Wye catchment. The weir on the Severn was replaced by a new critical depth trapezoidal flume sited further downstream.

Six additional sites for flow gauging stations were selected at the lowest available positions on the three major tributaries of each main catchment, with a seventh added in 1985 above the clear felled area in the Hore, to act as an experimental control.

Gauging the Severn and Wye

The Severn gauging station is a concrete critical depth flume of trapezoidal section (Plate 8a). The water level in the structure is measured in a stilling well connected by a pipe to the side of the flume at the invert level of the approach section (Smart, 1977). Initially, deposition of sediment on the upstream apron caused problems. These were overcome subsequently by the excavation of a 160 m^3 sediment trap in the boulder clay bed of the Severn; this volume was estimated by Hydraulics Research Station as approximating the annual budget of sediment. Experience has shown that this quantity was an overestimate and the trap only has to be emptied approximately once every five years. Similarly, there was erosion of the concrete invert early in the study but this was rectified by cladding with metal tiles in March 1975.

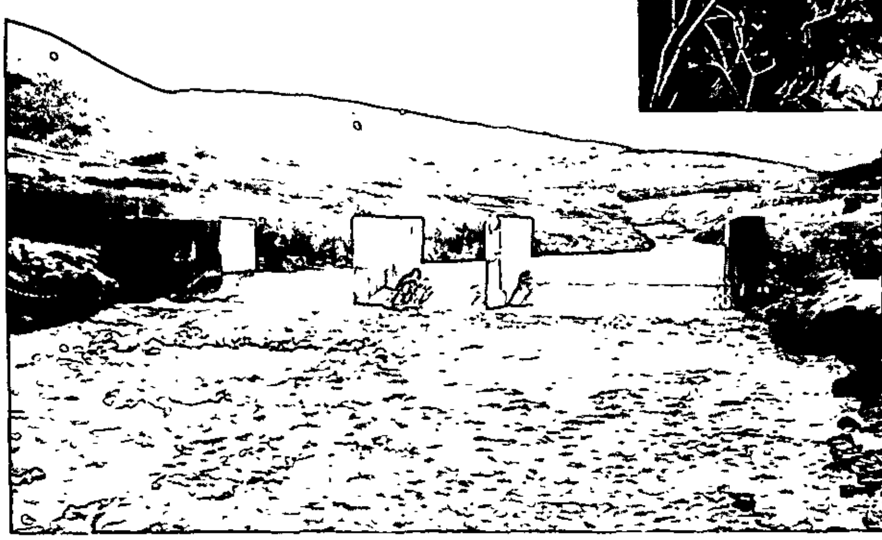
The Crump weir on the Wye (Plate 8c), with an upstream slope to its crest of 1 in 2 and a downstream slope of 1 in 5, was constructed in concrete, with two piers separating the lower centre crest from the two flanking sections. The crests themselves are sheathed in gunmetal and the water level in the structure is measured in a stilling well connected by a pipe to a sump in the approach apron of the left back section, covered by a drilled metal plate.

The stilling pool upstream of the weir at Cefn Brwyn extends about 50 m, and it was considered that sediment would not adversely affect approach conditions, particularly near the weir. However, application of lumped conceptual models to the Wye catchment (Eeles, 1978) indicated that a number of flood peaks were being flattened. The most likely cause was the build-up of sediment and algae on the tapping-point sump cover during a storm, causing total blockage of the well. On the recession, the drop in level in the structure to below the level in the well caused the blockage to be released and the evidence to be removed. The construction of a gabion sediment trap in the upper half of the stilling pool in 1983 has solved the problem. The conceptual model has been used to reconstruct the missing peaks.

(a) Trapezoidal flume on the River Severn

PLATE 8 Flow gauging structures at Plynlimon

(b) Steep stream flume



(c) Crump weir on the River Wye

The structures on the tributaries

The six tributary streams are characterised by their steep gradients, heavy sediment loads and high flood/drought flow ratios (Table 4; Plate 8b). The measurement requirements and the characteristics of the streams precluded the use of V-notch and other types of weir (Herbertson, 1970). Conventional critical depth flumes would have been suitable had the gradients of the streams been smaller. However, the Froude numbers of the streams at bank-full discharge were calculated to be around unity. For supercritical flow (Froude number greater than one) it would be necessary to render the flow sub-critical before it entered the flume approach. This would mean arranging for a hydraulic jump to form upstream of the flume and would lead to siltation problems because of the sudden reduction in transport capacity caused by the reduction in velocity downstream of the jump.

A solution to the problem was a flume (Harrison and Owen, 1967) where the cross-sectional shape of the approach channel is changed (Figure 12) from one that is wide and shallow, to one that is narrow and deep. By this method, Froude numbers can be halved by increasing the depth and decreasing the width by four times, while velocity is maintained. In practice, this neat theoretical solution only holds at bank-full discharge, when water levels in the natural channel and in the approach section of the flume are equal. At other times flow accelerates down the ramp and kinetic energy has to be disrupted by roughness strips on the bed and walls of the ramp forming an hydraulic jump at the base of the ramp.

With the exception of the Hore flume, none of the six minor structures have suffered from deposition of sediment. In all cases, the velocity of the water leaving the structure on its way downstream is dramatically reduced, leading to the formation of shoals. Under extreme conditions these can build up in a single flood and drown the structure, so prompt removal by excavation is required.

Calibrating the structures

Given that the 'as built' - rather than design - dimensions of the structures are known, it is possible to use a theoretical calibration equation that has been tested empirically under laboratory conditions and included in British Standards. This assumes firstly that a British Standard calibration is available, which it is for Crump weirs and conventional critical depth flumes, and secondly that the installation conforms to the design requirements of the standard.

TABLE 4: Physiographic and hydrological characteristics of the Plynlimon catchments and sub-catchments

	Stream	Catchment area	Main channel length	Main channel slope (S1085)	Design flood discharge	Design drought discharge	Flood/ drought ratio	Bed slope at structure site	Natural channel Froude No at bank-full discharge
		km^2	km	$m\ km^{-1}$	cumec	cumec			
	Afon Cyff	3 13	4.21	27 6	9.91	0 009	1166	0.021	1.03
WYE	Afon Gwy	3.98	5.73	20 3	17.83	0 014	1265	0.026	0.98
	Afon Iago	1.02	3 92	30.7	3.96	0.003	1414	0.022	0.82
	Afon Hore	3.08	4 69	70.5	14 15	0.011	1252	0.027	1.07
SEVERN	Afon Tanllwyth	0.89	2.99	109.5	2.26	0 003	807	0.056	1.21
	Afon Hafren	3.67	5 60	59.4	10.19	0 009	1200	0.022	0.75
	Wye at Cefn	10.55		37.23	52.4	0.020	2620	0.011	0.53
	Severn	8.70		63.47	41 03	0 023	1784	0 011	0.60

* *S1085 is the Flood Studies Report (NERC,1975) adopted estimate of stream slope.*

For the steep stream flumes which have no British Standard, it is possibile to develop a theoretical calibration using critical depth theory. It is assumed that discharge (by continuity) and total head (by the Bernoulli theorem) are equal in the approach and throat sections, that only the cross-sectional areas of flow and velocity have changed, and that the Froude number in the throat is equal to unity. In this way, total head – and hence water depth – in the approach section can be calculated using an iteration procedure. In practice, some allowance has to be made for the head lost by friction as the flow passes through its critical depth in the throat section. This is difficult to assess theoretically, because it depends on the finished roughness of the construction material. It was necessary therefore to back up the theoretical calibrations with other methods.

Dilution gauging was advocated as a suitable method of calibration, but set against it was the 'flashy' nature of the streams and the time needed to obtain a calibration over the full range of discharge. Using the technology of the early 1970s, automatic dilution gauging equipment was unreliable and the tracer used, chromium, was subject to strict control on toxicity grounds. After a sequence of unsuccessful trials this technique was set aside. Manual dilution gauging, with sodium iodide as a tracer, has since been used to check the calibration of the flumes (Plate 9). Velocity has been measured in the Severn flume and in each of the other six flumes using Braystoke current meters. In addition, the opportunity provided by very low flows during the 1976 and 1984 droughts allowed volumetric check gaugings at all the Plynlimon structures (Plate 10).

The results of the three calibration methods (dilution gauging using extended plateau times, current metering and volumetric gauging) can all be presented as a single calibration curve for individual structures (e.g. Figure 13) and compared with the theoretical values. Chapter 3 reveals that additional checks have been required at Cefn Brwyn (Wye) Crump weir and on the Hafren (Severn) steep stream flume in the light of discrepancies revealed by the long-term records from these sites.

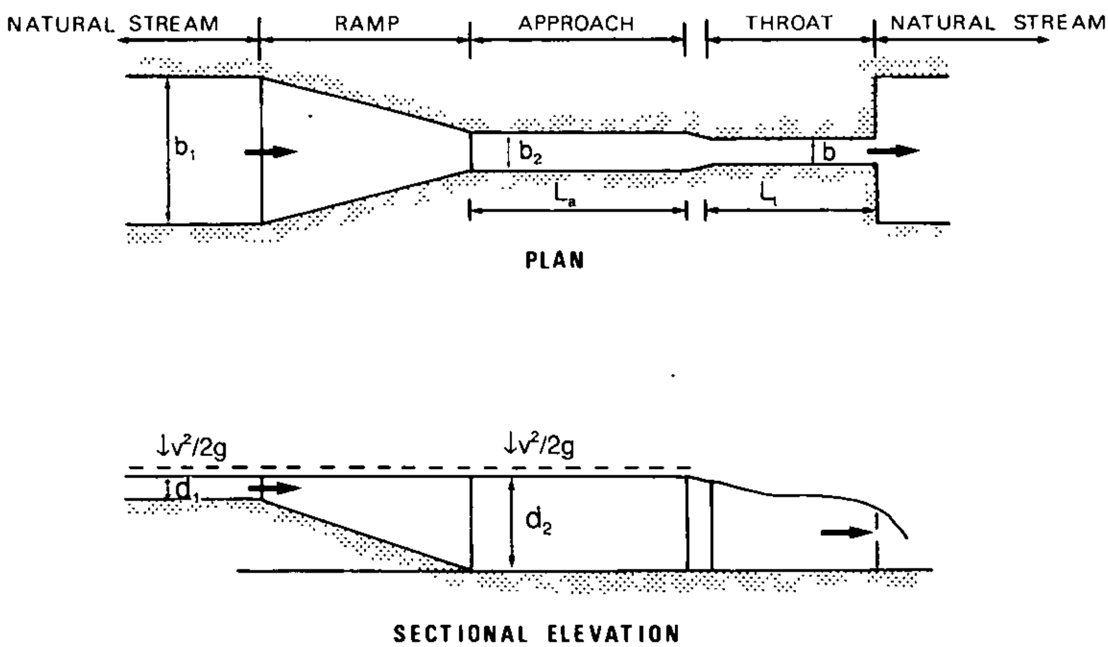


Figure 12 Plan and section of Plynlimon steep stream flume

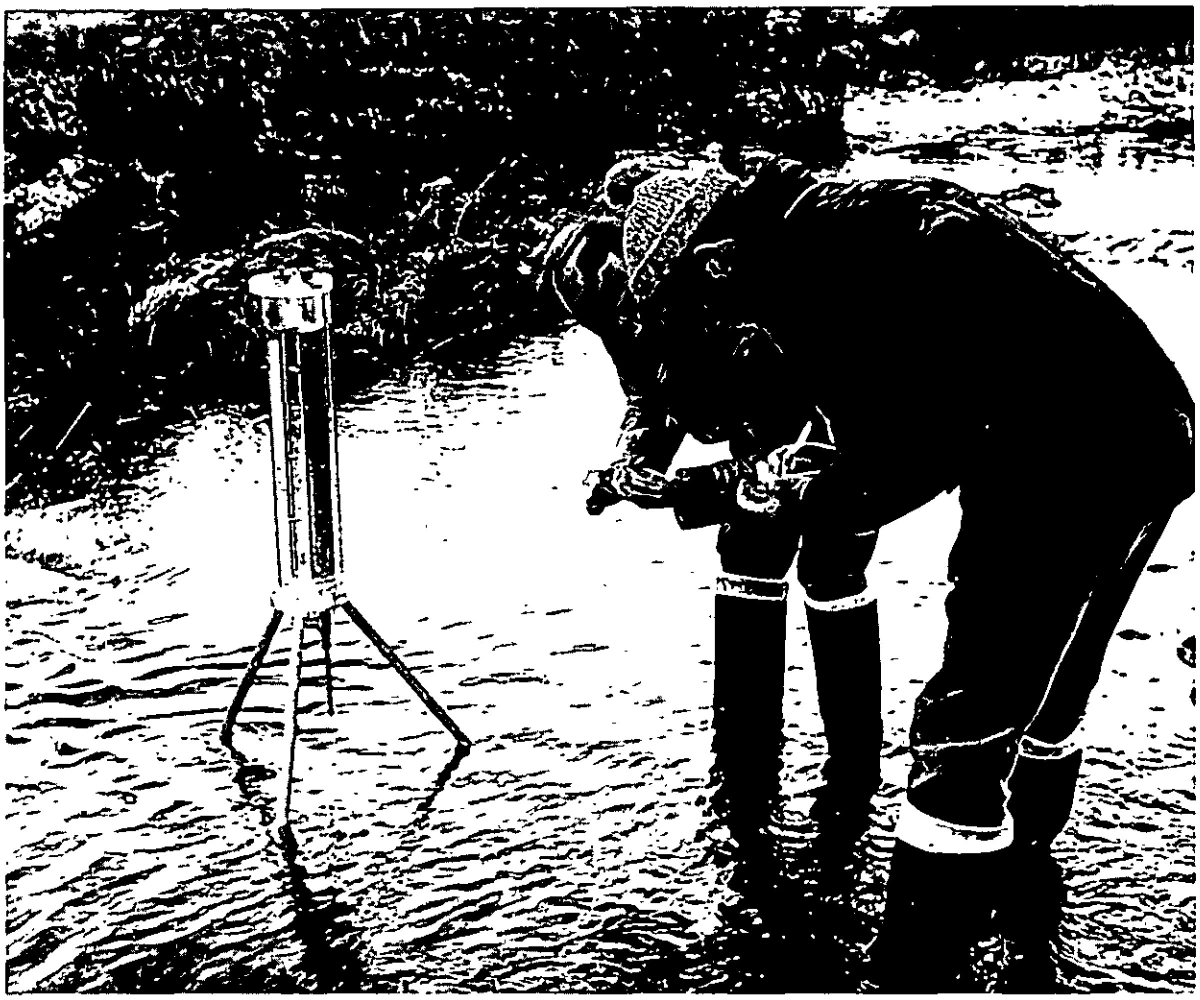


PLATE 9 Dilution gauging during the 1976 drought

Logging river level

Two different types of water level recorder were fitted on all eight structures, one to act as a back-up in case of failure of the main recorder. The different technologies ensure that the same problems are unlikely to afflict both recorders at the same time. Initially, Leupold and Stevens reversing chart recorders were employed, with Fischer and Porter punched paper tape recorders as back-up. As instruments have improved, the need for back-up recorders has become less frequent. For this reason, chart recorders are still used as back-up for their instant visual value. Clumsy data retrieval is less of a factor when it has to be used only infrequently. From 1977, the main recorder at all eight structures has been the compact cassette logger which was developed as part of the IH/Microdata system (Strangeways and Templeman, 1974). The water level sensor linked to the logger consists of float, counterweight, wire, pulley and potentiometer (Plate 11).

The Microdata compact magnetic tape data logging system, developed for recording hydrometeorological data at remote and unmanned sites, has been in use as part of the automatic weather station network for a number of years. Reading equipment to replay logger tapes and computer software to process the replayed data have been developed as part of a comprehensive data logging system. The same system was also applied to the monitoring of river level.

PLATE 10 Volumetric gauging during the 1976 drought

Although used as the front-line logging sytem for many years, the Microdata system has been superseded twice. The first replacement was the Mussel logger developed at IH and produced by Computing Techniques Ltd. Its use of replaceable solid-state stores enabled rapid translation of water level data to personal computers, allowing a faster turn-round of data and more rapid diagnosis of faults. More recently the whole system has advanced further with the introduction of the intelligent Campbell Scientific logger which has made it possible at last to calculate flow from water level in the field, and has opened up many opportunities for flow-related instrumental control, such as flow-proportional water sampling and automatic dilution gauging.

Datum checks at gauging stations

Because of the importance of maintaining the correct datum for water level recording at the gauging stations, an instrument was needed to check the zero settings of the

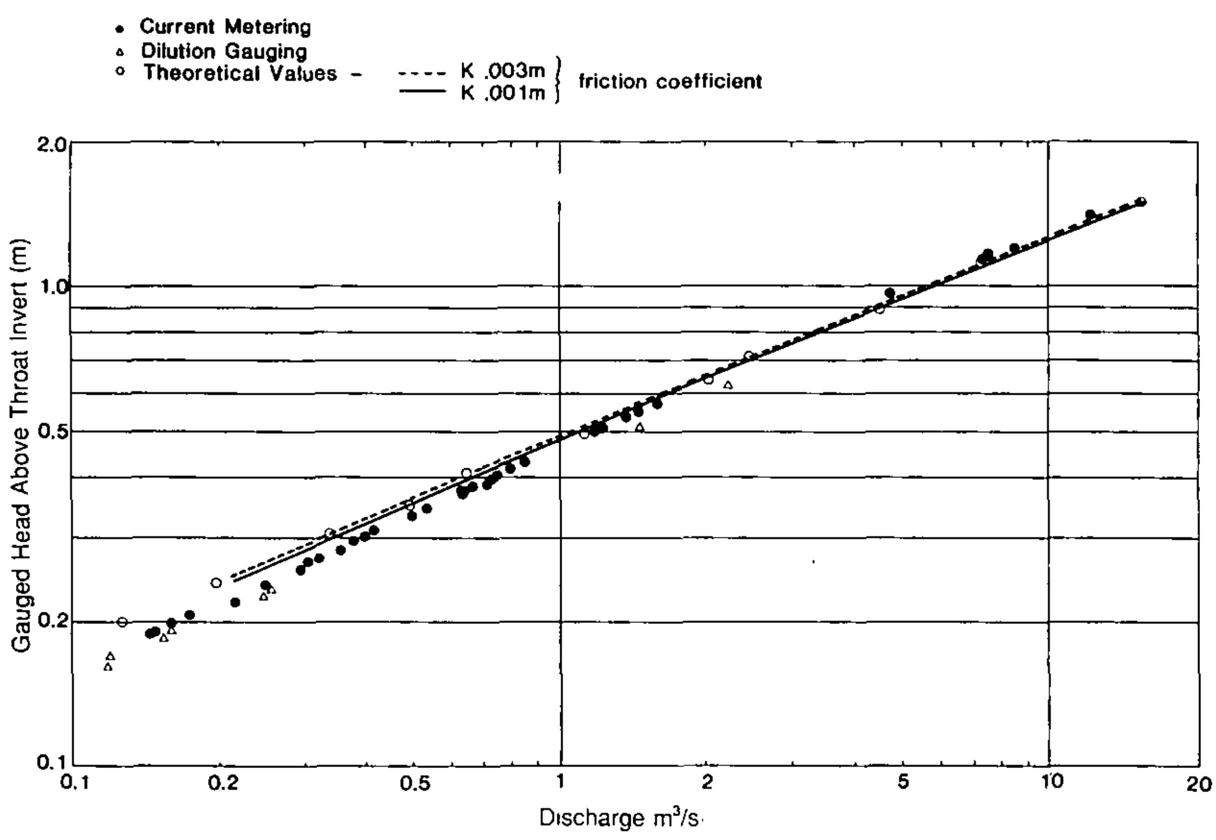


Figure 13 Ratings for the Severn trapezoidal flumes

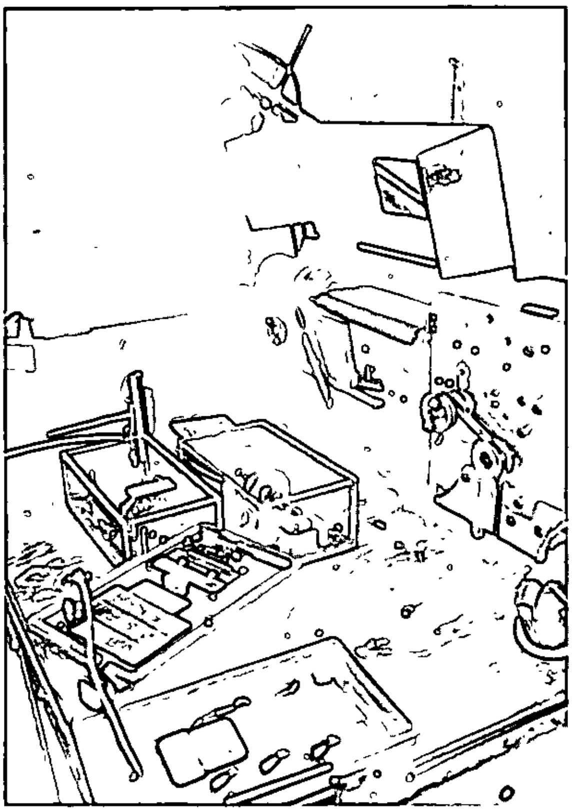


PLATE 11 Potentiometric water level recorder and Microdata logger

recorders. A prototype 'dipflash' was constructed to meet this need, contact with the water surface completing a circuit to energise a light-emitting diode (Smart, 1979). Further developments produced a device comprising a waterproof unit made of moulded silicon rubber, 350 mm long and 45 mm in diameter, containing the circuitry, dry cell batteries and display diode. This has since been further miniaturised, given better waterproofing and fitted with lower-power circuitry and long-life batteries.

The unit is suspended by a standard metal tape from a reel mounted on the table over the stilling well. The practice which has developed involves checking the datum on all nine stream gauges at least once every week, and the distance from structure control to dipflash unit every few years. This has eliminated a source of error which is often neglected in river gauging.

2.2.2 Evaporation

It is difficult to estimate short-term (within a year) evaporation rates from the water balance because of storage changes within the catchment. However, it was considered essential to have short-term estimates, independent of the variables measured for the catchment study, in order that water balance evaporation could be distributed over the year. This would allow the Plynlimon results to be used on catchments similar to Plynlimon in other areas of Britain, thereby precluding the requirement to set up new catchment experiments.

Although developed and tested initially in lowland Britain, the Penman (1948) method was selected as an appropriate means of estimating short-term potential evaporation using routinely measured meteorological

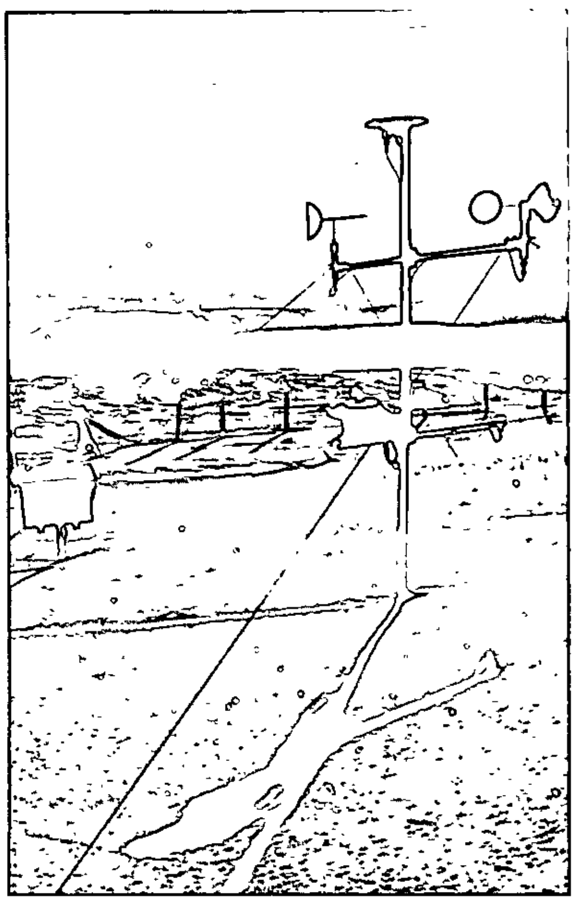


PLATE 12 An automatic weather station

variables. The need for information on the spatial distribution of these variables led to the development of a battery-powered weather station (Strangeways, 1972) which would record automatically on magnetic media the variables needed to compute evaporation values. Using these short-term estimates it became possible to accumulate daily E_T values and to calculate the ratio of annual P-Q to annual E_T for use as a means of calibrating evaporation process models.

Automatic weather stations
The automatic weather station (AWS) in its standard form (Plate 12) comprises seven sensors, mounted on crossarms attached to a heavy-gauge aluminium mast, with stainless steel and anodised aluminium fittings, a cast alloy base and a four-wire stainless steel guying system (Strangeways, 1985). All sensors are connected by plugs and sockets to a wiring harness, sealed to prevent ingress of moisture. Output from the sensors is sent to a Microdata logger through an interface where the analogue signals are converted to digital form and stored. These data are then converted to engineering units by calibration equations incorporated in data quality control computer programs. The recent conversion of AWS logging to Campbell Scientific loggers has enabled much of the data processing to be done automatically within the logger. This has resulted in increased accuracy, as 10-second scans are now possible rather than the 5-minute intervals previously available.

2.3 Measuring catchment storage

Water is held in both long-term and short-term storage in catchments. In upland Britain, short-term storage can be in the form of channel storage, ephemeral snow pack storage and canopy storage. Such stores can affect short-term water balance estimates by carryover from one accounting period to another, but they become decreasingly important over several months or years. To estimate losses up to seasonal scale – an increasingly important aspect of water resource assessment – accurate estimates of longer-term snow storage, groundwater storage and soil moisture are needed.

The Wallingford Neutron Probe System
This section is concerned with the measurement of soil moisture. *A priori* opinions on what constituted the variable part of the water storage considered that it occurred mainly in the soil mantle rather than in drift and impermeable bedrock. Soil moisture determinations can be made gravimetrically, by tensiometer and by various types of resistance block buried in the soil (Rodda, Downing and Law, 1976; Ward and Robinson, 1989). However, the only practical method of making repeated field measurements is by neutron probe.

Although neutron probes were in existence at the time the Plynlimon catchments were being planned and instrumented, these were cumbersome and not sufficiently easy to operate within radiological safety regulations or to transport and use over difficult terrain. However, developments at IH produced a light, rugged instrument which allowed large numbers of measurements of soil moisture to be made with a degree of precision and reliability not previously achieved.

The Wallingford Neutron Probe System for measuring soil moisture (Plate 13) was developed in conjunction with the United Kingdom Atomic Energy Authority for field use in all weather conditions (Bell, 1969). The system, which employs the neutron back-scattering method, comprises a probe, transport housing, cable and meter (Figure 14). The probe is lowered by cable into a permanently-installed aluminium access tube in the soil and readings are taken at the required depths. Fast neutrons emitted from an americium/beryllium radioactive source in the probe are slowed and scattered in the soil by collisions with the atomic nuclei of the soil elements, predominantly by the hydrogen of soil water, to produce slow neutrons. These are detected by a slow neutron detector in the probe and converted into pulses which are displayed as a count rate. The wetter the soil, the higher the probability of collision and the higher the count rate. Thus the count rate is related to the hydrogen content of the soil and changes in count rate are proportional to changes in moisture content.

PLATE 13 The Wallingford neutron probe in action

Soil moisture measurement

Aluminium access tubes ranging from 0.3 m to 2.5 m in depth were installed vertically in the soil at each site where soil moisture content measurements are required (Bell, 1976; Institute of Hydrology, 1981). Where possible, these were inserted from the ground surface down to bedrock or to soil zones where no measurable moisture changes occur. Count rate readings are taken at 100 mm depth increments through the soil profile and, after processing, a weighted average catchment moisture storage change is calculated in respect of each pair of reading dates, weighting each tube according to the area which it represents. Although each soil moisture value obtained is an absolute value, there can be zero errors introduced by such factors as soil chemistry and density, and so it is usual to work in terms of soil moisture deficit from an arbitrary winter field capacity and soil moisture differences between reading dates.

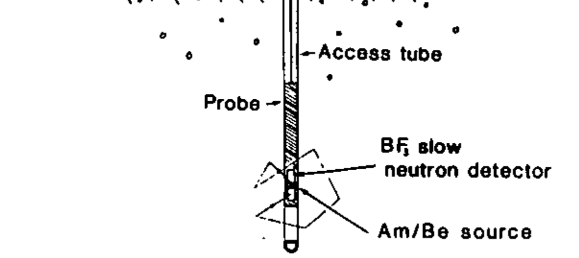


Figure 14 The Wallingford neutron probe in section

When the access tube network was being installed, the primary controls of soil moisture variability were thought to be: position on slope; soil type (found subsequently to be closely related to position on the slope), and slope aspect. Slope/aspect analyses showed three aspect modes for each catchment (differing slightly between the two catchments). Access tubes were installed in lines of six or seven tubes down each of three typical slopes from hill top to valley bottom, at least one access tube representing each of the following slope elements: flat hilltops with slopes of 1 in 10 or less; upper convex slopes; lower convex slopes; upper concave slopes; lower concave slopes; flat valley bottoms with slopes of 1 in 10 or less.

A secondary, randomised, catchment-wide network was installed, originally encompassing more high altitude sites. These readings were later discontinued, partly because of the lack of physical continuity between sites but mainly because of the difficulty of reading such large networks in a short enough time to prevent significant changes occurring during the readings. The total number of access tubes in these two networks was 54 and they were read monthly from 1968 to 1972. Monthly readings of the six lines (35 sites in all) were continued until the end of 1974. Examination of the data showed little significant difference between the mean behaviour of the 3 lines in each catchment. In 1974 the network was reduced to a single line in each catchment.

Two other important factors also emerged:

(1) There is little, if any, correlation between slope position and moisture storage or range of moisture storage changes. The effects of microtopography, soil variability and vegetation exceed larger scale systematic effects.
(2) The value of monthly readings is limited to their use for monthly water balances. The soil moisture varies quite rapidly and, to understand the behaviour of the soil reservoir, much more frequent readings are required: ideally these should be daily. Without automation this is impractical except for short-term process studies.

By 1982 sufficient comparative data had been collected to allow accurate calibration of soil moisture deficit models – e.g. MORECS, the Meteorological Office Rainfall Evaporation Calculation System (Grindley, 1970) – for subsequent prediction of deficits in the Plynlimon catchments. It was decided to abandon routine soil moisture readings because they offered little improvement over simpler calculations (except in notable dry spells).

2.4 Internal flows

In statistical terms, the Plynlimon experiment was based on the "alternative hypothesis" that there is a difference in evaporation between coniferous forest and grazed pasture. If this hypothesis is proven then the consequences for upland water resources could be serious and pressure will be brought to bear on forestry interests to modify their operations to minimise the impact of afforestation. However, this is difficult for foresters to do without some knowledge of the reasons for the differences in vegetation behaviour. A first step towards full process models of forest canopy behaviour is to split the processes of interception, direct evaporation from the canopy and biological transpiration. Interception is the result of subtracting rainfall reaching the forest floor (net rainfall) from rainfall reaching the top of the canopy (gross rainfall); the latter is already measured by canopy level gauges.

Net rainfall below the forest canopy
The two components of net rainfall are throughfall and stemflow. Throughfall is rain which finds a direct path, dripping through the canopy to the forest floor beneath. Stemflow is the remainder, which moves down branches to the trunk of the tree and the floor. Stemflow is localised by the trunk and can be caught easily and led to a measuring device (Plate 14). It is not feasible to measure stemflow on all trees in one interception site and so a subsample must be chosen. The difficulty arises in knowing how many trees to sample, or which ones, because stemflow is not related conservatively to girth. Throughfall is logistically more of a problem, because its variability in space and time requires very careful sampling. Unlike stemflow, the problem is essentially one of choosing a suitable random sampling technique which also takes full account of the known variation of throughfall with distance from the tree trunk (Johnson, 1990). The literature on forest hydrology mainly contains accounts of such sampling methods; a variety of throughfall gauges has been devised.

PLATE 14 Stemflow collar

PLATE 15 Throughfall trough

The first stemflow gauges, consisting of a rigid collar wrapped spirally around the trunk, performed reasonably well, although they were later modified and made of neoprene rubber to overcome some of the faults that arose. Collection bins were calibrated in litres and the areal stemflow was calculated by dividing the volume caught by an effective canopy area for the individual tree.

Troughs have been favoured for throughfall measurements at Plynlimon, some made of metal and others of glass fibre reinforced plastic (Plate 15). Initially, one trough made in resin-bonded glass fibre was installed at each of six interception sites located adjacent to existing canopy gauges.

The most important dimensions of the troughs are the internal length and internal width; these define the effective collecting area. They need to be deep enough to allow the storage of snow which can then melt and run out for measurement, and to allow a limited amount of extra storage in case the gauge becomes blocked by conifer needles at its outlet. The troughs should be kept as clean as possible to minimise evaporation loss from damp trash in the trough and the diameter of the outlet should be large enough to prevent frequent blockages. The troughs are tilted for rapid drainage of the water to the measurement bins. These are calibrated directly in mm of throughfall, related to the particular collecting area measure for each trough.

Interception has been investigated at Plynlimon at various locations and over different periods: as part of the intensive hydrometeorological studies, during lysimeter studies and as part of the routine data collection. The main site was located just outside the Severn catchment boundary. Six additional sites within the catchment, chosen to represent a selection of rainfall domains, were already equipped with a single throughfall trough. Later a seventh site was chosen beneath larch, the only deciduous conifer. At each site a single tree was selected as a focal point (by using random number tables) and thereafter six throughfall troughs of the type described were set out at randomly selected compass bearings and at random distances from this tree. Five trees were selected at each site to ensure sufficient variety of tree girth for the measurement of stemflow. Readings from both types of gauge were made on the first of each month to coincide with the raingauge readings and at mid-month to coincide with soil moisture readings.

The total number of collectors within the catchments now totalled 48 throughfall troughs and 35 stemflow gauges, with an extra 18 troughs at the main interception site. Analysis of the data (Gash *et al.*, 1980) showed no consistent patterns of throughfall and stemflow at the individual site level. However, when data from all sites were bulked together, consistent relationships between throughfall and stemflow were observed, stemflow being 23% of the throughfall value and therefore 19% of net rainfall, with throughfall making up 81% (Hudson, 1988).

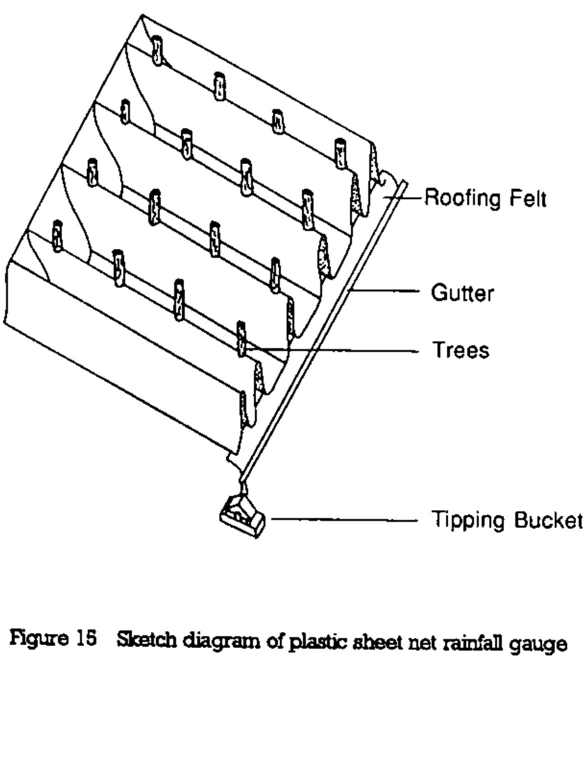


Figure 15 Sketch diagram of plastic sheet net rainfall gauge

PLATE 16 Plastic sheet net rainfall gauge and tipping bucket

The determination of interception by the separate measurement of throughfall and stemflow is informative, particularly for identifying chemical pathways within forest canopies, but it is not without its problems. Reigner (1964) showed that calibration of throughfall trough gauges for splash is difficult, while Leyton *et al.* (1967) found that large numbers of randomly situated throughfall troughs and stemflow gauges are required to give a statistically adequate sample. To overcome these factors a single large gauge, consisting of a plastic sheet suspended below the forest canopy by a rope network and sealed to each tree by a flexible collar (Figure 15 and Plate 16), has been used in more detailed studies of the interception process in the Hafren forest (Calder and Rosier, 1976; Rosier, 1979).

2.5 Data processing, quality control and archiving

The diverse nature and large volume of data collected during the course of the study required the development and use of a data processing system. Although the principles of the data processing system have remained constant during the course of the study, many details have changed because of the emergence of new data logging devices and changes in computer hardware.

With the advent of new logging devices (Strangeways, 1972; Strangeways and Templeman, 1974) a single system was developed in order to provide a common level of quality control and user access, to introduce more refined techniques of quality control and editing and to provide more flexibility to the user when assessing the final data values. This data processing system (Roberts, 1981) was written for the Wallingford UNIVAC and subsequently transferred to the NERC HONEYWELL 66DPS/300. In 1986 the Honeywell was replaced by an IBM 4381 and the Plynlimon data were transferred to a data base management system known as ORACLE. ORACLE stores all valid data on-line, and user-friendly programs have been written to streamline data retrieval (Roberts, 1989).

2.6 Data precision

The success of any catchment study ultimately depends on the realism of the measurements of the components of the hydrological cycle. How near the observations are to the real or true values is unknown. Techniques of measurement have been refined to reduce errors to a minimum: however, there are no absolute standards of measurement, and so the majority of measurements made at Plynlimon (and elsewhere) are relative. Their accuracy cannot be assessed in the strict sense and, at best, it is only their precision that can be determined. However, like all good experiments, Plynlimon relies on highlighting differences between experimental and control catchments, a method which reduces the impact of systematic error, provided similar measurement techniques are employed in both catchments.

TABLE 5 Number of storage gauges required to estimate mean monthly precipitation with a given precision

		Estimate to lie within d% of the true areal mean:				
		d=20%	d=10%	d=5%	d=2.5%	d=1%
Approximate number of gauges	Wye	1	2	8	31	196
	Severn	1	4	16	64	400

Precision of the estimate of mean areal precipitation

This problem has been considered by Clarke, Lees and Newson (1975) who demonstrated that the numbers of gauges required on the catchment were as shown in Table 5. The Wye and Severn catchments contain 21 and 18 gauges respectively. This suggests that the existing networks estimate mean areal precipitation to within less than 5% of the true areal mean (as measured by an infinitely dense network of gauges).

To examine the variability in mean areal rainfall (making no assumption about the type of statistical model required to describe the rainfall surface), subsets of gauges from the complete network were selected to see how the estimates made by the Thiessen polygon method varied from one subset to another.

The results for the Wye are shown in Figure 16(a): they suggest that the scatter amongst Thiessen estimates decreases markedly as the number of gauges increases to five. Beyond this number the curve of variance "flattens out". Hence for mean monthly rainfall, roughly five period gauges would be adequate. A similar exercise for the Severn (Figure 16(b)) shows a less regular pattern than for the Wye and indicates that more than nine period gauges may be required. This statistic also goes some way to justifying the use of a nine-gauge network of standard gauges during snow periods.

For completeness, the mean areal estimate of monthly rainfall for the period April 1971 - March 1973 was calculated using four different methods: arithmetic mean, Thiessen polygons, isohyetal method and, in the case of the Severn catchment, domain theory. No consistent difference was found between the various methods. This shows that the domain theory has correctly weighted the areal contribution of individual gauges.

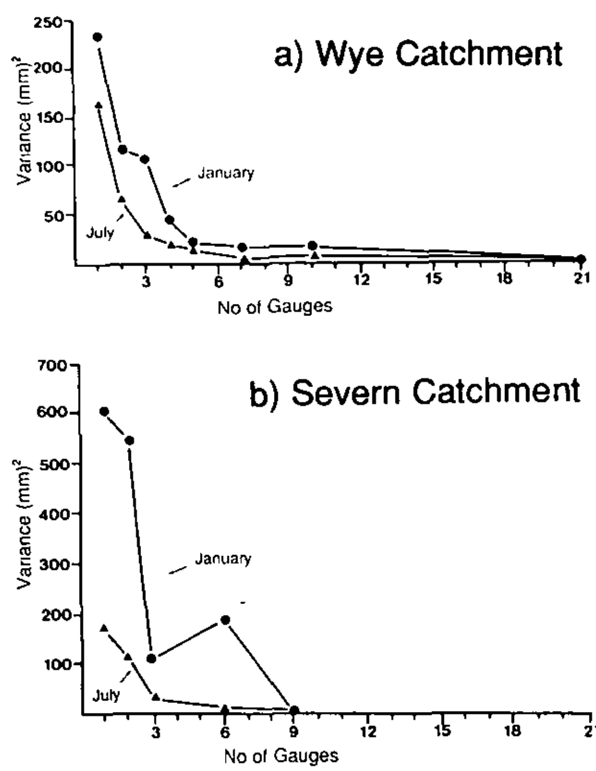


Figure 16 Variance of mean monthly rainfall estimates as a function of network size

Precision of the estimate of mean areal soil moisture change

To determine the adequacy of access tube network density, subnetworks containing varying numbers of access tubes were selected at random from the existing networks. As the number of access tubes in the sub-network was reduced from ten to about five there was little loss of information, as measured by the increase in $s^2(n)$ (the variance of the changes in soil moisture throughout the profile), but for sub-networks of five tubes or fewer $s^2(n)$ increases more rapidly. Thus it was considered that a network of about eight or ten tubes would have provided almost as much precision as a network of greater density.

Such statistics were used as a justification for reducing the soil moisture networks in 1974 to one access tube line in the Severn (11 tubes) and two in the Wye (13 tubes). With hindsight the quicker reading of the network and the consequent reduction in the impact of rainfall, evaporation and drainage changes was an advantage. However, following the discovery of systematic variation in the data related to the soil and vegetation type (Hudson, 1988), the numbers of access tubes remaining in some important soil moisture domains were insufficient for sensible analysis.

Precision of streamflow

Rating curves for all eight gauging structures were calculated from hydraulic theory, using the dimensions of the finished structures. These ratings were then verified by dilution gauging and current metering.

Using the theoretical, current metering and dilution gauging rating curves for the trapezoidal flume on the Severn, the monthly streamflows were calculated for the period June-December 1975. The total streamflow as estimated using the dilution gauging rating curve is 5.4% greater than that obtained using the theoretical rating curve. This represents the worst case, in the sense that this discrepancy was obtained by extrapolating the dilution gauging rating far beyond the range of stages used in fitting it. The streamflow for the period May-December, as estimated by the current metering rating curve (fitted using a much wider range of stages), differed from the estimates given by the theoretical rating by the much smaller quantity of 2.5%.

On the basis of this evidence, the error in streamflow estimation does not appear to be large enough to place in doubt the conclusions drawn later in this report regarding the difference in water loss from the two main catchments.

Chapter 3
Water balances for the Plynlimon catchments

The wet uplands of Britain experience conditions which make it extremely difficult to determine the water balance of a catchment to a fine degree of precision. Precipitation (P) and streamflow (Q) are the dominant terms in the balance and a very small percentage error in either can result in significant errors in the difference between them; this difference (P-Q) is employed as an estimate of water use through evaporation and storage changes.

To achieve water use estimates of acceptable precision, therefore, a rigorous approach was adopted to streamflow and precipitation measurements. This started with the instrumentation and the network design and continued through the quality control of the field observations to the storage and analyses of the data, as detailed in Chapter 2.

By 1975, confidence in the data from the main catchments was high enough for a preliminary analysis of the water balances to be presented as *IH Report No. 33* (IH 1976). These early results confirmed that the forested catchment was evaporating a higher percentage of rainfall than moorland and that the quantities involved were similar to results just beginning to emerge from process studies of forest evaporation, discussed later in Chapter 5. Yet internal inconsistencies in the data still left some doubts as to the magnitude of the differences found in the behaviour of the two main catchments. It was at this point that the original decision to instrument the subcatchments of the Wye and Severn was confirmed as a major contribution to the experiment for the following reasons:

• When added together they gave back-up estimates of water use from areas only slightly different from the main catchments;

• Individually they give some idea of the spatial variation in the evaporation process;

• The different flow gauging techniques used made it possible to reduce the impact of systematic error;

• There was the added long-term security if land use changes were taking place in part of the catchment only.

During the analysis for the 1976 report, however, few data were available from the subcatchments. Because of constructional and other difficulties, it was not until late in 1973 that continuous data collection began on five of the subcatchments, with the sixth, the Hafren, commencing in 1975.

It is imperative that quality control of data takes place as soon as possible after collection. However, because of the large year-to-year variations in precipitation, runoff, storage change and climatic controls, some systematic errors may not become apparent for years or even decades. Thus it was not until the early 1980s that the internal consistency of the dataset could be checked. Field programmes were implemented to check the validity of the precipitation networks and the ratings of the streamflow structures as described earlier. The network designs were vindicated, but departures from the theoretical ratings of some structures, particularly those on the Gwy, the Cyff and the Hafren, were identified (HRS, 1977). Consequently the parameters of the theoretical ratings for the Gwy and Cyff were adjusted to give the best fit on the current metering results and volumetric measurements of low flows. Similar techniques were also used to adjust the rating of the main Severn structure following modifications to its invert in 1975; however, the lack of an independent rating for the period before the modification has led to some doubt over the accuracy of the early data. The accumulated water level records were reprocessed using the corrected ratings. A number of systematic differences still remained, however, which required further investigation.

3.1 Within-catchment comparisons

The Wye catchment

A comparison of the summed water balances from the Gwy, Iago and Cyff with the Wye at Cefn Brwyn indicated similar trends in time but with a systematic shift in cumulative evaporation. The discrepancy could not be realistically explained by the calculated flows from the ungauged 26% of the catchment; nor could it be due to the raingauge networks which were essentially the same for both analyses. This left the gauging structures as the likely culprits. The steep stream flumes on the subcatchments had already been checked and their rating changed where appropriate. However, current metering checks were not carried out on the compound Crump weir at the Wye outfall during the 1976 exercise since the hydraulic theory of this design was considered to be well proven (HRS, 1977).

In the absence of any other explanation for the discrepancy, an exercise was mounted in 1984 which identified some survey errors but, more importantly, a departure from the theoretical rating of the centre section of the structure. This discrepancy was due to the inadequacy of the British Standard calibration when the low flow section of the weir was being used in isolation. This was the case for 74% of the time, accounting for 33% of the total flow.

Reprocessing the Wye flow data using the revised rating and a new stage zero value produced values for the Wye and its summed subcatchments which agreed well (Table 6). However, the individual subcatchment results were still not internally consistent: the Cyff was in reasonable agreement with the Wye but the Iago showed considerably more, and the Gwy

TABLE 6 Annual water balances for the Wye and its subcatchments

DATE	PRECIPITATION,P			STREAMFLOW, Q			P-Q		
	Wye	Cyff	Iago + Gwy	Wye	Cyff	Iago + Gwy	Wye	Cyff	Iago + Gwy
1975	2101	2160	2134	1687	1693	1740	414	467	394
1976	1722	1744	1750	1344	1294	1345	378	450	405
1977	2531	2539	2593	2118	2069	2172	413	470	421
1978	2349	2358	2402	2008	2044	2086	341	314	316
1979	2745	2752	2824	2378	2409	2481	367	343	343
1980	2559	2557	2637	2259	2270	2356	300	287	281
1981	2768	2799	2810	2418	2427	2534	350	372	276
1982	2286	2239	2376	1961	1961	2050	325	278	326
1983	2671	2698	2705	2273	2262	2327	398	436	378
1984	2087	2069	2136	1767	1745	1765	320	323	371
1985	2295	2323	2304	2037	2015	2060	258	308	244
MEANS	2374	2385	2425	2023	2017	2083	351	368	342

[No satisfactory explanation has yet been found for the small change in the relationship between the Cyff and the main catchment in 1978. All the water use values for 1982 are low by an estimated 20-40 mm. The reason for this is that blocked roads in January made it impossible to reach the snow sampling sites until some time after the melt had started.]

less, evaporation than the Wye. Computation using the cumulative totals indicated that a reduction in the area of the Iago of 13.8 ha to 93.8 ha and a corresponding increase to 402.8 ha in the Gwy would balance the streamflow. Over the 2 km length of the common watershed this represents a mean error in its location of some 70 m. For water balance purposes, therefore, the Iago and Gwy are combined and subsequently regarded as one subcatchment.

As a further check, the flows from the ungauged 26% of the catchment were calculated again and subtracted from the known precipitation of this area. The ungauged area, mainly on the drier eastern side of the catchment, is generally similar in vegetation and soils to the rest of the catchment. Consequently its water use can be expected to be similar. Differences still exist in the calculated P-Q values, indicating that some residual errors may still be present in the data.

The Severn catchment

A comparison similar to that carried out for the Wye indicated initially that the apparent water use of the combined subcatchments was significantly greater than that of the Severn. The Hafren subcatchment P-Q data looked particularly suspect, being much higher than would be expected from a subcatchment with the lowest proportion of forest cover. The HRS current meter ratings in 1977 had confirmed the reasonable performance of the Hore and Tanllwyth but doubts had always been expressed about the Hafren. This was because of the need to narrow its throat section to stop the hydraulic jump moving downstream and also because of the excessive aeration that still occurred at the tapping pipe position. Inspection of the original design criteria eventually showed that the tapping pipe had been installed too far upstream. As an alternative to moving the tapping point, which would have been difficult in a

TABLE 7 Annual water balances for the Severn and its subcatchments: revised flows (mm)

DATE	PRECIPITATION,P				STREAMFLOW, Q*				P-Q			
	Severn	Hore	Tanllwyth	Hafren	Severn	Hore	Tanllwyth	Hafren	Severn	Hore	Tanllwyth	Hafren
1975	2122	2217	2233		1454	1549	1619		668	668	614	
1976	1731	1785	1745	1732	1217	1220	1262	1265	514	565	483	467
1977	2720	2838	2735	2712	2040	2035	2093	2103	680	803	642	609
1978	2452	2555	2560	2442	1931	1863	1900	1906	521	692	660	536
1979	2797	2841	2851	2841	2219	2201	2185	2210	578	640	666	631
1980	2635	2692	2763	2641	2081	2047	2114	2097	554	645	649	544
1981	2776	2826	2938	2775	2215	2172	2266	2183	561	654	672	592
1982	2338	2333	2461	2335	1914	1881	2045	2010	424	452	416	325
1983	2650	2765	2751	2563	2101	2073	2277	2119	549	692	474	444
1984	2135	2178	2147	2102	1602	1566	1782	1655	533	612	365	447
1985	2355	2424	2451	2319	1897	1987	2149	1975	458	437	302	344
MEANS 1975-85	2428	2496	2512		1879	1872	1972		549	624	540	
1976-85	2459	2524	2540	2446	1922	1905	2007	1952	537	619	533	494

* Subcatchment flows are still under review

concrete structure, the flume was re-rated by installing a rectangular sharp crested weir at the entrance to the ramp. This confirmed the error.

After reprocessing and correction, the values produced for water use by the Severn and its subcatchments are shown in Table 7. The annual totals of streamflow are remarkably similar from 1976 to 1981, exhibiting much less spread than those for precipitation. In 1975 and again in 1982 and 1983 the reverse is true. During the latter period small areas (less than 5%) of both the Tanllwyth and the Hore were felled and some thinning was carried out. The proportional change in P-Q values relative to the main catchment is considered too great to be attributed solely to this minor change in vegetation.

With respect to the long-term P-Q values, the data now indicate a reasonable water use for the Hafren that is less than that for the Severn as a whole while the Hore, which has a combination of high rainfall and high percentage forest cover, has water use greater than the catchment average. The Tanllwyth water use appears to be similar to that catchment as a whole.

In spite of the more realistic results available following the correction to the Hafren rating, there are still residual differences between the main and lumped subcatchments. Determining whether the residual errors are in the flow or the precipitation values is no easy task. The seasonal isohyetal map of the catchments (Figure 17), derived from the snow-free April to October months from 1975 to 1983, indicates that the rainfall gradients are much steeper and the areal distribution more complex in the Severn than in the Wye. It has also been observed that the Severn is more prone to localised convective storms.

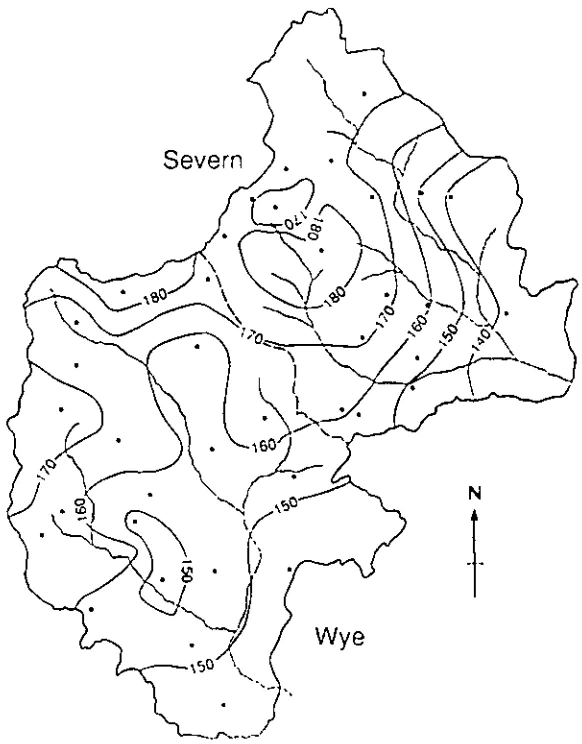


Figure 17 Isohyetal map of the Plynlimon catchments

3.2 Between-catchment comparisons

Annual water balances

Values of annual precipitation, streamflow and water use for the Wye and the Severn over the period 1969-1985 are compared in Figure 18. Considering first the period of more reliable data, 1975-1985, the year-to-year changes in precipitation totals have a very similar pattern in the two catchments though the magnitudes differ slightly, with precipitation in the Severn being marginally greater overall. The changes in streamflow parallel those for rainfall in both catchments, but with the Severn values consistently lower than the Wye. The year to year trends in both sets of P-Q values are less easy to

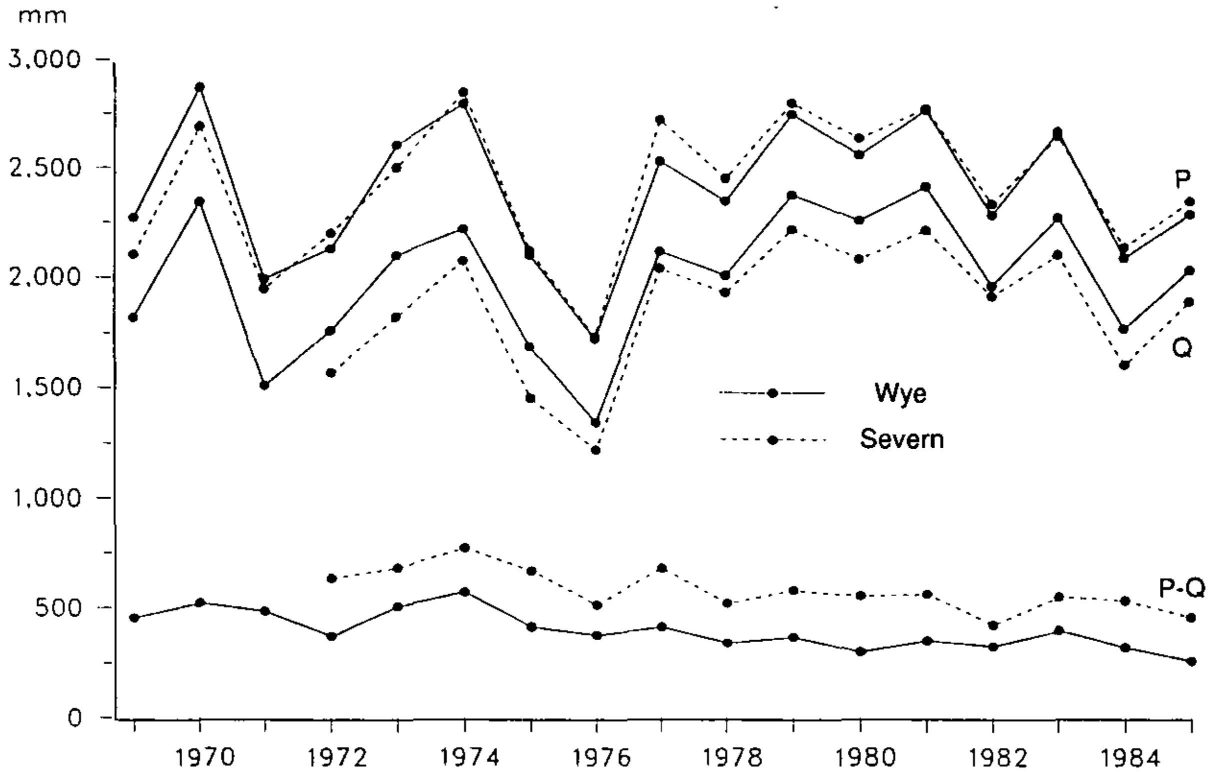


Figure 18 Wye and Severn water balance components 1969-1985

relate to precipitation. The highest values since 1976 occurred in 1977 in both catchments, whereas the highest precipitation was in 1979 in the Severn and 1981 in the Wye. The lowest values for P-Q occurred in 1982 in the Severn and 1980 in the Wye, as compared to the lowest precipitation and streamflow in both during the 'drought' year of 1976. As mentioned previously, the 1982 precipitation inputs, and hence P-Q for both catchments, are underestimated by the unknown amount falling in one snow event in January.

The eleven-year means are compared in Table 8. The mean difference P-Q of 198mm represents a 54% greater water use by the Severn, equivalent to 8% of the mean precipitation or a 9.5% reduction of the expected flow.

Inclusion of the pre-1975 data is desirable, to increase the length of the dataset in order to look for any systematic long-term trends. However, there is less confidence in these data because of errors which had been found to exist by 1975 and have been corrected in the subsequent data. These corrections are not so easy to apply in retrospect but it should be noted that the net effects of these sources of error on the data prior to 1975 would be:

(a) Some overestimate of P-Q in both catchments resulting from overestimation of the precipitation input because of the absence of snow corrections prior to 1977;

(b) An underestimate of P-Q in the Wye resulting from the systematic error in the rating, possibly offset in some periods by 'peak suppression' errors;

(c) An overestimate of P-Q in the Severn resulting from some underestimation of flow as the structure deteriorated before its repair in early 1975.

TABLE 8 Wye and Severn: means of water balance components, 1975-1985 (mm)

	Wye	Severn
Precipitation, P		
Mean	2374	2428
Range	1722-2768	1731-2797
Flow, Q		
Mean	2023	1879
Range	1344-2418	1217-2219
P-Q		
Mean	351	549
Range	258-414	424-680
Penman E_T		
Mean	482	502
Range	402-568	429-583
Difference P-Q (Severn and Wye)		
Mean	198	
Range	99-267	

For comparison, the current versions of the pre-1975 data, incorporating the Wye rating correction and 'peak suppression' corrections from 1973 and a revised estimate of the 1970 Severn flow, are shown in Figure 18. The 1970-1975 mean difference in P-Q between the Wye and Severn catchments is 229 mm as compared to the 286mm quoted in *IH Report No. 33* and the value of 198 mm for 1975-1985.

Correction for the non-forested area

The figures quoted relate to the complete catchments, the Wye being almost entirely under grassland, while the Severn contains 62% forest and 38% grassland.

The actual area of forest contributing to evaporation is an important parameter when correcting catchment results to give an evaporation rate per unit area of forest. The 'forest area', i.e. the total area within the forest fence, including roads, rides and clearings, is 67%. It would seem realistic to subtract the area of the largest clearings from this figure but there is a persuasive argument that the lack of interception and transpiration from the area taken up by roads and rides is compensated by the increased needle growth on the trees at the edge of each compartment and the increased aerodynamic turbulence caused by the gaps. A further problem is caused by the poor growth in the experimental plantation in the headwaters of the Hore which did not attain complete canopy closure until recently and therefore could not be considered as mature forest for most of the study period reported here. Taking all these factors into account, the estimate of 62% is probably not unreasonable and may even be too high. The estimates of P-Q for the forested area may therefore be on the low side.

Since it had not been considered cost-effective to gauge flow from the entire grass area in the Severn, no direct comparison can be made of the water use of the forested and grassland areas within it. It has been assumed, therefore, that the water use of the

TABLE 9 Comparison of Severn forested area and Wye: the precipitation - runoff difference

	Severn forested area			Wye	Forest-Wye
Year	P	Q_{est}	$P\text{-}Q_{est}$	P-Q	Δ(P-Q)
1975	2016	1230	786	413	373
1976	1638	1061	577	378	199
1977	2655	1852	803	413	390
1978	2390	1787	603	341	262
1979	2677	2002	675	367	308
1980	2560	1887	673	300	373
1981	2690	2030	660	350	310
1982	2207	1737	470	325	145
1983	2530	1912	618	399	219
1984	2074	1442	632	320	312
1985	2261	1711	550	258	292
Mean	2336	1695	641	351	290

grass area will be similar to that in the adjacent Wye catchment and the precipitation and streamflow data re-calculated accordingly.

The results of applying this approach to the period 1975-1985 are shown in Table 9. The mean water use for a completely forested Severn is estimated as 641 mm compared to 549 mm for the real catchment, giving an estimated mean difference between forest and grass water use of 290 mm. This represents 12% of the precipitation or a reduction of 15% in the expected flow. These values are different from those published previously (IH, 1976) as would be expected considering the improvements in the data quality achieved since this time.

3.3 Within-year distributions

For the results of hydrological experiments like Plynlimon to be of use to operational hydrologists, there is an increasing perception of the need to be able to quote evaporation rates and differences between vegetation types on seasonal, monthly or even a daily basis. It is possible, for instance, that the large annual differences between the forested area of the Severn and the Wye do not impact greatly on the water resources because of the large volume of excess runoff available for storage, either in the soil, in shallow aquifers or in man-made reservoirs. If, however, the bulk of the difference in evaporation occurs when resources are at a premium during summer and autumn when reservoirs are draining and refilling, the consequences could be serious.

To start with a crude comparison, the mean monthly values of P, Q and P-Q for the period 1975-1985 are shown in Figure 19 for the main catchments. Whilst there is a general similarity in these values, the pattern of the differences between catchments, illustrated in Figure 20 is of interest. The precipitation differences are minimal in spring and early summer but the Severn receives consistently more rain in the August to December wet months, with the greatest difference in November. Streamflow in the Severn is generally low throughout the year, but with the greatest differences in September, December and January. From zero differences in February the P-Q values increase to a broad peak in the September to January period.

Obviously all or part of these differences could reflect changes in catchment storage, this storage being recharged during the winter and drawn down in the summer. Hence autumn P-Q values are likely to be overestimates of water use because some

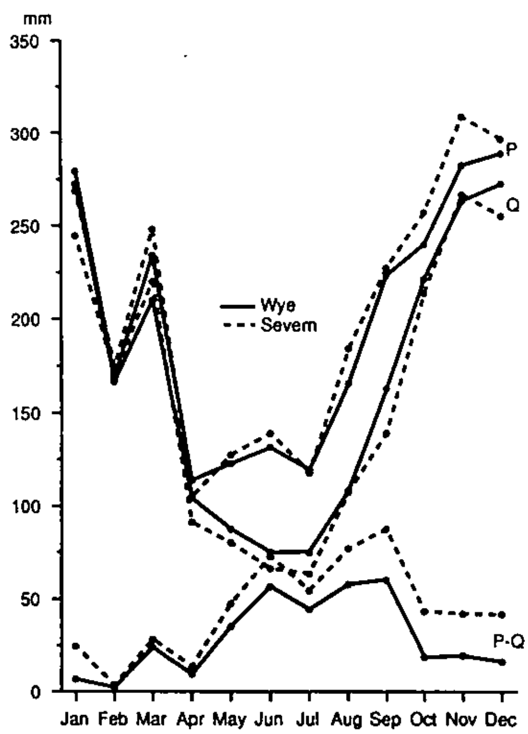


Figure 19 Mean monthly values of P, Q and P-Q for Severn and Wye catchments, 1975-1985

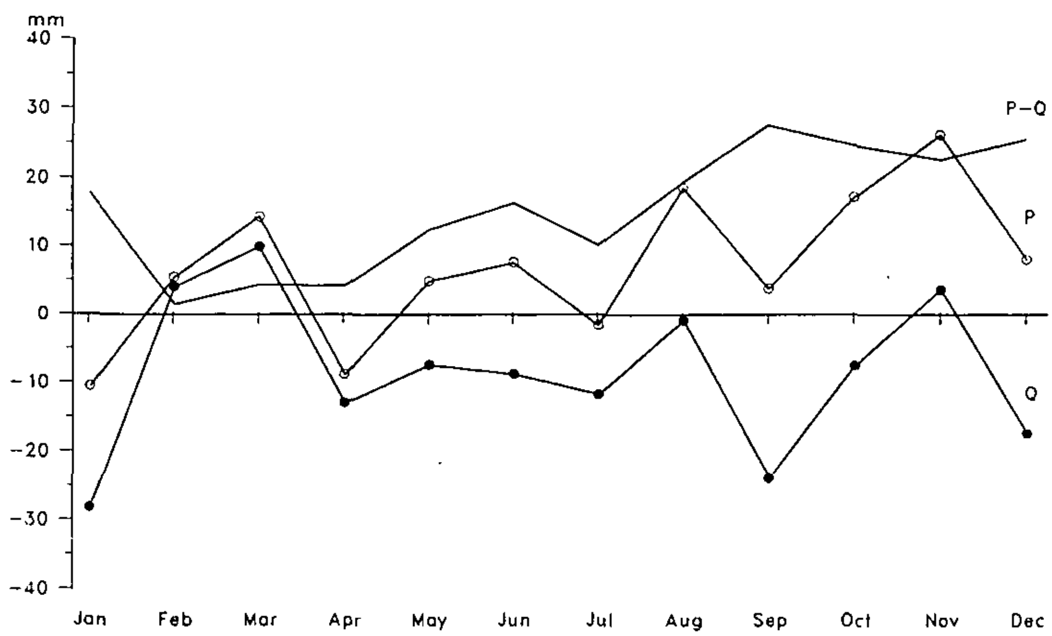


Figure 20 Seasonal variation in water balance components P, Q and P-Q, expressed as differences between Severn and Wye catchments

rainfall will be put into the storage resulting from summer depletion. Likewise spring values will be underestimated because the catchment storage will be full and much of the precipitation will run off.

The monthly distribution of water balance variables in the subcatchments is shown for the Wye in Figure 21(a) and Table 10, and for the Severn in Figure 21(b) and Table 11.

TABLE 10 The Wye and its subcatchments: monthly means of water balance components, 1975-1985 (mm)

DATE	PRECIPITATION,P			STREAMFLOW, Q			P-Q		
	Wye	Cyff	Iago + Gwy	Wye	Cyff	Iago + Gwy	Wye	Cyff	Iago + Gwy
J	279.5	281.5	286.4	272.7	271.6	270.0	6.8	9.9	16.4
F	169.3	167.9	172.5	167.0	164.3	170.5	2.3	3.6	2.0
M	234.1	232.1	239.3	210.2	209.7	213.3	23.9	22.4	26.0
A	113.9	114.2	116.5	104.4	98.9	109.5	9.5	15.3	7.0
M	122.9	123.2	127.5	87.7	85.1	96.5	35.2	38.1	31.0
J	131.8	135.1	132.6	75.1	77.0	82.5	56.7	58.1	50.1
J	119.6	121.4	123.3	75.2	77.8	82.9	44.4	43.6	40.4
A	166.2	167.6	170.5	108.4	110.8	118.5	57.8	56.8	52.0
S	223.8	227.3	225.8	163.5	167.5	168.1	60.3	59.8	57.7
O	240.2	240.7	244.2	221.5	220.4	228.1	18.7	20.3	16.1
N	283.3	284.6	290.6	263.8	265.0	273.2	19.5	19.6	17.4
D	289.5	289.7	295.5	273.2	269.0	270.1	16.3	20.7	25.4
TOTAL	2374.1	2385.3	2424.7	2022.7	2017.1	2083.2	351.4	368.2	341.5

TABLE 11 The Severn and its subcatchments: monthly means of water balance components, 1976-1985 (mm)

DATE	PRECIPITATION,P				STREAMFLOW, Q*				P-Q			
	Severn	Hore	Tanllwyth	Hafren	Severn	Hore	Tanllwyth	Hafren	Severn	Hore	Tanllwyth	Hafren
J	269.0	276 5	274.1	266.2	244.5	236.4	251.9	240.9	24.5	40.1	22.2	25.3
F	174.7	176.5	174.1	176.1	171.0	164.2	174.2	170.4	3.7	12.3	-0.1	5.7
M	248.3	253.9	252.6	246.8	220.1	210.6	223.7	216.9	28.2	43.3	28.9	29.9
A	105.1	107.6	106.5	103.6	91.4	90.7	97.1	96.8	13.7	16.9	9 4	6.8
M	127.8	130.5	132.5	127.3	80.3	80.1	86.5	85.4	47.5	50.4	46.0	41.9
J	139.4	145.3	140.4	139.0	66 4	71.0	72.4	71.5	73 0	74.3	68.0	67.5
J	118.0	126.8	121.6	114.7	63.5	6 8.2	66.7	68 1	54.5	58.6	54.9	46.6
A	184.7	190.0	192.5	185.6	107.5	111.4	119.3	117.2	77.2	78.6	73.2	68.4
S	227.6	235.7	237.6	224.6	139.7	146.1	148.7	144.1	89.9	89.6	88.9	80.5
O	257.4	262.9	275.6	255.0	214.0	212.9	223.1	218.7	43.4	50.0	52.5	36.3
N	309.4	314.5	328.7	310 8	267.4	262.0	279.2	264.7	42 0	52.5	49.5	46.1
D	297.5	303.6	303.0	296.5	255 8	251.2	264.5	257.7	41.7	52.4	38.5	38.8
TOTAL	2458.9	2523.8	2540.2	2446.2	1921.6	1904.8	2007.3	1952.4	537.3	619.0	532.9	493.8

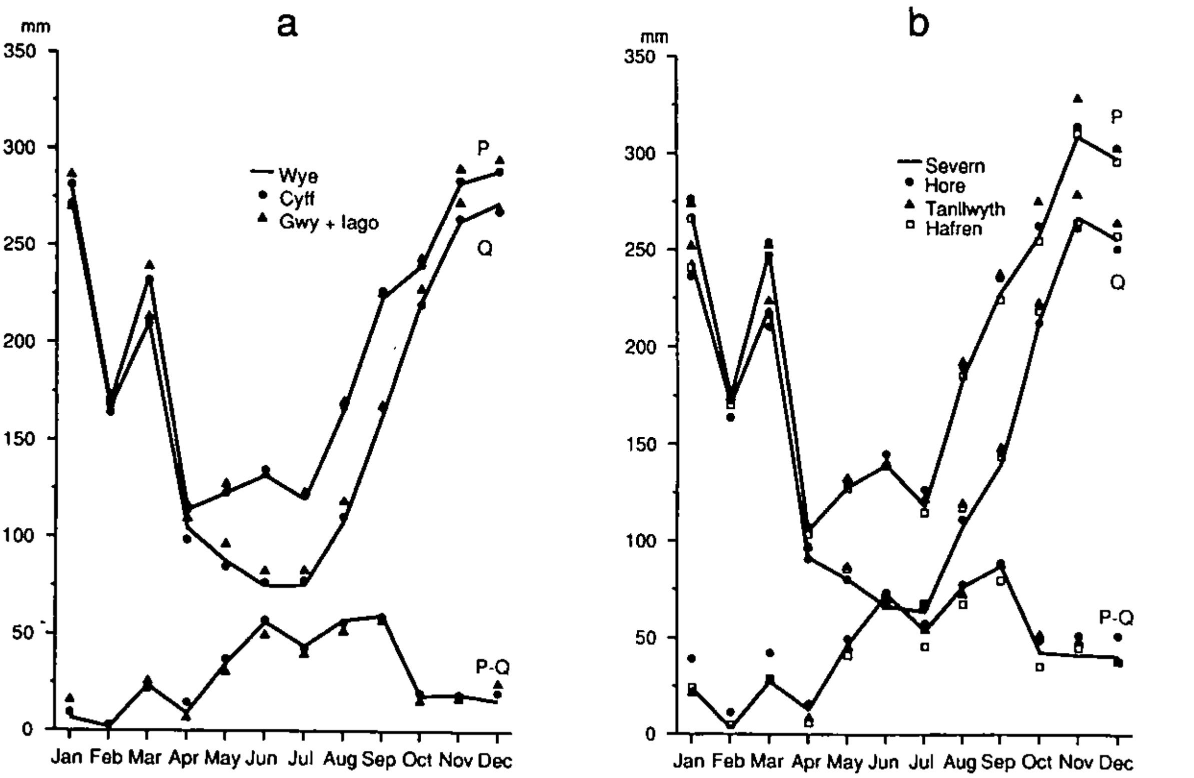


Figure 21 Mean monthly values of P, Q and P-Q: (a) for the Wye catchment and its subcatchments, (b) for the Severn catchment and its subcatchments

3.4 Catchment storage

If the within-year analysis of the water balances of the Wye and Severn and their respective subcatchments is to be taken to the logical conclusion of providing seasonal, monthly, even daily estimates of the total evaporation, then catchment storage becomes an increasingly important component of the water balance. In fact, at times of low rainfall and low streamflow, catchment evaporation can be sustained almost entirely by changes in storage, particularly soil moisture.

At the outset of the Plynlimon study, it was assumed that storage changes would occur mainly within the soil cover: the very small amounts of groundwater that exist in the unconnected faults and fractures and other voids in the bedrock would play no part in these changes. Chapter 2 describes the use of the neutron probe for measuring soil moisture changes (ΔS), employing 54 access tubes in 6 lines. In 1975 this network was reduced to a single line in each catchment, following an analysis of measurements (Institute of Hydrology, 1976) which showed no significant systematic spatial variation in soil moisture changes. For the period from 1974 onwards, these changes were measured from an arbitrary field capacity defined as the mean value at each site for the winter of 1974/75. The soil moisture network data was not weighted according to domain theory, the simple arithmetic mean being employed instead. This followed a comparison of the results from the two methods which showed that both sets of estimates agreed closely, the maximum difference being 19.2 mm for the Wye during the drought of 1976.

The annual balance

An analysis of the ΔS data for 1970-1974 indicated that soil moisture change played no significant part in the annual water balance. However, that particular period was characterised by summers with no great soil moisture deficits and no deficits that lingered into the winter months. This was not the case for the subsequent years (1975-1982) when the deficits persisted, particularly following the dry years 1975 and 1976, suggesting that ΔS can be important to the annual water balance (Hudson, in press). For 'normal' years, however, omission of ΔS caused errors of less than 5%, suggesting that it is a factor which could be ignored.

The seasonal water balance

As might be anticipated, the discrepancies caused in the estimate of monthly water use (P-Q) follow the general pattern of annual differences. The greatest percentage underestimate occurred in the drought summers of 1975 and 1976 and the largest overestimate in the autumn of 1976, as the soil was wetting up after the drought. For example, by not taking ΔS into account, evaporation totals in the Wye and Severn were underestimated by 76 mm and 71 mm between 19 July 1976 and 23 August 1976, when values of P-Q suggest there was a water use of 13 mm and 3 mm respectively.

Inclusion of ΔS, computed from soil moisture measurements, in the water balance improves the estimates of actual evaporation but still leaves large residual errors. Actual evaporation (P-Q-ΔS) is shown for the Wye in Figure 22 as a comparison with Penman E_T. When E_T is subtracted from estimated actual evaporation the residuals still show an effective recharge of stores in autumn and depletion of stores in the spring, a phenomenon which suggests that ΔS does not account for all the catchment storage change.

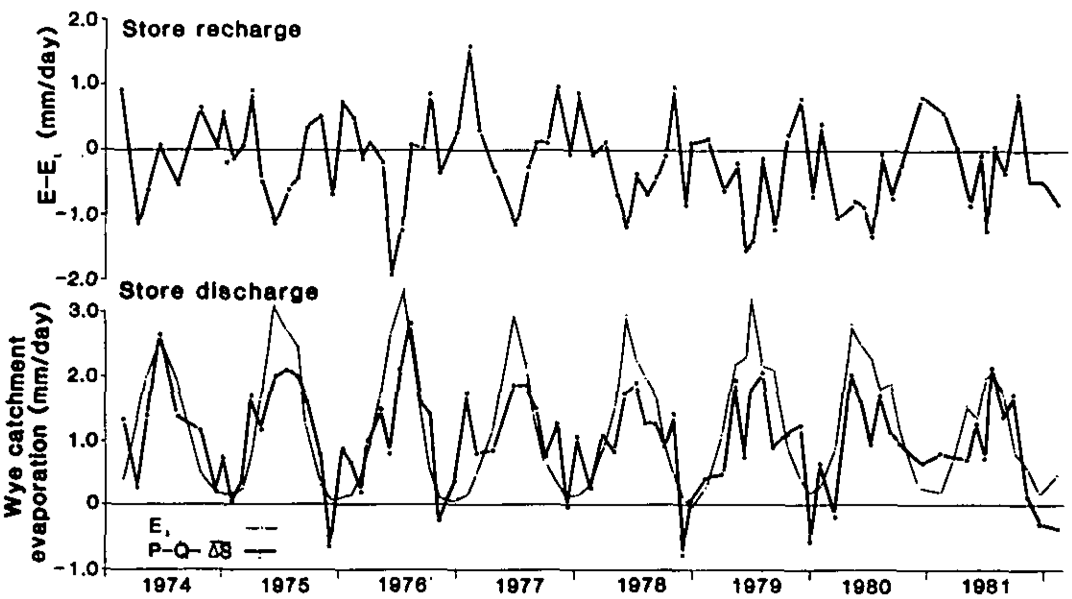


Figure 22 A comparison of within-year evaporation estimates for the Wye catchment and the residual differences.

Assuming that P-Q gives the best estimate of annual evaporation from the Wye catchment, Penman E_T can be used to give a reasonable estimate of the short-term distribution of evaporation if the short-term estimates are corrected by the ratio of annual P-Q to annual E_T. If actual evaporation is known, non-soil storage can be estimated by rearranging the within-year water balance equation:

$$\Delta G = P - Q - AE - \Delta S$$

and by accumulating these "groundwater" changes an estimate of groundwater level can be gained for comparison with soil moisture deficits (Figure 23).

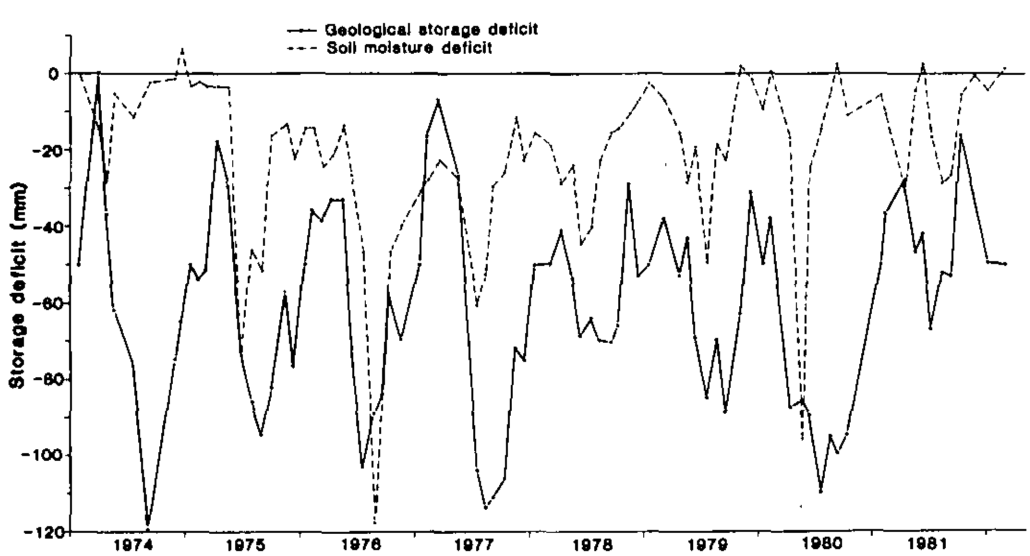


Figure 23 A comparison of soil moisture deficit with the estimated deficit of unmeasured stores.

It appears that the combined magnitude and hence the usable capacity of these unmeasured stores, as represented by the range of values estimated, is similar to the total soil moisture storage capacity (120 mm and 126 mm respectively). Thus ΔS accounts for only half the total storage change within the catchment. For the most part, the emptying and refilling of the geological storage occurs at the same time of year as that of the soil moisture storage, although with a slight lag.

The discovery of the existence and large size of these stores has an important influence on our view of upland catchments, not just in their impact on evaporation estimation: it has also been recognised that summer baseflow may be more reliable than was once thought, that the impact of artificial drainage on catchments would not affect these deep stores, that the catchment response to storm rainfall might comprise more than just near-surface runoff and that streamflow chemistry will be affected as much by well-buffered waters of relatively deep origin as by surface water.

The impact of forestry

Estimates of the within-year evaporation rates from the forested area of the Severn catchment have been derived in the same way as were the annual rates described earlier, by assuming that the unforested Upper Severn area evaporates at the same rate as the grassland in the Wye. Figure 24 shows the more rapid fluctuations and generally higher levels of actual evaporation compared to the smoother Penman E_T curve.

To explain the reasons for the greater evaporation from the Severn catchment it is necessary to split the interception and transpiration process within the forest. As the experiment included a study of interception at seven sites in the Hafren Forest using networks of throughfall troughs and stemflow gauges which were read on the same day as the soil moisture networks, it has been possible to subtract the interception terms for periods between 1977 and 1980 (inclusive) from total evaporation to give the amount of water transpired.

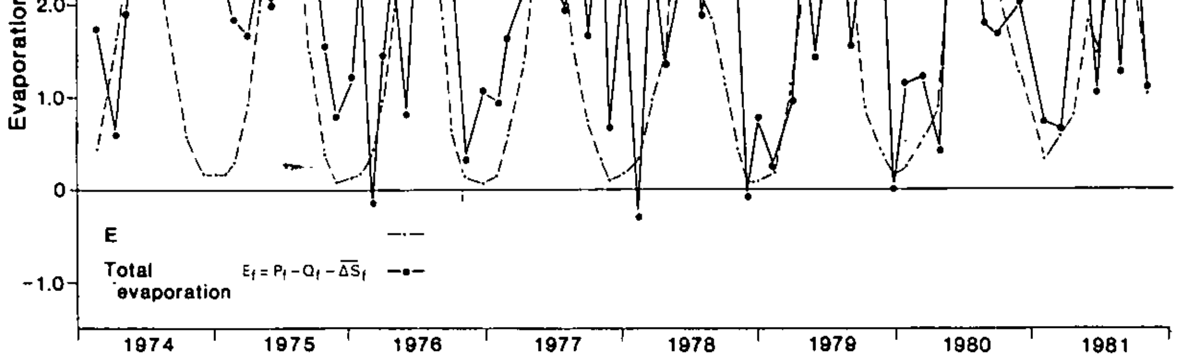


Figure 24 A comparison of the within-year evaporation estimates for the forested portion of the Severn catchment.

The main components of the evaporation from the forest are shown in Figure 25 for the years when net precipitation data are available (1977-1980). With the exception of winter 1978/79, the winter evaporation seems to be sustained almost entirely by interception. Transpiration contributes only during the summer months and even during these periods it is suppressed relative to grassland evaporation. Peak rates vary between 1.5 and 1.8mm a day compared to 1.9 and 2.8mm per day from the grassland catchment. For much of the winter period, transpiration appears to be negative. This is mirrored by a tendency during these same periods for interception to be greater than the water balance estimate of total evaporation. By definition this is impossible, and further points to the fact that the water balance evaporation is underestimated during the winter because of the operation of unmeasured stores in the catchment.

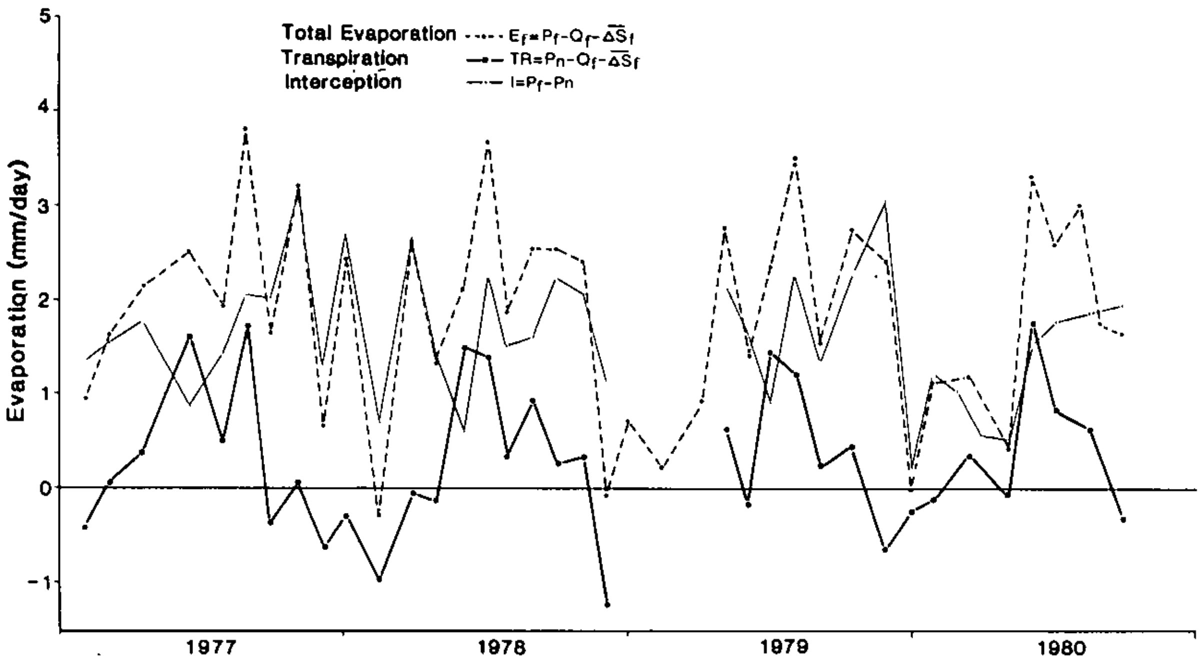


Figure 25 The relationship between total evaporation, interception and transpiration from the Hafren forest

TABLE 12 Water balance (mm) of the forested portion of the Severn catchment (* indicates incomplete years)

Year	P_F	Q_F	ΔS_F	E_F	E_F/P_F%	I	TR	I/P_F%	TR/P_F%
*1974**	*2443.3*	*1596.9*	*-17.2*	*863.6*	*35.3*				
1975	*2036.2*	*1258.2*	*-20.9*	*798.9*	*39.2*				
1976	*1657.1*	*1085.2*	*-37.0*	*608.9*	*36.7*				
1977	*2620.2*	*1821.7*	*27.6*	*770.9*	*29.4*				
1978	*2353.9*	*1750.1*	*8.4*	*595.4*	*25.3*				
1979	*2643.5*	*1970.1*	*6.3*	*667.1*	*25.2*				
1980	*2526.5*	*1858.4*	*- 2.0*	*670.1*	*26.5*				
*1981**	*2428.2*	*1886.5*	*0.4*	*541.3*	*22.3*				
1977	*2620.2*	*1821.7*	*27.6*	*770.9*	*29.4*	*591.4*	*179.5*	*22.6*	*6.9*
*1978**	*2253.9*	*1652.3*	*7.0*	*594.6*	*26.4*	*557.1*	*37.5*	*24.7*	*1.7*
*1979**	*1924.6*	*1323.3*	*7.7*	*593.6*	*30.8*	*492.1*	*101.5*	*25.6*	*5.3*
*1980**	*1585.4*	*1101.3*	*- 2.1*	*486.2*	*30.7*	*443.7*	*42.5*	*28.0*	*2.7*

Transpiration is the residual of total evaporation minus interception and must therefore also be underestimated.

The summation of these data to give annual estimates of the components of the forest water balance (Table 12) indicates that total evaporation loss represents 29.5% of the rainfall over the forest, assuming 68% forest cover. The 15.5% of rainfall evaporated by the grassland of the Wye catchment is therefore 14% less than from the forest. This is the vector resultant of the direct evaporation of 24.9% of the incoming rainfall counterbalanced by a suppression of transpiration of 11.2% of rainfall compared to the grassland catchment.

If a forest area of 62% is used, as discussed earlier, then the total evaporation loss represents 32% of the rainfall for the period 1974-1981 inclusive.

3.5 Conclusions

The water balances of grassland and forested catchments in upland Wales, as exemplified by the Plynlimon catchments, have been quantified to reveal a total evaporation rate of between 15 and 17% of rainfall from grassland, depending on the period used, and between 29 and 32% from forests, the range depending on the period used and the chosen estimate of percentage cover in the Severn. The losses from grassland appear to be sustained almost completely by transpiration although it is difficult to measure interception losses from short grass. Conversely, evaporation from forest is sustained mainly by interception, at 25% of rainfall, while transpiration is suppressed to between 4 and 7% of rainfall, values which are well below the potential rate suggested by Penman E_T.

Analysis of the data from 1969 to 1985 has also indicated a number of further lines of enquiry that should be pursued as a longer run of data comes on stream. In particular, the within-year distribution of evaporation is becoming increasingly relevant to the rational assessment of water resources. Research into this aspect using the water balance technique has been hindered by the lack of information on subsoil storage. The future research programme at Plynlimon will include measurement of deep storage but in the meantime there is advantage to be gained from a theoretical approach which predicts short-term soil moisture changes from rainfall/evaporation accounting models which relate groundwater discharge to baseflow. Refined techniques for hydrograph separation are now becoming available to facilitate this task (see, for example, Jakeman *et al.*, 1990).

A further point is that although the paired catchment approach to quantifying water balance differences as a function of vegetation cover and land management assumes that the systems under study are in equilibrium, there is increasing evidence that the main controlling influence, the climate, is likely to change significantly over a timescale similar to that of the catchment experiment. This will obviously have an impact on rainfall amounts, intensities and distribution, potential evaporation rates, vegetation growth, etc. and there are some indications from the long-term Plynlimon record that trends in P, Q and AE are already becoming evident. The next step is to explain these trends in physical as well as statistical terms and to derive models which can predict the impacts of further climate change. On top of this, rapid land use changes within the catchments, for example the clear-felling of the Hore, are being studied to assess their impacts on the water balance and streamflow response.

Chapter 4
The extremes of flood and drought

One of the most demanding questions in the natural sciences is how well the extreme behaviour of a system can be predicted from observations of its "normal" state. Since this question is central to many of the applications of hydrology, the Plynlimon study necessarily included intensive investigations of floods and droughts.

The significance of an extreme event is characterised by its return period, i.e. the period of time, usually in years, in which the event could be expected to recur. The data record is analysed by statistical methods to produce a frequency distribution of events. The expected frequency of an event of given magnitude may be calculated from this distribution. In the short lifetime of the Plynlimon experiment we have had the opportunity to observe two floods with a return period greater than 100 years, a hundred-year drought during the 1970s and a hundred-year rainfall in 1984.

The occurrence of rare events in a short record poses considerable problems for the routine analysis of flood frequencies, unit hydrographs and base flows. This is particularly true for the data from the Plynlimon subcatchments which are short in duration. Nevertheless, flood and drought analyses have been prepared for this report as a prelude to descriptions of individual extreme events.

4.1 Flood flow characteristics of the Plynlimon catchments

A major objective of the study from the outset was to compare the flood responses of the Severn and Wye and hence evaluate the effects of afforestation on flood flows. Although it was generally agreed that forests reduce flooding, little quantitative work on afforestation had been done in Britain and that which had been done related to a mature stand (Lloyd, 1953).

More recent research has shown that the relationship between flooding and land use is more complex, with the flood potential of a forested catchment varying through the crop cycle and with land management practice. In the initial stages it is the ground preparation and drainage, necessary for trees to make successful growth, which are the major influence on flood flows. Robinson (1980), however, argued that the effects of ditching were only a temporary phase: after canopy closure, the infilling of drains by vegetation, the deep ground litter of leaves and needles and the higher interception losses will result in a smaller flood response than from the original upland pasture.

Perhaps because of the complications of the crop cycle and management practices, there is little evidence from regional flood studies in Britain that the area covered by forest is a significant independent variable in the regressions used for flood prediction. In a pilot study in north west England, carried out as part of the Flood Studies Report (NERC, 1975), the proportion of forestry in each catchment did not provide significant additional explanatory power in regression equations for predicting the mean annual flood. This could have resulted from the wide range of catchment sizes considered and the generally small amount of forestry in each catchment. In addition, the presence or absence of forestry is highly correlated with other catchment characteristics related to 'uplandness' and this may account for its apparent lack of influence in the regressions.

Flood frequency analyses

Flood discharges for the Wye and Severn catchments have been analysed using the

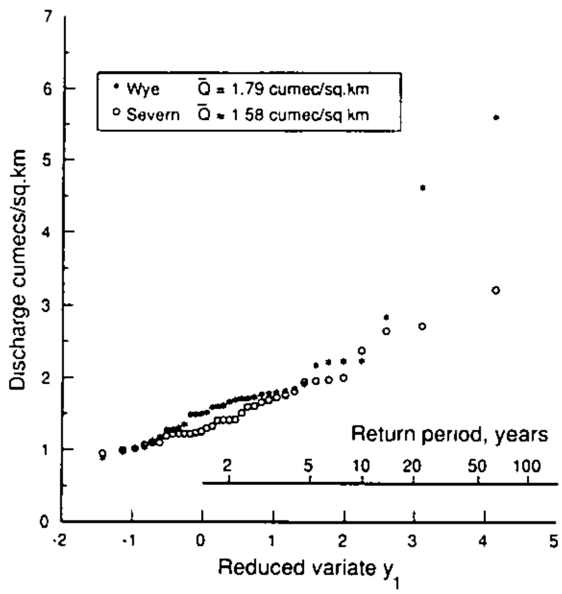


Figure 26 Flood frequency curves for the Wye and Severn.

methods set out in Volume I, Chapter 1 of the Flood Studies Report (NERC, 1975). Figure 26 compares flood frequencies derived from 35 annual maxima for the years 1951 to 1985. These records on both rivers incorporate data from gauging stations which pre-date the present Plynlimon structures, and which were, nevertheless, thought to have reliably measured flood peaks.

The annual maxima, arranged in ascending order, were each assigned a value of the reduced variate y_1 defined by the Gumbel or Extreme Value Type 1 distribution. These values can be computed from formulae given in the Flood Studies Report, and are also presented there as tabulated values (NERC, 1975, Vol. I, Section 1.3.4 and Table 1.16). The values of the return period T, plotted as an auxiliary horizontal axis, are given approximately by

$$T = \exp(y_1) + 0.5$$

Although the mean annual flood of the Wye (1.79 cumecs km^{-2}) is higher than that of the Severn (1.58 cumecs km^{-2}, the difference is not statistically significant. A very close similarity in flood peaks, especially for return periods below ten years, is evident and suggests that mature conifer cover has little effect on the magnitude of peak flows.

Figure 27, taken from Robinson and Newson (1986) compares flood peaks resulting from over 100 paired events from 1975 to 1978. For very small storms (discharge peaks less than $1mmh^{-1}$, which is equivalent to 0.28 cumecs km^{-2}) peak flows were consistently greater from the Wye catchment than from the Severn, while moderate events (in excess of $1mmh^{-1}$) showed no systematic difference in peaks. It would therefore appear that the relatively large interception losses are probably suppressing forest runoff for small storms, while in moderate events the drains are helping to increase forest peaks to equivalent levels to those from the grassland.

Although Figure 27 suggests that the Wye is more responsive to rare events, such an interpretation is complicated by a number of

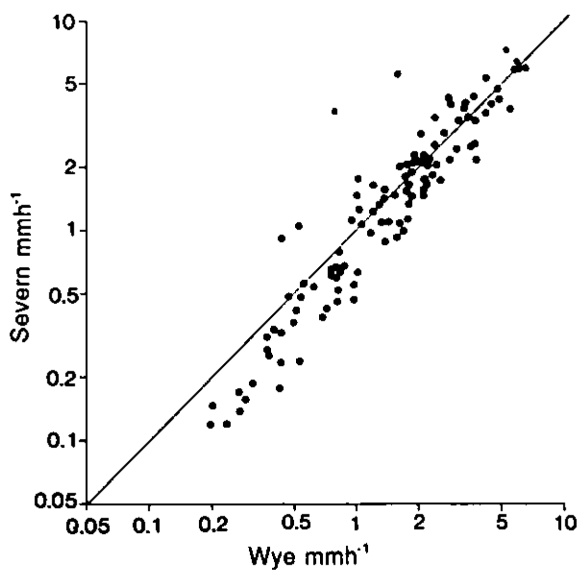


Figure 27 Comparison of peak flows for over 100 storms on the Wye and Severn (70% forested) catchments. Flows are expressed as hourly runoff rates: $1mmh^{-1}$=0.278cumecs km^{-2}.

factors. Several of the largest peaks are estimated and are the result of summer thunderstorms: these tend to localise the effects to one catchment. For example, a thunderstorm in August 1977 produced the second largest recorded flood on the Severn, but an insignificant response on the Wye. These factors, coupled with the inevitably small sample size, make accurate assessment of the return period of rare events on each catchment difficult.

Unit hydrograph analyses

Over 40 flood events on each main catchment were studied in detail by unit hydrograph analysis. Precipitation and runoff data, with 15-minute time steps, were examined carefully and snowmelt events and those events resulting from localised rainfall were excluded. Table 13 summarises the results and compares mean values of peak flows per unit area, percentage runoff (calculated as the volume of quick response runoff in relation to the total rainfall volume), and unit hydrograph parameters.

Both data sets exhibit the same overall similarity in the flood response of the Wye and Severn. No significant differences were evident in mean unit hydrograph parameters, mean peak flows or in catchment lag. Both catchments show a flashy response to rainfall with times to peak typically of 1.5 hours. Field work, under flood conditions, has confirmed travel times of this order of magnitude (Newson and Harrison, 1978).

No consistent trend, for example the reduction of response times for large events, as noted by Newson (1975, 1981) on a smaller data set, was evident although this may simply be a reflection of the low return periods (less than 5 years) of the events.

Catchment average 30-minute unit hydrographs provide a more accurate comparison of the shape of response. These were derived for each catchment by superposition and averaging of individual unit hydrographs, by the method of Boorman and Reed (1981), and are shown in Figure 28 for paired data sets. These unit hydrographs are in response to the same rainfall inputs and they confirm the close similarity in the shape and timing of response noted earlier.

The main difference between the catchments lies in their volumetric response to flood-producing rainfall. Mean percentage runoffs were significantly different, with, on

TABLE 13 Comparison of mean values of hydrograph parameters

	All events		Paired events	
	Severn	Wye	Severn	Wye
Number of events	52	42	18	18
Peak flow (cumec)	8 05	10.52	8.46	11.80
Peak flow (cumec km²)	0.93	0 99	0 97	1.11
Percentage runoff	43.1*	51.9*	45 5**	51.4**
Lag (hours)	3.3	3 1	3.2	3.2
Nash lag (hours)	4.6	4 5	4.9	4.5
Number of UH events	41	35	17	17
UH time to peak (hours)	1.53	1.45	1.35	1.38
UH peak (cumec km²)	0.81	0.82	0.81	0.84

* significant difference - 2 sample 't' test
* significant difference - 2 sample Wilcoxon paired rank test

'Paired events' are those events which were considered to yield useful data for both catchments.

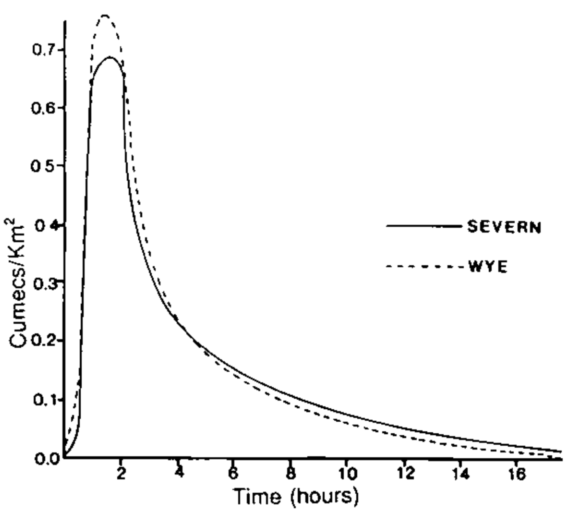


Figure 28 Catchment average 30-minute unit hydrographs for paired events

average, 52% runoff on the Wye compared with only 43% runoff on the Severn. This trend was consistent in 16 out of 18 paired events and reflects the generally drier antecedent condition of the soil beneath a tree cover (Robinson and Newson, 1986).

The percentage runoff from a catchment for a given rainstorm depends strongly on the storm rainfall P and the antecedent conditions, characterised by the catchment wetness index CWI (both variables expressed in mm). A regression equation in which the independent variables are (P-10) and (CWI-125) has been found satisfactory for UK catchments (Flood Studies Report, Vol. I, Chap. 6). Regression equations derived for the Wye and Severn are:

$$\text{Wye:} \quad \frac{Q}{P} \times 100 = 35.59 + 0.29(P-10) + 0.39(CWI-125)$$

($n = 42$, $r^2 = 0.526$, Standard error of estimate = 11.83)

$$\text{Severn:} \quad \frac{Q}{P} \times 100 = 27.40 + 0.33(P-10) + 0.37(CWI-125)$$

($n = 52$, $r^2 = 0.647$, Standard error of estimate = 7.25).

On both catchments the sensitivity of percentage runoff to total storm rainfall and antecedent conditions is similar and interestingly is somewhat greater than is suggested by the Flood Studies percentage runoff prediction equation. The constant term in the above equation represents the response under 'standard' design conditions, i.e. CWI = 125 mm and P = 10 mm, and again demonstrates higher runoff from the Wye catchment. Similar trends are evident if regressions are based on just the 18 paired events.

The catchment wetness index (CWI) depends on the soil moisture deficit (SMD), normally estimated from the nearest weather station (Grindley, 1967), and an index of antecedent rainfall. In this study, an attempt was made to calculate a more realistic SMD value directly from the Plynlimon climate data. The above equations indicate that both catchments show a similar sensitivity to CWI, despite the drier soil conditions which are known to exist under forest stands. This may be due to the inadequacy of applying calculated SMD values to forested catchments, which in turn leads to unrepresentative CWI values.

Future analyses of this type clearly need to incorporate net rainfall or soil moisture measurements made beneath the forest cover, to investigate more closely the role of interception in determining flood response under mature conifers. These field measurements may in turn facilitate more realistic modelling of the distribution of interception losses throughout a flood event and might provide an explanation for the anomaly that significant differences in volumes of runoff exist between the two catchments, despite close similarities in

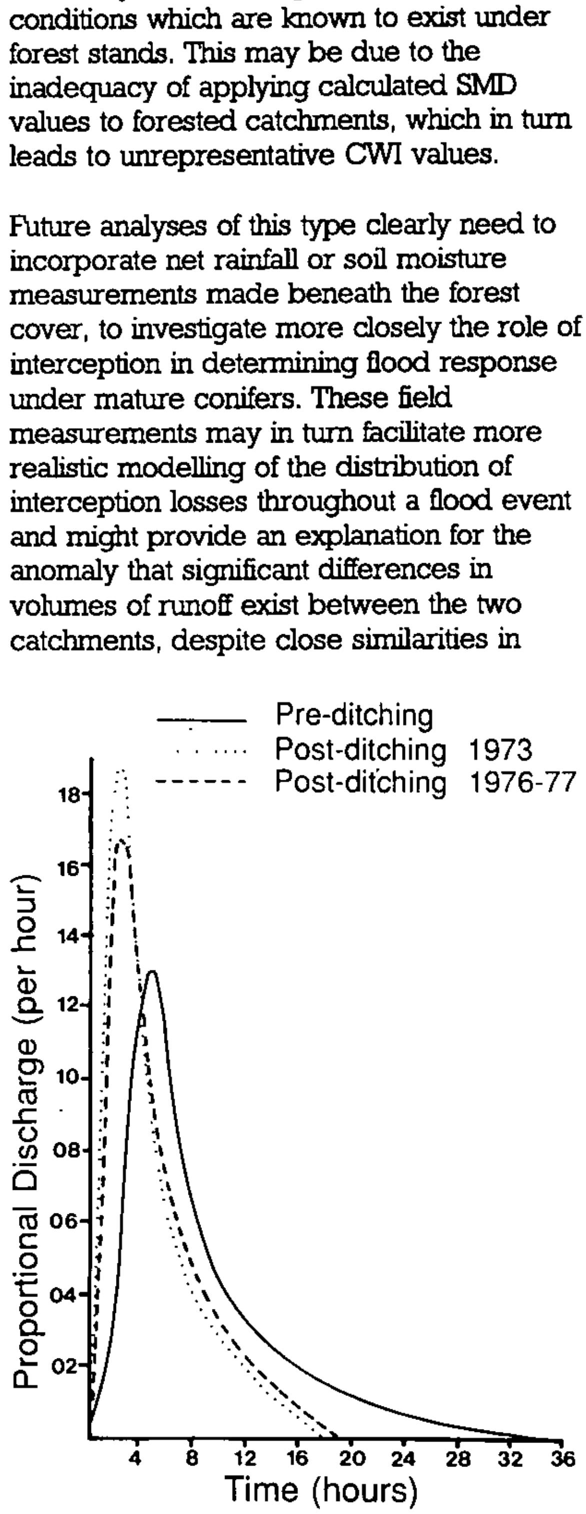


Figure 29 Average one hour unit hydrographs before and after drainage of the Coalburn catchment.

other hydrograph parameters. The model adopted for distributing losses allowed for a reducing loss, whose rate was determined by the catchment wetness at the start of the event. Although appropriate for the Wye it might be more realistic for the Severn, in view of findings of the interception studies, to allow a larger initial loss followed by reducing rates.

In summary, it would therefore appear that the mature closed forest canopy of the Severn, despite drainage, attenuates floods sufficiently to give on average (i.e. for more frequent or less extreme events) a comparable response time to the neighbouring grassland Wye catchment, though the volume of runoff is somewhat lower. In the absence of a forest cover, the steeper slopes and dense network of drains in the Severn might have produced a more flashy response than the Wye.

The results agree with observations that the initial adverse effects of drainage on flood flows reduce as the forest grows. For an immature forest such as at Coalburn in northern England (Robinson, 1980), forest drainage was still the major influence six years after planting and led to much peakier unit hydrographs and reduced times to peak than the pre-drainage hydrographs (see Figure 29). In contrast, the mature Severn forest, averaging 30 years old, is now similar in its average flood response to the Wye, an undrained, moorland catchment.

4.2 Low flow characteristics

Records from the main catchments and all the subcatchments have been used in the investigation of low flows, with the periods 1972-1984 and 1976-1984 selected for analysis. The first period provides the longest reliable common record for the main catchments, while the second (with the exception of three months' data for the Hafren) provides the longest common record for all the experimental catchments. The daily data from each of the eight catchments were converted initially to cumecs km^{-2} to assist the detection of differences between catchments. To facilitate comparisons with regional studies, hydrograph analysis techniques, which were developed during the Low Flow Studies (Institute of Hydrology, 1980), have been applied.

The base flow index, recession curves and flow duration curves

A general index of hydrograph behaviour, the base flow index (BFI) was developed during the Low Flow Studies. A computer program applies simple smoothing and separation rules to the flow hydrograph (Figure 30), from which the BFI is calculated as the ratio of the mean base flow under the separated hydrograph to the recorded mean total flow. Values of the index, which is a measure of the proportion of flow derived from groundwater or slow throughflow processes, range nationally from 0.17 for an impermeable catchment with a very flashy flow regime to 0.98 for a permeable chalk catchment with a very stable flow regime.

Table 14 shows values of the base flow index for the Plynlimon catchments for the period 1976-1984. In comparison with the national range of values, these data reflect the impermeable nature of the upland areas. However it is apparent that there are real differences in the response of the subcatchments, with BFI values ranging from 0.27 (Nant Iago) to 0.39 (Hafren).

Table 14 also shows values of Q95(1), the daily mean discharge exceeded for 95% of the time, and MAM(10), the mean annual 10-

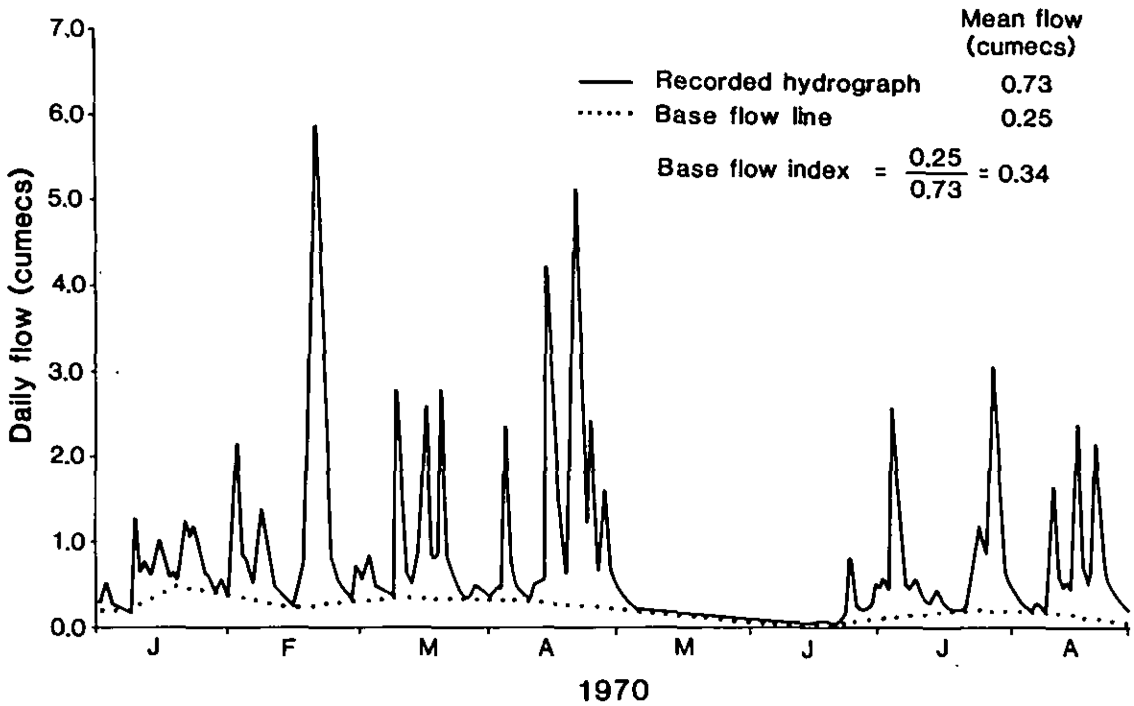


Figure 30 Hydrograph base flow separation

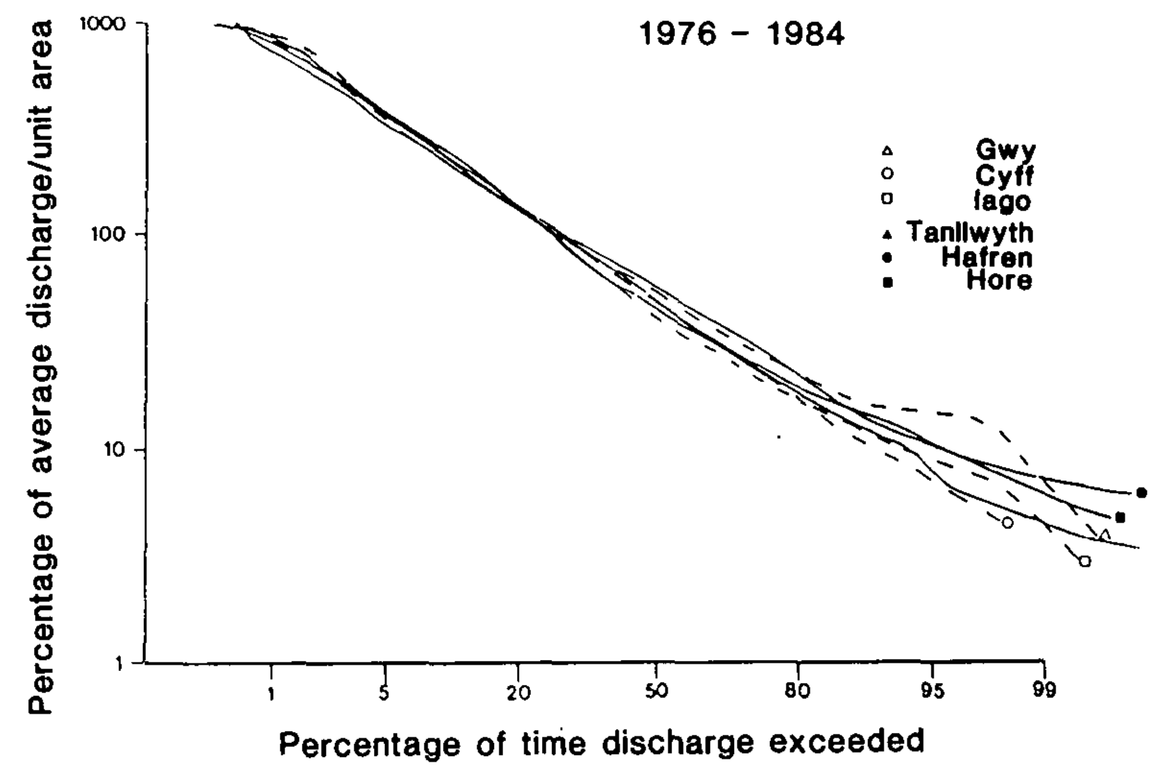


Figure 31 Flow duration curves of sub-catchments

TABLE 14 Summary of flow statistics for Plynlimon catchments 1976-1984

	Average flow*	BFI	Q95(1)*	MAM(10)*	KREC (per 2 days)
Severn	0.062	0.35	0.006	0.006	0.90
Hafren	0.064	0.39	0.007	0.0066	0.89
Hore	0.060	0.32	0.007	0.0064	0.89
Tanllwyth	0.066	0.29	0.005	0.0049	0.86
Wye	0.065	0.32	0.006	0.0055	0.90
Gwy	0.072	0.34	0.011	0.0105	0.88
Nant Iago	0.060	0.27	0.006	0.0053	0.85
Cyff	0.067	0.30	0.005	0.0047	0.86

day minimum. Both indices are expressed in cumecs km^{-2} which allows the variability of river flows from catchments with different areas to be compared. It can be seen that there is little numerical difference between the two low flow indices on the same catchment, although there are consistent differences between catchments. Most notable are the well sustained low flows for the Gwy and the very low discharges of the Cyff - both subcatchments of the River Wye draining the Ordovician grits of the core of the Plynlimon anticline.

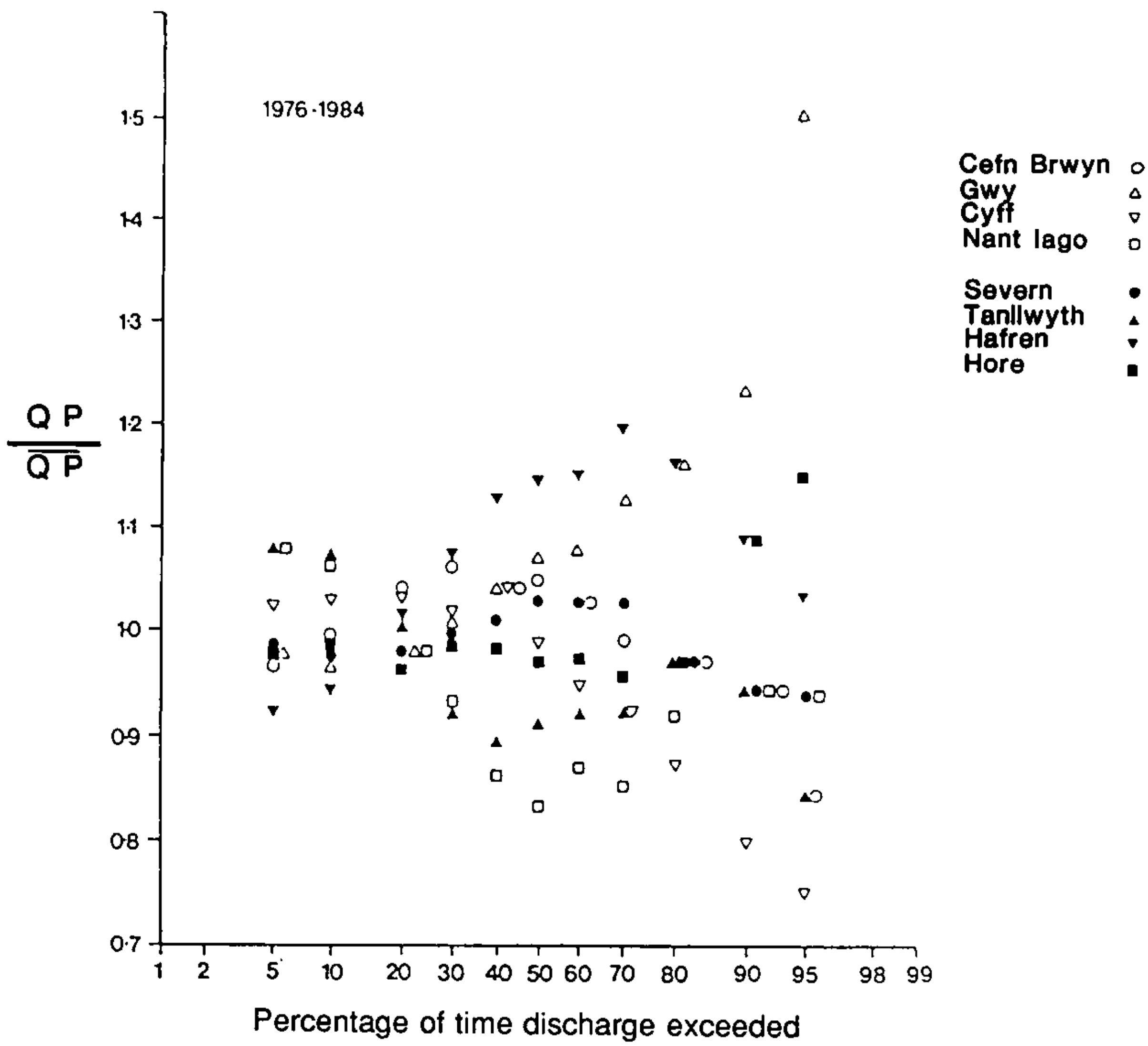


Figure 32 Ratio of QP to $\overline{QP}$ for percentiles shown - all catchments.

The flow duration curves of the subcatchments are shown on Figure 31. Comparison between curves is assisted in Figure 32 by expressing the discharge corresponding to a given percentile QP as a multiple of the average value over all eight catchments $\overline{QP}$. The Cyff and Gwy stand out once again as experiencing the largest departures from the average over a range of low flow percentiles. The performance of the Hafren in Figure 32 is also noteworthy: at intermediate low flows, e.g. from the median to the 80 percentile levels, it is clearly the best-supported stream of the Severn catchments. However, these reserves appear to become depleted, so beyond the 80 percentile point the flows are similar to the Hore.

Recession curve analysis based on mean daily flows has been used to estimate the value of the 2-day recession constant (KREC) at a discharge of approximately 25% of the average daily flow (Institute of Hydrology, 1980). Again, as can be seen on Table 14, differences between catchments are small with values ranging from 0.85

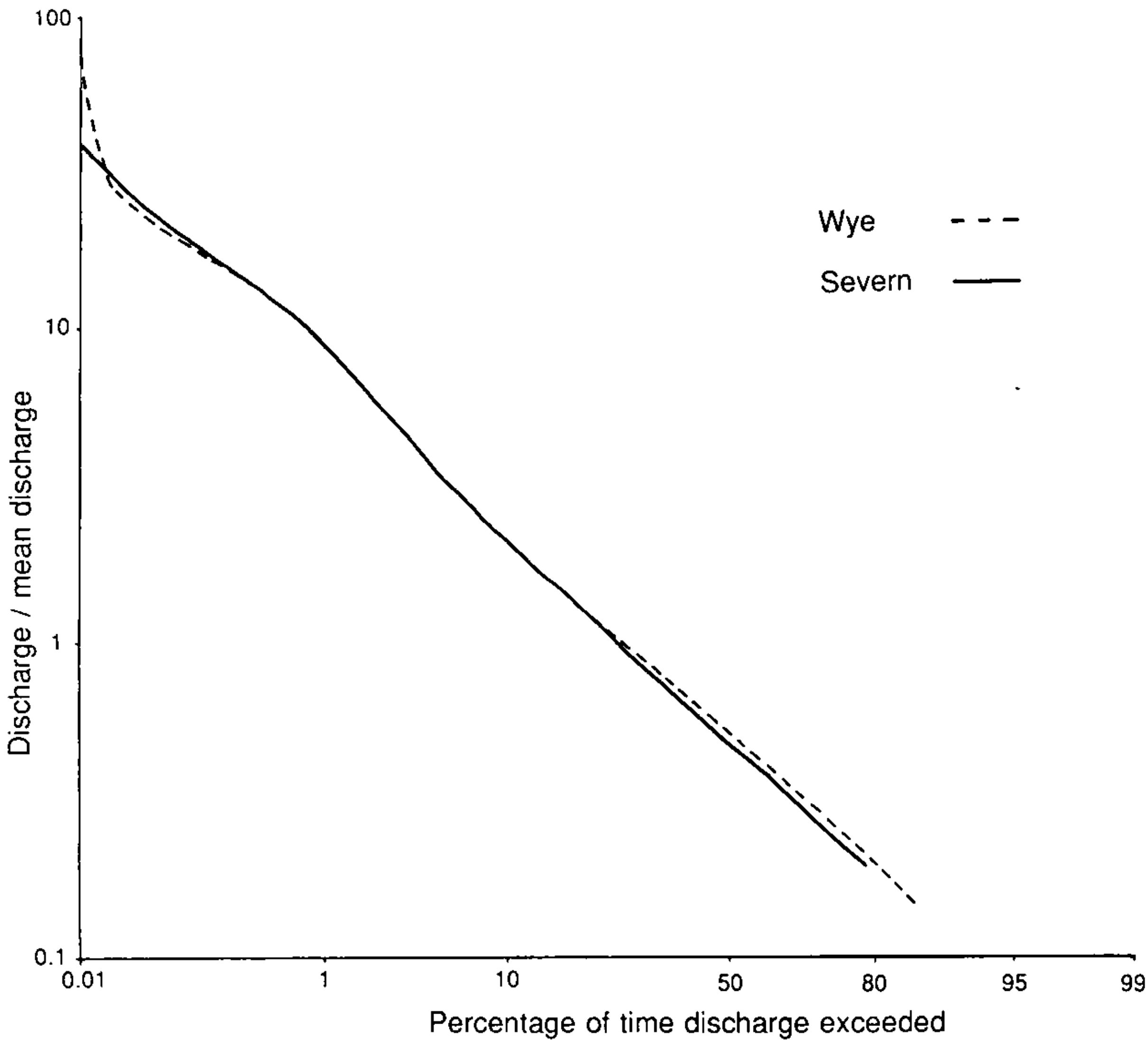


Figure 33 Flow duration curves for Severn and Wye

(Nant Iago) to 0.90 (Severn). Detailed inspection of individual recessions shows some distinct contrasts, with the Nant Iago and Tanllwyth having the greatest variability of recessions and the Hafren having the least. Thus, event-to-event variability appears greatest in those catchments which experience the steepest recessions. The explanation for this behaviour may be the dominance of shallow soil processes which are more susceptible to climate effects in sustaining the steeper recessions

Seasonal variability of flows

Figure 33 compares flow duration curves for the Wye and Severn over a common period, 1972-1984. As before, flows are expressed as cumecs km^{-2}. Only during low flows (below Q85) is flow in the Severn comparable with or slightly higher than in the Wye.

Figure 34 shows that relatively higher monthly mean flows occur on the Severn in the winter and on the Wye in summer.

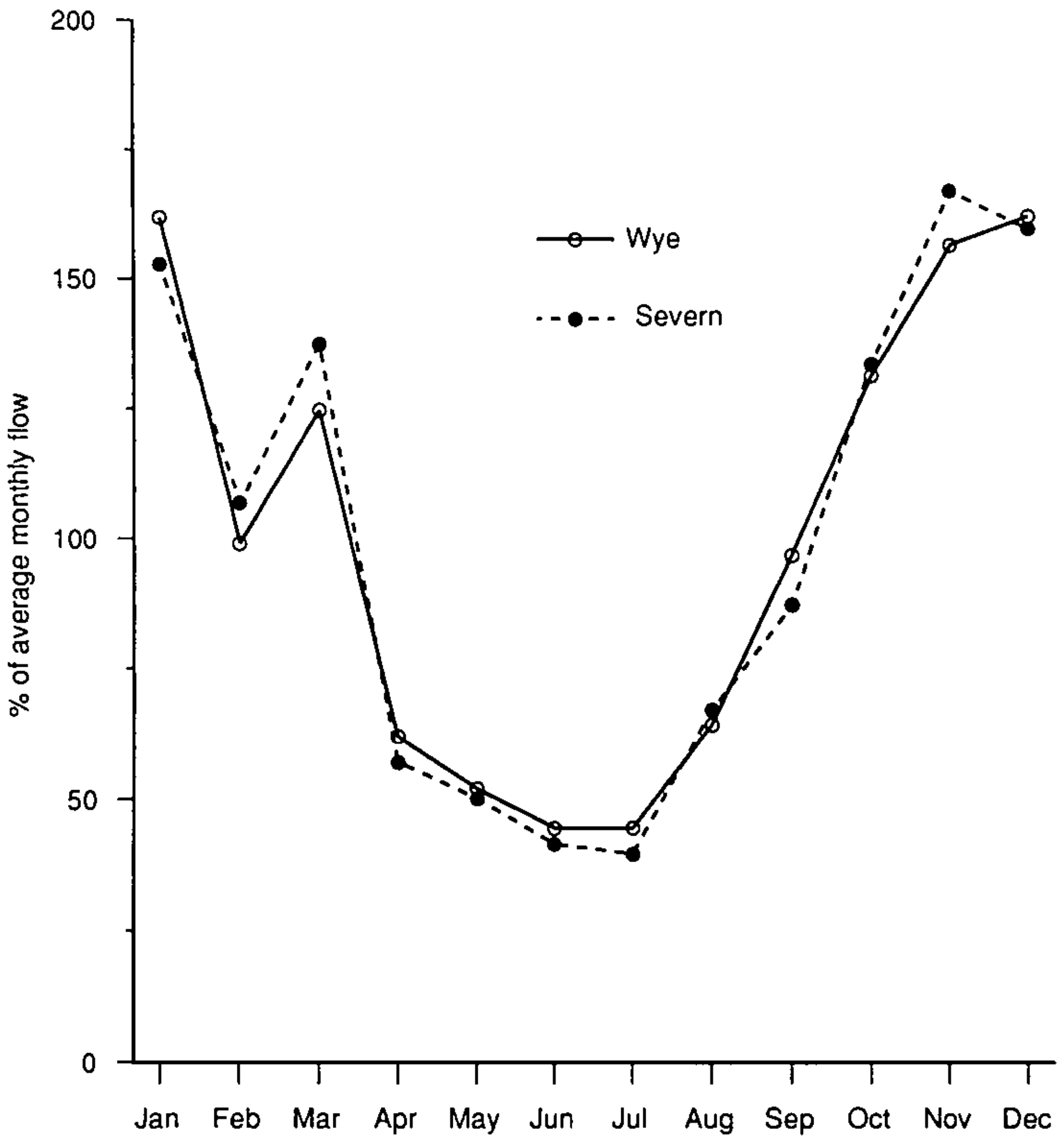


Figure 34 Variation in monthly runoff for Wye and Severn

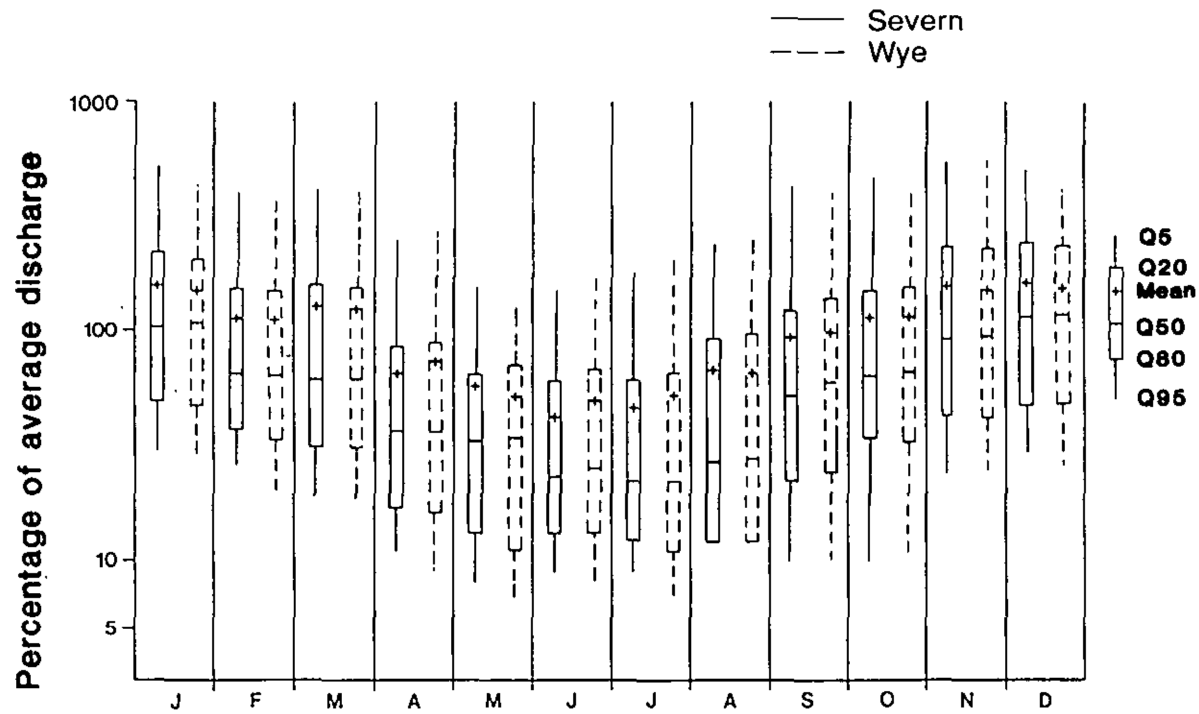


Figure 35 Seasonal variation of percentile flow for Severn and Wye

Figure 35 gives a more detailed breakdown of the seasonal distribution of flows by showing the monthly values of Q5, Q20, Q80 and Q95. The main features of the diagram are the similarity in flow distribution between catchments in each month of the year and the greater range of discharge experienced in the Autumn months. This reflects the fact that this time of year can suffer the extremes of very low flows after a prolonged summer drought or relatively high flows due to very high daily rainfalls. Small differences between the catchments can be seen in Figure 35. For example, between April and August there is a wider range of flows on the Wye than on the Severn.

The effects of land use relative to those of geology

Base flow indices, recession constants, flow duration curves and mean annual minima all support the conclusions that, in terms of the variability of mean daily flows, there are definite differences in the flow regimes of the Plynlimon sub-catchments. However, differences between sub-catchments with the same vegetation, e.g. Tanllwyth and Hore (forested) and Cyff and Gwy (grassland) are as large as the differences between catchments with different vegetation (Figure 32).

Table 15 summarises some of the characteristics of the Plynlimon subcatchments which may influence low flows. It is noteworthy that of the three forested sub-catchments, the Tanllwyth, which experiences the lowest drought discharges, has the highest proportion of the catchment which is ditched. However the most consistent relationship is for the Hafren, Hore and Gwy which drain the highest areas of Plynlimon and have the highest minimum flows. Within each of these sub-catchments there are significant areas of the Upper Ordovician Fan formation whose massive grits provide a minor unconfined aquifer which maintains the base flow.

TABLE 15 Characteristics of the Plynlimon subcatchments likely to influence the generation of low flows, as at 1984

	%Forest cover	%Blanket peat	%Valley mires	%Ditched	%Improved pasture
Severn	67	38	16	29	-
Hafren	48	52	16	22	-
Hore	78	33	12	25	-
Tanllwyth	100	42	25	72	-
Wye	1	22	21	6	27
Gwy	0	37	20	3	7
Cyff	0	14	24	7	42
Iago	3	30	7	5	23

More detailed field investigations during the 1976 drought provided further insight into the low flow processes at Plynlimon. During the drought, streams draining blanket peat on Plynlimon and elsewhere in mid-Wales sustained higher minimum flows than those draining podzol or brown-earth soils. The difference is even established in the Welsh names of two of the mid-Wales rivers: Hafren = summer flowing; Hafesp = summer dry.

Evidence from fieldwork at Plynlimon suggests that low flows were sustained by drift deposits beneath the peat rather than by the peat itself. Boreholes driven into the base of two extensive peat haggs dried up completely by the end of the drought, whilst small springs along the nearby channel of the Upper Severn were still flowing strongly. Springs were also observed in the Upper Wye catchment and both areas have a mantle of periglacially fractured bedrock fragments, often gritty in texture, beneath the peat.

TABLE 16 Range of BFI values in upland Britain

Region	Number of catchments	BFI Mean	S.d
Scottish Highlands	41	0.449	0.135
Southern Uplands	19	0.462	0.128
Lake District	5	0.400	0.061
Pennines	33	0.361	0.106
Wales	31	0.385	0.087
South West	5	0.450	0.065

These results indicate that the differences in flow regimes may be due primarily to the bulk permeability and storage characteristics at the catchment scale rather than land use, a conclusion supported by detailed plot studies carried out in the Wye and Severn catchments (Robinson and Newson, 1986).

Low flow analyses in a regional and national context

To assess the validity of applying the results from the Plynlimon catchments to other areas of upland Britain, it is useful to compare their flow characteristics with those from other gauged catchments. The base flow index (BFI) is perhaps the most useful way of making such comparisons because of its close relationship with other low flow and flood characteristics. Figure 36 shows values of observed BFI for a number of upland catchments in mid-Wales having a similar Silurian or Ordovician solid geology. The low range of BFI values (0.31-0.50) would suggest that extrapolation to other areas of mid-Wales can be made with confidence. Table 16 shows the mean and standard deviation of BFI values from catchments predominantly above 300m in other regions of upland Britain. The range of BFI values, particularly in the Pennines, suggests that in terms of daily flows the Plynlimon area is typical of much of upland Britain and that the variability between the Plynlimon sub-catchments is relatively low.

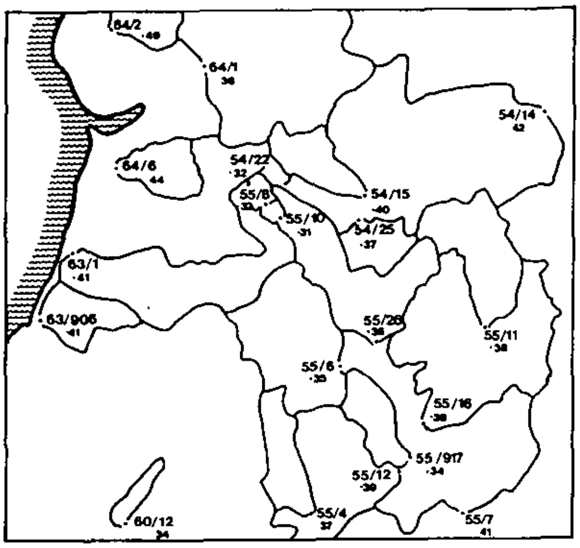


Figure 36 Base flow indices for mid-Wales catchments

The low flows from the Plynlimon catchments can be compared with those predicted using the Low Flow Studies Report. The regional equations for Wales and south west England are:

$$\sqrt{Q95(10)} = 7.60\sqrt{BFI} + 0.0263\sqrt{SAAR} - 2.16$$

$$\sqrt{MAM(10)} = 8.50\sqrt{BFI} - 2.01$$

where both Q95(10) and MAM(10) are expressed as a percentage of the average daily flow and SAAR is the annual average rainfall in mm, strictly over the standard period 1941-1970.

Table 17 shows values of observed and predicted Q95(10), the 10-day 95 percentile low flow and MAM(10), the mean annual 10-day minimum estimated from the observed value of BFI. The predicted values of MAM(10) are on average 20% lower than the observed, while the regression equation for estimating Q95(10) shows no consistent tendency to over- or under-predict on the Plynlimon catchments.

The methods set out in the Low Flow Studies report can also be applied to the problem of estimating the return period of a given event. Figure 37 shows the 10-, 60- and 180-day annual minima frequency curves for the Wye based on observed flow data. It can be seen that for short durations the 1976 minima were the lowest on record, with the 1984 drought ranking fourth lowest. For

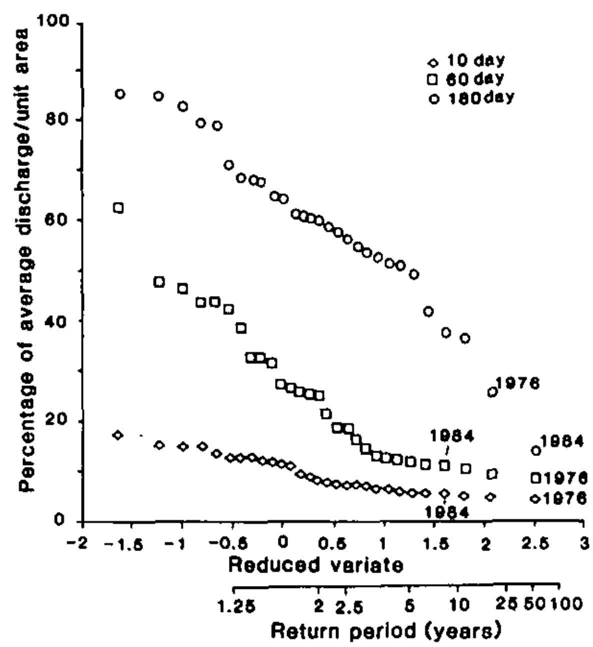


Figure 37 Annual minima diagram for the Wye

TABLE 17 Observed 1976-1984 and predicted low flow statistics

	MAM(10) %ADF observed	MAM(10) %ADF predicted	Q95(10) %ADF observed	Q95(10) %ADF predicted
Wye	8.3	7.8	9.5	12.0
Gwy	14.2	8.7	16.6	12.9
Cyff	7.0	7.0	8.1	11.1
Nant Iago	9.2	5.8	9.5	9.7
Severn	10.1	9.1	10.8	13.2
Tanllwyth	8.1	6.6	10.3	10.5
Hafren	10.8	10.9	12.2	15.1

longer durations the 1984 drought was more severe, with the 180-day minimum being the lowest on record. Estimated return periods ranged between 25 and 50 years for the 1976 annual minima and from 10 years (for the 10-day duration) to 100 years (for the 180-day duration) for the 1984 minima. This wide range of return period for 1984 is supported by Table 18 which includes an analysis of the naturalised flow record for Vyrnwy reservoir which is 25 km to the north of Plynlimon. A national comparison between the 1976 and 1984 drought (Marsh and Lees, 1985) indicated that the 1976 drought was more widespread and for much of eastern, southern and south west England was more severe than the 1984 drought. It was only in parts of Wales, north west England and south west Scotland that the 1984 drought was more severe, with some catchments experiencing drought return periods in excess of 100 years.

TABLE 18 Return periods (years) of 1984 and 1976 annual minima for a given duration (days). All return periods were rounded.

			1984					1976				
Station No	Station name	Years of record	10	30	60	90	180	10	30	60	90	180
25006	Greta at Rutherford Bridge	21	10	5	10	10	100	100+	100	100	50	10
28018	Dove at Marston on Dove	18	5	5	5	10	5	100	50	50	50	20
36006	Stour at Langham	22	2	2	2	2	2	100+	100+	100+	100+	10
50001	Taw at Umberleigh	23	20	10	20	20	10	100	100	50	20	50
52005	Tone at Bishops Hull	24	5	5	5	5	5	100+	100+	100+	100+	50
54003	Vyrnwy at Vyrnwy Reservoir	54	5	5	5	20	100+	100+	100+	100+	100+	50
57004	Cynon at Abercynon	25	10	10	10	50	20	20	20	20	20	10
73010	Leven at Newby Bridge	46	5	10	50	50	100+	20	100	10	20	5
79002	Nith at Friars Carse	27	50	50	20	20	50	50	50	20	50	10

4.3 The 1975-76 drought

The advantage of droughts over floods, from the point of view of *ad hoc* data gathering, is the length of time they take to develop. However, it is impossible to judge the onset of a drought period to initiate any special measurements. Drought flows can be difficult to gauge because of algal growth on the structure, or because the level of water falls below the tapping point of the gauging structure, or because the flow is beyond the lowest portion of the theoretical calibration. Many point measurements must be made over and over again on the assumption that the drought will soon break. Such were the field problems of the 1975-76 drought at Plynlimon.

During the drought, the most intensive period of rainfall deficit was between May 1975 and August 1976 (National Water Council, 1977). Table 19 compares measurements of rainfall, runoff, Penman's

TABLE 19 Comparison of May 1975 - August 1976 with pre-drought means for the same duration

Station	Raintall (mm)	Runoff (mm)	Penman E_t (mm)	Gross catchment loss (rainfall-runoff)	Runoff coefficient	Key
Severn	2249	1465		783	0.65	Drought total (mm)
	* -24.75	* -28.65		* 16.3	* -5 8	% deviation from pre-drought mean
	2989	2053		935	0.69	Pre-drought mean
	4.8	4.9		5 2	0.2	Standard deviation % of pre-drought mean
Wye	2213	1798	776	415	0.81	Drought total (mm)
	* -25 7	* -24 8	2.5	* -29.2	+1.2	% deviation from pre-drought mean
	2979	2392	757	586	0 80	Pre-drought mean
	2 3	2 4	2.5	4 2	0 8	Standard deviation % of pre-drought mean

* indicates drought total greater than 3 standard deviations from mean, indicating at least a 100-year return period

potential evaporation (E_T) and two derived terms (gross loss and runoff coefficient) made during the drought with the average of the same variables calculated over pre-drought periods of 16 months from May to August. Since the severity of droughts is often expressed in terms of percentages of mean rainfall or river flow, Table 19 shows mean values for the pre-drought period, together with standard deviations calculated as a percentage of the mean. Those drought values which can be regarded as extreme have been marked with an asterisk. Rainfall and runoff deficits, compared with average, were extreme for both the Severn and Wye, though not as high as those for the Cam and Ray catchments in south east England (Clarke and Newson, 1978).

In neither catchment did gross catchment loss approach potential evaporation, although apparently loss from the mature forest (62% cover) of the Severn was less restricted by moisture deficit than that from non-forest vegetation. Measured soil moisture values indicate that the maximum deficits set up on forested slopes during the drought were on average almost twice as severe as those on grassy slopes; deficits beneath the trees were also slower to recover after the drought. The inclusion of soil moisture changes in water balance calculations for the two Plynlimon catchments (i.e. P-Q-ΔS) shows the net losses in the Severn catchment to be by 63% greater than those of the Wye for the drought period. The major factor which normally operates to produce greater loss from the Severn catchment is the interception of rainfall by, and evaporation from, the forest canopy. During the long rainless periods of 1975-76, however, interception losses were negligible.

It is known that xerophytic plants such as conifers can limit their transpiration more effectively than can grass under similar conditions of moisture stress. Thus it is difficult to determine the effect of the mature forest on catchment losses during the drought. There appears to have been extensive uptake of moisture from the soil beneath the trees before transpiration became limited by the soil moisture deficit. This transpiration loss, together with interception losses during and shortly after the rain which fell over the period, kept actual losses close to potential evaporation, taking account of soil moisture changes as small as possible over this period. However, it can be proven that the greatest differences in losses between the two catchments occur during wet periods, when interception losses exceed those by transpiration. Under such conditions net losses greatly exceed potential evaporation.

4.4 The 1984 drought

The early 1980s witnessed a dominance of drier summers (Morris & Marsh, 1985) and both 1983 and 1984 brought dry conditions to Plynlimon, with water levels in tributary structures falling below flume tapping points. In 1983 the months of June to August had only 53% of average rainfall (209.1mm compared with an average of 398.2mm). In 1984 the driest March recorded so far on the catchments preceded a six-month period of extreme drought (Table 20). March, April, May and July also all recorded 30% of average rainfall or less (April 14%) and July was also the driest on record. Rainfall for the six months was 2.4 standard deviations below the mean and the summer was widely reported to be the driest this century over a wide area.

TABLE 20 Rainfall totals for the Moel Cynnedd (Plynlimon) climate station for six-month periods (March-August)

Year	Total (mm)		
1968	916.3		
1969	914.4		
1970	1029.8		
1971	698.1		
1972	1040.7		
1973	937.9		
1974	761.4		
1975	649.8		
1976	490.9		
1977	897.4		
1978	929.5		
1979	1172.1		
1980	812.8		
1981	995.9		
1982	891.5		
1983	703.3		
1984	349.5		
Mean	834.8	S.d	210.4

TABLE 21 Volumetric spot gaugings of streams in the Plynlimon catchments: minimum flows (litres per second) in droughts of 1976 and 1984

Stream	Area km²	1976 August	1984 July	Land use
Severn	8.70	39.07	29.95	Forest
Hafren	3.67	15.07	16.00	
Tanllwyth	0.89	1.91	1.50	
Hore	3.08	7.61	10.00	
Upper Severn	0.92	6.80	5.96	(Moorland in
Nant Arwystli	0.37	3.86	3.56	the Severn)
Wye	10.55	41.88	40.50	Grassland
Cyff	3.13	6.46	8.60	
Gwy	3.98	14.71	16.20	
Nant Iago	1 02	2.46	3.20	

The following autumn months produced a rainfall 20% above average and returned river flows to normal. However, during July 1984, as Table 21 shows, flows in the main catchments and some sub-catchments were even lower than in 1976. There is a great deal of variation between catchments when considering the two droughts, almost certainly due to the fine detail of timing and duration of rainfall on the highly variable superficial aquifers of the catchments.

The 1976 drought was an extreme event which would not have been expected to fall within the period of study when the Plynlimon experiment began. That a record drought of even greater severity occurred within the next eight years would not have been anticipated under the usual laws of probability. Add to these events the extreme floods that occurred in 1973 and 1977 and it becomes apparent that the Plynlimon study has in its 20-year duration experienced a far wider range of extreme conditions than statistics might have foretold.

Chapter 5
Hydrological processes

Hydrological process studies were undertaken to try to answer questions related in varying degrees to the water balance experiment. The principal question was that of catchment yield but a number of others arose concerning the movement of water across the interfaces between the various components of the catchment system and its storage in them. These studies demanded the development of instruments and methods and the establishment of experiments within the overall water balance study. The results have been employed for modelling the processes involved to improve the interpretation of the Plynlimon results.

5.1 Hydrometeorological studies of interception

Following extensive research undertaken by IH into the micro-climate of Thetford Forest in East Anglia (Stewart and Thom, 1973), interception studies were mounted at several widely scattered sites within Great Britain, one of which was the Hafren Forest. Stewart's (1977) results for Thetford had shown that the very different rates of two related processes, transpiration from forests and evaporation of intercepted water, make it important that these two components of the water balance are determined separately.

Stewart showed that a forest is able to evaporate water from its surface at a greater rate than would be possible from available radiant energy alone. The deep band of turbulence above the canopy allows the extra energy to be obtained by the large-scale cooling of the air passing overhead. In areas of Britain where the trees are wet for a significant portion of the year, such as at Plynlimon, the interception loss will usually be the largest component of the total evaporation.

Previous attempts to model interception loss have been based on its relationship either with the potential rate of evaporation from grass or with rainfall. Regressions of interception loss on rainfall may have some physical basis but are unlikely to be satisfactory when used away from the site where they were derived, or on a different species, or for a forest with a different structure.

It was therefore important that reliable predictive models were developed and tested, so that there is some confidence in being able to predict the water balance of a forested area. Physically-based models in which the empiricism is restricted to the values of parameters, whose conceptual significance is understood, are more likely to provide accurate estimates in conditions outside those for which they were tested.

Models of interception

At the start of the project, the only physically-based model of interception loss was that developed by Rutter (Rutter *et al.*, 1971; 1975). During the course of the Plynlimon project, however, two major disadvantages became evident: the requirement for hourly meteorological data, which is unlikely to be available at most sites, and the need for computing facilities.

A model devised by Gash in 1979 (known as the Analytical Model) overcame these disadvantages by abandoning the step-by-step numerical approach in favour of an analysis by individual storm events. The model retains Rutter's rigorous conceptual basis and uses the same forest structure parameters, but by the consideration of some simplifying assumptions, the meteorological requirements are reduced to the record from a recording raingauge.

These assumptions are (Gash 1979):

1. The real rainfall pattern may be represented by a series of discrete storms, separated by sufficiently long intervals for the canopy and trunks to dry completely.

2. The meteorological conditions for the duration of the storms are sufficiently similar such that mean rates of evaporation and rainfall can be considered to apply to all storms in the accounting period.

3. There is a simple relationship between the 'drip-rate' and the degree of canopy saturation (Rutter *et al.*, 1971). There is no drip from the canopy during wetting-up, and the amount of water on the canopy at the end of the storm is quickly reduced to the minimum value necessary for saturation.

Evaporation from the trunks is calculated from a simple running water balance (Gash *et al.*, 1980). The evaporation from the canopy is calculated as the sum of a number of components, taking into account small storms insufficient to saturate the canopy, evaporation during rainfall and evaporation from the wetted canopy. The effect of this modelling procedure is to separate the interception loss due to the structure of the forest and its interaction with the pattern of rainfall events from that due to evaporation under saturated conditions.

During a given accounting period, if there are m small rainstorms, each insufficient to saturate the canopy, the interception loss owing to these small storms is

$$(1-p-p_t)\sum_{j=1}^{j=m} p_{Gj}$$

where p is the proportion of rainfall reaching the ground as free throughfall, i.e. not touching the canopy. Total throughfall is the sum of this component and drip which occurs after saturation. P_t is the proportion of rainfall reaching the ground as stemflow. P_{Gj} is the total recorded rainfall relating to the j'th storm.

If there are n larger rainstorms whose total exceeds p'_G (the rainfall necessary to saturate the canopy) the interception loss from these storms during wetting-up of the canopy is

$$n\,(1 - p - p_t)\,p'_G - nS$$

where S is the canopy capacity. Rather than using the integrated total of evaporation under saturated conditions, a mean evaporation rate, $\overline{E}$, is divided by the mean rainfall rate, $\overline{R}$, above a certain threshold, assumed to be indicative of saturated conditions (below this threshold all rainfall is evaporated). If hourly meteorological data are available above the forest, these can be used to calculate $\overline{E}$ directly: if they are not, an empirical value of $\overline{E}$ can be inserted. From previous work with this model (Gash *et al.*, 1980) it appears that the range of values of $\overline{E}$ is sufficiently narrow to obtain long-term estimates of loss in this way.

The evaporation from the saturated canopy, until rainfall ceases, is

$$\frac{\overline{E}}{\overline{R}}\sum_{j=1}^{j=n}(p_{Gj}-p_G)$$

After rainfall ceases, it is assumed that all of the water on the saturated canopy is evaporated:

$$nS$$

In applying the model there is a further assumption, which is necessary to avoid the need for a subjective assessment of what constitutes a storm. It is assumed that there is only one "storm" per rainday. This assumption has the considerable advantage of allowing the interception loss to be calculated from the daily rainfall amounts and the empirical values of $\bar{R}$ and $\bar{E}$, the mean rainfall and evaporation rates.

Interception studies

The necessary instrumentation for this detailed study of interception was installed in a plantation of Sitka spruce (*Picea sitchensis*) towards the south of the Hafren forest and 2 km outside the Severn experimental catchment at an altitude of 410 m. The site was flat with an afforested fetch of at least 900 m in all directions, and an undulating surrounding topography of about 2° slope. The stand, which was planted in 1947, had a density of 4250 stems per hectare and had not been thinned. By 1976 the trees had reached an average height of 8.9 m.

Instrumentation and measurement techniques were similar to those described by Gash and Stewart (1977). Interception loss was measured as the difference between gross rainfall and net rainfall, i.e. total throughfall plus stem-flow. Gross rainfall was measured using gauges mounted at the canopy level and in a nearby clearing. The clearing gauge was a tipping bucket device installed with its orifice at ground level. Each canopy level gauge consisted of a 125mm-diameter funnel mounted on a mast, such that its orifice was just at the level of the tops of the highest trees: rainfall was led by a tube to a tipping-bucket device on the ground.

A precise measurement of weekly throughfall was obtained from twenty 125 mm diameter storage raingauges, moved at random every week, within a 20 m by 20 m plot. For individual storm analysis a network of 36 troughs was used, each trough having a collecting area of 0.1 m x 2 m and a depth of 0.3 m. The troughs were randomly arranged in a plot 45 m by 75 m, but were connected in pairs and constrained such that there were four troughs in each of the nine 15 m by 25 m sub-plots. Stem-flow was measured on 18 trees (two within each of the nine sub-plots) using rubber collecting-collars as described by Wright (1977). The water outlet from the throughfall troughs and stemflow gauges was led into Rimco tipping bucket gauges.

Canopy capacity, S, (defined as the amount of water remaining on the canopy after drainage has ceased), can be determined by the method of Leyton *et al.* (1957) from a plot of throughfall against gross rainfall for individual storms (Figure 38). Storms included are those large enough to saturate the canopy, with at least eight hours of dry conditions before the storm to ensure that the canopy is dry at the onset of rain. A line is drawn to indicate the upper envelope of the points: this line crosses the throughfall axis at –S.

The value of S obtained by this method is dependent on only a few data points and is likely to be an overestimate. The estimate for the Hafren Forest site is 1.2 mm. The stemflow parameters which relate to rainfall are derived by a method similar to that described for the canopy capacity. Stemflow totals from storms that have been preceded by at least 24 hours with no rain are plotted against gross rainfall, and the parameters are obtained by a regression equation.

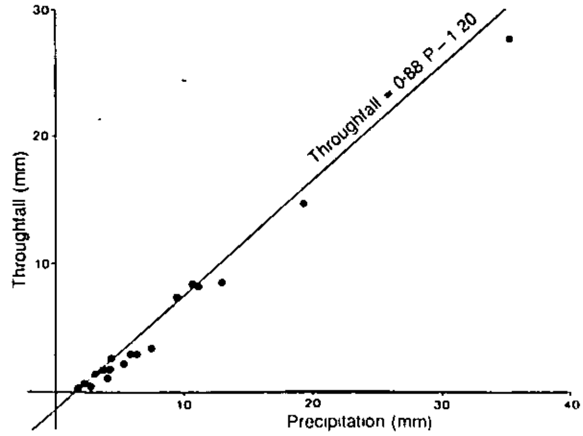


Figure 38 The relationship between rainfall and throughfall for storms preceded by at least eight hours daylight without rain

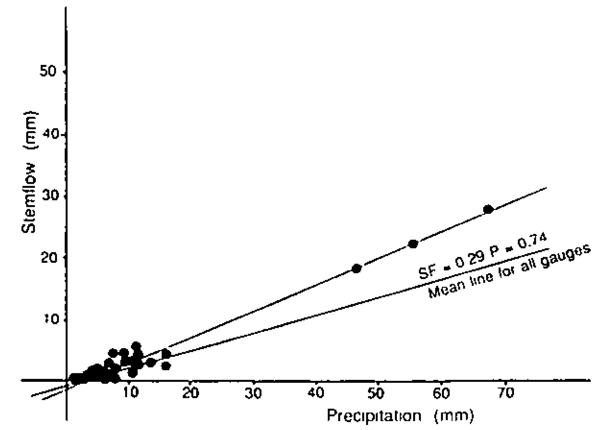


Figure 39 The relationship between rainfall and stemflow for an individual stemflow gauge

The line of the upper envelope in Figure 39 should strictly be of gradient $1/p_t$ and provides an independent check on the proportion of rainfall that is diverted to the trunks, p_t. Figure 38 indicates a value for p_t of 0.12, whereas the mean of the stemflow gauges gave 0.29. This difference is probably due to the sampling of trees for stemflow measurement, and is always likely to arise unless all trees are sampled within the throughfall measurement plot.

The 'free-throughfall' coefficient, p, can be determined from the gradient of a regression of throughfall against gross rainfall for small storms insufficient to saturate the canopy. It can also be estimated from a measure of canopy cover, obtained using an anascope, a device designed to assess objectively the presence or absence of overhead vegetation at a point (Ford, 1976). From an analysis of small storms and confirmation by anascope, the value of p for the Hafren site was not significantly different from zero.

The error in measuring interception loss is likely to be dominated by the error in the rainfall measurement. This is difficult to quantify, but considering the difficulty of siting raingauges for canopy input, it is estimated that the gauges may introduce a systematic error of at least 15%. Throughfall can be measured more accurately because of the low wind-speeds beneath the canopy, and because the gauges were rearranged after every reading the errors may be treated as random. Over a year the error in throughfall is typically less that 2%. The observed variability in stemflow measurement is more likely to be due to variation from tree to tree rather than to the errors of measurement. With a typical interception loss of 30% of the rainfall, neglecting all other errors, an error of 5% in the rainfall measurement would result in an error of 17% in the interception loss.

Previous work with the Rutter and Analytical models at Thetford has shown that the errors in the estimate of individual forest structure parameters can vary between 10 and 30%. However, their combined effect on the estimate of interception loss is generally less than 10%.

Calder (1977) has demonstrated the sensitivity of the Penman-Monteith equation to errors in the wet-bulb depression. Unfortunately automatic weather stations are liable to errors in the measurement of this variable, particularly during rainfall when the wet-bulb depression is generally small. Errors may be caused by electronic drift, or in the case of Plynlimon, which is often above the cloud base, by condensation on the dry-bulb (George, 1970). During the analysis of data from the Kielder forest (Gash *et al.* 1980) it was found that a not unrealistic systematic error of 0.1° Celsius in the wet-bulb depression produced an error of 19% in the calculation of the mean evaporation rate $\bar{E}$.

The error in the estimate of interception loss is also dependent on the assumptions made in the evaluation of the aerodynamic resistance. These assumptions, which are discussed by Rutter *et al.* (1975), take account of atmospheric stability and black body radiation and allow the estimation of the aerodynamic parameters d and Z_0 from

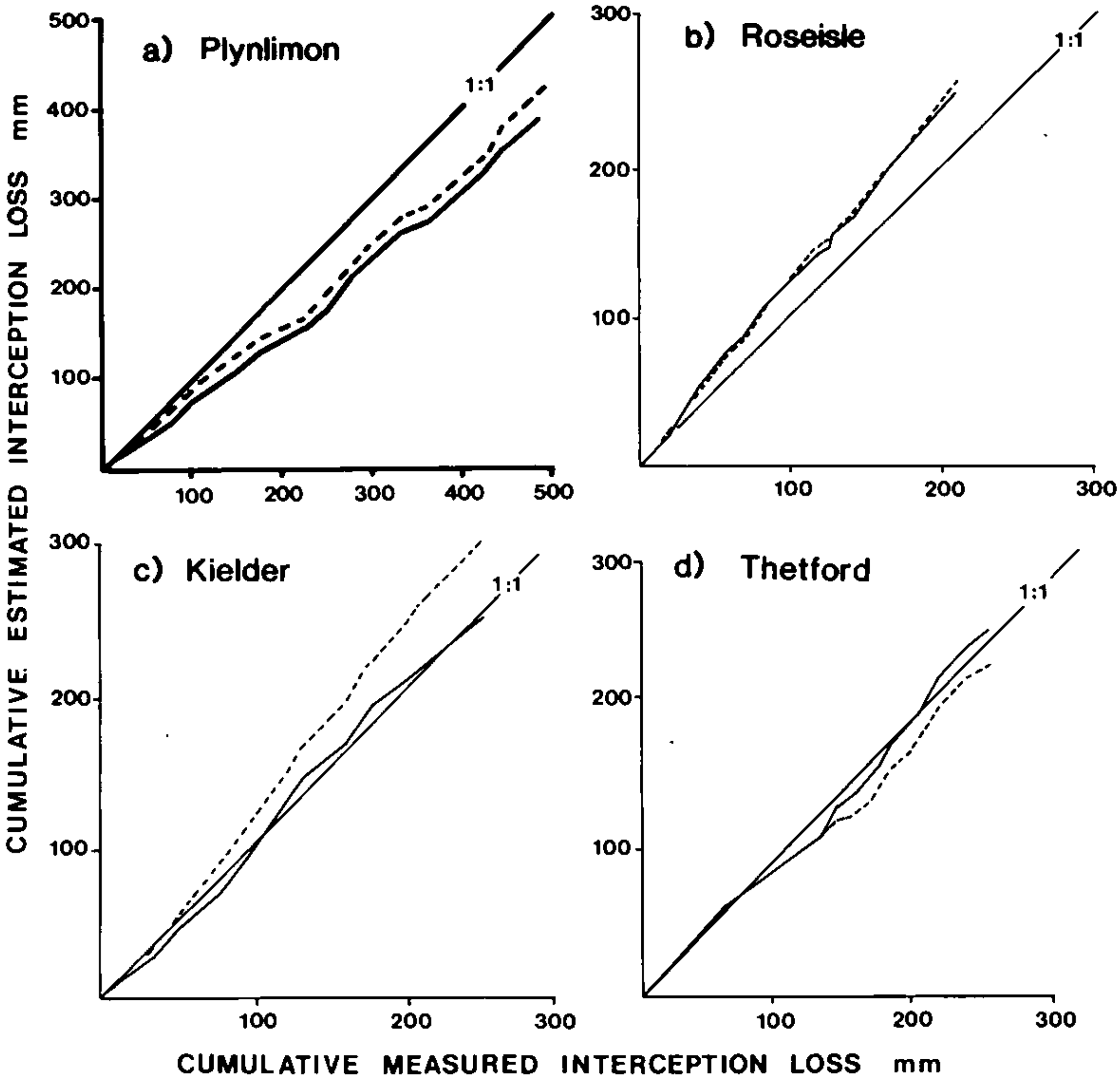


Figure 40 The estimated interception loss using the Rutter model (- - - -) and the analytical model (——) versus the observed loss, for four sites in the UK

empirical relationships. Work by Gash *et al.* (1980) and Rutter (1977) has shown that the evaporation rate is very sensitive to the parameter Z_0 and is likely to account for 10% of the error in the estimate of interception loss by either of the models.

The Plynlimon results in relation to the models

The Rutter and Analytical models of interception loss have both been applied to the Plynlimon data. Periods during which snow fell or where data were incomplete have been omitted. The results for the Hafren site shown in Figure 40 are presented as the degree of under- or over-estimate of the percentage difference. Results from the three other coniferous sites, Roseisle in north-east Scotland, Kielder in northern England and Thetford in East Anglia are shown for comparison (Gash and Stewart, 1979).

The Rutter model has proved to be a reliable and rigorous technique for estimating interception from forest canopies and has provided much of the conceptual basis for all subsequent work. Unfortunately, as noted earlier, in the majority of practical situations where estimates of evaporation are required, no hourly data will be available. However, it would be possible to use the Analytical model with previously determined values of the mean evaporation rate, $\bar{E}$, estimating the evaporation from a wet canopy using daily values of rainfall and rainfall duration.

The analysis outlined above and described in detail by Gash *et al.* (1980) has demonstrated that much of the error in the estimation of $\bar{E}$ from meteorological data may be attributed to the error in the estimate of the roughness length, Z_0, which must be obtained from a crude empirical relationship. A more sensible approach would be to determine the value of $\bar{E}$ which, when used in the Analytical Model, gave the best fit to the observed interception losses and thus avoided any previous empiricism. Gash *et al.* (1980) found that optimum empirical values of $\bar{E}$ for the four coniferous sites ranged from 0.20 mmh^{-1} to 0.24 mmh^{-1} with a mean of 0.22 mmh^{-1}. This small range of variation of $\bar{E}$, despite the large range of altitude and latitude, together with the similarly small variation in $\bar{R}$ (the mean rainfall rate), suggests that the major cause of the variation in the absolute magnitude of the interception loss across the UK is not a result of variation in the rate of evaporation, but rather of the size of the canopy capacity and the length of time over which evaporation occurs during saturated canopy conditions.

In the application of the two models to the four coniferous sites, the Plynlimon results are typical in producing errors which are within 20% of the measured evaporation, which in itself may be subject to an uncertainty of around 17%. Both models therefore could be considered to have estimated the evaporation to within acceptable limits at sites very different from those for which they were originally derived. If estimates of interception loss are required from rainfall data, the results of this work suggest that for the climate of Great Britain, the mean optimum value of the mean evaporation rate, $\bar{E}$, 0.22mm/h would at present be the most appropriate estimate to use.

Fog drip

The British uplands are well known for fog drip or hill mist, conditions of high humidity and low visibility. The division between hill mist and the persistent light rainfall (drizzle), which typifies parts of the passage of frontal systems over upland Britain, centres mainly on the lack of strong winds during hill mist conditions. Since advected energy explains much of the interception loss from canopies, it was considered that hill mist might produce an unmeasured precipitation input from condensation on the trees: in other words the reverse effect of evaporation.

A study of this effect linked to that of interception was carried out on the same site. The work centres on direct, continuous measurement of canopy moisture storage (Hancock, 1978; Hancock and Crowther, 1979).

For the duration t of a storm, the integrated precipitation input at a rate P is partitioned between the instantaneous canopy storage, C(t), the integrated net precipitation at a rate T and the integrated evaporation rate E, according to the equation:

$$\int_0^t P.dt = C(t) - C(O) + \int_0^t T.dt + \int_0^t E.dt$$

where C(O) is the water stored on the canopy at the onset of the precipitation. For a storm event of substantial magnitude and duration it may be assumed that the canopy is saturated and, after rapid drainage at the end of the storm but before appreciable evaporation, C(t) = S, defined as the canopy storage capacity. The quantity S depends on wind speed, being larger on a still day.

The potential usefulness of continuous canopy storage measurement is considerable. In particular, novel methods of estimating other hydrological variables become possible. Differentiating the above equation and rearranging it gives

$$E = P - T - \frac{dC}{dt}$$

This allows the determination of the evaporation rate during rainfall from a knowledge of the input precipitation rate P, the net precipitation rate T, and the rate of change of canopy storage C.

Another application concerns estimation of those forms of "occult" precipitation which are not readily measured with a raingauge. Interception of fog, mist and low cloud may be of underrated importance in upland forest regions. Fog drip has long been well-reported in the literature (Hori *et al.*, 1953; Grunow, 1955; Kerfoot, 1968).

However, those regions where fog drip produces significant inputs of precipitation, for example over 25 mm per night per tree in some coastal Californian redwood forests (Parsons, 1960), are climatologically very different from Plynlimon. Hancock devised a "fog diary" scheme of visibility observations from the Institute's Plynlimon office. Just over 10 per cent of the 600 entries record a cloud base lower than 500 m but less than one per cent record fog. The conditions likely to lead to fog drip input dominating the interception loss are thus of restricted occurrence, and the balance of the study swung towards calibrating canopy storage for interception models. Nevertheless, work on the theoretical development of fog drip on tall and short vegetation points to the likelihood of rapid changes in moisture between atmosphere and forest canopy and in the reverse direction (Shuttleworth, 1977). There is clearly further opportunity to make direct measurements of this process if apparatus can be developed.

If F is the fog interception rate then, in the absence of rainfall, the equation above becomes

$$F = \frac{dC}{dt} + T + E$$

and at the beginning of the event T will also be small. If the vertical gradient of relative humidity is very close to zero and the wind speed low, E may be small enough to leave

$$F = \frac{dC}{dt}$$

and allow a direct measurement of fog interception.

Similar reasoning allows inputs from thermal phenomena such as dew and hoar frost to be estimated. The basis of the method developed was to use the bending of branches in response to added surface water: in effect using the branches as cantilever weighing-machines. The extrapolation of measurements made on a number of branches to the water storage of a complete forest canopy has been given some consideration. From the theory discussed by Hancock and Crowther (1979), either the surface strain of the stem of a branch or the displacement of a fixed point on the branch could be monitored and related to the surface water storage. Both of these measurements proved feasible in preliminary work.

Wire strain-gauges were successfully attached to the stem of a cantilevered branch and sealed against the environment. However, for reasons of cost and practical convenience this method was abandoned in favour of DC linear-variable-differential-transformer displacement transducers. The displacement measured was that of a point on the branch (typically 0.1 m from the

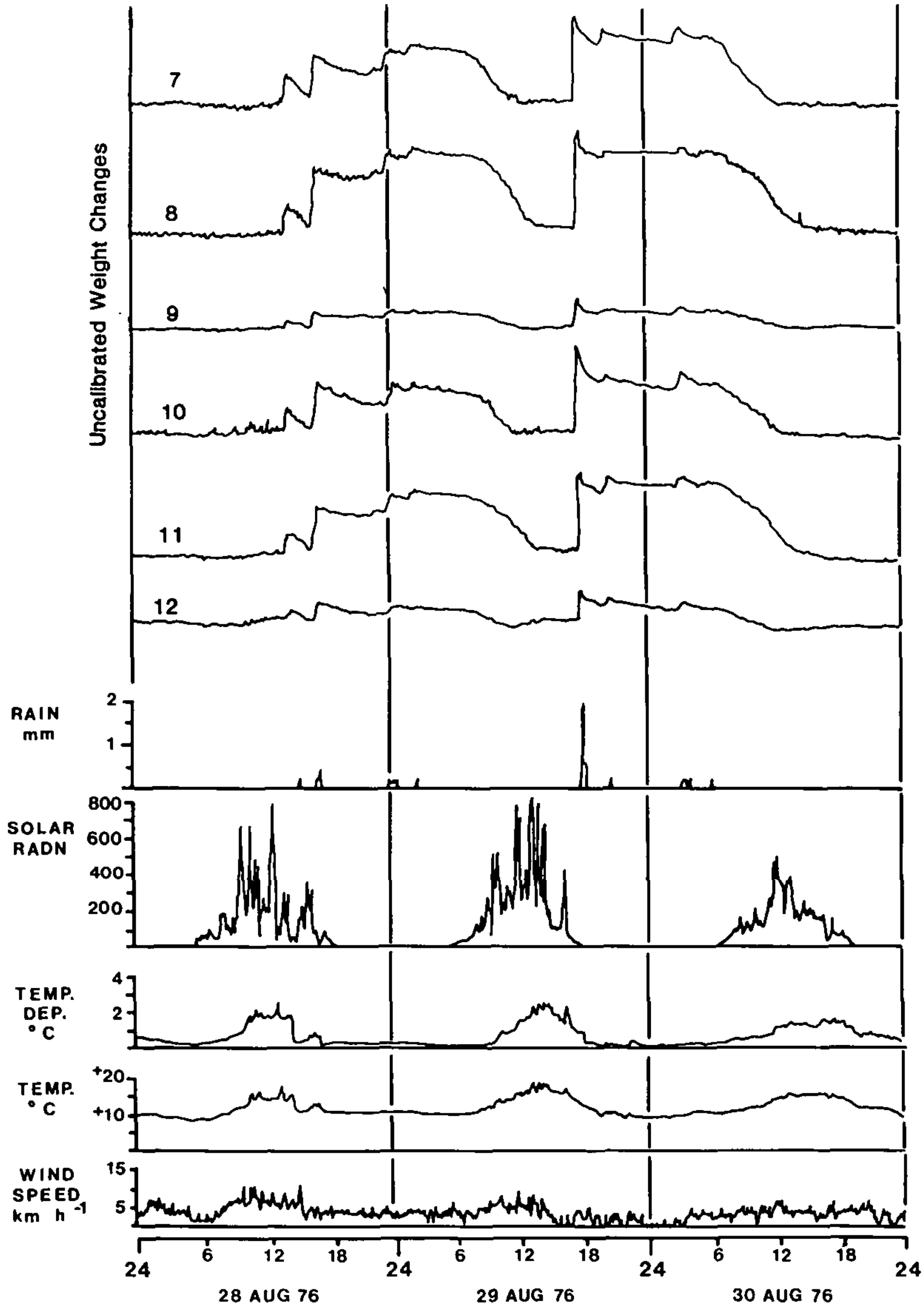


Figure 41 Data from the Plynlimon interception site for six of the cantilever strain gauges

trunk) with respect to a point on the trunk (typically 0.2 m above the branch).

For a sample of twenty branches, estimation by eye of the centre of mass distance was found to introduce no statistically significant bias when compared with the measured values, and an estimated precision of 6% was achieved. The data presented in Figure 41 were used by Hancock and Crowther to test some of the hypotheses incorporated in the Rutter Model.

5.2 The forest lysimeter study in the Severn

During the period from February 1974 to September 1976 a "natural" lysimeter was operated within the Hore subcatchment. This was used to measure transpiration and interception loss from the forest and to provide data for the development of evaporation models which would allow extrapolation of the Plynlimon results to other areas.

Experimental method

The 84 m² lysimeter, described more fully by Calder (1976), enclosed 26 Norway spruce trees growing on a peat soil overlying impermeable clay. The clay formed a natural seal at the base of the lysimeter, the sides being formed by a watertight screen of corrugated iron sheeting grouted into the clay (Plate 17 and Figure 42).

To use a water balance method for calculating transpiration and interception loss, it was necessary to measure rainfall above the canopy, net rainfall (the rainfall transmitted to soil surface), changes in soil moisture, and surface runoff and drainage from the lysimeter.

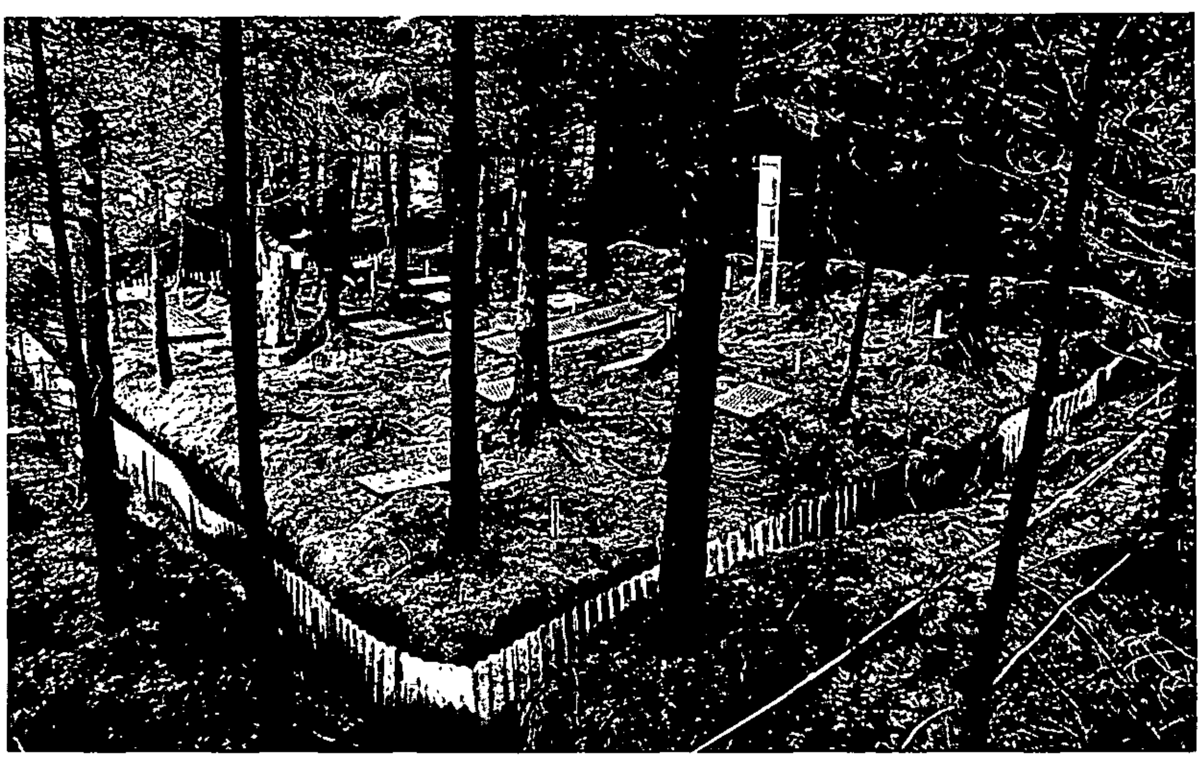


PLATE 17 The forest lysimeter

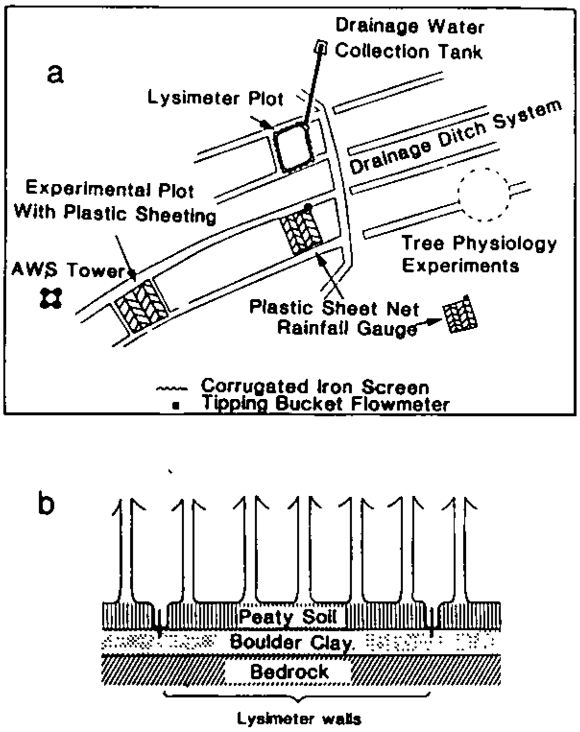


Figure 42 Forest lysimeter: (a) site layout, (b) section across the plot.

Rainfall was measured with a recording gauge whose funnel was situated above the canopy and a ground level storage gauge located in a clearing 400 m distant from the lysimeter. Rainfall records from the recording gauge were corrected so that periodic totals matched those of the ground level gauge.

Preliminary measurements of net rainfall obtained with four 0.4 m^2 throughfall troughs and two stemflow gauges indicated a large spatial variability with coefficients of variation of 27% and 41% respectively. To overcome this formidable sampling problem, a novel design of plastic sheet net rainfall gauge was devised (Calder and Rosier, 1976) to replace the former system. These plastic sheet gauges were in continuous operation for two and a half years and proved to be both reliable and accurate: a replicate pair of gauges differed by less than 4% in long-term measurements of net rainfall.

Changes in soil moisture were determined initially with a grid of eight neutron probe access tubes. This was later extended in 1975 to 20 tubes in order to increase the accuracy of this measurement. Drainage from the lysimeter was measured with a large tipping bucket flowmeter and, as a further check, the drainage water was collected and measured independently in a 2000 litre tank. The increments of rainfall, net rainfall and drainage, measured by tipping buckets, were all recorded on a magnetic tape logger at five-minute intervals. Climatological data were collected by two automatic weather stations (AWS) situated at Moel Cynnedd in a clearing 400 m from the lysimeter and one AWS located on a tower above the forest canopy.

Summary of results

In 1974, interception losses from the lysimeter amounted to almost twice the Penman (1948) estimate of transpiration (Calder, 1976b). This result clearly demonstrates the importance of interception losses in this environment and underlines the need for more realistic methods of estimating forest evaporation from climatological data. An evaporation model which considers interception and transpiration losses separately, based on the Penman-Monteith equation (Monteith, 1965), has been developed and is described in papers by Calder (1977; 1978; 1979a).

The interception model, of a similar form to that proposed by Rutter and others (1971; 1975), was derived by comparing model predictions of net rainfall with observation on a five-minute timescale (Figure 43). The canopy drainage parameters and the canopy aerodynamic resistance were calculated by a least squares technique, using the Rosenbrock (1960) algorithm to minimise the sum of squared residuals. The aerodynamic resistance, using this method, was found to be 3.5 s m^{-1}.

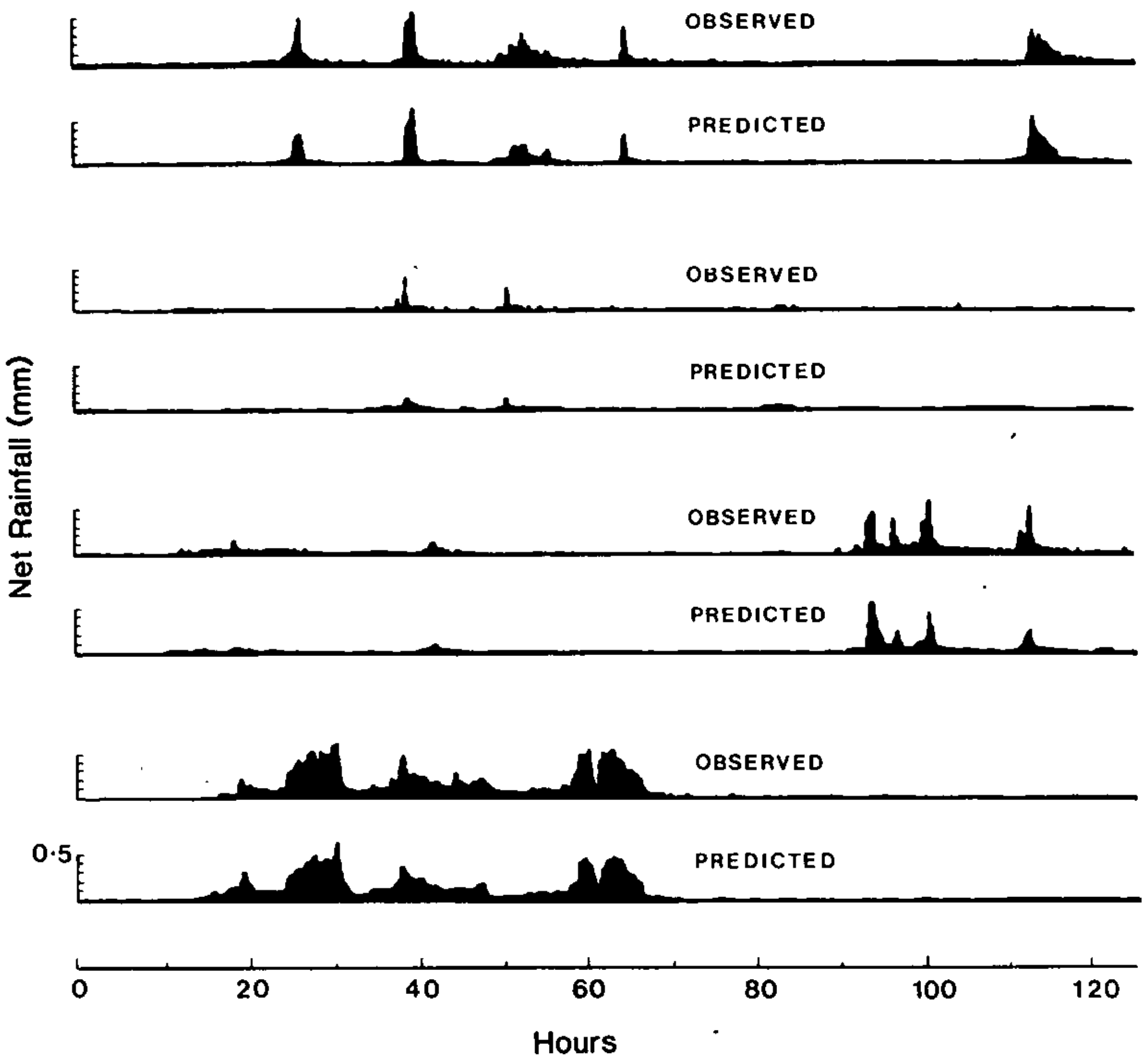


Figure 43 Five-minute values of observed and predicted net rainfall using the threshold model and data from AWS1 in the clearing, for storms in 1974 (June and July)

A similar procedure was used to derive a function which describes the canopy surface resistance in the Penman-Monteith equation, by comparing model predictions of cumulative transpiration with those observed. Good agreement was obtained with a surface resistance function dependent only upon D, the day number in the year, and δe, the vapour pressure deficit in kPa; r_s is the surface resistance:

$$r_s = \frac{74.5\{1 - 0.3\cos[2\pi\frac{(D-222)}{365}]\}}{1 - 0.45\delta e} \quad \ldots \delta e < 2.2$$

$$r_s = \infty \quad \ldots \delta e > 2.2$$

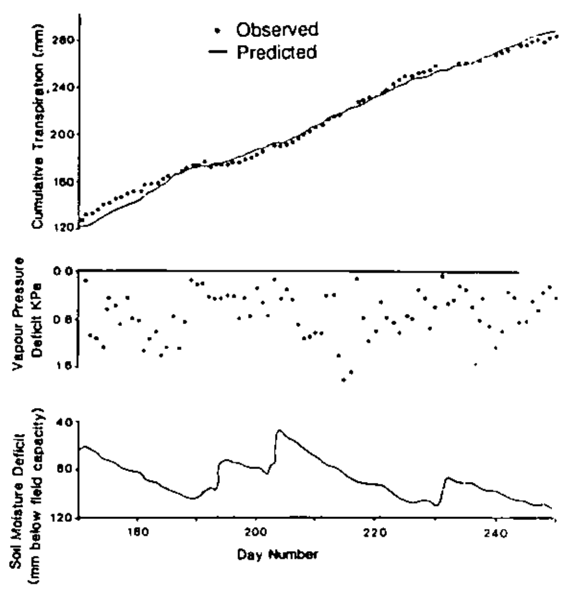


Figure 44 Observed and predicted cumulative transpiration loss, soil moisture deficit and vapour pressure deficit (recorded at noon) for summer 1975

The surface resistance is commonly assumed to be controlled by the soil moisture deficit, but this is not indicated in the lysimeter results. Even though soil moisture deficits in excess of 100 mm were recorded during 1975, no clear relation was found between surface resistance and soil moisture, as there was little correlation between the residual errors and soil moisture deficit: the seasonal variation and dependence on vapour pressure deficit were apparently sufficient to account for the observed transpiration response (Figure 44).

Analysis of data from 1976 also supports this view: deficits exceeded 200 mm and little reduction in transpiration rates was observed. It would appear that the concept of a Penman type of root constant would not be applicable in this situation. However, the feedback in the surface resistance, atmospheric demand system (where r_s increases, reducing transpiration, in response to an increase in vapour pressure deficit) is such that annual transpiration losses may be significantly different from those expected if this feedback were not taken into account. For example, if transpiration losses for 1975 are calculated using a mean value of r_s derived from data collected in 1974 (a year with lower mean levels of vapour pressure deficit than 1975) the estimate would exceed the observed value by 100mm. It would appear therefore that considerable errors could result from models of surface resistance which do not take into account the dependence of surface resistance on time of year and vapour pressure deficit.

Figures 45 and 46 shows the observed cumulative interception and transpiration losses, together with model predictions obtained using data from the two Ewes in the clearing. The considerable discrepancies between predicted and observed interception loss introduced by using data from AWS2 are a reflection of the small (0.3 deg C) underestimate of the wet bulb depression made with this station. This sensitivity to small zero offset errors arises because large percentage errors are produced in the vapour pressure deficit estimate during storm conditions when deficits are normally small. Extreme accuracy in this measurement is therefore necessary if reliable predictions are to be made with this type of interception model.

Predictions of transpiration loss are not particularly sensitive to errors in the wet bulb depression measurement (deficits are usually much larger during non-storm conditions) and fairly good agreement is obtained using data from both AWSs (Figures 45 and 46).

Tree cutting experiments adjacent to the forest lysimeter

Whilst the results obtained from the lysimeter have furthered the understanding of the processes determining forest water use, additional studies were conducted on the process of transpiration. For not only do

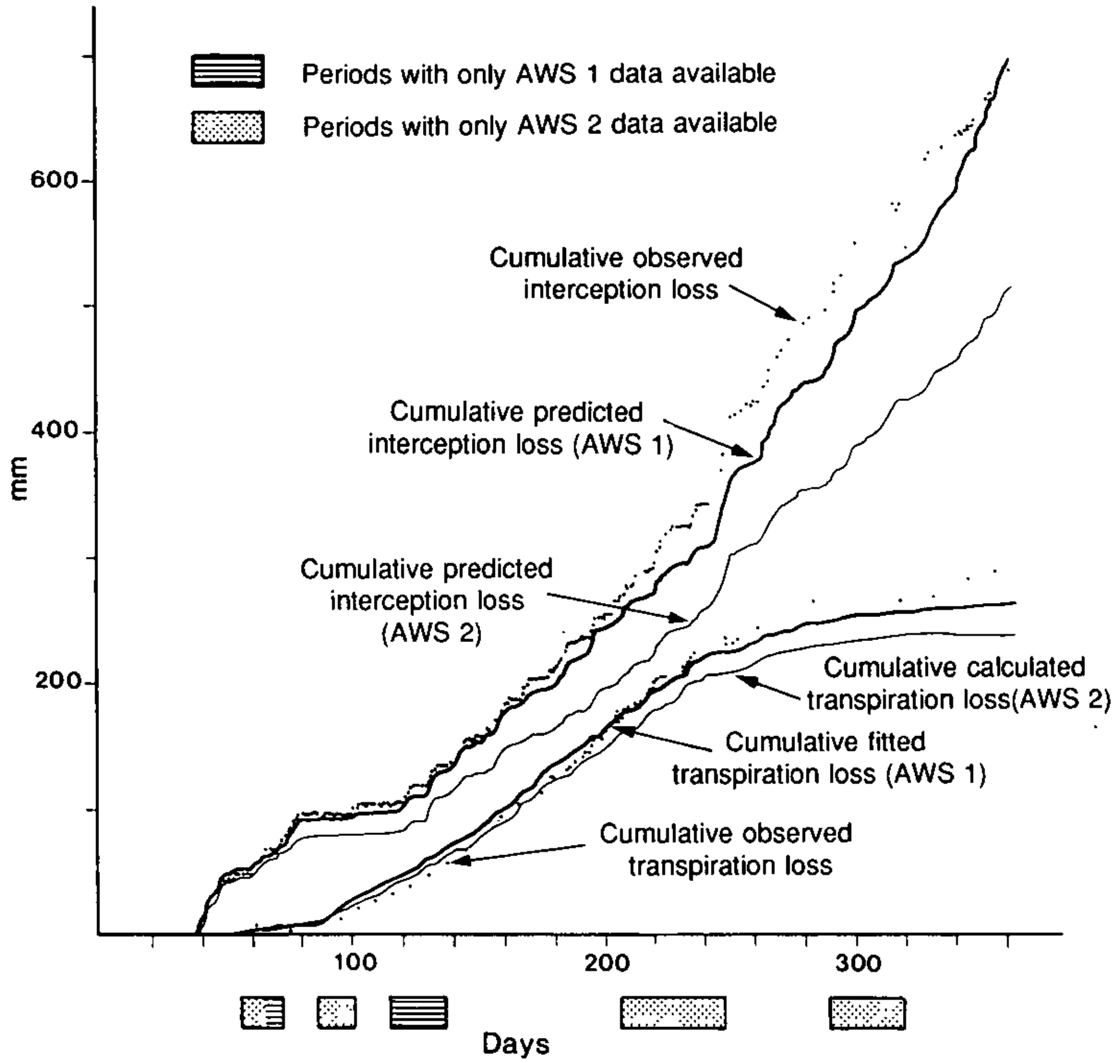


Figure 45 Cumulative interception and transpiration losses observed and predicted using data from AWS1 and AWS2 in 1974

environmental conditions affect transpiration, but the stomatal resistance of individual leaves (bulked up to be the canopy resistance) also has a marked effect. The work described by Roberts (1978) complements Calder's studies by examining the factors controlling stomatal resistance. The physiological study consisted of routine measurements of stomatal resistance to relate stomatal behaviour to plant and environmental variables, and also alteration of the possible controlling factors of stomatal behaviour, so as to understand this control.

The use of 'tree cutting' techniques in the examination of the water relations of Scots pine, *Pinus sylvestris L.*, in plantation conditions has been described by Roberts (1976, 1977). The technique is valuable in indicating the rôle of needle water potential in influencing stomatal behaviour. In this investigation, the freshly cut tree was placed in a plastic tank full of water and then recut under water (Plate 18). Water uptake by the cut trees was measured by adding water to raise the level to a fixed point on a manometer at least twice daily at approximately 0800 and 2000 G.M.T.

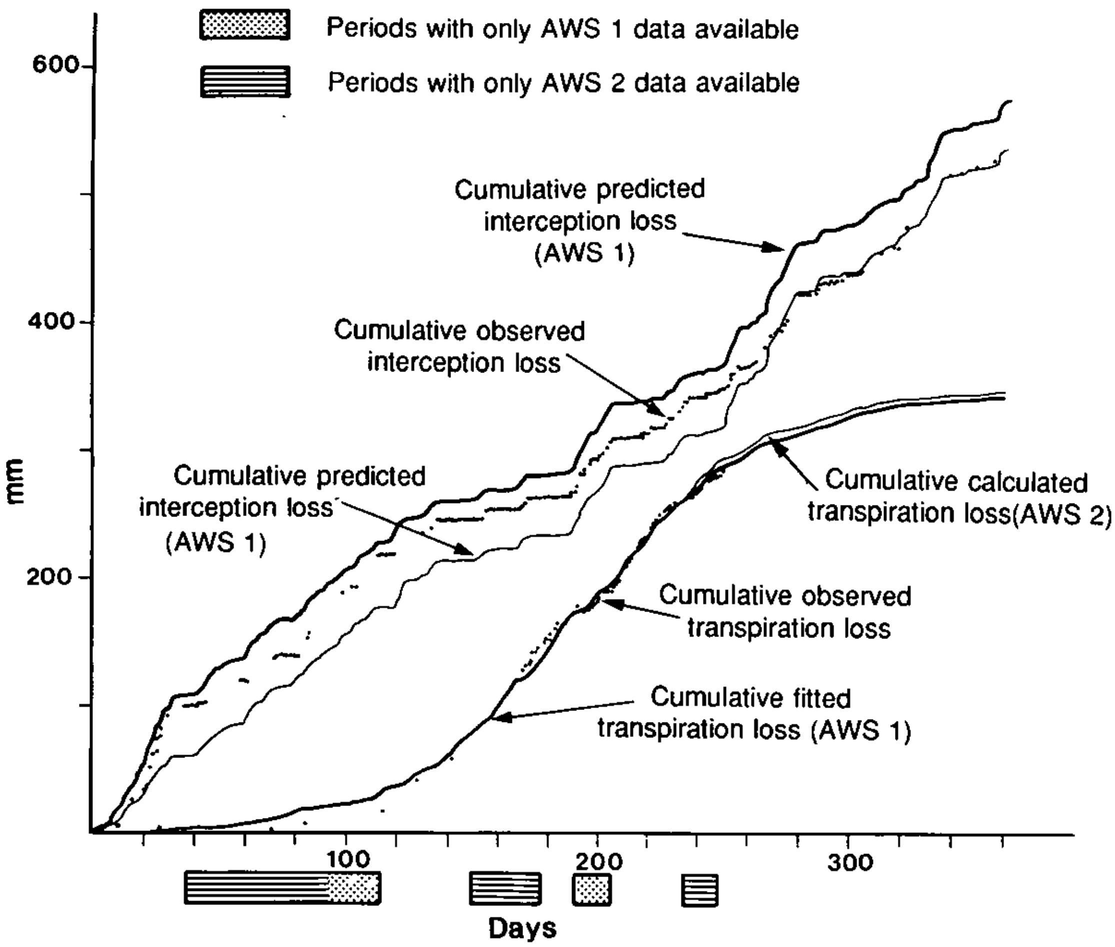


Figure 46 Cumulative interception and transpiration losses observed and predicted using data from AWS1 and AWS2 for 1975

Needle water potential of individual spruce needles was measured with a pressure chamber and ancillaries. Measurements of stomatal resistance of both cut and control trees were made with a porometer measuring the diffusion resistance from individual shoots. The needle area enclosed in the porometer chamber was measured by counting the numbers of needles on a particular shoot and measuring the area of a sample of 20 needles after the shoot had been used for the porometer measurements for several days. An area of approximately 6000 mm^2 was generally assessed at each shoot sampling site; there were four sampling sites in the mid-crown position of each tree. Five trees surrounded the sampling tower: two were cut on 26 August 1975 and these were then compared with the other three. Two of the remaining trees were cut in the middle of September. The behaviour was similar in both parts of the experiment so the results described are those obtained in August when two cut trees were compared with two control trees (Figure 47). The 'natural' lysimeter described by Calder was within 100 m of the 'tree cutting' experiments; the nearby continuously-operating AWS was sited on an aluminium tower above the forest canopy.

Plate 18 Tree cutting experiment close to forest lysimeter

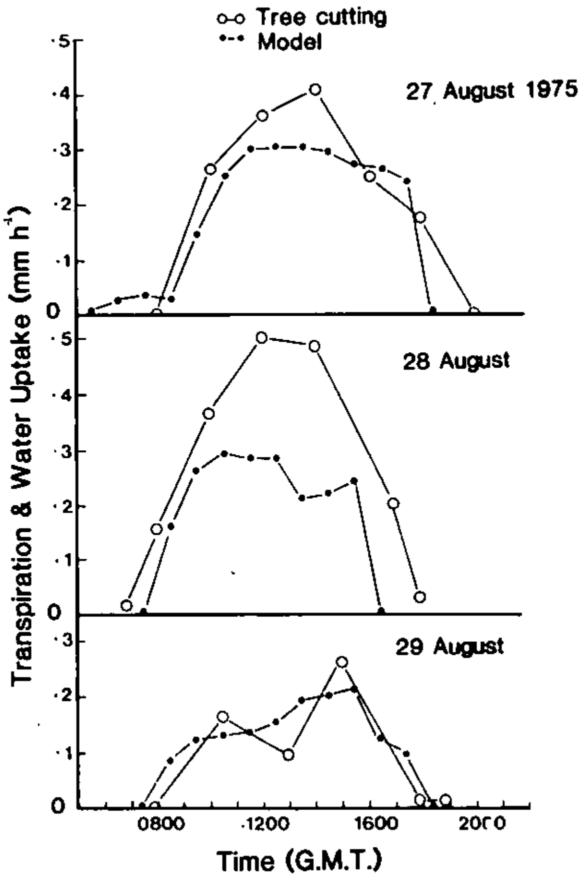


Figure 47 Comparison of transpiration rates measured by tree cutting with those estimated by a model derived from the lysimeter data

The measured uptake of water by the cut trees suggested that they were 'transpiring' at rates much higher than those predicted by the transpiration model using parameters determined from the lysimeter and data from the AWS. This higher rate was consistent with the lower stomatal resistance observed on the cut trees, emphasising that plant water status (improved in the case of the cut trees) has a major role in controlling stomatal opening.

5.3 Runoff processes

Runoff processes acting on slopes and in channels are difficult to elucidate by field research because of spatial variability. There is, moreover, a shortage of recorded streamflow information in the British uplands, and a model which can be calibrated with a minimum of fieldwork, whilst retaining physical reality, is clearly desirable. There has been much debate in hydrology over the merits of detailed process investigations of runoff: the outcome may be a conceptual model of catchment response to rainfall which is too unwieldy to computerise and make into a practical predictive tool.

The initial runoff process studies at Plynlimon concentrated upon the grassland Wye catchment where runoff processes, soils and morphology are more visible than in the Severn and less interrupted by artificial influences such as drainage ditches. Later, the spatial organisation of physiography, soils and vegetation on Plynlimon was deliberately rationalised in a way that was accessible to mathematical modelling (Newson, 1976a; Newson and Harrison, 1978). The basis of the rationalisation was the concept of runoff domains, based on natural vegetation indicators in the Wye (Newson, 1976b), but eventually extended to the Severn on the basis of soil type.

There has been much progress in interpreting the indicator value of natural vegetation in hydrology (Gurnell, 1981). Vegetation types may also be identified conveniently by remote sensing. Accordingly, Newson (1976a) used vegetation as a major guide in setting up *a priori* runoff domains in the Plynlimon catchments. Although the geometrical constraints of mathematical modelling do not allow true spatial depiction, these domains were crucial in guiding fieldwork on runoff processes and the sampling strategies for soil moisture networks and stream chemistry investigations. The basis for these domains is the information available in the botanical literature on the relationships between vegetation types, soils and their moisture status (for example, Smith, 1981; H. Jefferies, 1917; T. A. Jefferies, 1915; Ingram, 1967).

Slope runoff in drainage basins: concepts past and present

Slopes make up the majority of the surface area of drainage basins, yet only recently has the slope phase of runoff generation in humid temperate river basins received detailed attention through field research. Over most of the history of hydrology it was assumed that the entire area of the drainage basin contributed to a flood event. Overland flow was considered to be a major runoff process, while the strong correlation between flow and measured morphological characteristics added to the impression that the surface of each catchment in some way represented the integration of hydrological and geomorphological processes.

The inclusion in hydrological concepts of subsurface flow on hillslopes, or throughflow, represents a major change necessary to account for the observed pattern of runoff from many drainage basins, especially well-vegetated ones. Overland flow is still incorporated in many basin models but it is considered to result from the saturation by throughflow of small areas at the base of the hillslopes ('saturation overland flow') rather than by rainfall exceeding the infiltration capacity ('Hortonian overland flow'). This has led to a change in the basis of the assessment of the runoff potential of soils, from infiltration capacities measured at the soil surface to the storage and lateral flow properties of the whole soil profile.

The basis for this new approach is the subdivision of the drainage basin into areas which, in terms of flood runoff, are contributing and non-contributing. The contributing area has not been strictly defined but is taken to be the area from which saturation overland flow quickly reaches the permanent or temporary channel network. 'Non-contributing' is a term seldom used because in fact much of the remainder of the drainage basin, by providing throughflow, is responsible for maintaining saturated conditions at the slope base.

A characteristic of upland humid-temperate slopes is the presence of irregularities, ranging in scale from micro-relief declivities to major gullies dissecting otherwise planar slopes. These irregularities not only encourage seepage, and indeed may be formed by it; they also form routes by which the permanent channel network and its associated contributing area extend upslope during floods. One of the most intriguing of such runoff routes is within the soil profile - in the form of a network of natural soil pipes.

Soil pipes in the Wye catchment - a special study

Gilman and Newson (1980) reported the results of a comprehensive study of soil pipes in peaty soils on the eastern slopes of Plynlimon. Soil piping was quickly recognised to be potentially an important influence on storm runoff: this hypothesis is supported dramatically by the numerous springs and even jets of water escaping from the pipe network all over the longer slopes during and even after heavy rain (Plate 19).

The origin of soil pipes is open to many interpretations (Jones 1981), but Gilman and Newson found that the alternation of wetting and drying is more likely to produce soil cracking (and hence pipes) than freeze/thaw cycles. Although some aspects of pipes were studied at sites distributed throughout the Wye catchment, more intensive work was localised in the Nant Gerig basin and on the convex upper portion of the Cerrig yr Wyn slope (Figure 48). Both sites were mapped in detail and pipes were excavated and photographed (Plate 20). In the Nant Gerig basin, flow measurements were taken during and after rainstorms to establish the form of the pipe flow hydrograph: in the

PLATE 19 Soil pipe 'spring' under wet conditions

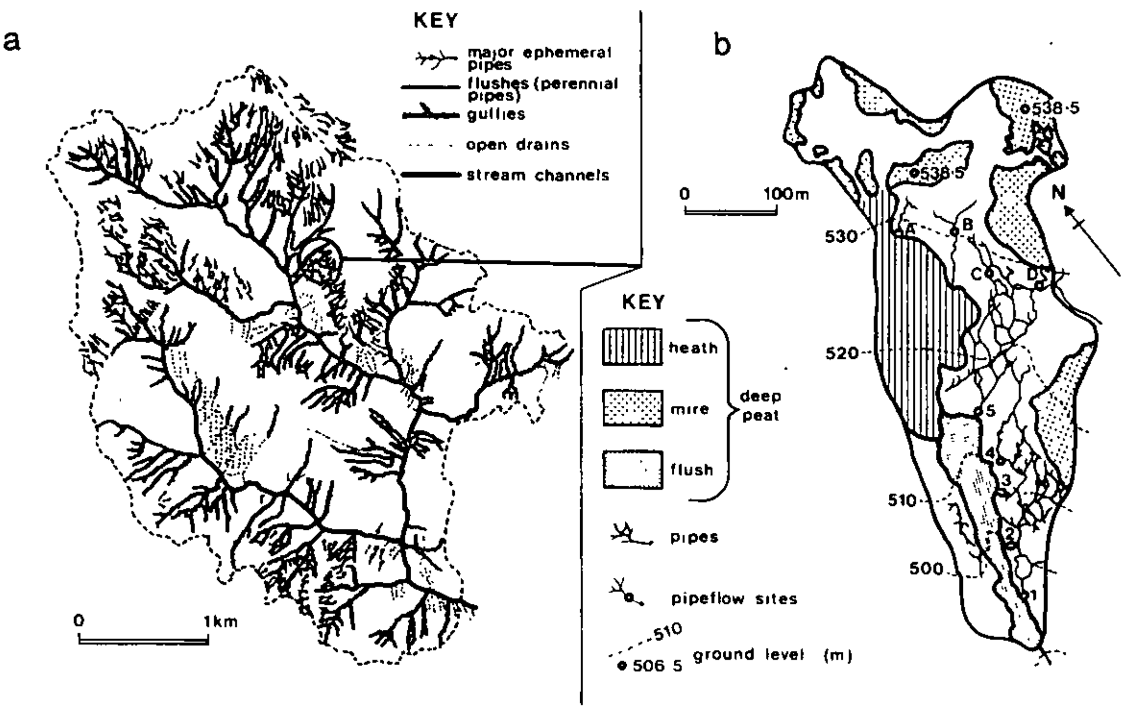


Figure 48 Soil piping in the Wye catchment: (a) Sketch survey at a catchment scale, (b) Detail from Cerrig yr Wyn

PLATE 20 Cross-section of soil pipe revealed by excavation

Cerrig yr Wyn network, tracers were used to determine the hydraulic properties of the pipes.

Gilman and Newson (1980) established a classification of the types of pipe observed in the Wye catchment. For example, certain of the larger pipes may be considered as peat-bridged streams occupying the base of drift-filled channels, and flows may be seasonal or even perennial as these streams drain areas of deep blanket peat. They are described by Newson and Harrison (1978) as "rush flushes". Mass movement of the flushes' peaty fill has been measured, and they may 'burst' in floods (Newson, 1975b). Exposed sections suggest that the rush flushes originated as first-order channels, which were later infilled. Flow from most rush flushes continued throughout the 1975/1976 drought. The ephemeral pipes are mainly confined to peaty podzols, the exceptions being associated with slumping and tension cracks. For a hydrological study of seasonal pipes in the Plynlimon area the reader is referred to work by Jones (1978) on the west side of the mountain.

The maps of natural pipes in the Wye catchment and in the Cerrig yr Wyn first-order basin (Figure 48) illustrate the complexity of their distribution and network properties. They are not uniformly distributed over the catchment flanks, but are locally common, confined mainly to south-facing slopes with gradients between ten and twenty degrees.

The gradient restriction is a consequence of the mode of formation of pipes; authorities are agreed on the requirement for a steep hydraulic gradient to give the necessary erosive potential. This hydraulic gradient is generally available in subsurface flow towards the free face of a gully or the edge of a terrace. On the map, piping is predominantly on slopes having an aspect between southeast and southwest. Other authors have recorded a similar dependence of piping on aspect. Desiccation, which in the northern hemisphere would be most severe on southwest-facing slopes exposed both to the sun and to the prevailing wind, has an important role in pipe formation.

Pipe flow measurement

Pipe networks proved difficult to assess in hydrological detail. Flow gauging is always a problem in ephemeral systems, and when they are buried it is even more difficult. An instrument of the propeller-meter/siphoning tank type was used at first in the experiment on the Gerig (Gilman, 1977), but later an improved automatic system was devised, using weir tanks with autographic recorders (Plate 21). The weir tank is a simpler version of the type described by Truesdale and Howe (1977).

Natural pipes as ephemeral components of the flow net, draining small catchment areas

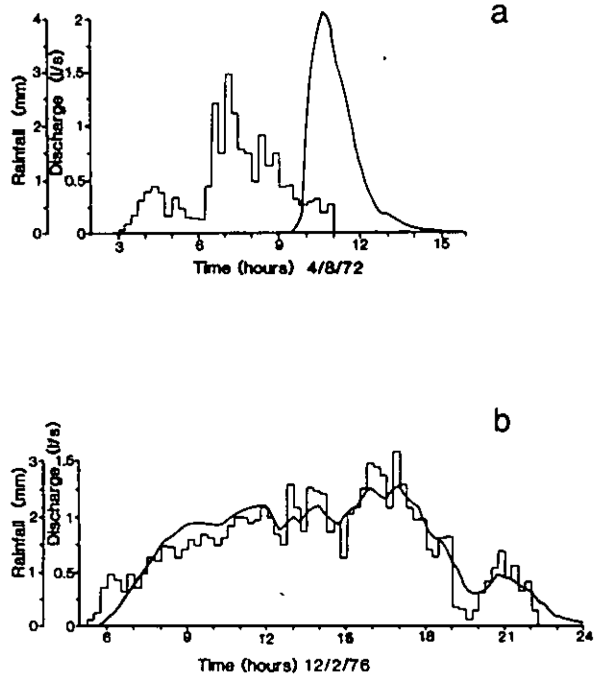


Figure 49 Pipeflow hydrographs (Nant Gerig) for (a) short rainstorm and (b) long rainstorm

PLATE 21 Weir tank used to gauge pipe flows (top) and detail of equipment recording rainfall on water-level chart (bottom)

through complex channel systems, have hydrographs showing a number of unusual features. The most obvious aspects (Figure 49) are the commencement of flow some time after the onset of rain, a jagged outline showing an immediate response to subsequent changes in rainfall intensity and a rapid recession to zero flow. In general terms, pipes can be expected to flow after about ten millimetres of rain has fallen, but this figure may be as high as 50 mm. Rainfall intensity may also have an effect: a very intense storm on 5 July 1976 yielded immediate pipeflow, with a shorter recession than that normally observed. This would suggest that the usual routes by which water enters a pipe were bypassed by the high intensity rainfall, and the recession could not be sustained. The timing of this storm is significant: in the middle of the 1976 drought, the pipes were laid open to rainfall by cracking of the soil, while the dry soil around was at its most hydrophobic and impermeable.

The recession of a pipe hydrograph begins when there is a marked decrease in rainfall intensity. It is not exponential in form, except over short periods; nevertheless the exponential model is useful in suggesting a time scale for the recession:

$$Q = Q_o \exp(-\alpha t)$$

where Q is discharge, t is time and Q_o is a constant.

The recession constant α is usually in the range 0.2 to 0.7 h^{-1}, implying that the time taken for the discharge to decrease to 1/e (= 0.3679) of its current value is between 1.4 and 5 h. As the pipe discharge decreases the recession gradually becomes faster. This behaviour, opposite to that of a perennial stream, where lower discharges are yielded by ever slower runoff processes, may be explained by losses from the pipe and its contributing macropore network into the surrounding soils. These losses, which probably occur at all times when the pipe is flowing, acquire more significance as the quantity of water in the pipe decreases.

The hydrological response of a single pipe is 'jagged' and depends considerably on antecedent moisture conditions and rainfall intensity. The low storage capacity and high velocity of flow in pipes makes routing through them relatively unimportant, and the emphasis for routing flows passes to the runoff domain below the piped slopes, i.e. surface flow across valley-bottom mires or flow in interrupted perennial pipes. The short length and broken nature of pipe networks makes them less efficient than, say, a network of tile drains, and times-to-peak are not therefore drastically reduced in a piped catchment.

Other slope runoff routes in the Wye

While soil pipes are the more spectacular downslope flow routes, both the morphology and mantle of soils of these slopes suggest that deeper throughflow routes may also be important and surface runoff may predominate locally. Knapp (1970; 1974) established four soil pits on the Cerrig yr Wyn slope in the Wye. At each he used a tipping-bucket and weir flow measurement system, logging hydrograph data at each prominent soil horizon. The study indicated the following sequence of hydrological processes controlled by soil characteristics and slope angle:

(a) The blanket peat topping the slope acts as a slowly permeable storage reservoir, releasing water to the adjacent slope.

(b) The podzol soils are thin and have a strongly prismatic structure; thus, both vertical and lateral movement of water is relatively easy, promoting important throughflow response (including piping as a special case). This is not confined to the soil profile but also occurs, more slowly, in the underlying soliflucted material.

(c) Near the base of the slope throughflow once more becomes limited by the less permeable peaty and gley soils; water is forced to the surface and most flow is overland.

Knapp contrasted his interpretation of the partial contributing area pattern of runoff domains with that of workers such as Weyman (1970) who considered more or less permeable soils, relatively undifferentiated between hill-top and channel banks. He also stressed that soil physical parameters of importance in modelling runoff downslope in the Wye could not be measured easily in the laboratory, mainly as the result of the importance of macropores of various types. Knapp suggested modelling the slope by means of a series of cascading reservoirs; this was the suggestion taken up by the isolation of runoff domains.

Knapp's study slope was south-facing and the importance of aspect has already been mentioned in the context of soil-piping. Because the aspect of the slopes in mid-Wales has controlled processes in recent geological time, particularly during periglacial phases, it now affects both the steepness of slopes and their deposits. It is perhaps not surprising, therefore, that a study made during the early 1970s of a first order gully on a north-facing slope opposite Knapp's slope revealed very different flow processes. Surface flows were regularly observed on both the hill-top and hill slope regions of this first-order, ephemeral stream.

The combination of propeller meter and siphon flowmeter, already referred to for measuring pipeflow, was used at two points in the gully floor. Hydrographs were compared with rainfall measurements from two recording raingauges and 13 storage gauges over the plot. Neutron probe readings provided soil moisture volumes and tensiometers revealed the detailed pattern of soil moisture movements.

The results obtained from the gully experiment indicated that certain runoff processes were of only minor significance to the hydrology of this basin:

(a) Unsaturated lateral flow within the soil profile. Tensiometric data indicated that the downslope soil moisture tension gradients were smaller (typically two orders of magnitude) than the vertical gradients caused by infiltration and evaporation. The lateral flux of unsaturated soil water under the influence of this potential gradient must also be small.

(b) Overland flow. The simple exponential decay of the streamflow hydrograph following the cessation of rainfall with a recession constant of 2.67 h^{-1} was not compatible with flow through the soil if reasonable values were assumed for the saturated conductivity, specific yield of the soil, and slope characteristics of the region. However the recession curve was compatible with overland flow draining into the ephemeral channel and indicated bulk overland flow velocities of the order of 0.2m/min. The conclusion was that within the hill top and hill slope regions of the basin, the principal process transporting water to the ephemeral gulley was overland flow, with the proviso that saturated flow might occur at the bedrock interface following periods of prolonged rainstorms.

The hill top and hill slope region thus appeared to be the source of overland flow in the classic Hortonian sense, the equilibrium streamflow being the difference between the two variables, rainfall intensity and soil infiltrability, the maximum infiltration rate through the soil surface. The soil infiltrability is known to be a complicated function of the moisture content of the soil and exhibits hysteresis phenomena depending upon whether the soil is wetting or drying. The different hydrological processes occurring on two opposite slopes in the Wye indicate clearly the need for a detailed spatial approach to flow modelling, a need which was fulfilled by several of the distributed models to be discussed later.

Indirect studies of runoff processes in the Wye

The measurement of throughfall, surface flow and pipeflow rates and their hydrological analysis with rainfall and soil moisture data constitute a direct approach to process studies of runoff. However, there remains the problem of integrating the contributions the individual flow routes make to the hydrographs of larger catchments and to the flow over longer time intervals.

It has often been considered that some form of labelling of the source of water flowing out of a catchment would be an appropriate technique for bridging the gap between plot-scale and catchment-scale processes. Stream chemistry and temperature have been used as natural "tracers", but both suffer from practical and theoretical problems.

Truesdale (1973) conducted a lengthy study of source area chemistry at the head of the Nant Gerig subcatchment of the Wye. It was intended to be the prelude to an attempt to partition the hydrograph of the Wye at Cefn Brwyn by flow process and origin based on continuous sampling of water chemistry. However, the predominance of peat in the area studied and the interaction of many other factors eventually forced Truesdale to conclude that chemical labelling in upland catchments would not provide a sound basis for source area identification of outflowing water.

Cryer (1980) reported results from the Maesnant catchment on the west side of Plynlimon and suggested that the chemical compositions of pipeflow and streamflow were intermediate between surface water containing more solutes (the effect of dry deposition?) and the purer interstitial peat water. Cryer used a mixing model to predict the sources of water flowing in perennial pipes but, like Truesdale, stressed the problems of working with a chemical system dominated by precipitation and buffered by organic soils.

At a less ambitious level, readings of the electrical conductivity of stream water made at several points in both Plynlimon catchments suggest that it is possible to distinguish at least two flow sources. The two sources are the deeper throughflow or shallow aquifer flows and flows in the more superficial ephemeral pipes or overland. Student dissertations concerned with both the Severn and Wye have illustrated the higher electrical conductivity of water from deeper sources, and catchment storm hydrographs have shown reductions in conductivity at high flows. Shallow aquifer outputs are also cooler in summer and warmer in winter than rainfall reaching the stream by surface or near-surface routes, but this is a distinction rapidly blurred by mixing in surface channels.

There have been two short experiments at Plynlimon to investigate the use of isotopes as indicators of source area. The first measured tritium (^3H) concentrations of the Wye at Cefn Brwyn and showed rising concentrations in the early stages of floods. The second, a stable isotope study of the Severn, revealed the influence of storage processes in maintaining relatively stable concentrations despite flow variability (Brunsdon, 1981).

Clearly, however, the indirect methods of indexing source areas are too coarse, especially considering the methodological problems they pose, to compete with direct measurement and modelling of all the complex flow routes so far identified in the Wye. Progress is likely as a result of the much more detailed investigation of stream water chemistry accompanying the investigation of acidification in the Severn.

Runoff investigations in areas of peat erosion and drainage in the Severn

Soil moisture and channel flow data were collected to compare the hydrology of open blanket peat moorland (550–630 m OD) around the source of the Severn, with that of forested basin peat sites lower in the same catchment (360–460 m OD) (Robinson and Newson 1986). Channel flows were measured at a number of sites, both on natural streams draining moorland and on artificial ditches dug for forestry. Flows were measured using thin plate weirs equipped with continuous water level recorders. The study also used rainfall data and soil

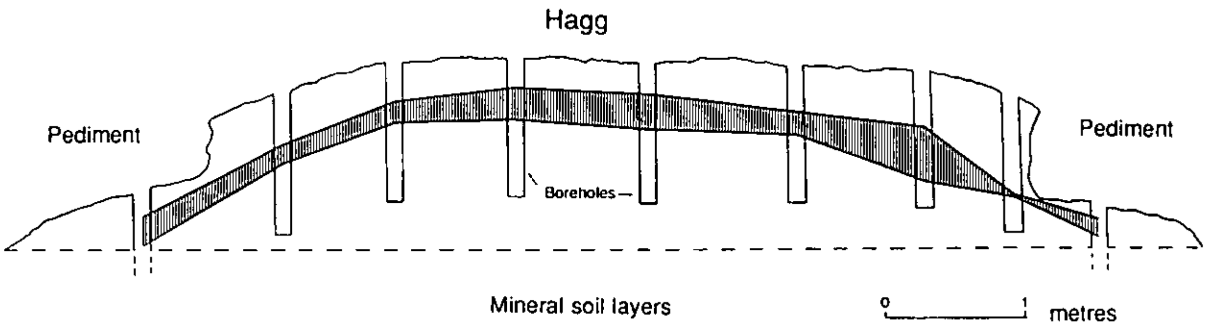


Figure 50 Cross-section of a peat hagg showing the water table depths exceeded for 25% and 75% of the time (from Robinson and Newson, 1986)

moisture data collected by neutron probe. While the neutron probe readings provide detailed information on soil moisture content at 20 locations, it was thought appropriate to supplement them with fairly simple measurements at a large number of other sites. Two common features at Plynlimon were thought to be of hydrological interest and were studied for one year from October 1975 to October 1976 by means of a large number of boreholes. These were:

(a) the natural system of drainage gullies and intervening residual 'haggs' which occur in the eroding blanket peat areas;

(b) the artificial network of ditches in the coniferous plantations.

Over 100 boreholes lined with 0.1 m diameter perforated pipe were installed around these features to provide a simple measure of soil saturation (e.g. MAFF, 1982).

The open moorland site in the upper Severn has remained as sheep pasture because the deep peat (maximum 2.6 m), the exposure and the surface irregularity have so far precluded the planting of trees. The peat has been eroded into classic 'hagg' forms; dissection comprises inter-connecting channels on the gentle slopes of the plateau.

Measurements by erosion pins over a five-year period indicate that the hagg faces are retreating by about 30 mm year^{-1}. Frost and drought are important in the supply of loose material whilst wind and rain effect its removal; the "pediment" surrounding the hagg acts as an important storage element.

In an earlier reconnaissance study of peat hydrology in eroding areas, a transect of wells was installed across a peat hagg in the upper Wye catchment. The upstanding mass of low-conductivity peat will support a water body which mirrors its outline shape. Peat hagg groundwater levels were measured in two areas of the upper Severn catchment. At both sites, ten haggs of widely differing sizes were selected. A well was located in the 'centre' of each hagg (the mid-point along the shortest diameter between eroding faces), and water levels were measured at weekly intervals. The average water levels were largely dependent on the diameter of the hagg and show a steep decline for haggs less than about 10 metres in diameter. Measurements of permeability by the auger hole method in the upper Severn haggs found surface values of 5.5×10^{-1} mm s^{-1} (similar to surface runoff velocities), declining steeply to 8.8×10^{-6} at 0.25 m and 7.4×10^{-7} at 0.5 m. The auger hole method used in recharge failed to show any water level response below 0.75 m, conductivity presumably being virtually nil.

Piezometers were installed at 0.25 m to 1 m depths in one of the peat haggs and indicated a downward flux of water. However, due to the low measured hydraulic conductivity, the volume of this flux must be small, and falls in the water levels in the haggs must be due to losses to surface layer flow and evaporation. A study of water samples taken at different depths in a hagg showed that the surface water chemistry was very different from that at depth, confirming the small amount of vertical water transfer. Thus eroded blanket peat can hardly be said to act as a "sponge". However, small parts of this topography can act as significant storages of water. It appeared that the largest volumes of storage in the upper Severn catchment were accounted for by areas of redeposited peat and by a shallow aquifer comprising an approximately 0.5 m thick layer of fractured periglacial grits. A transect of wells across one of these areas of granular peat showed that such areas retain high water levels except in severe droughts.

To consider the gross hydrological effects of plantation forestry on peat hydrology, three transects of wells were installed in grass rides, three under mature trees, and two across ditches which had trees on one side and grass on the other. Water depths in the wells were measured weekly. A number of factors influenced water depths:

(i) Drain depth: despite the range from 0.7 to 1.2 m, the drain depth had little effect on water levels beyond a metre away. This reflects the very low hydraulic conductivities of the peat below the surface layers.

(ii) Ground slope: the water table was usually lower on the downslope side of the ditch, confirming that although the drains had a restricted effect in terms of drawing down the water table, they were acting to intercept the movement of water downslope.

(iii) Vegetation: on average the water level in boreholes under forest was about 120 mm lower than under moorland. For transects crossing from grass into forests, the water levels under the forest were generally about 200 mm lower. This indicates a higher loss from trees at the edge of the forest than in the middle, and may be due to greater transpiration as a result of the denser foliage, or greater interception loss caused by greater air turbulence.Thus on peat soils alone, vegetation type appeared to be the most important factor controlling the soil water levels.

The change in soil moisture contents beneath the forest resulting from the interception loss is also illustrated by data from the neutron probe soil moisture measurement sites in the Wye and Severn catchments (Robinson and Newson, 1986).

Clearly, since the neutron probe access tube sites were chosen to minimise the influence of artificial drains, this result indicates the extent of "biological drainage" under mature trees, especially where vertical moisture exchanges predominate on deep peats. On naturally well-drained slopes the effect of interception losses on moisture deficits is less pronounced, although forested slopes are still drier than grassland slopes.

To consider the effect of forest drainage on runoff response during rain storms, the flow discharges from six small catchments were continuously recorded for a year (October 1975 to October 1976). Two comprised the open moorland area around the headwaters of the Severn, while the other four catchments were situated in forested areas. The two forested catchments in the lower Tanllwyth area were similar in respect of their soils, surface gradient, age of trees and rainfall. The Aberbiga catchment contained a young plantation on a much more permeable soil, and had a lower average rainfall.

Instantaneous flows were read off the water-level recorder charts at six-hourly intervals throughout the period and have been used to plot flow duration curves (Figure 51). Because of the variation in catchment sizes, the flows were standardised by dividing by the mean flow. The curves for five of the six catchments were broadly similar, but the moorland peat bog catchment was quite distinct: flow for most of the time was within ± 50% of the mean, and it was not observed to dry up. The forested upper Tanllwyth had the next highest baseflow, with flows ceasing for approximately 12% of the time. The upper part of that catchment is fed by a spring emerging from a natural soil pipe. The four remaining catchments (three forested, one moorland) have similar curves: all dried up for about 30% of the study period.

The response of each catchment to heavy rainfall was examined by reference to the largest storms in the measurement period. Unit hydrographs were derived from about ten storms on each catchment. Because of a number of breaks in the data it was not possible to analyse the same set of storms on all catchments. It should be noted, however, that the storms sampled did not

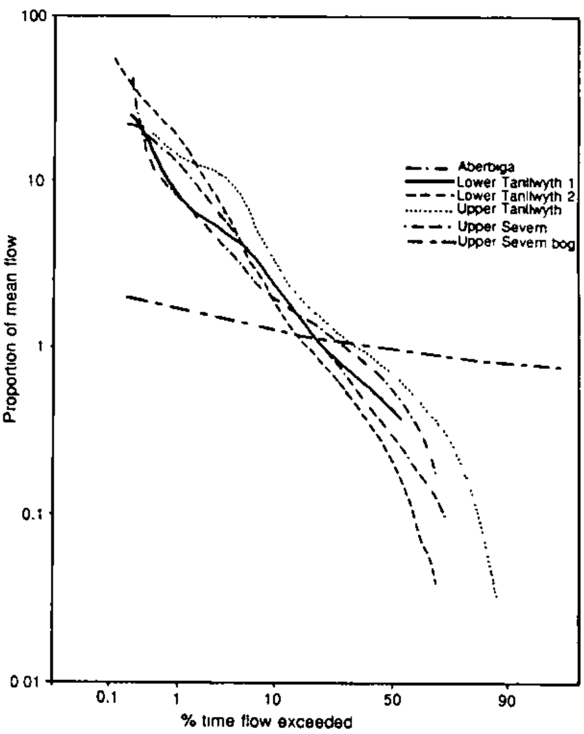


Figure 51 Flow duration curves

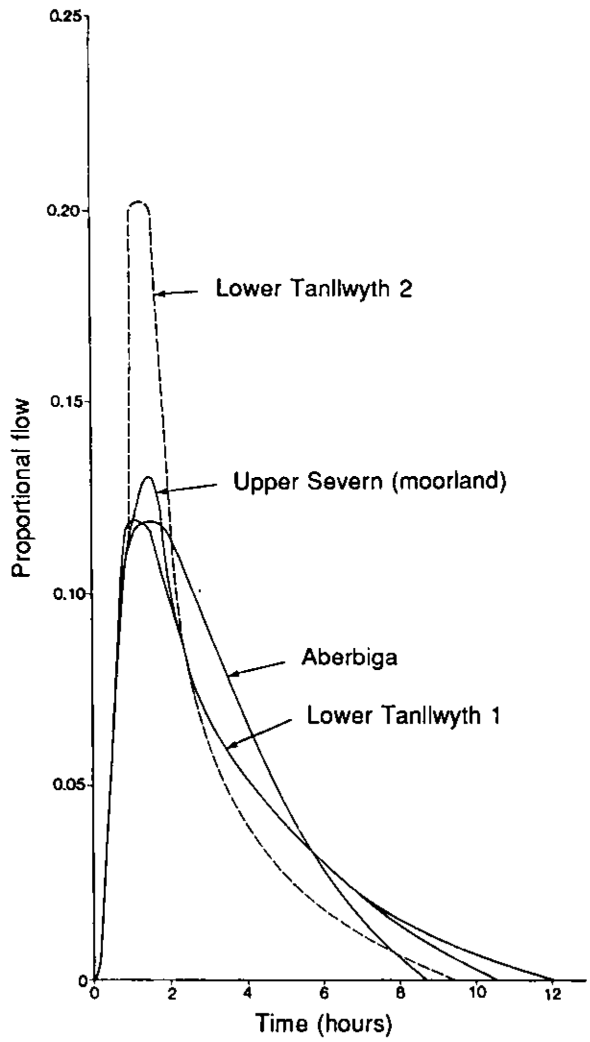


Figure 52 Average unit hydrographs for ditched and moorland catchments

include any really large events, and that although most storms were in winter months, the preceding summer (1975) had been relatively dry and runoff volumes were low. Average unit hydrographs (Figure 52) were obtained by the method of Boorman and Reed (1981). It is evident that the response from the moorland catchment falls well within the variation between the three forested catchments.

The Aberbiga catchment had a slightly longer response, despite the relatively small size of the trees. This may result from its more permeable soils. The forested catchments had apparently similar physical characteristics, but the catchment with the more peaky response and a shorter lag had a much denser network of drainage ditches.

The storm runoff varied greatly when it was expressed as a percentage of the rainfall in each storm, but it was not possible to make valid comparisons of average values between catchments because a different set of storms was available on each one. However, for those storms available on more than one catchment, there was an apparent tendency for slightly higher runoff from moorland than from forest.

5.4 Routing runoff from source area to catchment outlet

Numerical information for detailed, distributed mathematical models has to be based on the routing characteristics for runoff from all the source areas through the range of possible pathways. Prior to a study of open channel routing, it is necessary to consider the influence of the slope processes, soil pipes, flushes and surface runoff. Simple flow measurements of all three types of runoff, in conjunction with salt tracer/conductivity measurements (Newson and Harrison, 1978), gave rise to Figure 53,

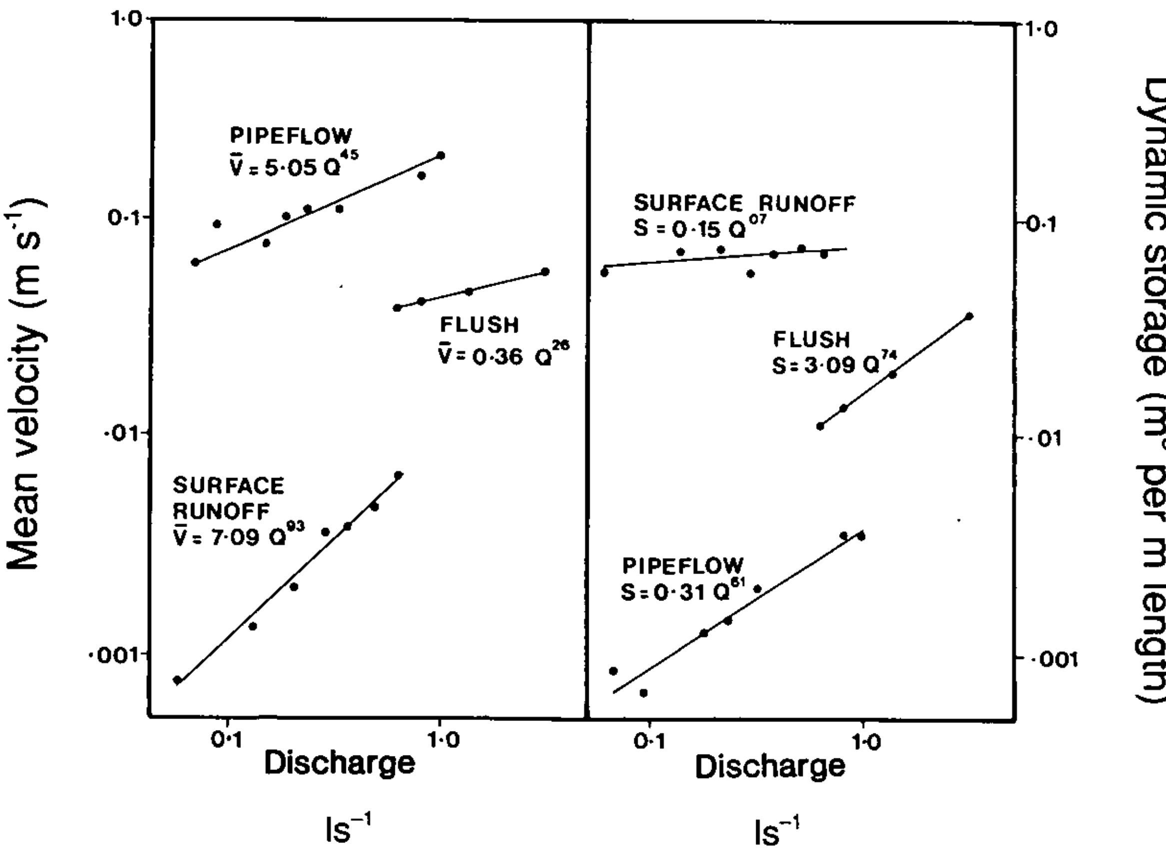


Figure 53 Mean velocity and dynamic storage for pipe, flush and surface flows, plotted against discharge

which illustrates mean velocity and dynamic storage/discharge relationships for pipeflow, flush and surface runoff. The discharges calibrated are one to two orders of magnitude lower than those seen in open stream channels.

The velocity of pipeflow is much higher than that of surface runoff. However, as the flow increases, there are increases both in storage or cross-sectional area and in velocity, and the large exponent of the velocity discharge equation for surface runoff (0.93) implies that the mean velocity of surface runoff at high discharges is comparable with that of the other processes. In contrast, the storage capacity of the surface runoff regime is high but relatively constant, with an exponent of 0.07. The storage capacity of the flush is high and increases more rapidly with discharge than would be the case for an open channel. The pipeflow storage/discharge exponent is also high but only comparatively small amounts of storage are available.

In fact, by measuring sample cross-sections in the test pipe it is obvious that, at the maximum discharge tested, the pipe has little further storage potential. Efflux of water occurs at the surface, although it sinks elsewhere on the plot. The cross-sections indicate a mean cross-sectional area of 0.00435 m^2 and at the highest test discharge dynamic storage was equivalent to 0.00420 m^2, 96.6% of the pipe cross-sectional area. Some indication that surface outlets are not the only leaks in the pipe comes from the fact that output discharges in the unbranched system were frequently only half of input, suggesting leakage along cracks or the peat/silt-clay interface. Output discharges were used in the calculations.

Newson and Harrison's studies (1978) on the surface runoff plots seem to indicate the importance of micro-relief in determining velocities, to the exclusion of gradient (13° to 32.5° slopes were tested). Roughness is a significant variable as it is an index of the degree of micro-channel relief of the plot.

Mean depths of surface water varied between 5 mm and 20 mm on the main plot, with a positive but irregular relationship with increasing flows. Dynamic storage volumes converted to average depths on the plot showed a 68 mm to 90 mm storage for 1 m width (this may be an underestimate of the width). Thus much of the flow considered as surface runoff is obviously occurring below the surface in the fibrous root zone just above the soil surface; this may explain the low velocities reached by surface flows compared with those reported from less well vegetated surfaces.

Channel classification and measurement

The channel classification arrived at by Newson and Harrison (1978) has been used as a basis for detailed studies. A mixture of field survey and interpretation of aerial photographs was used to extend the classification to both catchments. Pipes were mapped by two people walking every slope in the Wye in the quarter and three-quarter slope position. Thereafter typical examples of gullies, flushes and pipes were treated in more detail by conventional field survey techniques and a sampling programme was initiated to quantify the geometry of all permanent open channels, and the detailed hydraulic geometry of some reaches.

Hydraulic performance of channels: time-of-travel and storage behaviour

Soluble tracers are frequently used to determine the time of travel, and hence the mean velocity, of flow in open channels. In time-of-travel studies covering part or whole of the Wye and Severn catchments the fluorescent dye Rhodamine WT has been used to investigate the flow velocity in the main channels at a wide range of discharges.

Three techniques of dye sampling have been adopted:

1. Manual collection of water samples;

2. Use of vacuum samplers (at one hour, half-hour intervals);

3. Use of the Turner fluorometer in the field powered by a generator in conjunction with a peristaltic pump for sampling and a potentiometric recorder.

The results are described by Newson and Harrison (1978) and are shown for three sites in Figure 54. They indicate convergence on both axes, times-of-travel becoming infinitely long at low flows and approaching a constant value at high flows.

Seven reaches of length 50 m in the Severn catchment were gauged using salt dilution on several occasions (Oestrem, 1964; Calkins and Dunne, 1970); the results were used to evaluate the storage characteristics according to the power law

$$\text{Storage (S)} = KQ^{m} \qquad [\text{Flow Q ls}^{-1}].$$

The equations for each reach, with constants and exponents determined by regression analysis, are shown in Table 22(a). The value of K gives some indication of the comparative volume of storage in the reach, with the deep plunge pools of reach 5 (Blaenhafren Falls) having a pronounced effect. Beven (1976) found an exponent of 0.43 for Crimple Beck, a steep stream in Yorkshire, and suggested that uniform flow would yield a value of m of 0.6 to 0.8. Apart from reach 2, all the calculated exponents are significantly lower than this. The low exponent in the storage discharge relationship indicates that the increase in discharge is largely accounted for by greater flow depths rather than higher mean velocities.

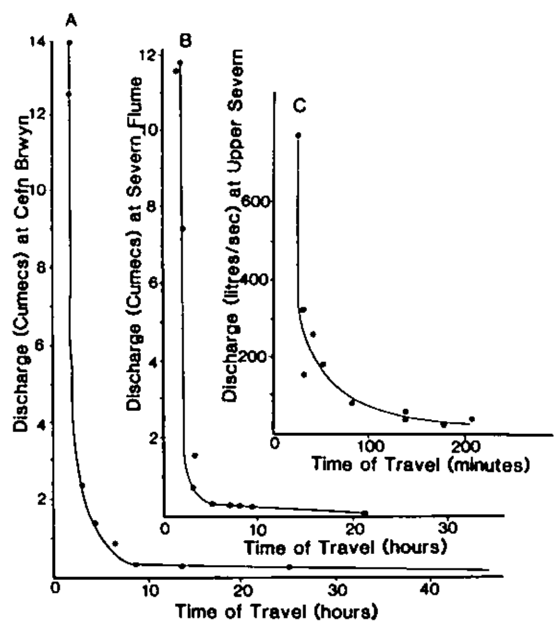


Figure 54 Time-of-travel curves for Plynlimon channels
(a) The Wye
(b) The Severn
(c) The Upper Severn (grassland area)

TABLE 22 Reach storage characteristics

a) Total storage

Reach No.	Reach equation	Coefficient of determination
1	$S = 3.29\,Q^{0.48}$	$r^2 = 0.95$
2	$S = 1.00\,Q^{0.64}$	$r^2 = 0.96$
3	$S = 2.93\,Q^{0.46}$	$r^2 = 0.94$
4	$S = 1.95\,Q^{0.50}$	$r^2 = 0.91$
5	$S = 23.9\,Q^{0.12}$	$r^2 = 0.88$
6	$S = 3.72\,Q^{0.32}$	$r^2 = 0.91$
7	$S = 2.24\,Q^{0.28}$	$r^2 = 0.76$

b) Active storage

Reach No.	Reach equation	Coefficient of determination
1	$S_{active} = 1.33\,Q^{0.59}$	$r^2 = 0.94$
2	$S_{active} = 3.92\,Q^{0.32}$	$r^2 = 0.66$
3	$S_{active} = 3.07\,Q^{0.40}$	$r^2 = 0.86$
4	$S_{active} = 1.42\,Q^{0.53}$	$r^2 = 0.92$
5	$S_{active} = 16.1\,Q^{0.18}$	$r^2 = 0.20$
6	$S_{active} = 3.15\,Q^{0.32}$	$r^2 = 0.42$
7	$S_{active} = 2.13\,Q^{0.51}$	$r^2 = 0.25$

The work described was used in a wider context by Beven, Gilman and Newson (1979). Defining flow relationships for these shallow, rocky and irregular channels has been neglected in past studies of open channel flow because of the exceedingly complex nature of the processes involved. Flow in steep streams is characterised by slow pool sections, fast riffle and rapids sections, with waterfalls and other irregularities in the channel bed creating rapid changes in flow depth and width, frictional effects and the energy slope of the water body. Even in small catchments, the timing of hydrograph peaks suggests that the effects of routing through the channel network, although superimposed on the changing nature of the storm flow generation processes with increasing catchment size, may be significant.

The high values of the roughness coefficient confirm that flow in this type of channel is predominantly influenced by channel form and that the effect of the skin resistance of the bed and banks is relatively small. At low flows the values are very high. The highest values (Darcy-Weisbach coefficient $f = 48$, equivalent to a Manning's n of about 1) are comparable with the highest values for overland flow. The highest value of all in the present study was $f = 1328$, calculated for site 5 in the River Severn at a discharge of $0.015\ m^3s^{-1}$.

5.5 Distributed models

There are three fundamental reasons for constructing a model of a physical system:

(i) to aid in the understanding of the working of the complete system and its component processes;
(ii) to make predictions about the responses of the system to hypothetical, often extreme, inputs (in hydrology the flood prediction problem is of this type);
(iii) to make predictions about the behaviour of a related but not identical system (in hydrology the prediction of the response of an ungauged catchment).

It has always been an objective of the Plynlimon catchment experiment to apply results as widely as possible, and the distributed model, which bases its predictions on the simulation of the physical processes in the catchment using properties measured in the field, is a key element in this philosophy.

Distributed models differ in the way they approach the simulation of flows on hillslopes and in open channels. Three models that have been used on the Plynlimon data are described briefly in this section and a comparison is made with other modelling approaches.

The Institute of Hydrology Distributed Model (IHDM)

The IHDM is a rainfall-runoff model based on the physics of catchment processes and it allows the incorporation of spatial inhomogeneities of the catchment. It has undergone a number of stages of development involving different degrees of complexity of process description and associated methods of solution. The current version, No. 4, is described in IH Report No. 98 (Beven, Calver and Morris, 1987).

IHDM Version 4 maintains the original modular cascading structure of hillslope and channel sections of the catchment, through which flows of water are calculated. The hydrological processes modelled are saturated and unsaturated subsurface flow, hillslope overland flows and channel flow. The equations of flow are solved by numerical approximation methods.

Overland flow occurs if the infiltration capacity of the soil surface is exceeded, or from the subsurface build-up of water in excess of the capacity of the surface layers. Surface characteristics of the catchment are classified into plan zones of like attributes, with respect to vegetation type and microclimate for example. The basic hillslope calculations are undertaken for two-dimensional vertical planes, using sufficient planes to represent the whole catchment: the plan-defined zones are represented as different parts of the surfaces of these planes. Effects of contour curvature on flow convergence and divergence can be accommodated by using variable slope widths.

Channel flow and any overland flow are represented in a one-dimensional downslope sense by a kinematic wave equation, solved using a finite difference scheme. Thus

$$b_c \frac{\partial Q_c}{\partial t} + c \frac{\partial (b_c Q_c)}{\partial y} - c b_c i = 0$$

where Q is discharge, y downslope distance, t time, b flow width, c kinematic wave velocity (defined by dQ/dA where A is cross-sectional area of flow), and i is lateral inflow rate per unit downslope length.

Saturated and unsaturated subsurface flows are modelled together using the Richards equation, incorporating Darcy's Law and consideration of conservation of mass, which may be expressed as

$$b_s \frac{\partial \theta}{\partial t} - \frac{\partial}{\partial x}[b_s k_x \frac{\partial \phi}{\partial x}] - \frac{\partial}{\partial z}[b_s k_z \frac{\partial \phi}{\partial z}] = Q_s$$

where θ is the volumetric soil moisture content, ϕ the hydraulic potential, k the hydraulic conductivity, x the horizontal distance from the drainage divide, z the vertical distance (above an arbitrary datum), b the slope width, Q a source/sink term and t is time. This is solved for hydraulic potential using a finite element method for the two space dimensions and a finite difference method for the time dimension.

Using the IHDM on Plynlimon data

Applications of earlier IHDM versions to the Plynlimon catchments are described by Morris (1980) and Rogers *et al.* (1985). Morris used a simple soil water store component with the Saint-Venant equations for distributed overland flow: attention was focused on the calibrated values of surface roughness for the grass and forested subcatchments. Rogers *et al.* used the same equations for surface flow but with a two-dimensional subsurface flow component solving the Richards equation by a finite difference method. In calibrating for the Tanllwyth subcatchment the parameters to which the IHDM Version 3 were seen to be most sensitive were surface roughness and saturated hydraulic conductivity.

An example of the use of IHDM Version 4 on the forested Tanllwyth catchment is given by Calver (1988). Such measured catchment data as were available were input directly into the model: parameters whose values were unknown or uncertain were optimised against recorded catchment discharge. In practice, these were hillslope roughness coefficient, soil porosity and hydraulic conductivity. Initial moisture content – though not strictly a parameter in this sense – was also derived by calibration. Having established the physical parameter values, these were found to hold for temporal transposition to flood events of similar size to the calibration event and also for spatial transposition to the adjacent physiographically similar Hore catchment (when similarly forested). This was seen as an important test for the potential use of such models in areas where little monitoring is undertaken.

IHDM Version 4 has also been used on the Gwy grassland catchment. In this case the unknown parameter values were optimised for five storms of about mean annual flood size. These values were then tested to see whether they held across a range of events of differing magnitudes. The results (Figure 55) show good performance for events varying from return periods of less than one year to ten years. The IHDM Version 4 parameters were also tested on the large runoff event of August 1973 which has an estimated return period of 50-100 years, using the regional frequency curve. Discharge records do not exist for the Gwy for this event but a slope-area estimate (Newson, 1975a) of peak discharge gave 16.9 m^3s^{-1}. The IHDM predicted a peak of 15.6 m^3s^{-1} occurring one hour into the three-hour-long period when the highest stage readings occurred.

The SHE model

The Système Hydrologique Européen (SHE) model shares many of the modelling aims of the IHDM. It was developed jointly by IH, the Danish Hydraulic Institute and SOGREAH of France. It differs from the IHDM in its approximation to three-dimensional catchment geometry, notably in that the SHE operates in two-dimensional plan form for overland flow and saturated subsurface flow, and in one, vertical, dimension for unsaturated subsurface flow. The interception and evapotranspiration elements of the two models are very similar. In the SHE, surface

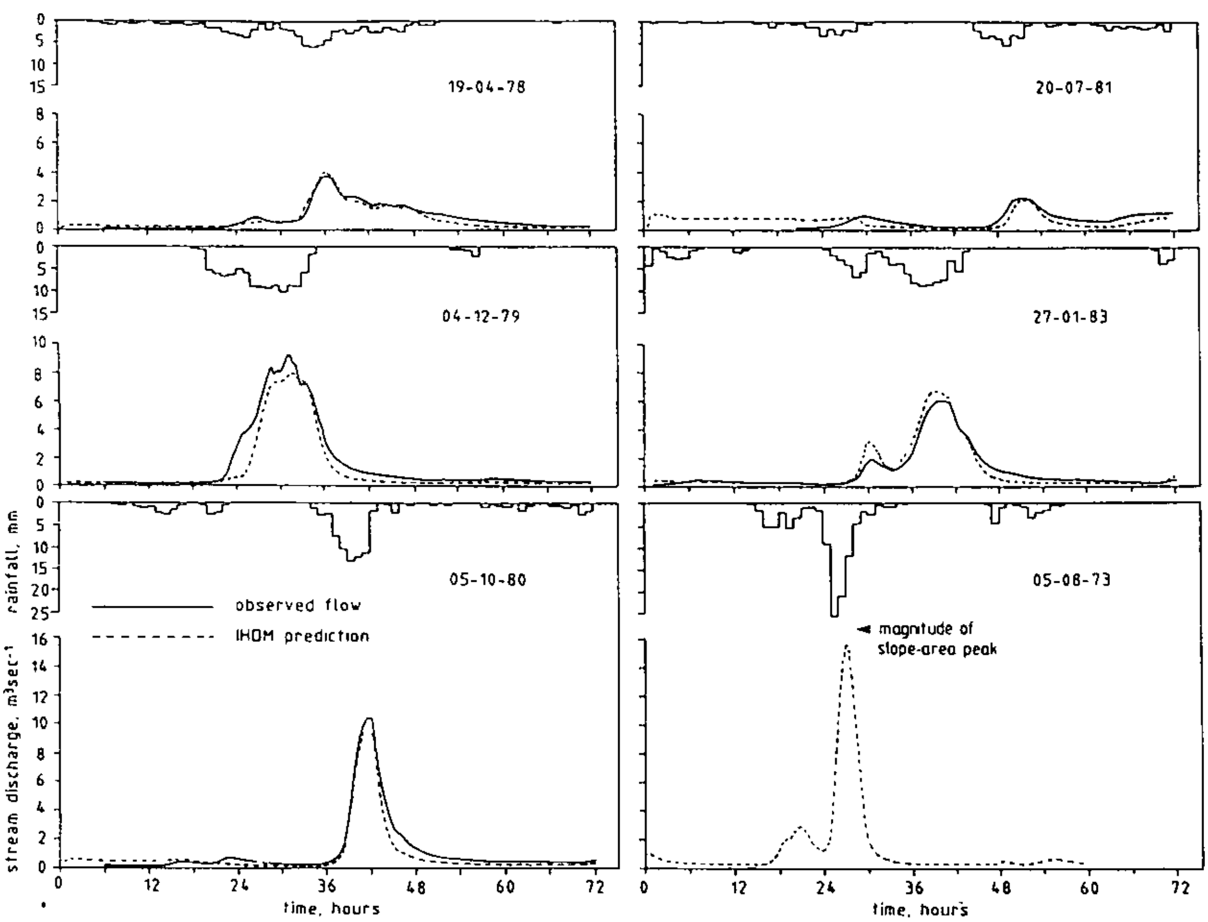


Figure 55 Comparison between IHDM results and observations

flow is modelled by the Saint-Venant equations in two dimensions for overland flow and one dimension for channel flow. Unsaturated flow is modelled by the Richards equation and saturated flow by the Boussinesq equation, based on Darcy's Law and mass conservation. All solutions are obtained by finite difference schemes.

Bathurst (1986a and b) has presented an application of the SHE to the Wye and assessed the sensitivity of model components in this context. Calibration was undertaken, as with the IHDM, on the basis of available hydrological data and hydrological reasoning. Five events on the main Wye and its subcatchments were studied in the calibration exercise: hydraulic conductivity and initial moisture status were again of major importance.

Other attempts at modelling rainfall/runoff for Plynlimon

The availability of large amounts of reliable data for the Wye and Severn has stimulated the interest of mathematical modellers outside the Institute, notably those concerned with distributed models. Like IHDM and SHE, the model produced by Jayawardena and White (1979) demands a geometric subdivision of catchments into subcatchments and runoff strips. Each strip was based upon the concept of flow occurring orthogonally to the contour pattern, by throughflow on slopes and by overland flow where slope elements converged to produce 'drainage paths'. Each strip was then divided into a convenient number of elements and kinematic wave equations solved for overland flow, diffusion equations for throughflow with physically-identifiable parameters such as Manning's 'n', hydraulic conductivity and porosity obtained from the literature.

The semi-distributed TOPMODEL (Beven *et al.*, 1984) makes important progress in two directions. Using the Wye as a test catchment, the model employs a realistic spatial subdivision reflecting the partial contributing area concept and fixes parameter values by field measurements. These measurements include sprinkle infiltrometer and stream dilution gauging, complementing the field data obtained for each significant contributing area and channel. The model includes interception store, infiltration store and saturated zone store and for the Wye makes a spatial subdivision of 14 subcatchments, eight of which are headwater elements. Successful predictions of hourly flows over an annual period were obtained. Nevertheless, the authors admit that their results were improved by using accurate local data and taking a wet period for calibration. A modified version of TOPMODEL has been satisfactorily used (Beven, 1987) to generate hourly mean flow frequency data for the Wye catchment. The Institute has always devoted considerable effort to rainfall/runoff modelling and it is not surprising that the Plynlimon catchments have been used to test two other types of model: lumped models and stochastic models. A version of the lumped model was first described by Douglas (1974) but there are now enough examples of its use to permit Blackie and Eeles (1985) to prepare a thorough review of its strengths and weaknesses. As they observe, in modelling catchment systems "the choice of what to simplify and to what extent" is dictated by a wide range of considerations. The most common simplification made in catchment modelling is lumping or 'spatial averaging'. Whilst it might therefore be thought appropriate to apply lumped models only to small homogenous areas, they have been at their most successful, in practical terms, at the scale of large river basins (Bailey and Dobson, 1981).

Blackie and Eeles describe the advantages of lumped models for quality control, relying heavily on the use of Plynlimon data, record extension and water resources development and management. Rigorous analytical expressions describing the movement of water through the system are not employed; in spite of this the IH lumped model can compete in efficiency with TOPMODEL and SHE in hourly predictions for the Wye and can be used with equal success on the Severn. Because of the need for fast, efficient model operation, as well as optimum use of available data, Moore and Clarke (1981) devised a statistical approach to modelling the interception and soil moisture stores in a simple moisture accounting model. Good records of streamflow and soil moisture contents from neutron probe readings were used to calibrate the model for the Wye and it then produced acceptable hourly predictions of runoff from rainfall and evaporation data for 100 days in 1976.

The performance of the various models has shown the potential of both distributed and lumped approaches. Beven and O'Connell (1982) advocate continued effort in the field of distributed, physically-based models despite the many practical applications of lumped models. For those sensing conflict amongst the modelling approaches, Beck (1981) helps clarify the issues. It is also clear that the early decision to pay great attention to hydrological process studies at Plynlimon has proved of great value to the extension of the findings of the main catchment experiment.

Chapter 6
Water quality implications of land use and land management

The Plynlimon study was designed originally to investigate changes in quantity of runoff arising from land-use change. Water quality, other than sediment yield, was not considered in the original experiment. As environmental issues came to the fore in the last decade, however, it was realised that the waters of the Plynlimon catchments were similarly susceptible to the problems found in lowland rivers and streams. This chapter deals with the studies of those problems.

6.1 Sediment yields, land use and management

Ironically, one reason why reservoir operators in upland Britain preferred forestry in their catchment areas was its supposed effect in reducing erosion (Rodwell, 1936; Ministry of Health, 1948). However, these opinions date from the era before extensive upland drainage ditching was practised and the Plynlimon study reveals that open drains, whether for forest or moorland drainage, enhance erosion and consequently increase sediment inputs to reservoirs. In addition, some of the effects of other forest practices, such as road or track construction and felling methods may also raise sediment transport rates.

Erosion and fluvial sediment transport can have impacts on water quality, stream ecology and channel stability. Increasing recognition of the value of "whole catchment" approaches to river management has heightened awareness of the implications of change in the sediment outputs from the headwaters of major British catchments. Examples of water treatment problems as a result of elevated suspended solids concentrations have been reported by Austin and Brown (1982) and Stretton (1984). Maitland *et al.* (1990) review some of the adverse ecological impacts of elevated fine sediment transport rates and increased deposition of fines in the freshwater habitat including, adverse effects on fisheries and invertebrates. Movement of coarser sediments (mainly of sand up to boulder size material) is a critical factor with regard to channel form and stability in both the upland catchments and lowland reaches of river systems (Newson and Leeks, 1987).

In mid-Wales, Palaeozoic shales and mudstones have produced highly erodible drifts, screes and colluvial mantles beneath a protective vegetation, soil and peat cover. Both this cover and the occurrence of large areas of upland plateau result in low rates of natural erosion (Lewin, Cryer and Harrison, 1974; Oxley, 1974), although Slaymaker (1972) deduced higher rates by less direct methods. Natural erosion occurs mainly from channel banks and bluffs, with little contribution from plateaux and slopes.

Particulate fluvial transport is usually divided into suspended-load and bed-load movement. The relative contributions of these classes of transport to the total sediment yields show considerable variation between subcatchments. For example, bed-load yield ranges from 32% to 76% of the total particulate yield. The present sediment sampling network at Plynlimon is shown in Figure 56.

Bed-load studies in the Cyff and Tanllwyth

The initial approach to the study of bed-load at Plynlimon has been described by Painter *et al.* (1974); at that stage only nine months of data were available from two bed-load traps, one in the Cyff and one in the forested Tanllwyth (Plate 22). The ratio of yields from

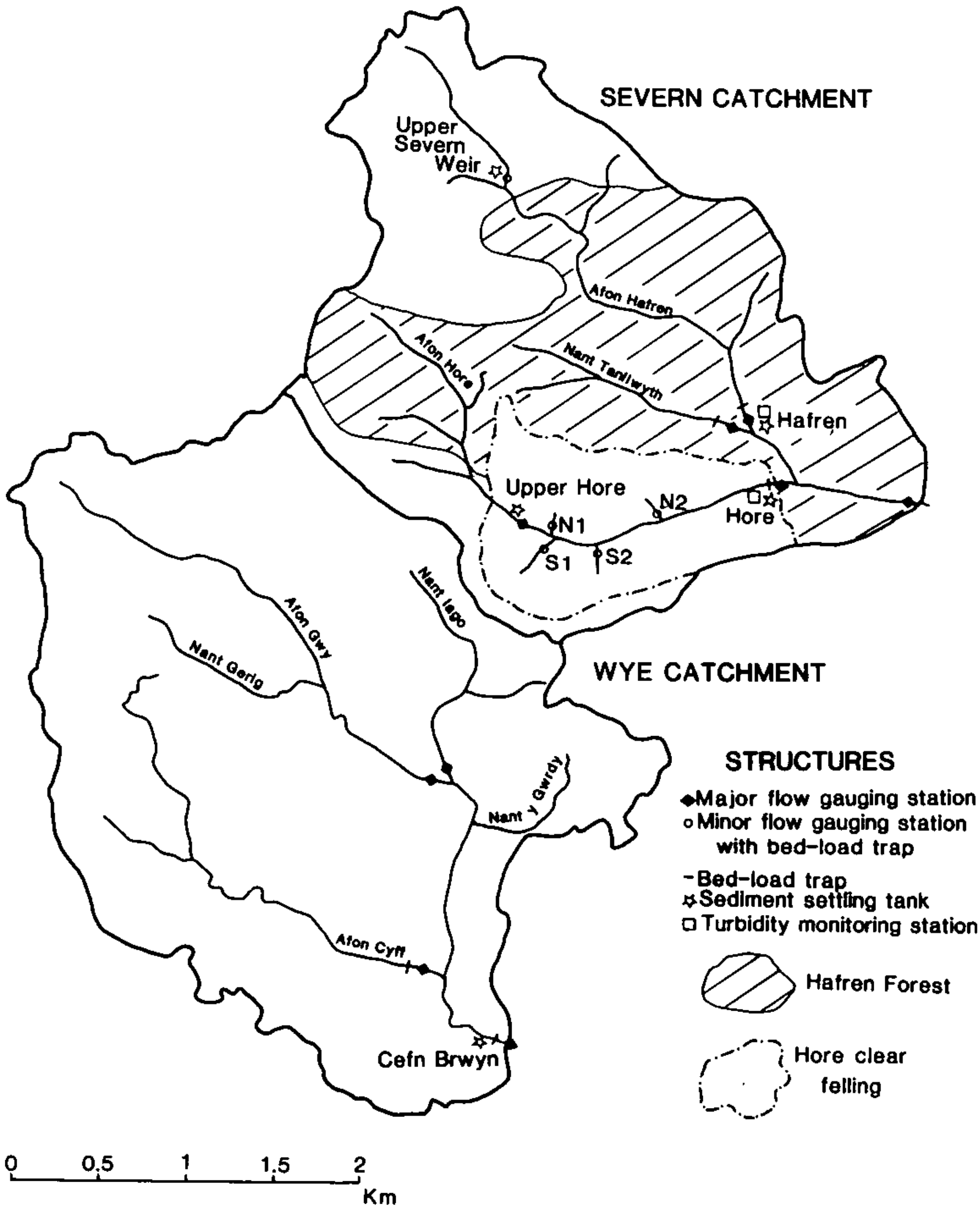


Figure 56 The current Plynlimon sediment sampling network.

the two catchments is still close to that shown by the first nine months' data, the forested catchment yielding five times more bed-load per unit catchment area. Rainfall and runoff records over the period are comparable. Problems of interpretation have been introduced by the severe storm which affected the Tanllwyth, but not the Cyff, in August 1977. Like the August 1973 flood, which affected both catchments equally severely, the 1977 flood produced not only a direct increase in the volumes of bed-load trapped but also an aftermath of high yields (Newson, 1980a).

TABLE 23 Sediment yields (gravel bed-load) from 'natural' and disturbed small catchments in Mid-Wales. Catchment areas from 0.25km² to 13.0km².

Land use Catchment	Annual yield m³km⁻²	
Grassland, undisturbed		
Cyff	2.5	
Cownwy	2.5	
Pen y Banc	9.9	
Maesnant	1.1	a
Iago	1.2	b
Forested, ditched		
Tanllwyth	8 4 - 307.7	#
Groes	44.4	
Marchnant	30.9	
Moorland, ditched		
Bugeilyn	57.1	
Hengwm	2.0 - 17.9	#
Llyn Pen Rhaidr	3.5 - 38.8	#

a from Lewin, Cryer and Harrison (1974)
b from Lewin and Wolfenden (1978)
main catchment and sub-catchments

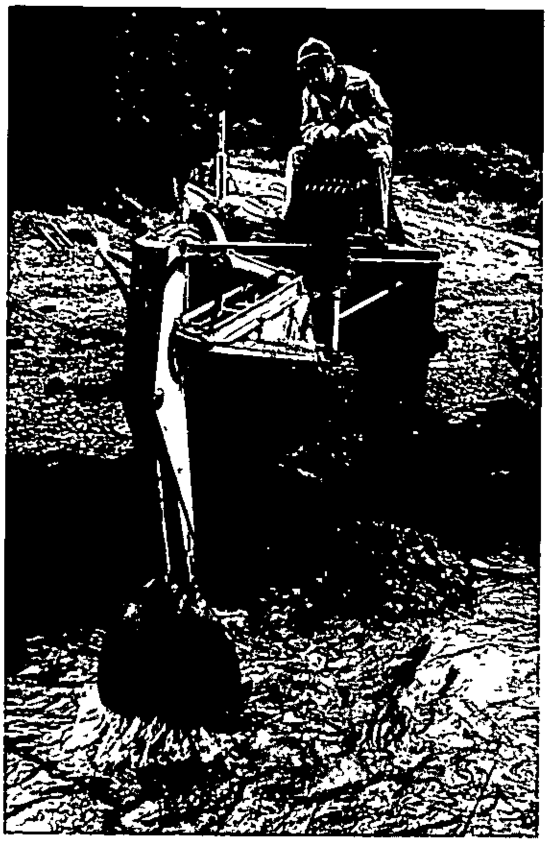


PLATE 22 Emptying the Tanllwyth bed-load trap.

The most obvious explanation for the higher bed-load yields in the Tanllwyth is the network of drainage ditches within the catchment (Figure 57). Whilst each area of problem upland soils requires different establishment techniques for successful tree growth, the Tanllwyth ditches are typical of the type of hand-dug herring-bone drain networks which preceded the tractor plough era. Two approaches were used to assess the applicability of the Tanllwyth/Cyff comparison of bed-load to other regions. In the first, the area of study was extended to other parts of mid-Wales, to include forests without such dense drainage networks (Lake Vyrnwy) and areas of ditched treeless moorland (Nant y Moch). A comparison of ten yields of gravel similar to the Plynlimon material is shown in Table 23.

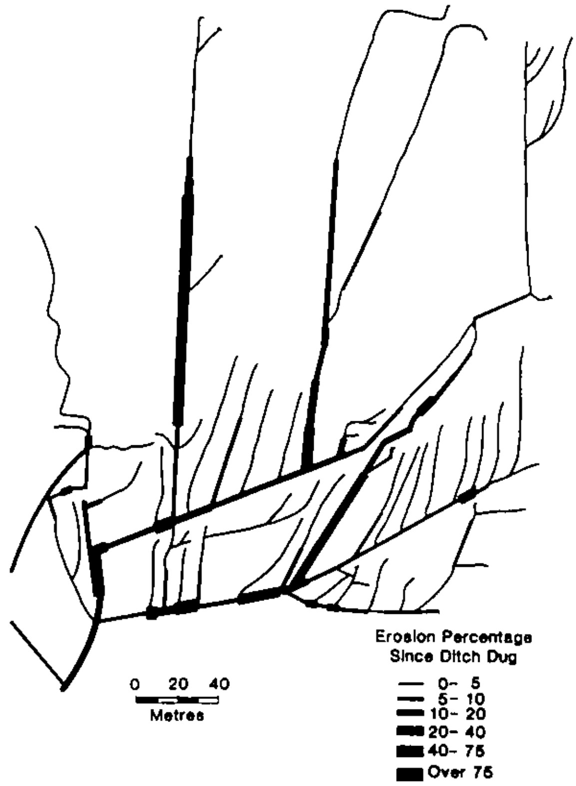


Figure 57 Plan of typical network of forest drainage ditches, Tanllwyth, showing the extent of erosion since the ditches were dug.

Clearly, the excavation of ditches through the protective cover of vegetation and peat in the British uplands exposes the subsoil to erosion. Field measurements were made in the extended study area to compare gradients and flow velocities of open ditches.

A revised approach to the design of drainage ditches for forestry (Thompson, 1979) used design rainfalls, catchment areas, peak flows and flow velocities to select ditch gradients. The velocity viewed as suitable for upland soils by Thompson was 2 ms^{-1} and it was recommended that slopes in excess of 3° should be avoided. No equivalent design procedure appears to be available for agriculture, although advisers on drainage schemes try to select gradients which are 'sufficient to move water away without producing scour'.

By surveying both eroded and stable ditch sections in the two most problematic areas, the following points can be made in respect of future design and excavation:

1. In all cases, ditches floored by blanket peat or gleyed soil (bulk densities 0.9 and 1.3 respectively) were stable at gradients up to 15°.

2. Where the colluvium below the peat or gley has been breached (bulk density 1.6), scour has produced irregular longitudinal profiles, lateral undercutting, collapse and blockage.

3. Critical velocities for erosion and transport of the colluvial material in these cases range from 0.36 ms^{-1} to 2 ms^{-1}, much lower than suggested previously. Clearly, gradients of ditches in such sensitive materials should be very gentle: in the cases studied all those over 2° and floored by colluvium had scoured.

The second approach to studying the causes and effects of ditch erosion was to make an intensive study of bed-load yields and movements within the major Tanllwyth ditches. Three small bed-load traps on tributary drainage ditches (Plate 22) in the Tanllwyth catchment were operated between February 1976 and February 1981.

The first flow variable to be investigated in relation to yields was the instantaneous maximum flow (measured at a small weir downstream of each trap) for the month or for an individual flood event. There appears to be a general trend towards a positive relationship but this is corrupted by a wide variation in the work achieved by flood flows and by the lack of any bed-load movement during even some moderate floods.

The most obvious implication is that supply of material can be limiting in this and perhaps other upland channels. Data from the main traps on the Cyff and Tanllwyth also illustrate supply-limited and transport-limited phases of channel activity (Newson, 1980a). Sediment supply is extremely difficult to measure. However, this may be partly elucidated in a new joint study with Birmingham University in which it is intended to monitor bank erosion inputs to the channel using photo-electronic bank erosion pins (Lawler, 1989).

To refine the work on bed-load transports, it was decided to use sediment tracing techniques. This permitted the investigation of sediment transport mechanisms within the ditches and streams.

Bed-load tracer studies in drainage ditches

The attempt to use magnetically-enhanced natural bed-load as a tracer arose from the observation that subsequent to the major forest fire in the Gwydyr forest, North Wales, in 1976, it was possible to assess the downstream movement of material derived from the fire by making magnetic measurements on river shoals. Initial studies were designed to identify the best practical means of raising the magnetic susceptibility of large volumes of bed-load by laboratory heat treatment. The full range of variables used and their effects on the magnetic properties of the samples are summarised by Oldfield *et al.* (1981).

The first field trials at Plynlimon were carried out in forest ditches upstream from regularly emptied bed-load traps (Plate 23). Shoals some 100m upstream from the traps were dug out and replaced with magnetically-enhanced material in the original particle size proportions (Arkell *et al.*, 1982). Qualitative field monitoring of loss from 'seeded' shoals, of gain to downstream storage, and of the location of bed-load during transit proved feasible using modified versions of appropriately-tuned sensitive metal detectors.

In subsequent studies magnetic measurements in the field and in the laboratory have been carried out using a range of sensors and a magnetic susceptibility meter (Plate 24). Two experimental lengths of forest ditch were chosen to examine the efficiency of the technique in tracing two broad particle size classifications: gravel (1.4-5.6 mm) in one and pebbles (5.6-22.4 mm) in the other. In each case, a substantial shoal was chosen and samples were removed and dry sieved for size. The specific size ranges to be monitored experimentally were then removed and replaced with magnetically enhanced material of the same size which was remixed with the original shoal material.

The shoals were reconstructed within each ditch at their original position and left to stabilise under low flows. A series of fixed

PLATE 23 An eroded forest drain, part of the drainage ditch network used for magnetic sediment tracing.

PLATE 24 The magnetic susceptibility probe used to detect tracer material.

survey points were set up at 1 m intervals along each experimental reach and a background survey of surface susceptibility was carried out using the search coil at each survey point between the shoal and the trap.

The rate over six months of recovery of tracer from one of the experiments are given in Figure 58. Hand separation of the trapped particles following each event shows that at the close of the study the ditch had yielded 63% of the original weight of tracer added. For each size range the percentages are 71% (5.6 mm), 71% (11.2 mm) and 45% (22.4 mm). Cumulative plots of trapped magnetized material exhibited remarkably similar features for both ditches. The trapping rate has been influenced by three main periods of floods, separated by low recovery rates from more moderate events (Arkell *et al.*, 1982). Whilst there is a relationship between peak flow and the trap concentration of tracer material, the relationship is not a simple one. It shows that even in the within-channel transport system alone there is some supply limitation.

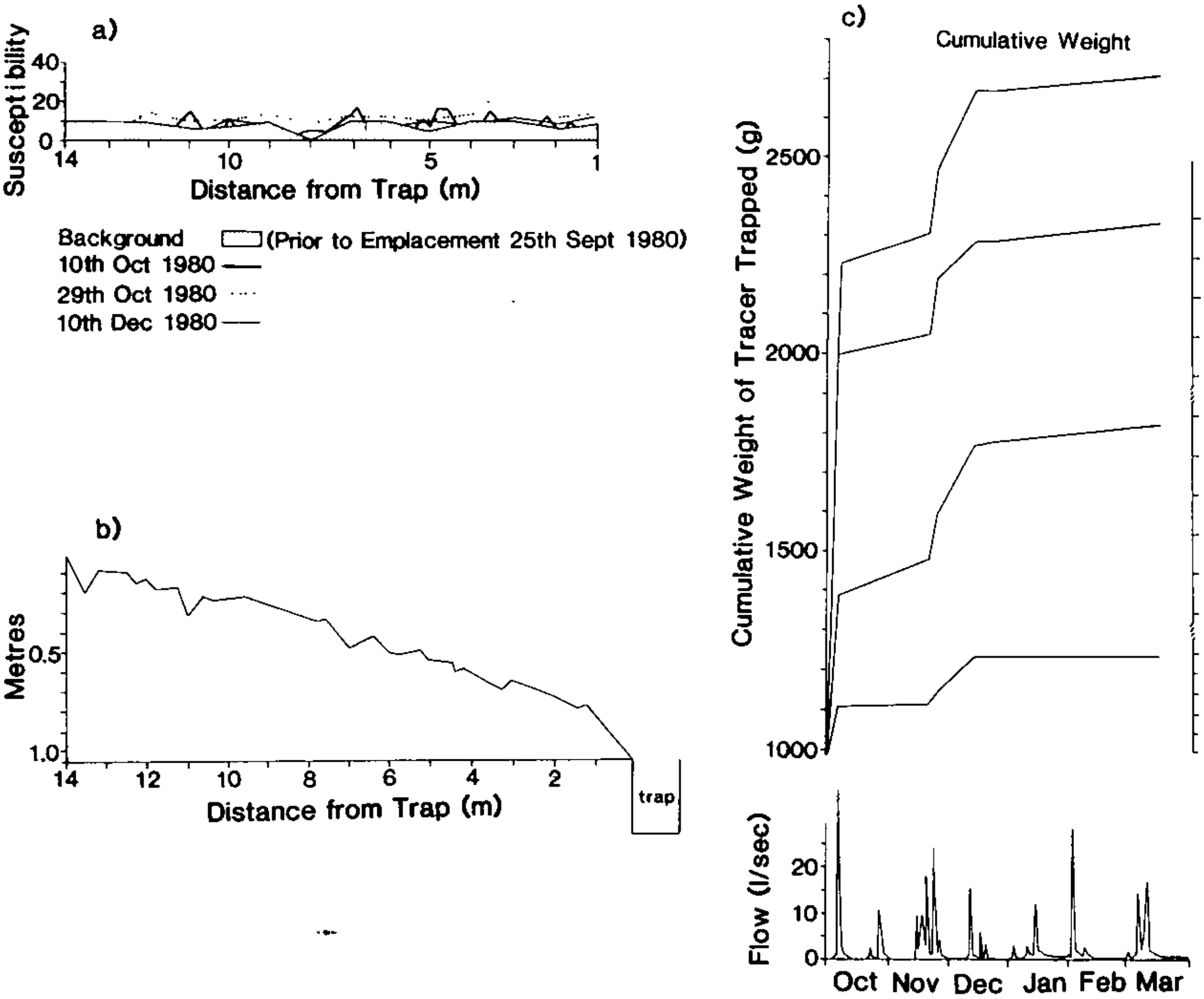


Figure 58 Tracer studies in drainage ditches:
(a) Sequential magnetic susceptibility surveys during the tracer study (down long profiles of the ditch)
(b) Longitudinal section of one Tanllwyth ditch
(c) Tracer recovery and flow record

It is concluded that even within small channel systems such as those of drainage ditches, storage of sediment ensures that output is not solely governed by stream power. This, added to the control of sediment availability by weathering, further confirms the irregularity of coarse, upland sediment systems at least at moderate flows. If the routing of sediment through rough upland channels is similar to that of flood waves themselves (see Beven *et al.*, 1979), it may be necessary to take a storage-based approach to field studies, although, as with flow routing, it is possible to find convergence towards a more regular, more linear system at high rates of output.

Modelling bed-load movement in the natural channels

Although the Plynlimon bed-load traps have been run for long periods and although source-area surveys and tracer studies have been carried out and floods given detailed attention, the operation of coarse sediment systems are understood only in outline.

In an attempt to measure those bed-load movements relating to just one flood event, the Tanllwyth main trap has been dip-surveyed (cross-bar to sediment surface) after every significant flow event over a twelve month period, in order to identify flow thresholds for sediment transport in the reach upstream. The size of sediment in motion is an important variable, as is stream velocity and a flood-watch has been kept at the Tanllwyth trap with a Helley-Smith sampler and velocity meter in use from a bridge upstream. The geometry and sediment properties of the upstream reach have also been used by Bathurst *et al.* (1982) in a flume study of coarse sediment transport.

Moore and Newson (1986) constructed a model of supply and transport by statistical analysis of seven and a half years of trap data. A matrix of data was analysed, with weight trapped as the dependent variable and independent variables representing sediment supply and transport factors. The chosen variables were investigated first through a correlation analysis and then employed as independent variables in regression against bed-load yield.

In choosing variables for regression against sediment load, it is essential to bear in mind supply as well as transport processes. The cohesiveness of bank material prior to and during the flood event can be an important factor in determining the susceptibility of bank material to erosive forces. Channel banks subjected to excessive wetting, drying or frost action can supply material to the stream bed in even modest floods (Wolman, 1959).

The following climatic variables were chosen as indices of sediment supply factors:

i. WET, the number of wet days (rainfall greater than 0.1 mm) between bed-load measurements;

ii. DRY, the number of dry days between bed-load measurements;

iii. FROST, the number of ground frosts between bed-load measurements.

These variables were computed from data obtained from the climate station at Moel Cynnedd.

The transporting capacity of the stream may be characterised in part by the magnitude of the storm event, and in part by the duration of discharges capable of significant bed-load transport. Storm magnitude was characterised by two factors: QPK, the instantaneous maximum storm discharge (m^3s^{-1}) and QPKD, the maximum daily discharge (mm of runoff) between bed-load measurements. The total discharge QTOT (mm of runoff) over the period of trapping was also included as a gross indicator of the capacity of the stream to transport material. An additional, derived variable, PEAK = QPK/QPKD was included in the analysis as an index of flood peakedness.

A number of flow thresholds was chosen on the basis of field observations (e.g. provisional Helley-Smith sampler results) to characterise the duration of effective discharges: these are a compromise between likely thresholds for bed-load movement and convenience of stage and discharge levels. Seven thresholds were chosen for the Cyff: 1.0, 1.23, 2.0, 2.39, 3.0, 3.77 and 5.22 m^3s^{-1}; and six for the Tanllwyth: 0.19, 0.5, 0.9, 1.0, 1.44 and 1.5 m^3s^{-1}. The duration of competent discharge above these are referred to as QTI, QT2, etc. Logarithmic transformation of these variables and some climatic values requires the addition of 1.0 to avoid zero values.

Multiple regressions were performed using the mass (kg) of bed-load trapped (LOAD) and also CONC, the concentration, expressed as LOAD/QTOT. In every trial regression, LOAD was predicted much better than CONC. A big difficulty in applying regression analysis of this type is that until recently (in the case of Tanllwyth at least) measurements of bed-load increments have not been made after every flood event. The current analysis has therefore provided only a baseline model with which subsequent and more sophisticated approaches can be compared.

The optimum model for the Tanllwyth was found to be

$$\text{LOAD} = (3316 \pm 1188)\text{QPK} + (1768 \pm 883)\text{QT5}$$
(Percentage explained variance = 59.9%).

The flow threshold variable, QT6, and the climate variable, DRY, included in the model of the Cyff are only marginally significant, and excluding them would result in a model explaining only 4% less of the variance in the load measurements. This preferred, simple model for the Cyff is

$$\log_{10}\text{LOAD} = (2.600 \pm 0.191) + (1.094 \pm 0.371)\log_{10}\text{QPK}$$
(Percentage explained variance = 42.3%)

The regression results (Table 24) are disappointing in terms of low explained variance (especially in the Cyff) and the order in which the highly intercorrelated 'independent' variables appear. The failure of climatic variables to help index sediment supply rates is surprising. Only a few kilometres to the north of Plynlimon, Blacknell (1981) discovered a strong relationship between precipitation, air frost and bank erosion data. However, his Afon Crewi is a much wider channel whose banks are composed of non-cohesive sandy gravels.

Thorne and Lewin (1979) also describe climatic effects on the undercut banks of the Severn, though sequences of flows are crucial in that case. The channels of the Cyff and Tanllwyth are much more stable than either of these and, significantly, hung with vegetation down to the levels reached by flows well within the bank. The lesson of the ditch tracing experiments - that channel storage may also exercise a supply-controlling role - may be relevant and the sequence of floods may also be important.

Without such explanations it is difficult to understand why the climatic variables used in the regressions do not have a more direct effect on sediment supply; in fact they may well control the release of finer material which contributes little to the bulk of trapped sediment. Particle size analyses of each set of trap increments would clearly be an advantage and these data may become available after more extensive use of Helley-Smith samplers. It may be assumed from the greater percentage explained variance that supply is not so limiting in the Tanllwyth (because of ditching activity). In an unmodi-

TABLE 24: Regression models and their error statistics

(a) Tanllwyth

Regression type	% explained variance	Explanatory variables
Load, linear	61.8	QPK, QT5
Load, linear, zero intercept	64.6	QPK, QT5, WET
Load, logarithmic	60.1	QPKD, QT5+1
Concentration, linear, zero intercept	57.2	QPK, QPKD, WET
Concentration, logarithmic	35.6	QT5+1, QPK, WET+1

(b) Cyff

Regression type	% explained variance	Explanatory variables
Load, linear	27.2	QPK, QPKD
Load, linear, zero intercept	28.8	QPK, QPKD
Load, logarithmic	46.4	QPK, QT6+1, DRY+1
Concentration, linear, zero intercept	31.5	PEAK, DRY, FROST
Concentration, logarithmic	11.5	QT2+1, PEAK, DRY+1

fied catchment such as the Cyff, in-channel control on release of material to the trap may be considerable, the mass of bed material trapped depending on the random movement of shoals down the measuring reach.

Studies of suspended sediment

In the early stages of the Plynlimon experiment little consideration was given to fluvial transport of sediment in suspension. The low concentration of suspended sediment apparent in these headwater streams, relative to lowland streams, was viewed as sufficient justification to discount the need for detailed monitoring. Under most conditions the waters are clear or slightly brown in colour because of finely divided organic matter from the peaty banks, with suspended sediment concentrations of less than 0.001 gl^{-1}. However, from 1979 a large-scale regional study, commissioned by MAFF, of the fluvial geomorphology of mid-Wales adopting a whole-catchment approach (Newson and Leeks, 1987) led to the initiation of detailed suspended sediment monitoring. From calculations of yields of both forms of particulate transport, it became apparent that although concentrations are relatively low, the suspended sediment outputs are as significant as bed-load in terms of total sediment yield. The investigation of the impact of clear felling of the Hore catchment also led to an intensification of the suspended sediment monitoring networks.

Monitoring techniques and flood sampling strategies are described by Leeks (1983). The peak of the flood hydrograph, around which the highest concentrations of suspended sediment usually occur, is of short duration; the basic manual sampling approach - depth-integrating bulk sampling using USDH-48 samplers - is very labour intensive. Flood events require a fast response by field staff and there is also a need for laboratory analysis by vacuum filtration. However, a large number of sites can be visited during the course of a flood and the filtered sediment can be used subsequently for other analyses, e.g. nutrients attached to the particulate load (Reynolds *et al.*, 1990). To overcome the need for rapid response by staff to high flows, stage-triggered automatic vacuum samplers were installed, with increasing frequency of sample collection as successive predetermined stage thresholds were exceeded. However, difficulties were experienced in synchronisation of sampling times and the flow record. In addition, because of the limited flow depth available in many headwater streams, it was apparent that in some cases bedload and saltating load were also being collected by the samplers. The disparity between bulk samples taken from the streams manually and the samples taken by automatic samplers was considered too great and automatic sampling to give concentration data was abandoned.

Turbidity monitoring has proved more successful. Portable turbidity meters have been used to give continuous data on the Hafren, Hore and Tanllwyth subcatchments. The turbidity measurement is of the absorptiometric type and is calibrated against actual suspended sediment concentrations and Fuller's earth standards. The dual-path sensor head is immersed in the flowing water. Data are output to a chart recorder or to electronic logger systems.

Suspended sediment rating curves for the major catchments are shown in Figure 59. In

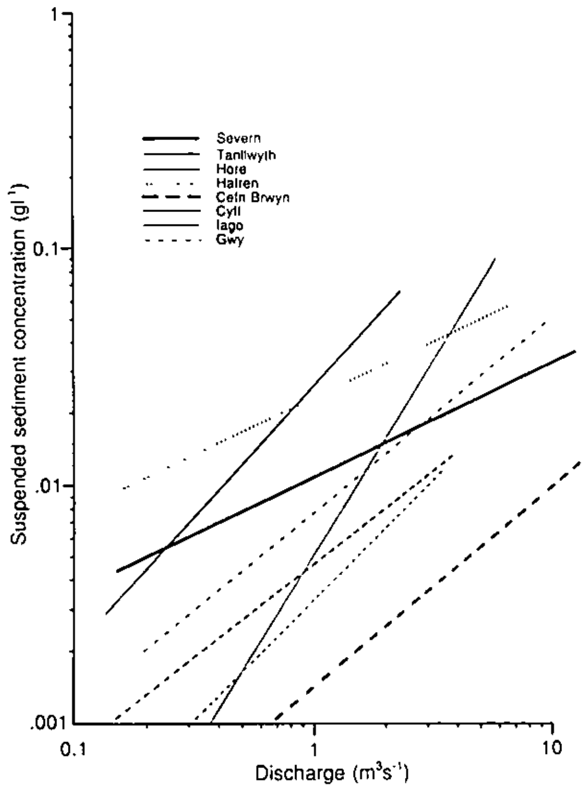


Figure 59 Suspended sediment rating curves for the Plynlimon catchments

the case of those subcatchments for which bed-load results are also available, the suspended sediment load varies between 24% (Tanllwyth) and 68% (Hore) of the total load. It is also notable, as shown in Table 25, that the ratios between forest and grassland

TABLE 25 Average annual bed-load and suspended load yields in forested and unforested catchments

Catchment	Area (km^2)	Bed-load yield ($t\ km^{-2}\ y^{-1}$)	Suspended load ($t\ km^{-2}\ y^{-1}$)	Land use
Hore	3.08	11.8	24.4	Mature forest – first year of felling operations
Hafren	3.67	NA	35.3	Mature forest
Tanllwyth	0.89	38.4	12.1	Mature forest
Cyff	3.13	6.4	6.1	Pasture

NA = not available

The figures for the Hore catchment indicate the effect of felling operations on suspended load.

yields are broadly similar to those for bedload, i.e. in comparison with the Cyff, varying between 1.98 and 5.79 times higher yields per unit area in subcatchments with mature forest cover.

In recent years, as the Hafren forest has entered the felling stage in the forest rotation, the first effects of clear-felling upon suspended loads have been monitored. Results have varied depending on felling methods and associated practices, for example road widening to permit access to the forest by large articulated lorries. A small scale study of a felled section of the Hafren forest in winter 1980-81 revealed that the use of aerial winching for extracting the timber prevented ground damage and there was no detectable increase in the mineral sediment load of streams in the area. However, there was considerable accumulation of organic debris (needles, etc.) in ditches and even larger pieces of conifer "brash" across main channels.

From 1983 the Hore catchment has been extensively instrumented to provide background sediment transport data for two years leading up to major clearfelling and to identify post-felling impacts. At the beginning of the felling operation there was an immediate rise in suspended sediment concentrations for any given discharge. This was initially associated with road-widening. Road material was carried direct to the stream network through road drains. Considerable ground disruption by machinery used during the felling work, including forwarders and skidders (in contrast to the predominantly aerial cable techniques used in 1980-81) made large amounts of fines available to the streams. Rating curves of the pre-felling and first year of the felling operations indicate an increase in sediment concentrations by an order of magnitude for moderate to high flows. This increase in turn is reflected in higher annual yields of suspended sediment from 24.4 t km^{-2} $year^{-1}$ up to 57.1 t km^{-2} $year^{-1}$.

A further change in the variations in suspended load has been the occurrence of short-lived pulses of high suspended load during low or moderate flows which are unrelated to natural entrainment processes. These are associated with the movement of heavy machinery through the channel or ditch system, drain or culvert clearance and road modifications, sometimes involving the use of explosives (Leeks, 1990). In each case, a degree of within-channel deposition has been observed with fines covering the normal gravel and cobbles of the stream bed. This may have a deleterious effect upon channel habitat.

Tracing of suspended load sources and the Chernobyl fall-out

Joint work with Liverpool University and the UK Atomic Energy Authority (Harwell) has led to the development of field techniques and laboratory analysis which have clarified the likely sources of suspended sediment in Plynlimon streams. Arkell (1985) analysed filtered bulk samples of suspended sediment from a downstream location on the Severn at Abermule. These were compared with measurements of magnetic parameters from *in situ* sediments within the Plynlimon experimental catchments and alluvial reaches of the Severn to indicate sources including forested areas, stream channel and banks.

The use of magnetic analysis techniques in the experimental catchments has been extended in combination with radiometric techniques following the nuclear accident at Chernobyl in April 1986 (Bonnett *et al.*, 1989). The strong fixation of caesium-137 to clay minerals provided an opportunity to study sediment transport through the upland system. Chernobyl-derived debris was deposited on Plynlimon in early May 1986. An extensive network of soil coring sites was established. The cores were up to 0.3 m deep. The deposition of Chernobyl-derived caesium could be distinguished from nuclear weapons fall-out because of the characteristic association of ^{134}Cs with ^{137}Cs. Sites were chosen approximately 50 metres from monthly storage raingauges in the network so that data were representative of all the domains covering more than 2% of the total area of each catchment, as defined for the water balance study (Clark *et al.*, 1973). The expected distribution of deposition was partly derived from a sample of rainwater from May 1986 taken at the Plynlimon office which gave 720 Bq m^{-2} of ^{137}Cs and 420 Bq m^{-2} of ^{134}Cs for local deposition in a known quantity of rainfall. Assuming that ^{137}Cs and ^{134}Cs deposition were proportional to rainfall, the patterns of rainfall and radiocaesium deposition would have been the same. This distribution was then combined with rainfall data from the Plynlimon networks to produce a map of the distribution of Chernobyl deposition.

Comparison between the expected distribution of deposition and the measured Chernobyl fallout activity in the soil cores indicated zones of soil erosion and deposition in the two years following May 1986. Decline in the expected ^{137}Cs inventory by more than 20% was interpreted as evidence of erosion of fine topsoil. Erosion was apparent in the upper Hore and particularly in the lower half of the Hore, Tanllwyth and Cyff catchments. Soil cores from lower parts of the Iago and Gwy down to the Cyff confluence had more than expected activity, indicating deposition. Hence there is evidence of post-Chernobyl redistribution of topsoil although some of the losses may be due to vertical and lateral migration of radiocaesium from surface peats in the highest parts of the catchments.

There is also evidence of the removal of caesium from the catchments attached to the fluvial sediments in both the suspended-load and bed-load. Both bed-load traps and specially-designed suspended-load settling tanks have a high Chernobyl content

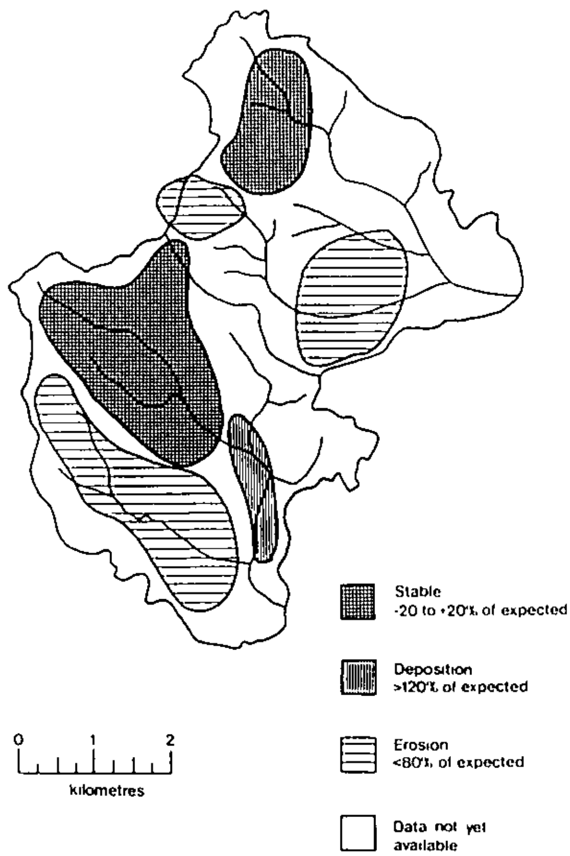


Figure 60 Chernobyl soil activity zones (after Bonnett *et al.*, 1989)

(Bonnett and Leeks, 1989). Total radiocaesium activity of 60% in suspended load and 32% in bed-load is an indication of the relative importance of top-soil as a source for the different types of transport. The high Chernobyl component in suspended sediment points to a topsoil source while the lower activity levels in bed-load suggest a sub-soil source of sediment supply, e.g. the drains. This is backed up by regular analyses which point to channel and subsurface sources for bed-load and surface sources for suspended load.

The above study also provides evidence of supply limitations in the fluvial entrainment of Chernobyl-tagged sediments. Bed-load trapped in the Severn catchment between November 1987 and January 1988 did not contain Chernobyl material, indicating temporary exhaustion of this source of bed-load sediments. Changes in the caesium budgets have also taken place as a result of clear-felling practices. Preliminary evidence indicates that there has been an enrichment in Chernobyl-derived caesium in the lower Hore catchment in comparison with other parts of the catchments. Bonnet *et al.* (1989) point out that little attention has been paid elsewhere to the attachment of radio-caesium to the bed-load. Forest harvesting and mechanical site preparation may result in an increased supply of ^{137}Cs and ^{134}Cs to the bed-load part of the sediment outputs from the upper Severn.

Walling and Bradley (1988) have reported preliminary results on the fluvial transport of Chernobyl fallout in suspension through lower reaches of the Severn.

The effects of the ditching/ploughing processes on both suspended and bed-load sediment yields have been studied in Coalburn in the northern Pennines (Robinson, 1980; Robinson and Blyth, 1982). A larger scale study of these effects has now been carried out in the Cwm catchment on the Llanbrynmair Moor, some 20 km north of Plynlimon (Leeks and Roberts, 1987) and studies of the effects of both clear-felling and ditching/ploughing began on the Balquhidder catchments in Scotland in 1986 (Stott *et al.*, 1987; Johnson, 1988). Other papers on enhanced sediment yields associated with afforestation include Austin and Brown (1982), Burt *et al.* (1984), Francis (1987), Stretton (1984) and Soutar (1989). Some of the recommendations to reduce enhanced sediment yields from forested catchments, derived from the Institute of Hydrology's studies at Plynlimon and Llanbrynmair and compiled from other British research, are listed in Leeks and Roberts (1987). They include the need to keep heavy machinery out of the stream channel, isolation of the road and forest drains from the stream system and modification of old drain systems, similar to those in the Hafren Forest, which continue to erode. New official guidelines have been produced by the Forestry Commission (1988) which incorporate some of the lessons from the case studies, in addition to the views of the water industry, FC researchers and forest managers.

The importance of floods in upland sediment systems

The output of sediment is a complex balance between the limits of supply and transportation. Man's activities in exposing new supplies of sediment are occasionally dwarfed by the effects of big floods. Only those natural slope developments which occur in floods can compete with the impact of man-made features, such as drainage ditches, in making sediment available. For this reason the two major floods in the Plynlimon record have been given special geomorphological attention.

The August 1973 flood was mainly characterised by slope failures: bursts, slides and gullies (Newson, 1975b). Gullying was restricted to sites where unconsolidated material had already been eroded into intermittent channels on upper slopes. Slides were much more common and it is clear from field notes and photographs that each slide was prompted by either diffuse or channelized subsurface flows. The slide planes were contact horizons either between weathered and fresh boulder clay or between mixed slope deposits (colluvium) and bedrock. Slope angles of 20° to 30° were involved, mainly on the channel side of drift terraces and solifluction lobes. The term 'burst' was used to describe the spectacular failure of flushes in the area. These first-order channels, buried beneath a peaty infill, are a common feature of the Wye catchment. A major occurrence of this type at Cerrig yr Wyn (Plate 25) consisted of the failure of nearly 300m of a 12° slope, large peat rafts being spread in a

PLATE 25 Catastrophic burst of flush feature, Cerrig yr Wyn, Wye catchment, 6 August 1973.

100 m-wide fan along the channel banks of the upper Wye. The term burst was applied to stress the probable role of full-bore flow or surcharged flow in the perennial pipe flowing beneath the flush.

The conclusion is that the high antecedent precipitation before this storm, together with the occurrence of the six-hour storm 'core' at the end of an eight-hour period of steady rain, both resulted in subsurface flow systems being activated prior to the critical storm. High pore water pressures and, in some cases, supercharged pipe flows, linked to a rapid surface saturation during the storm core, produced major slope failures. In hydrological terms, the dynamic contributing area had extended well upslope into zones which were possibly approaching a stability threshold; such thresholds have presumably been crossed many times on these glacial and periglacial deposits as the catchment has adjusted to a fluvial regime over the last 12,000 years. A close watch is therefore kept on both the sites which failed and similar ones which did not, in an attempt to detect the approach to the next threshold of stability. Re-surveys of many sites in 1983, ten years later, indicated that recolonisation by wetland plants is one major way in which upland slopes recover.

Channel changes during the August 1973 event were not spectacular. Slope failure deposits reaching channels were not moved far downstream; their removal occurred over a period of months during the following winter. Nevertheless, despite the restricted effectiveness of the flood in terms of channel morphology, both bed-load traps were filled. Lack of morphological channel change after major flooding and extensive sediment movement has been reported elsewhere (Wolman and Eiler, 1958; Ritter, 1974).

The second major flood in August 1977 was distinguished by its channel effects; slope effects were negligible with just two small rotational slides occurring in the upper Severn catchment. The 1977 storm was centred over the Tanllwyth and Hafren sub-catchments and both these channels were spectacularly affected in terms of their geometry through erosion and deposition. These channels are dominated by bedrock or coarse glacial deposits on their beds and therefore most adjustments were of width.

The most spectacular effect, compared with any observed in 1973, was the redistribution of gravel/cobble shoals. The main feature revealed by photographic survey is the importance of the larger cobbles and boulders in controlling the stability of gravel banks both by forming an armouring layer and a dam. Channel changes since the flood have consisted mainly of short rolling movements by the armouring material which exposed considerable amounts of gravel to entrainment and helped to establish a new (or re-establish an original) channel Thalweg. At channel bends the rather irregular point bars created by the flood have not been redistributed; instead opposite banks have suffered undercutting and sinuosity has increased as a result of the flood.

6.2 Water chemistry

The flux of soluble material from catchments is a much less obvious process visually than that of sediment transport, yet chemical denudation of the landscape in temperate lands is often considered to equal or exceed mechanical erosion. In contrast to arid or semi-arid areas, the main flux of chemicals - and hence the main control on streamflow chemistry - is the input in the form of precipitation. For most determinands, and in the absence of major land disturbance, the contribution to streamflow from chemical weathering is small compared to the input flux. In terms of chemical cycling, acid buffering and release of some metals, notably aluminium and base cations, it can be a major source.

The low solute load characteristic of most upland streams is one of the major factors, along with the huge volume of water available, which make upland sources of water so important to the United Kingdom as a whole. The major challenge facing water engineers is to maintain or even improve this situation and this can only be done if the process of natural and artificial enrichment of surface water supplies are well understood. Methodology is all important here. First, it is necessary to establish, accurately and precisely, the volume fluxes of solvent, a prerequisite which brings sharply into focus the advantages of studying chemical cycling on established catchments where the water balance fluxes and storages are already well known. Second, the chemical analysis of low conductivity waters has, until recently, been difficult and upland water resource research and exploitation has spawned a compendium of new analytical techniques. Third, traditional sampling routines, developed on major rivers where flow and concentrations change slowly, are inappropriate to flashy, chemically unpredictable upland streams.

Reynolds *et al.* (1990) describe the main considerations of sampling practice in terms of frequency, sample hygiene, filtration and storage, and compare the relative merits of the various methods of sampling and calculation of the solute load. These include: spot sampling, time proportional and flow proportional composite sampling, continuous monitoring with spot calibration samples, and the setting up of concentration-discharge relationships from which loads can be calculated using flow duration curves. However, the concentrations of many determinands are not related directly to flow; they may be climatically - and therefore seasonally - dependent, influenced by biological activity or antecedent wetness of the soils. In such cases continuous sampling and flow measurement is crucial, and needs to be continued for a number of years to take into account the considerable inter-annual variability of hydrological conditions in upland catchments.

Investigation of natural chemical cycling therefore requires proper budgeting of inputs, outputs and changes in storage; 'balancing' is an incorrect word to use here, as it implies that, in the medium term, as is the case with water, the inputs and outputs are equal. The potential storage of water in a catchment is small relative to precipitation and streamflow over an annual cycle, yet the opposite is the case for chemicals, some of which are held in vast reserves in the soil and underlying material and which leak slowly over geological rather than hydrological time.

Outputs from this storage can be hastened by anthropogenic influences, particularly those involving soil disturbance such as draining or ploughing. Changes in land use, for instance from rough to improved pasture, afforestation or clear-felling, can upset the equilibrium of soil chemistry, initially as a result of soil disturbance and later by changes in internal chemical cycling within the new crop. A prime example is the increasing acidic inputs from dry and aerosol deposition of anthropogenic origin, particularly SO_2 and NO_x on to aerodynamically rough forest canopies. These in turn release metals from soil previously in equilibrium with grassland rates of cycling. New crops, such as plantation forest, also act as an extra output of chemicals, particularly nutrients, which are locked up in standing biomass and eventually exported from the catchment. Such a reduction of the nutrient pool, mirrored by the export of livestock from grassland catchments, is compensated by the introduction of artificial fertilisers, N, P, K and trace minerals, all of which can upset delicate chemical equilibria in the soil and lead to increased runoff of unwanted solutes.

It is clear that the processes of anthropogenic pollution cannot be understood unless the 'natural' patterns of input, cycling and output are known. The following section deals with natural cycling as a prelude to specific studies of nutrients in a later section. As it is impossible to split anthropogenic atmospheric sources from 'natural' without some form of manipulation, e.g. acid exclusion experiments, then acidification processes have to be considered as part of the natural cycle.

Atmospheric inputs

The atmospheric inputs to the Plynlimon catchments were first monitored as part of the study of concentrations of trace elements in the atmosphere over Britain, based on a network of seven widely scattered stations maintained by the United Kingdom Atomic Energy Authority (Harwell) to provide:

(i) information on element concentrations in rural areas to compare with urban measurements made by Warren Spring Laboratory, and

(ii) long-term information on atmospheric concentrations and the deposition of trace elements to the ground.

Air particulates, rainwater and dry deposition were sampled continuously, with monthly maintenance of samplers. The samples were bulked for quarterly analysis, although there was an option to analyse separate monthly samples for specific elements, if required. All samples were collected 1.5 m above ground to avoid splash and to ensure reasonable ventilation (Cawse and Peirson, 1972), and were analysed for some 36 elements.

Results of the analysis of samples for 1972-1976 are shown in Figure 61 (derived from Cawse, 1976). They indicate first the large input of elements of an oceanic origin, a feature of rainfall and dry deposition in western Britain. Second, they show the consistent seasonal variation in most determinands which indicates that air masses of different origin through the year contribute varying amounts of pollutants.

Average concentrations in air at the rural "background" sites of Colla Firth (Shetland) and Plynlimon were compared with measurements made in Stoke-on-Trent and Leeds by Warren Spring Laboratory, showing concentrations of Cr, Mn, Sb and Pb between 10 and 20 times higher in the urban areas.

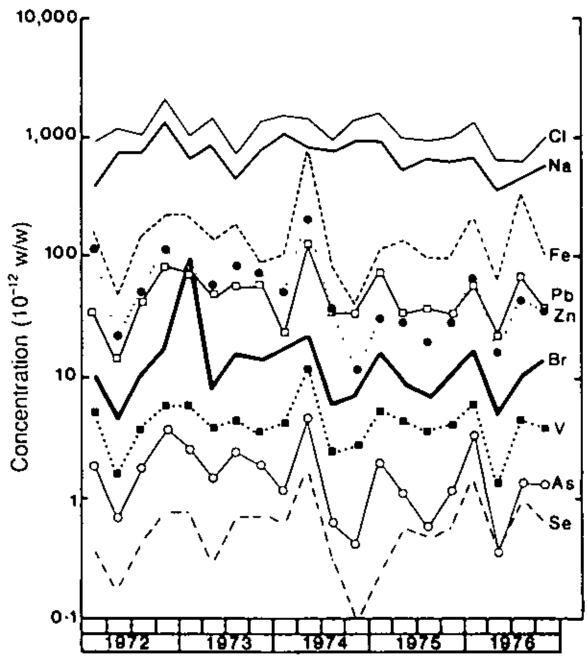


Figure 61 Variations in air quality sampled by UKAEA, Harwell, for the period 1972-76.

Studies of rainfall and streamflow acidity

There have been many reports of acid rainfall resulting from industrial air pollution (largely by SO_2) in northern Europe in

TABLE 26 Chemical analyses

Element	Storage	Pretreatment	Analysis
Na K Ca Mg B Li SO_4 Sc Sr Y Ba Mn Cu Fe V Cd Zr Co Zn La Cr Ni Mo Al Pb	Polyethylene bottle	0.45µm cellulose membrane filtration; acidification with "Aristar" HCl to 1% v/v; pre-concentrated (x 20) by evaporation	Inductively-coupled plasma emission spectrograph
NO_3 NH_4 PO_4 (F) Cl Br I Si	Glass bottle	1µm glass fibre filtration	Colourimetry
DOC	Glass bottle	1µm glass fibre filtration	Phase separation/ flame ionisation (Tocsin II)
Alkalinity, pH & HCO_3	Glass bottle	1µm glass fibre filtration	Titration
Conductivity	Stream water measured directly in the field; rain water stored in glass bottle.		Conductivity meter

recent years. Martin (1979) analysed rainfall acidity at 100 sites in the UK and showed the mean pH to be 4.3. Four low values of acidity were recorded for south Wales (pH 4.9), but a valley in mid-Wales without adequate smoke dispersion showed a value of pH 4.1. The Harwell results for 1976 give an average pH of 4.6. More recently, a nationwide survey of wet acidic inputs by Warren Spring Laboratory, which included a site on Plynlimon, also indicated an average pH of 4.6 and SO_4-sulphur and NO_3-nitrogen deposition of 9 $kgha^{-1}$ and 3.5 $kgha^{-1}$ respectively.

To develop an understanding of the importance of land use change and hydrological factors in controlling stream water quality in upland areas, a project was initiated in 1983 to study water quality changes in forest streams before, during and after deforestation. Two subcatchments of the Severn (Hafren and Hore) were selected for study, because the Hore was to be cleared of trees in 1985, and complementary soil, plot and catchment chemical studies were being undertaken within the Plynlimon area by the Institute of Terrestrial Ecology.

Weekly sampling of rain and streamwater began in May and stream water samples were also collected during periods of high flow - two samples of water were taken and filtered immediately, one through a 0.45 µm cellulose membrane, the other through a 1 µm glass fibre filter, the samples being stored in polythene bottles and acidified to 1% v/v with Aristar® hydrochloric acid. Two rainfall samples were collected, one at the Gwy, the other at Carreg Wen. These samples were bulked together to give an average chemistry for the altitude range of the catchments. The bulked sample was then split, filtered and put into polythene and glass bottles in the same way as for the stream waters.The stream water and rainfall samples were analysed for the 38 determinands listed in Table 26 which also shows the analytical methods used for their determination. Conductivity, alkalinity, pH and bicarbonate were analysed within two hours of sample collection in order to avoid changes which might occur during storage. Such a wide range of elements were chosen to see

(1) whether "chemical fingerprinting" techniques could be used to identify hydrological pathways,
(2) to identify which chemical components change during deforestation, and
(3) to categorise the major hydrochemical processes operating.

The rainfall chemistry indicated wide variability in the concentrations of virtually all the determinands, with a range of values up to an order of magnitude (Table 27). Of the 25

TABLE 27 Rainfall and stream water chemistry of the Afon Hafren and the Afon Hore

Element	Rainfall mean	Rainfall range	Hafren mean	Stream Water range	Hore mean	Stream Water range
Major components (concentrations in mg l^{-1})						
Na	3 62	2-15	4 09	3-5	4.18	3-5
K	0 17	0 05-0 50	0.16	0 07-0.27	0.14	0 07-0.27
Ca	0.25	0.1-0 6	0 91	1 0-1 6	1 81	1-4
Mg	0 46	0 2-1 6	0 80	0 7-1 0	0 91	0 8-1 3
SO_4	2.05	1-5	4 22	3-6	4.79	3-6
Si	0 28	0 02-0 05	2.01	1-3	1 90	1.5-5 0
DOC	0 34	0 2-0 8	1 05	0 5-2.5	1 01	0.5-2.5
HCO_3	-	-	2.75	1-6	5 33	2-17
NO_3	0 68	0 2-3.0	1 31	0 3-3 0	1.18	0.5-2 5
Cl	6 96	2-25	7 42	7-12	6 31	7-11
Minor and trace element components (concentrations in µg l^{-1})						
B	3 13	2-9	3 21	2-7	4 21	3-15
Li	0 00	0 00	2.51	1 6-2.8	2 03	1 3-2 3
Sr	1 32	0 1-9 0	5 49	4-7	5.70	4-8
Y	0 00	0 00	0 25	0.1-0 6	0.19	0 1-04
Ba	1.32	0 8-4 0	1 99	1-6	2 99	2-8
Mn	2.28	0.2-9 0	35 5	10-70	26 0	10-45
Cu	6 26	1-40	1 45	1-6	2 86	1-40
Fe	7 36	0-30	71 6	50-150	63 7	10-120
Co	0 00	0 00	1.73	1-4	1.64	1-3
Zn	18 31	10-120	13 6	5-30	20 6	5-30
Al	12 90	0-100	218 8	25-600	140 3	25-600
Br	24.7	10-80	20 9	15-45	20 8	10-32
I	2.71	2-10	0 98	0 5-1.5	0 80	0 5-1 5
Acidity (concentration in µM l^{-1})						
H^+	24 1	10-150	14 8	1-60	10 3	1-50

Elements analysed but less than the detection limits of the analytical methods used were Sc (0 05), La (0 5); V Cd, Zr, Cr (1 0), Ni, Mo (5 0), Pb (10 0)

NH_4 and PO_4 values not included due to uncertainties in the stream water mean concentrations (many values being less than the detection limit) and the large range in rainfall values.

TABLE 28 Mean concentrations of major, minor and trace elements in baseflow and stormflow for the Afon Hafren and the Afon Hore

Element	Baseflow flow < 0 01 mm 15 min^{-1} Hafren	Baseflow Hore	Stormflow flow > 0 10 mm 15 min^{-1} Hafren	Stormflow Hore
Major components (concentrations in mg l^{-1})				
Na	3.97	4 15	4 48	4 56
K	0 16	0 17	0 22	0 15
Ca	1 05	3 01	0.71	0 84
Mg	0 82	1 13	0 78	0 75
SO_4	3 67	4 80	4 61	4 83
Si	2.06	2.11	1 76	1 43
DOC	1.05	0 95	1.60	1 32
HCO_3	5 23	10 3	1 23	1 47
NO_3	0 78	0 86	2.13	1 66
Cl	6 48	7 58	9 01	0 52
Minor and trace element components (concentrations in µg l^{-1})				
B	2.88	4 62	3.99	4 07
Li	1.96	1.89	2 10	2.01
Sr	5 34	7 11	5.30	4 83
Y	0 15	0 11	0.36	0 31
Ba	0 36	1 09	3 66	5 91
Mn	18.7	24 0	42.1	27 4
Cu	1 18	1.42	2.49	5.75
Fe	54 2	79 8	96 7	63.5
Co	0 69	0 97	2.49	2.32
Zn	7.05	11 0	18 4	29 8
Al	56 6	85 8	506	427.
Br	27 6	23 2	19 6	20.8
I	1.19	0 92	1 01	0 75
Acidity (concentration in µM l^{-1})				
H^+	1 9	1.8	35.0	26.2
pH	5 80	6 06	4 47	4 62

NH_4 and PO_4 values not included due to uncertainties in these estimates (many values being less than the detection limit) and the large range in rainfall values.

Stormflow and base flow were defined as flows >0.1 and <0 01 mm 15min^{-1} respectively, samples taken at intermediate flows were not used in the calculations.

samples analysed, 21 show high correlations between the major ions Na, K, Ca, Mg, SO_4, Sr, Br, Cl and the ratios of their concentrations to the concentration of Cl are similar to sea water. The low concentrations of major, minor and trace elements and the moderate acidity in these samples probably reflect 'natural' rainfall concentrations. The remaining samples are anomalously acidic (pH <4) and are enriched in SO_4, NO_3, Cu, Zn, Ba, Mn, Fe and Al indicating that industrial pollution is significant for part of the year. In general, the rainfall samples enriched in Na, Mg and Cl are associated with westerly winds and represent an oceanic chemical signal: the more polluted waters represent rainfall derived from a more complex meteorological condition.

The stream chemistries of the Hafren and Hore are internally variable, with large differences between the two catchments for some determinands, notably HCO_3 and Ca. The range of values differs for the various determinands (Table 27, Figure 62 and 63). The main "sea salt" components show only a two-fold variation while many of the minor and trace elements show variations of up to an order of magnitude. Hydrogen ions and several of the major and trace elements are strongly related to flow; they fall into two groups (Table 28), one having moderate acidity and relatively high concentrations of Ca, Sr, Mg, and HCO_3 at low flows, the other having relatively high acidity and relatively high concentrations of Li, SO_4, Y, Ba, Mn, Cu, Fe, Co, Al, DOC, NO_3 and B at high flows.

Despite this broad relationship, for several elements the link between flow and concentration is complex and linear correlations do not describe the relationships well (as

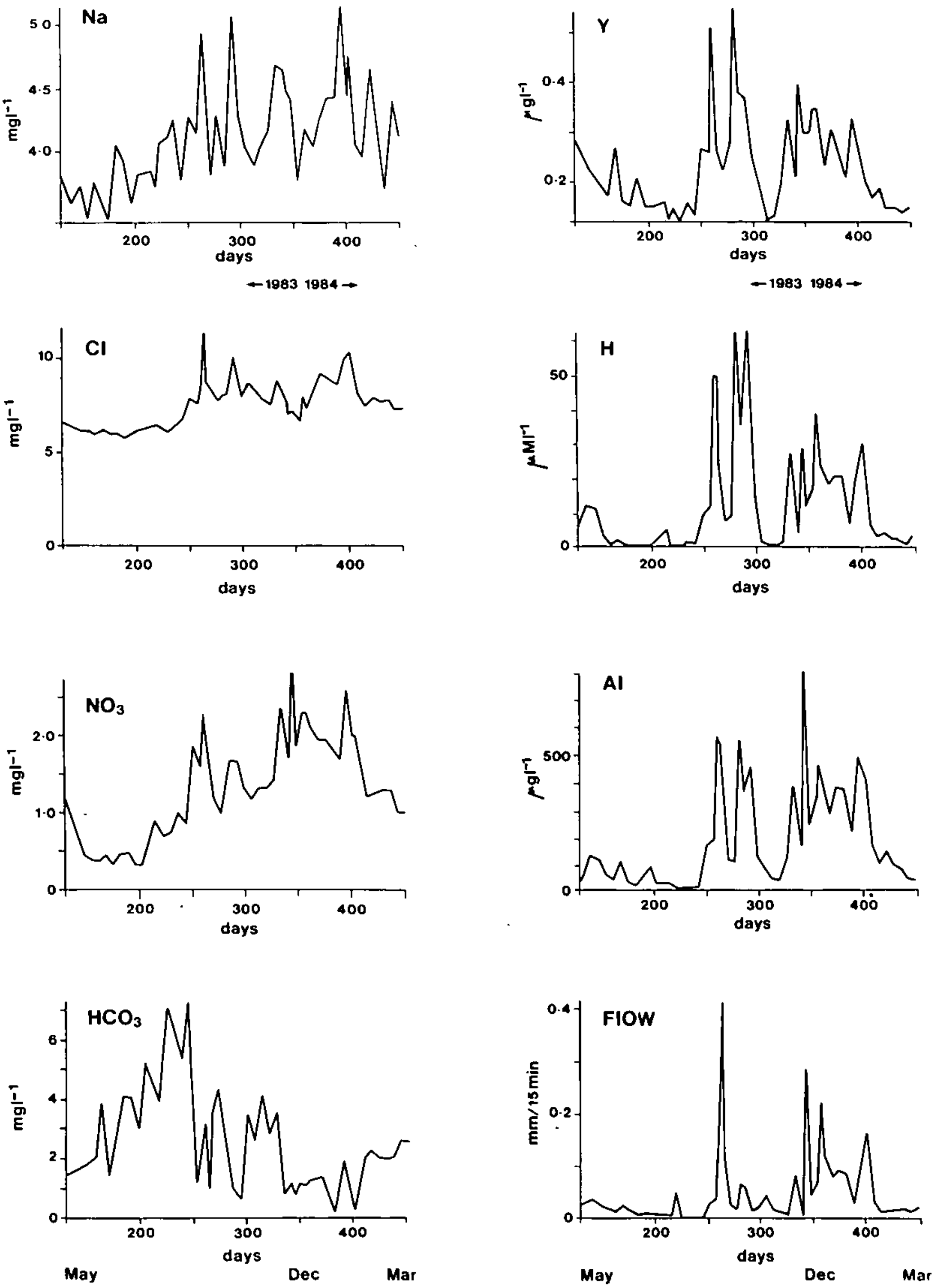


Figure 62 Variations of Na, Cl, NO_3, HCO_3, Y, H^+, Al concentrations and flow with time for the Afon Hafren during the period May 1983 - March 1984

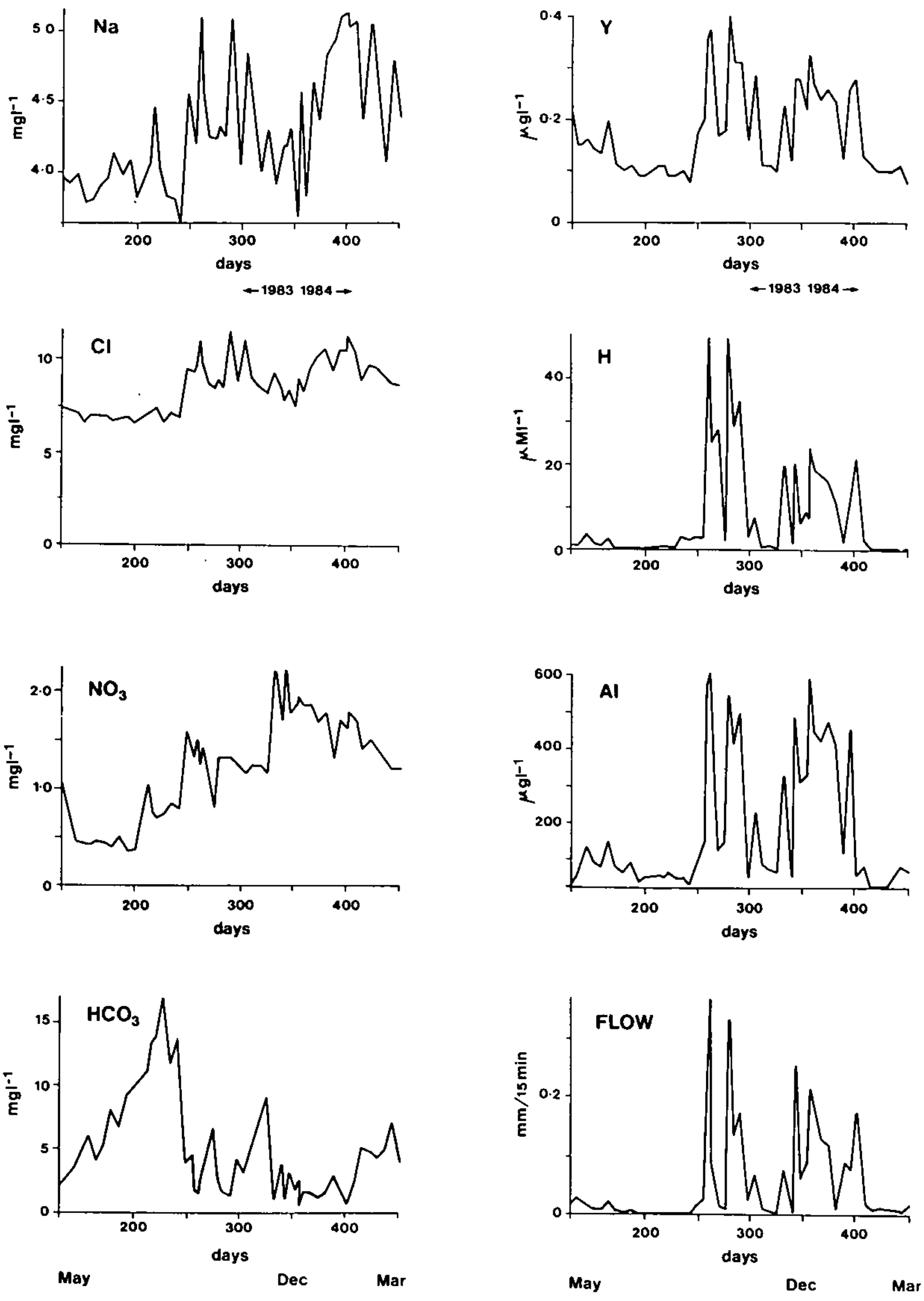


Figure 63 Variations of Na, Cl, NO_3, HCO_3, Y, H^+, Al concentrations and flow with time for the Afon Hore during the period May 1983 - March 1984

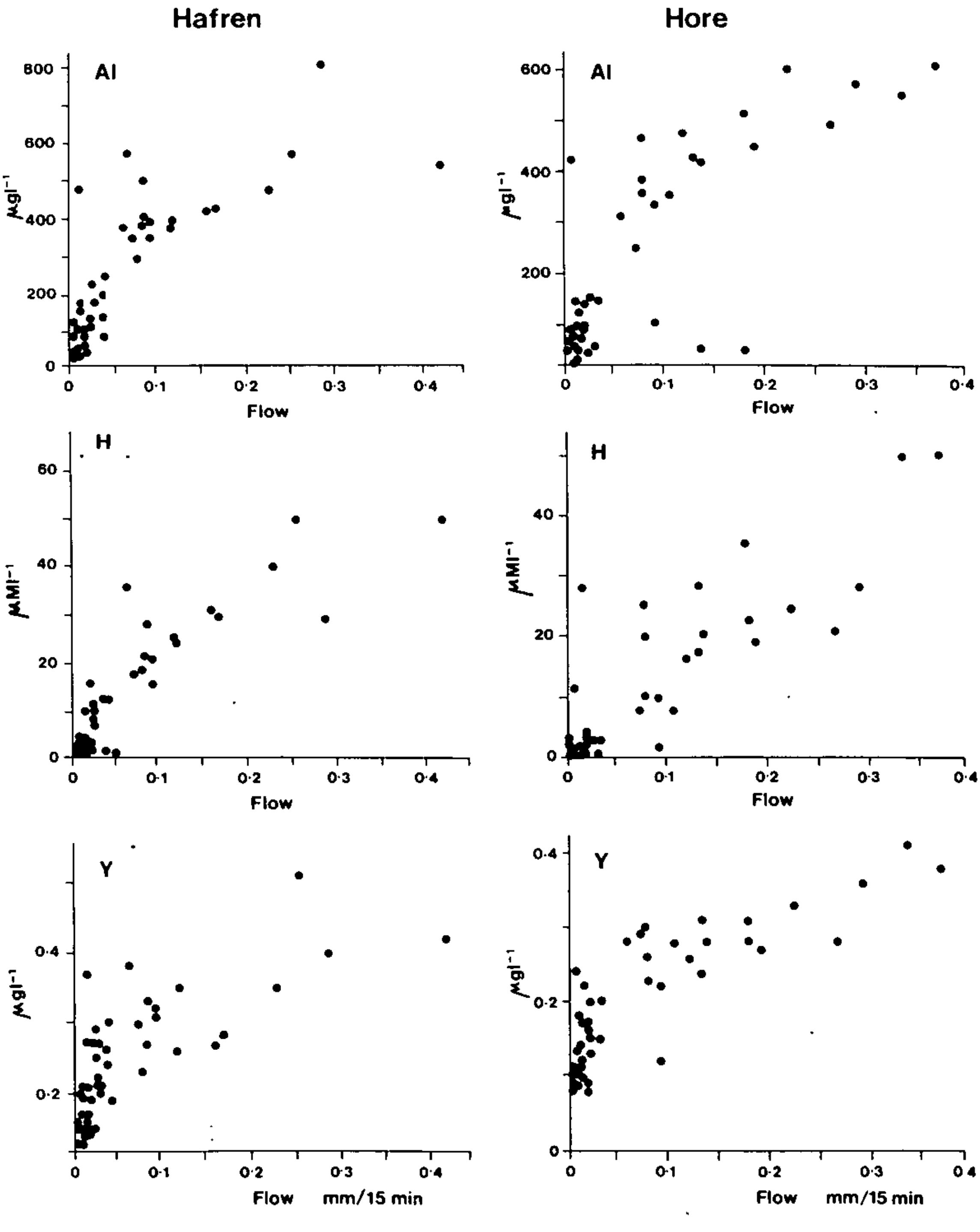


Figure 64 Plots of Al, H^+ and Y concentrations against flow for the Afon Hafren and the Afon Hore

shown in Figure 64). For example, Li, Mn and Co all show higher concentrations during the autumn storm period while total iodine shows increased concentrations during long periods of recession. Variations in Si concentration show a strong relationship with the occurrence or absence of storms, although the magnitude of the change is not directly related to flow rate. A seasonal variation is observed for Na, Cl, K and NO_3, concentrations increasing from May 1983 to February 1984 although an increase in concentration is observed during the first storm flush period of the autumn for Na, Cl and NO_3.

Al and Y concentrations are presented in Figure 64 to show the importance of soil waters from the lower soil horizons in generating the storm hydrograph. Al and Y are mobilised from the breakdown of amorphous oxides under acidic conditions. The H^+ concentrations are presented to show the importance of the acidic soil waters in general to the generation of the storm hydrograph.

It is clear that the large variation in the concentrations of the "sea salts" in the rainfall are not reflected in the subsequent patterns of stream water chemistries. For example, the range of concentrations of chloride in rainfall is 2 to 25 mgl^{-1}: in both of the streams sampled the range is only 7-12 $mg\ l^{-1}$. In spite of this difference in range there is an apparent net flux of Cl from the catchment, as rainfall inputs are about 30% less than streamflow. The concentrations of many trace elements (Fe, Cu, Zn, etc.) in rainfall are occasionally very high and associated with high acidity as well as enhanced levels of SO_4 and NO_3. Similarly, the variation in the concentrations of the trace elements in the rainfall is greater than in the streamflow.

Apart from these anomalous rain events, which are probably associated with air masses originating in industrial areas in mid- and east England, the variations and mean concentrations of the trace elements in rainfall are smaller than those in the stream waters. The concentrations of the chemical species in the stream water vary either seasonally or are related to hydrological change: they are not due to variation in the rainfall chemistry. This relationship between chemistry and hydrological change takes three forms:

(1) Direct flow response where the concentration increases and decreases as flow increases and decreases;
(2) Damped flow response where the concentration increases (or decreases) in the autumn-winter period when high flows prevail and decreases (or increases) when flows return to low levels in the spring and summer; this is related to soil and aquifer water levels and may be a baseflow response.
(3) Compound flow response where the variations in concentration are related to hydrological changes (though their relationships with flow are complex).

The processes determining stream chemistry can be described in terms of the flushing and mixing of water from the near surface organic and underlying inorganic horizons. Dry deposition washed from the trees, together with the products of organic matter decomposition, result in acidic conditions (pH ~ 4) in the near surface horizons. This produces mobilisation of the easily hydrolysable transition metals, e.g. the trivalent metal ions such as Al and Y from oxide solubilisation, a process enhanced by organic complexation and sometimes by reducing conditions in the podsol and gley horizons. Reactions in the inorganic horizons involve the hydrolysis of silicate minerals, clay transformations of chlorite to vermiculite and dissolution of carbonates resulting in the release of Ca, Mg and Si to solution together with the consumption of hydrogen ions.

In the inorganic layers of the soil this H^+ consumption results initially in the mobilisation of the easily hydrolysable metals, e.g. the trivalent metal ions such as Al and Y from oxide solubilisation. However, as H^+ consumption proceeds the pH can rise sufficiently for these components to precipitate out. Losses of these metals from the catchment are therefore limited under low flow conditions.

Superimposed on these reactions are biological processes producing release/

consumption of NO_3, HCO_3 and K. The stream water composition thus reflects a combination of mixing processes, mineral and organic reactions and flushing out of the different water types from the various horizons. Under summer low flow conditions the soil moisture deficit is high and water is supplied from the inorganic horizons. During the autumn storm period the soil moisture deficit decreases and the stream water is supplied from both matrix and macropore flow, mainly from the upper organic horizons.

Several observations imply that not all of the processes can be described simply by the main controls cited above. For example:

(1) Rapid, damped and compound flow responses are observed for different chemical elements. This must indicate that the chemical reaction rates are different for the different mineral phases in the different soil horizons, that several hydrogeochemical processes (mineral dissolution, adsorption and Redox reactions) are operating and that there are complex hydrological flow routes.

(2) Cl concentrations in the stream waters are highest during the autumn and winter storm periods when soil moisture deficits are at a minimum. This indicates that evapotranspiration has produced high concentrations of Cl in the near-surface horizons during spring and summer.

(3) Despite the geological similarity between the two catchments, the low flow Ca, SO_4 and HCO_3 concentrations are higher in the Hore than in the Hafren. This shows that small differences in the amounts of mineralisation can strongly affect the baseflow chemistry. Differences in base flow compositions also reflect the differences in water source areas, in that at very low flows the main supply of water in the Upper Hafren seems to be derived from the peat areas and from the shallow aquifers.

(4) Sr and Mg are highly correlated in both the Hafren and the Hore. However, the variation in the concentrations of these elements with changes in flow is different for the two streams. This shows that even when the geological and vegetation types are similar, different hydrochemical controls can operate.

(5) The large variation in the concentration of major maritime elements in rainfall is not reflected in the stream water. This shows that either rapid mixing of the rain inputs with the stored water occurs or that there is a large volume of water stored in the catchment.

(6) During winter storm recessions, concentrations of Al, H^+, Y and HCO_3 return to baseflow levels even though the soil moisture deficit is low and the saturated zone extends to the organic horizons. This illustrates the rapid cessation of soil moisture drainage and the importance of macropore flow, since micropore flow would continue to give stream water chemistry characteristic of the upper organic zone.

(7) Increases in Cl concentrations in the stream water are not fully matched by increases in Na concentrations. Since both Cl and Na are from a "maritime" source and Cl is a "conservative" element, Na is being lost to the catchment. This is an example of cation exchange processes in the catchment.

Dissolved load budgets show that the elements being lost from the two catchments are Ca, Mg, SO_4, NO_3, DOC, HCO_3, Li, Sr, Y, Ba, Mn, Fe, Co, Al, Zn and Si, while those being gained are Na, K, Cu, Br and I (Table 29). Hydrogen ion shows an approximate balance between input and output. However, these determinations do not include throughfall and stemflow measurements which are known to have pH values one unit lower than those sampled by a standard rainfall collector. The rainfall collectors do not collect mist and dry deposited materials. As a consequence of this, major element, S and N budgets are extremely difficult to

TABLE 29 Afon Hafren and the Afon Hore catchment budgets (all values are rainfall/flow weighted)

Element	Rainfall Estimates++		Runoff+		Catchment Loss	
	Afon Hafren	Afon Hore	Afon Hafren	Afon Hore	Afon Hafren	Afon Hore
Major elements (kg ha^{-1} y^{-1})						
Na	71.7	78.1	65.4	68.0	-6.3	-10.1
K	3.07	3.34	3.05	2.24	-0.02	-1.10
Ca	3.98	4.2	11.9	15.3	8.0	11.1
Mg	9.0	9.8	11.9	11.9	2.9	2.1
SO_4	34.4	37.5	68.0	73.1	33.6	35.6
Si	3.5	3.9	26.1	23.6	22.6	19.7
DOC,	7.5	8.1	21.3	19.4	13.8	11.3
HCO_3	0.0	0.0	23.9	31.7	23.9	31.7
NO_3	1 2.0	13.1	28.8	23.3	16.8	10.2
Cl	129.	141.	129.	141.	0.0	0.0
Minor and trace elements (g ha^{-1} y^{-1})						
B	76.9	83.8	61.7	63.3	-15.2	-20.5
Li	0.0	0.0	31.5	30.9	-31.5	-30.9
Sr	56.8	61.9	82.5	75.3	25.7	13.4
Y	0.0	0.0	4.92	4.32	4.92	4.32
Ba	19.7	21.5	53.1	82.7	33.4	61.2
Mn	34.2	37.3	626.	444.	592.	407.
Cu	63.4	69.1	32.9	65.4	-30.5	-3.7
Fe	214.	233.	1322.	974.	1108.	741.
Co	0.0	0.0	35.7	35.0	35.7	35.0
Zn	150.	163.	237.	429.	87.0	266.
Al	255.	278.	6203.	5897.	5948.	5619.
Br	475.	517.	297.	318.	-178.	-199.
I	31.7	34.6	14.5	11.6	-17.2	-23.0
Acidity (mol ha^{-1} y^{-1})						
H^+	379.	413.	423.	357.	44.	-56.

\+ An average value of 1500 mm y^{-1} runoff is used in the calculation
++ Dry deposition of sea salts allowed for by assuming Cl conservative in catchments; values probably underestimated for dry deposition of non sea salt

obtain: the SO_2 and NO_x inputs provide additional problems for the H^+ ion budget.

To put this imbalance in context by considering the sulphur budget, previous estimates of the sulphur dry deposition rates are of the order of 30 kg SO_4 $ha^{-1}year^{-1}$ and this corresponds very well with the differences between the input and output values for the Hafren and Hore catchments (33.6 and 35.6 kg SO_4 $ha^{-1}year^{-1}$ respectively). Consequently if allowance is made för dry deposition of sulphur, there is a net balance for the catchments. Assuming the dry deposited sulphur occurs as SO_2, this corresponds to an additional rainfall input of 625 Mol $ha^{-1}year^{-1}$ of hydrogen ion with the consequence that the amount of hydrogen ion activity gained by the catchment represents 60% of the total acid input.

Nutrient concentration in the Wye and Severn

During the 1970s, the major water quality concerns in the uplands were the impact on nutrient losses of the proliferation of forestry schemes and the increasing rate of grassland improvement, involving ploughing, drainage, reseeding, liming and fertiliser application. Concern was voiced that contamination of surface reservoirs with nitrogen, potassium and, particularly, phosphorus (which is limiting to biological production in upland waters) would lead to algal blooms and associated deoxygenation, odours, foul tastes, increased treatment costs and possible premature eutrophication of upland sources.

It was always thought likely that the greatest changes in streamwater chemistry, detrimental or beneficial, would be evident during periods of land use disturbance: afforestation, deforestation, remedial fertiliser applications to forests and grassland improvement. However, to assess the impacts of disturbance it was imperative that the background quality of upland streams under stable land uses was known. As the two most common land uses were established forestry and rough pasture, a study was initiated in 1976 to determine nitrogen, phosphorus and potassium concentrations in the discharges of the main Wye and Severn catchments, to gain an insight into the processes governing nutrient release in the uplands. The data collected were analysed to determine short-term (storm event) and long-term (seasonal) variation and to investigate any differences in the nutrient concentrations in the discharges from the two different land uses (Roberts, Hudson and Blackie, 1983; 1984).

Streamflow sample collection at the outfalls of the Wye and Severn began in July 1976 and continued until July 1980. Originally two vacuum-operated, automatic liquid-samplers were employed in each stream, one collecting a daily sample (bulked eight-hourly samples) and the other, triggered by rising stage, collecting an hourly sample (bulked half-hourly samples) during high flow periods. This 'storm' sampling was discontinued in October 1977. The samples were stored in brown glass bottles and collected once a week. No chemical preservative was added.

To facilitate the calculation of nutrient budgets, rainfall sampling began at the Nant Iago lysimeter site (see page 140) in the Wye catchment in November 1977 and at the Hore flume in the Severn catchment in December 1979. The samples were collected in brown glass bottles from a Meteorological Office standard raingauge at weekly intervals, but if an insufficient sample was obtained, it was stored in a refrigerator and added to the sample from the following week. The samples were unfiltered and no chemical preservatives were added.

All the samples were analysed, at the nearby laboratory of the Ministry of Agriculture, Fisheries and Food, for ammonium-N, nitrate-N, total unoxidised N (thus giving total N and organic N), phosphorus and potassium. Nitrogen and phosphorus were determined colorimetrically and potassium by flame photometry, all according to recommendations by the Department of the Environment (DoE, 1972). The limit of detection of each of the chemical determinations was 0.02 mgl^{-1}. pH measurements were also taken for a short period during the study.

The results of the chemical analyses for the daily streamflow samples are shown in Figure 65. The data are presented as weekly mean concentrations in mgl^{-1} (not flow-weighted) in order to illustrate better any trends and variations by damping the considerable short-term variability: the average total weekly flows of the Wye and Severn are included for comparison. The concentrations, particularly those of ammonium-N and phosphorus, were sometimes below the limit of detection of the analyses used: in such cases a value of 0.01 mgl^{-1} was substituted.

The most interesting long-term variation is shown by nitrate-N: this exhibits a seasonal distribution which is negatively-skewed sinusoidal, with a marked winter peak. Similar trends were found by Reid *et al.* (1981) in their study in northeast Scotland and by Hill (1978) during his study of

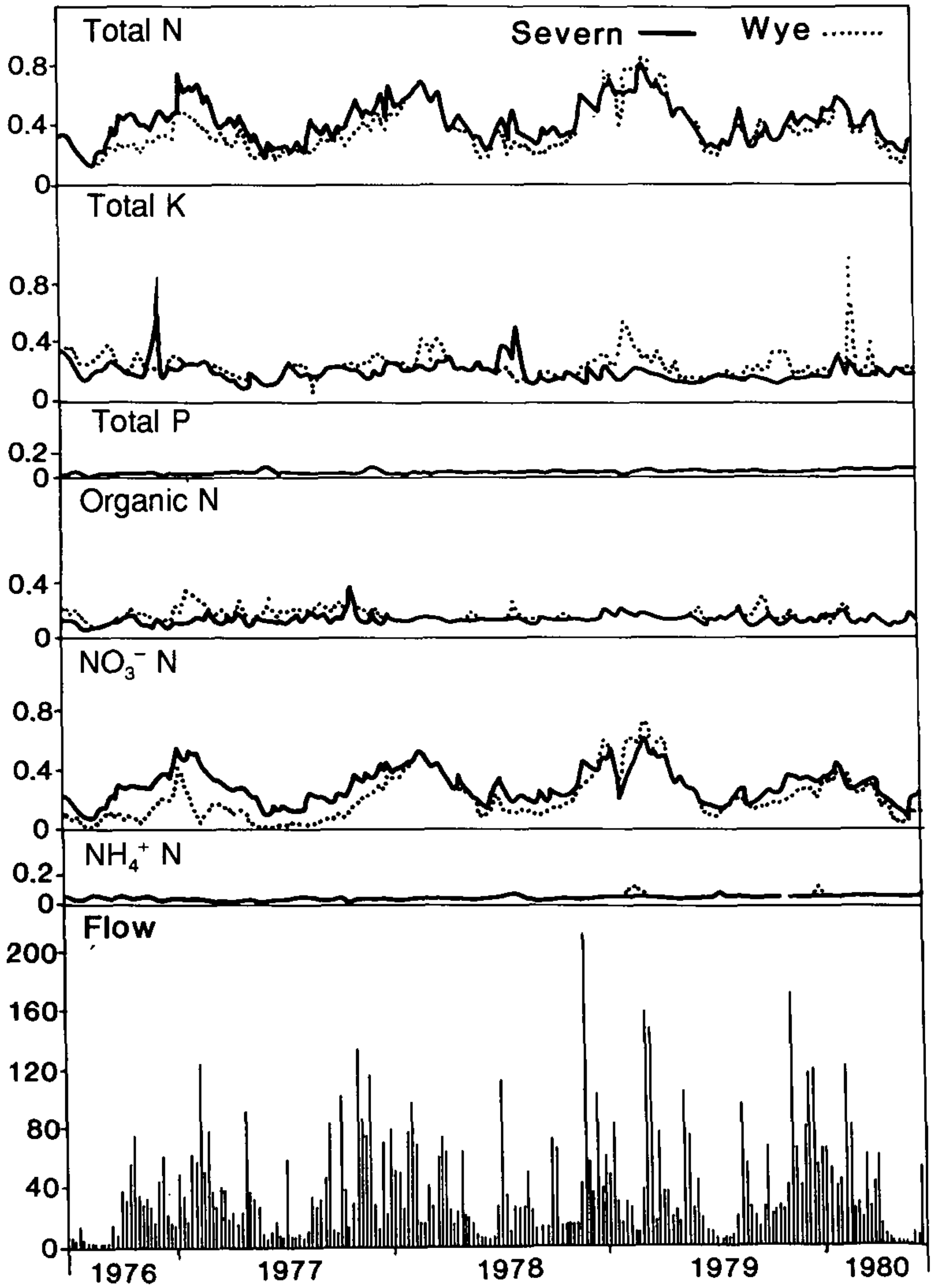


Figure 65 Time series of weekly discharge (mm) and nutrient concentrations (mg l^{-1}) for the Wye and Severn at Plynlimon

several drainage basins in Toronto. The nitrate-N concentrations in the discharge of the Severn were higher than in the discharge of the Wye, particularly during 1976 and 1977.

The results obtained from storm sampling are rather variable and depend on the antecedent conditions. Generally, increases in flow following hot dry periods produce increased nutrient concentrations: subsequent storm peaks, though often higher, do not produce the same effect. This confirms the findings of Walling and Foster (1975): early autumn runoff is the major flushing agent.

The range of nutrient concentrations in the rainfall samples collected in the Wye catchment (Figure 66) was much greater than that of the streamflow samples collected in both catchments. In particular, very high concentrations of all nutrients (up to 8.0 mg N l^{-1}, 0.1 mg P l^{-1} and 2.5 mg K l^{-1}) were found during the summer months, albeit at the time of lowest rainfall and hence lowest volumetric input. A comparison with the results obtained from the rainfall samples collected in the Severn catchment during 1980 showed generally similar trends, but at certain times, particularly during hot, dry periods, obvious differences were evident. Occasional high concentrations of organic-N were caused, in all probability, by organic matter, both animal and vegetable, entering the sample bottles. For this reason, some of the concentrations found in the rainfall samples, particularly in the summer months, when the problem of contamination is greatest, may be an overestimate of the input to the catchments as a whole.

If a comparison is made between the nutrient concentrations in rainfall and in streamflows, particularly the nitrogen concentrations, two distinct phases emerge. During the period April to October, the concentrations in rainfall are greater than those in the streamflows, whereas the reverse is true during the period November to March. If nutrient loadings, in units of kgha^{-1}, are compared, then similar trends are found. In the case of phosphorus and potassium, however, this is a manifestation of the increased flow during the winter months. This suggests a net input of nutrient into the catchments during April to October followed by a net output during November to March. An estimate of the annual balance for both catchments indicates a net input of nitrogen of almost 10 kgha^{-1} and parity between inputs and outputs for phosphorus and potassium.

Seasonal and land-use effects

In terms of potential pollution in the uplands, the level of nitrogen in streams draining established forest and rough pasture does not cause concern. Peak levels only reach 0.5 mg N l^{-1}, which is one-twentieth of the World Health Organisation's recommended level for N in drinking water. Levels of K are similarly low and levels of P are barely detectable, rarely rising above 0.02 mg l^{-1}.

Two phenomena, observed in this monitoring exercise, whose explanation gives further insight into the workings of the geochemical system, are the seasonal variation in nitrate-N (and, to a much lesser degree, potassium) and the differences in nitrate-N concentrations between the two streams, particularly during 1976 and 1977.

To explain the first phenomenon it is instructive to compare the relative concentrations in the rainfall and streamflows during the summer and winter periods and to relate these concentrations to the growth and decay cycle of plants. During the spring and summer (April to October) the concentrations in rainfall are greater than those in the streamflow. This coincides with the growing season when transpiration reaches the maximum and nutrient-rich interstitial water is taken up and stored as

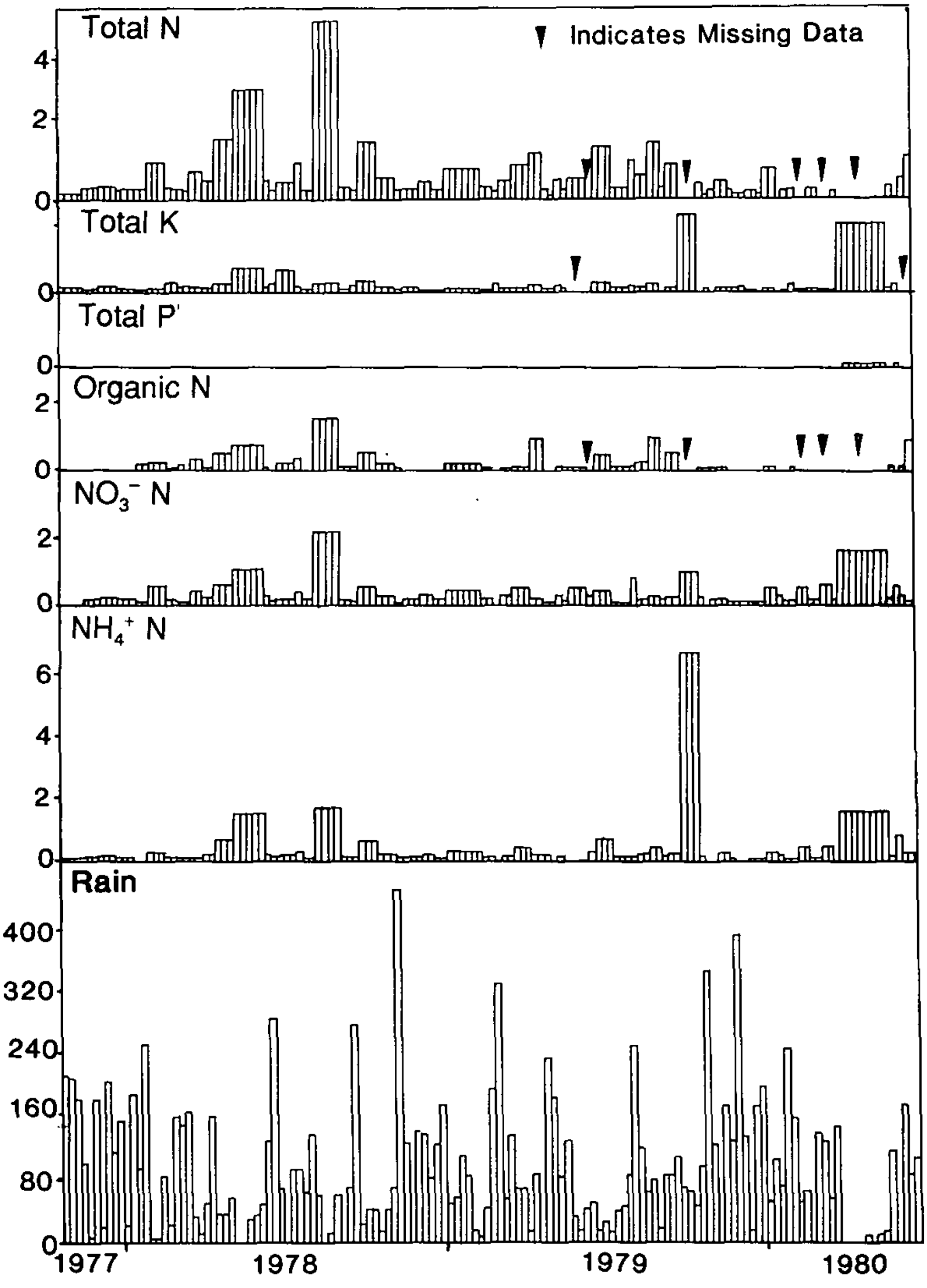


Figure 66 Time series graph of weekly rainfall (mm) and nutrient concentrations (mg l^{-1}) in the rainfall at Plynlimon

biomass. As the temperature rises, populations of micro-organisms increase and begin the task of completing the growth cycle by breaking plant debris down to its constituent parts. During this initial phase all living material requires a net input of nutrients. In consequence, the relatively rich rain water is depleted of nutrients before contributing to summer baseflow, ensuring an upper limit of nitrogen concentration in streams set by the nitrogen concentration in the rainfall.

Stream water occasionally approaches the rainfall value during wet summer periods when near-surface runoff occurs. During the winter months decay replaces growth as the dominant process. This boosts the organic nitrogen content of the soil which, in turn, accelerates the rate of conversion of organic nitrogen into mineral nitrogen by mineralisation, this rate being determined by a combination of soil temperature, soil moisture, pH and available organic nitrogen, the latter appearing to be the most important factor (Stanford and Epstein, 1974; Cassman and Munns, 1980). This means that a supply of mineral nitrogen is produced in the soil, which, as it is not removed by growing plants, is readily leached into the streams.

The timing of the nitrate-N peaks in the streams gives a clue as to the relative rates of plant debris decay and mineralisation. Decay is a gradual process resulting in a build-up of organic nitrogen in the soil, its peak preceding the peak nitrate-N concentration in the streams, as the rate of mineralisation must be a slower process than the rate of organic nitrogen production. This assumption is supported by Job and Taylor (1978) whose studies of grassland production in the Wye catchment indicated that litter-fall experiences slow, only partial breakdown. The green proportion of plants is at a minimum in March of each year, coinciding with peak nitrate concentrations in the streams.

The choice of July 1976 as the starting date of the monitoring exercise, following the dry winter of 1975-1976 and the very dry summer of 1976, was statistically fortuitous but experimentally unfortunate. It is very difficult to ascertain the effect of drought on nutrient concentrations in the streams when there are no data for comparison from antecedent "normal" conditions. However, assuming that the effect of drought does not extend for more than two years, it appears from the data for 1979 and 1980 that the norm is for similar nitrate-N concentrations in the two streams and that the effect of the drought was, in fact, to depress the nitrate-N concentrations below the norm in the Wye catchment. Two studies were initiated in 1980 to look more closely at the differences in nutrient concentrations in the two streams and to try to determine the cause of the depression in nitrate-N concentration in the Wye catchment following the drought.

Throughfall samples were collected at the Hore lysimeter site (see page 82). These samples were analysed to determine whether the higher nitrate-N concentrations in the Severn catchment were due to nitrogen enhancement of the throughfall by the forest canopy. Interception of rainfall by the forest canopy can cause nutrient enhancement of the throughfall and stemflow in two ways. First, a proportion of the rain intercepted is evaporated, thus increasing the nutrient concentration in the net rainfall. Second, the throughfall and stemflow may well pick up nutrients by leaching the foliage or by dissolving the aerosols or airborne dust particles trapped in the canopy (Miller, 1979). However, the results over a twelve-month period show that, for the majority of the periods sampled, the total nitrogen concentrations in the throughfall samples are less than those in the rainfall samples, whereas the reverse is true for potassium.

This confirms the results obtained by other workers (Miller *et al.*, 1976; Henderson *et al.*, 1977) and suggests that foliar absorption of

TABLE 30 Results of the areal sampling

NO$_3$ - N (mg/l)	SEVERN	LOWER HAFREN TRIBUTARY	UPPER HAFREN	TANLLWYTH	HAFREN	UPPER TANLLWYTH	UPPER HORE	HORE	UPPER HAFREN TRIBUTARY	HAFREN SOURCE	ARWYSTLI	HAFREN PEAT HAG PIPE	WYE	CYFF	WYE-CIFF	GWRDY	GWY	IAGO	UPPER CYFF	COLWYN	CYFF SOURCE	GERIG	UPPER GWY
Date	ST	H1	H2	H3	H4	H5	H6	H7	H8	H9	H10	H11	CB	G1	G2	G3	G4	G5	G6	G7	G8	G9	G10
29.11.79	.34	.29	.26	.54	.32	.37	.26	.32	.23	.26	.26	.23	.26	.17	.37	.34	.29	.32	.17	.18	.34	.26	.37
09.01.80	.34	.23	.30	.37	.29	.29	.29	.33	.26	.29	.27	.23	.29	.20	.37	.32	.34	.29	.23	.19	.40	.34	.43
30.01.80	.46	.29	.54	.37	.46	.32	.45	.45	.43	.47	47	.41	.57	.34	.68	.32	81	.40	.47	.23	.86	.67	.89
05.03.80	.39	.25	.34	.44	.27	.30	.29	.27	.25	.29	.25	.18	.22	.15	.25	.25	.25	.19	.18	.19	.36	33	.39
02.04.80	.30	.23	.27	.32	.27	.25	.22	.25	.25	.27	.25	.25	.25	.16	.27	.19	.30	.19	.15	.11	.25	.27	.45
02.05.80	.15	.13	.18	.17	.18	.15	.19	.16	.15	.22	.19	.27	.05	.01	.11	.15	.08	.09	.01	.08	.06	.01	.12
04.06.80	.18	.16	.20	.19	.19	.25	.18	.18	.19	.19	.20	.13	.12	.06	.18	.16	.15	.18.	01	.06	05	.12	.08
15.07.80	.13	.12	.18	.11	.15	.11	.15	.13	.10	.15	.16	.06	.04	.01	.09	.13	.06	.08	.01	.06	.01	.01	.09
06.08.80	.17	.27	.18	.17	.18	.15	.15	.14	.08	.11	.08	.13	.02	.02	.06	.13	.04	.08	.03	.08	03	.03	.06
30.10.80	.37	.32	.23	.54	.26	.34	.23	.29	.14	.16	.17	.17	.17	.17	06	.23	.15	.17	.01	.08	.10	.06	.17
09.12.80	.34	.27	.30	.43	.33	.32	.27	.30	.19	.27	.25	.18	.23	.16	.26	.26	.23	.22	.11	.15	.26	.18	.29
MEAN	.29	.23	.27	.33	.26	.26	.24	.26	.21	.24	.23	.20	.20	.13	.25	.23	.25	.20	.13	.13	25	.21	.30
STD DEV	.11	.08	.11	.16	.10	.08	.10	.09	.09	.11	.10	.10	.16	.10	.08	.06	.20	.10	.14	.06	.25	.20	.25
STANDARD ERROR	.03	.02	.03	.05	.03	.02	.03	.03	.03	.03	.03	.03	.05	.03	.05	.02	.06	.03	.04	.02	.08	.06	.08

nitrogen rather than foliar leaching is the dominant process. If nitrogen loadings are considered, it is found that those in the throughfall are generally much less than those in the gross rainfall. Clearly then the higher nitrate-N concentrations in the Severn could not be caused by nitrogen enhancement of the rainfall as it is passed through the forest canopy.

To examine the variability of concentrations within the catchment, spot streamflow samples were collected at the outlets of the sub-catchments in the Wye and Severn and at points within the sub-catchments. The network consisted of 11 sites in the Wye and 12 in the Severn, sampled monthly. All the samples collected during each visit were taken within 30 minutes of each other to minimise bias. With the exception of those taken on 6 August 1980, samples were taken on the recession limb of the hydrograph, which, while unrepresentative in terms of sampling flow condition, at least ensured reasonable comparison between sites by ensuring that large changes in discharge did not occur during the sampling period. The concentrations of nitrate-N are shown in Table 30 and in Figure 67.

The lowest mean nitrate-N concentration was found at the outfall of the Cyff, G1, whilst the highest mean was found at the outfall of the Tanllwyth, H2. If the contributions of the Tanllwyth and Cyff were subtracted from the nitrogen loads of the Severn and Wye respectively then the residual loads would be almost identical. The Cyff drains through a mire area before reaching the stream channel proper and the mire may be acting as a nitrogen sink, slowing down the movement of water and

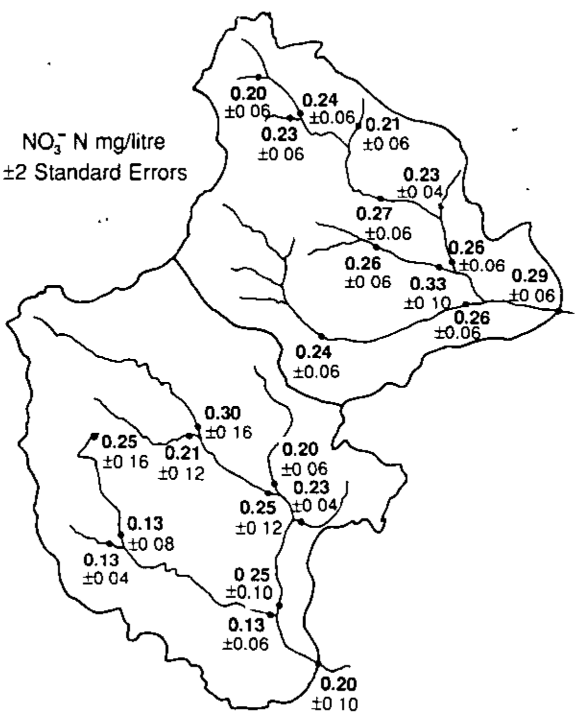


Figure 67 Spatial nutrient survey results for nitrate

providing ideal conditions for denitrification by anaerobic bacteria. In the drought of 1976 the mire did not dry out appreciably and this, coupled with the very high temperatures experienced, and the moderate pH resulting from a history of agricultural liming in the catchment, provided good conditions for very high rates of denitrification. This observation has wide ranging repercussions for the management of wet riparian areas, not only for nitrogen but for other potential pollutants, and has spawned further research on the role of these areas in modifying stream water chemistry at Plynlimon and other Welsh sites (Roberts *et al.*, 198?).

In contrast, the lower reaches of the Tanllwyth is an area which has a very active set of drainage ditches where rates of erosion and sediment transport are high. These ditches and associated plough lines also ensure a rapid movement of water to the stream channel and locally lower the water table, thus removing the conditions conducive to the loss of nitrogen by denitrification while encouraging mineralisation.

The lower nitrate-N concentrations in the Wye characteristic of the summer of 1976 were continued through the winter of 1976-1977 and, if anything, were exacerbated in the summer of 1977. The concentrations in the Wye only recovered to the Severn values in January 1978, mirroring the slow recovery of soil moisture deficits following the drought (Hudson, 1988). This highlights the fundamental point that the major control on nitrate-N concentrations in streams is nitrogen availability in the soil and the availability of drainage water for flushing the soil profile. The low concentrations in the Wye must have been caused by stress-induced low grassland production in the summer of 1976 which resulted in less material to decay and mineralize in the autumn and winter and a consequent knock-on effect to the following summer and winter.

Lysimeter study of grassland improvement

As a sequel to the catchment scale study of nutrient concentrations and as a first step towards the investigation of potential impacts of land use change on water quality, it was decided to investigate the release of nutrients from improved grassland. Partly because of favourable financial incentives but also because of technological advance, grassland improvement became very popular with farmers in mid-Wales in the mid-1970s. To this extent, the rough pasture of the Wye catchments is not representative of many of the neighbouring reservoired catchments, e.g. Llyn Clywedog, where the water resource authorities do not have complete control over land use.

The plot chosen for the experiment was an area of 1.5 ha at an altitude of 400 m on the left bank of the Nant Iago (Figure 68; Plate 26) with a slope of 1 in 10. It consisted originally of rough pasture on peat, overlying seemingly impermeable boulder clay. The average depth of peat was 1.5 m, and before any improvement could be carried out, it was necessary to drain the plot. The area was split into two roughly-equal sections and a main drain was installed in each. Lateral tile drains were constructed at a spacing of 10 m in each section (Figure 67) and all the trenches were back-filled. A 10 m by 10 m 'natural' lysimeter, similar to that described in Chapter 5, was constructed in each section (Plate 26). Trenches were cut down to the impermeable clay and lined with rigid plastic, cemented at the base, to seal off each lysimeter block. Tile drains were placed in the trench both inside and outside the plastic sheeting and covered with a layer of gravel before backfilling and replacement of turves. It was considered that many of the usual criticisms levelled at lysimeter studies, notably the edge effects, were minimised in this case because the walls were installed to coincide with zero flux planes introduced by the drainage lines.

The turves on the inside of the plastic sheeting were angled in such a way that any surface runoff would move away from the sheeting and be led into a collector at the lowest corner of the lysimeter. An exit for the subsurface flow was constructed through the plastic sheeting at the peat/clay interface. Both the surface and subsurface flows were led through 100 mm diameter plastic pipes into the instrument hut (Plate 26 inset).

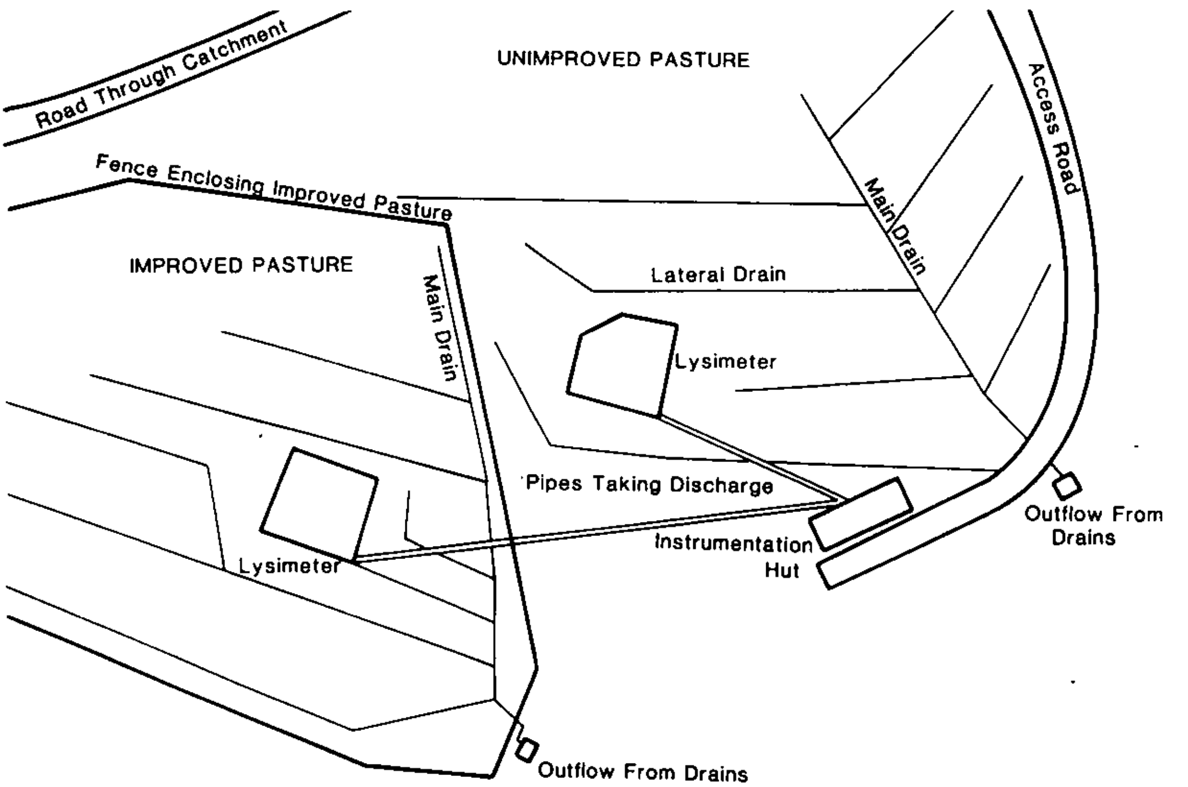


Figure 68 Plan of the Nant Iago plot, showing the lysimeters and pattern of drainage

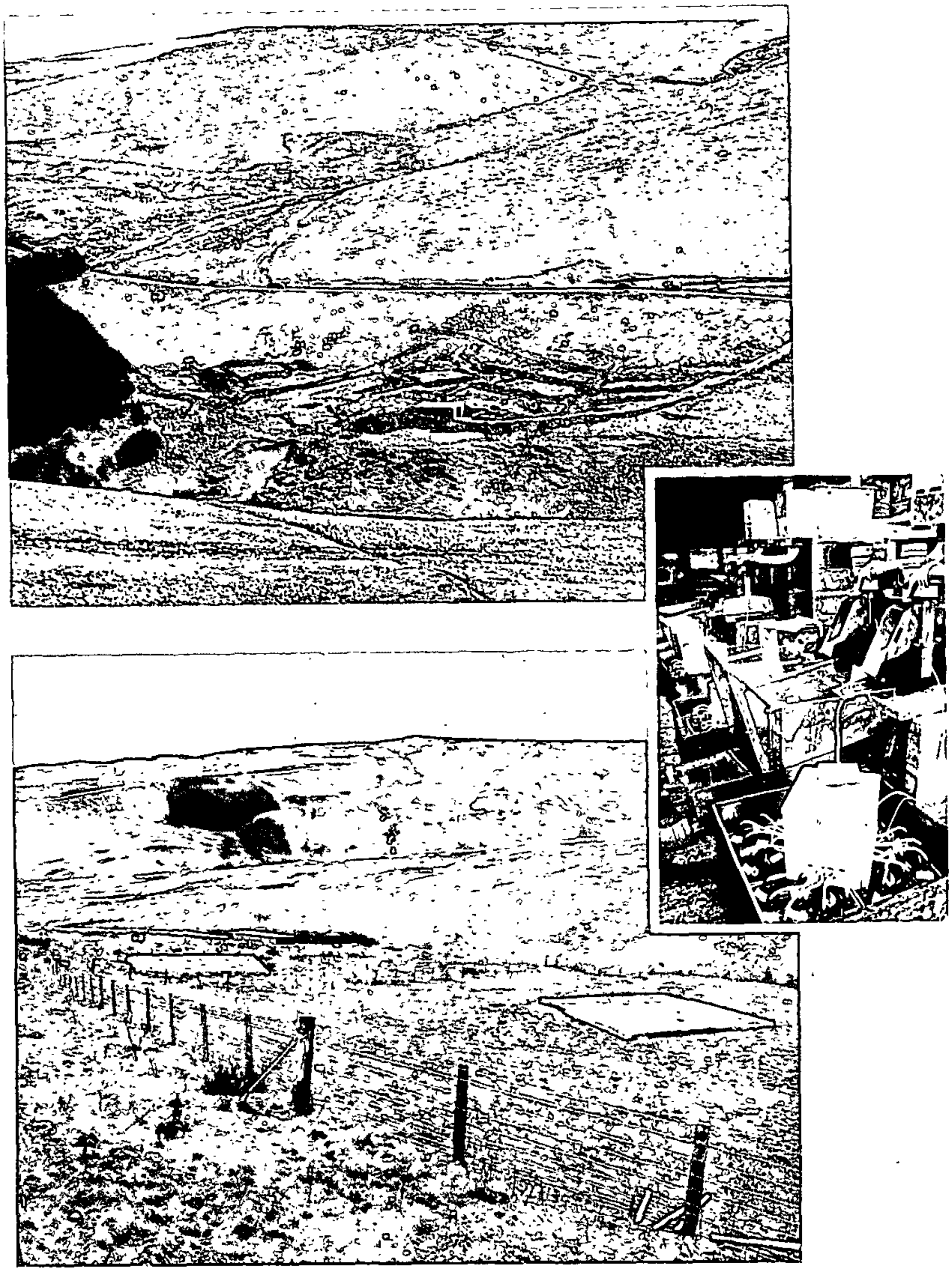


PLATE 26 Nutrient lysimeters, Nant Iago sub-catchment, showing installation phase (top) and completed site with the lysimeters covered (bottom). Inset: Measuring and sampling equipment inside the instrument hut.

Each of the four flows (surface and subsurface from both improved and control) was measured by a v-notch weir box with punched tape stage recorder and also a tipping bucket discharge recorder. A small proportion of each flow was led into a water sampler. The tipping bucket meters, the primary means of flow recording, were connected to a Microdata logger. Both these and the back-up punched tape recorder produced a 5-minute record.

Water samples were collected on a flow proportional basis (Holdsworth and Roberts, 1982). For the subsurface flows, an integrated one litre sample was obtained for every 800 litres of flow (equivalent to a discharge of 8 mm over the lysimeter), whilst for surface flow an integrated one litre sample was obtained for every 100 litres of flow. In addition, water samples were collected at the outfalls of the main drains, at daily intervals in the case of the improved plot and at weekly intervals for the control. Rainfall inputs were measured using a weekly-read storage gauge which also acted as sample collector. The weekly rainfall was time-distributed using the record from a nearby recording raingauge. All water samples were analysed for ammonium-N, nitrate-N, organic-N, phosphorus and potassium.

Data collection began in October 1977 and continued until October 1981. The period between October 1977 and May 1978 was used to compare the results from the two lysimeters after under-drainage but prior to the start of the grassland improvement scheme. Remedial fertiliser applications were made subsequently during the springs of 1979 and 1980.

The improvement of one section of the plot, including the lysimeter, was carried out under the supervision of agricultural advisors from the Ministry of Agriculture according to recommended practice. It consisted of liming at the rate of 862 $kgha^{-1}$, followed by rotary cultivation, reseeding and a fertiliser application at the rate 191 $kgha^{-1}$ of slag, 430 $kgha^{-1}$ of compound fertiliser (15:15:15) and 173 $kgha^{-1}$ of a nitrogen fertiliser (37.5%). A corollary of the improvement was the adoption of an intensified grazing routine for the plot and it was fenced for this purpose. Subsequent top-dressings of a nitrogen (33.5%) fertiliser were made to the improved plot at the rate of 44.5 $kgha^{-1}$ during May 1979 and April 1980.

Analysis of the flow records obtained from the two lysimeters indicated very few instances of surface runoff before or after the grassland improvement. Even when it did occur, nutrient concentrations were low, similar to rainfall. These low concentrations together with the infrequent occurrence of surface runoff meant that there were negligible nutrient losses from the lysimeters by this route. In contrast, nutrient concentrations from the subsurface flows were higher than expected even before the improvement had taken place. These concentrations are shown in Figure 69 as weekly flow-weighted means, together with daily rainfall totals. Nitrate-N concentrations in particular were very high during this period, especially during storm events, with peak spot values of 19 mgl^{-1} and peak weekly means of 12 mgl^{-1}. The losses were probably due to mineralisation and subsequent leaching of the organic nitrogen in the dried out peat used as backfill in the trenches surrounding the two lysimeters.

These high concentrations are seen to decay gradually through the study period. This may result from a combination of a decline in readily-mineralisable organic nitrogen and the return of anaerobic conditions in the backfill arising from saturation and consolidation of the peat. Although these high concentrations do mask the effects of the improvement to a certain extent, it is noteworthy that the nitrate-N concentrations before improvement were similar in the two subsurface discharges.

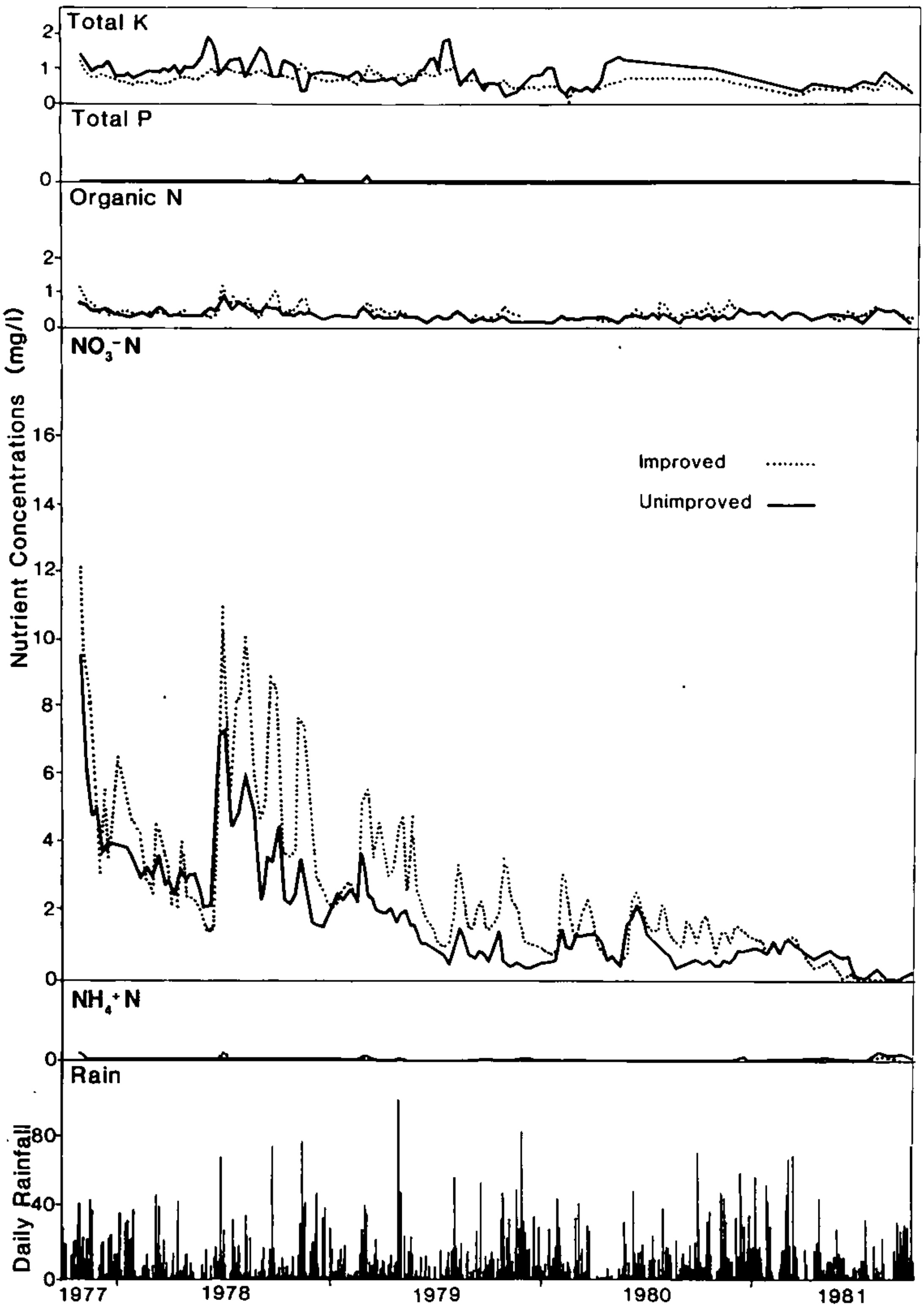


Figure 69 Nutrient losses from the improved and unimproved lysimeters: flow-weighted weekly means in mgl[1]

Because of the dry May and June 1978, the effects of treatment on the quality of the discharge from the improved lysimeter were not seen until the end of June, when the nitrate-N concentrations in both discharges increased, a greater increase being observed for the improved lysimeter. They then decreased gradually to the end of the year when, again, the two sets of concentrations were similar. This pattern was repeated in the following two years, though the extent of the spring/summer increases was less, the timing different and the differences in concentration substantially smaller than in 1978. The analyses of the samples from the outfalls of the main drains show similar trends though the effect of the improvement on nitrate-N concentrations was more pronounced; the same was true, but to a lesser degree, for the other nutrients.

The complex experimental framework makes it very difficult to differentiate the impacts on nutrient concentrations in the discharges of the two lysimeters between grassland improvement or subsequent fertiliser applications alone. The fact that the nitrate-N concentrations in the discharges of both lysimeters increased during the spring/summer months of 1978, 1979 and 1980 indicated that the release of nitrogen from the backfill was not confined to the 12 months following installation and may still have been the dominant source of nitrogen in subsurface flows three years after the improvement. The indications are that applied nitrogen and mineralised nitrogen in the plough layer were taken up efficiently by the established grass.

The results obtained from the lysimeter study have been extended to a catchment scale by combining nutrient concentrations from the subsurface discharges with the recorded flows from the Nant Iago to calculate nutrient losses in kgha^{-1} from improved and unimproved areas. These are shown in Table 31 as annual (April to March) totals, to coincide with the improvement and subsequent fertiliser applications. Phosphorus and potassium were not analysed after June 1980 so no losses can be quoted for 1980/81. The phosphorus losses are approximate as the concentrations were often below the limit of detection (0.02 mgl^{-1}) when a value of 0.01 mgl^{-1} was substituted.

Table 31 shows that the only significant differences are in total N losses, these being

TABLE 31. Nutrient losses from improved areas (I) and unimproved areas (U) and the differences (I-U) (kg ha^{-1})

	Improved areas I	*Unimproved areas* U	*Difference* I – U
Total nitrogen			
April 1978 - March 1979	119.5	79.8	39.7
April 1979 - March 1980	56.7	27.9	31.8
April 1980 - March 1981	46.1	30.3	15.8
Total phosphorus			
April 1978 - March 1980	0.6	1.0	-0.4
April 1979 - March 1980	0.4	0.3	0.1
Total potassium			
April 1978 - March 1979	16.9	14.6	2.3
April 1979 - March 1990	13.2	13.5	-0.3

almost solely due to differences in nitrate-N concentrations in the two discharges. The calculated differences in total N losses are 39.7 kgha^{-1} in the year following the improvement and 31.8 and 15.8 kgha^{-1} in succeeding years. These compare with total nitrogen fertiliser applications of 122.5, 14.9 and 14.9 kgha^{-1} respectively.

Obviously the results quoted in Table 31 are only very crude estimates of the effects of grassland improvement on a catchment area. It is highly unlikely that an improvement scheme in the uplands will extend over a whole catchment: the 30% improvable proportion quoted by Ministry advisors seems realistic for the Nant Iago. This means that the high concentrations noted from the lysimeters would be diluted by the normal low concentrations in runoff from rough pasture. However, it is clear that if drainage is considered as part of the improvement procedure it produces nutrient effects similar to if not greater than those of liming, rotavation, reseeding and applying fertiliser.

The improvement of grassland also has an impact on the hydrological response of catchments due to changes in flow routing through underdrainage systems, along steeper piezometric gradients and through decompacted plough layers. Evaporation rates from rye grass pasture can also exceed those from indigenous vegetation, as indicated by a study carried out on the lysimeter site (Roberts, 1983) which found peak rates 40% higher than from adjacent *Juncus/Molinia* pasture.

Newson and Robinson (1983) report that tile drainage installed at a depth of 750 mm and a spacing of around 10 m (similar to the nutrient lysimeter network of drains) produced a measurable lowering of soil water levels in peaty podzol and peaty gley soils, similar to those found in the Wye catchment. Drainage reduced the flood peak and increased the time to peak over the range of conditions studied. This is a very different effect from open ditch drains on peat (see Robinson, 1986) where water table lowering is very limited and flood peaks are increased. It is not surprising, therefore, that on the deep peat of the lysimeter site itself, Hudson and Roberts (1982) report very little drainage effect on soil moisture content at greater distances than 1 m from the line of the drain.

Ironically, one major hydrological spinoff of the lysimeter study was only noticed because of an inability to balance the water fluxes in either lysimeter to give a sensible evaporation rate from this type of pasture. In fact, flow exceed rainfall input on the improved lysimeter for much of the study period. This could only be explained by an upward artesian input of groundwater into the lysimeter from the boulder clay, previously considered 'watertight'. The existence of significant hydraulic heads and Darcian hydraulic conductivities in these clays (Allen and Bird, 1981) explains to a large extent the low flow behaviour of the catchments. It suggests that there is a larger groundwater component to flow and goes some way to explain the anomalous chemistry of the streams which were hitherto thought to be mainly of near-surface origin.

There have been few other studies of nitrate runoff in upland areas, the interest in Scotland, for example, being more in phosphate fertilisers applied to forests or as a remedial measure. At Coalburn, Robinson (1980) records that approximately 2% of the phosphate applied at the establishment of the forest reached the stream, producing concentrations which were 15-20 times the natural background but lasting only five months after the application. At Plynlimon there was an aerial application of fertiliser to Hafren Forest in the autumn of 1974 when the fertiliser applied consisted of 375 $kgha^{-1}$ of rock phosphate (as at Coalburn) and 200 $kgha^{-1}$ of potash. Whilst daily water samples were taken between September 1974 and January 1975 at the Severn flume, the Severn Trent Water Authority who analysed the samples found no significant change in the phosphate or potash concentrations over the period.

6.4 The river channel environment: water temperature, bacteria, invertebrates and fish

The complexity and sensitivity of the upland stream environment to factors in the catchment have been revealed by a variety of studies of environmental variables in the stream channels by Institute staff and others. Nutrient concentrations are of concern for water suuply and the management of downstream reaches, but the value of upland streams as natural habitat depends on other factors also. These streams are potential trout and salmon waters, and the higher reaches are crucial to the breeding of these species. It is obviously important that food organisms are present in sufficient numbers, but it should also be remembered that low bacterial concentration was once a deciding factor in preferring forest planting on reservoir catchments.

The effect of dense forest cover on water temperature

Despite its importance as an indicator of stream habitat quality (Smith, 1972), water temperature has received little systematic study in Britain outside thermally-polluted reaches of industrialised rivers (Langford and Aston, 1972). There are very few studies of the temperatures of upland headwater streams (e.g. Mecan, 1958), and fewer still where land use is considered (e.g. Gray and Edington, 1969).

The Wye (1978-79) and the Severn (1979-80) were equipped with weather stations adjacent to the streams, including water temperature probes. Temperature screens were also set up within the forest and water temperature sensors were installed. More intensive monthly spatial surveys were made at many sites in the stream network, alongside micrometeorological studies which investigated the energy balance of stream reaches.

The basic units chosen for analysis were the hourly water outfalls of the main catchments. Of the three analytical techniques tested — time series, regression analysis and physically-based modelling — regression analysis proved to be the simplest and most immediately usable for river management (Crisp and Howson, 1982). The gross differences between water temperatures under grassland and forest can be judged from Figure 70. The spring and summer cooling experienced by the Severn is clearly visible.

The significance of these results for the stream habitat is difficult to determine. Much attention has been given to the effect of temperature on the growth and behaviour of trout. The brown trout (*Salmo trutta*), which predominates in the Plynlimon streams, is a cold water fish. However, in a review of some of the literature on trout growth, Smith (1980) suggests that temperature under forest (which shades the stream) is likely to be near the optimum for a shorter period in the year than temperature under short vegetation canopies. Indeed it is becoming accepted forestry practice not to plant right up to channel banks.

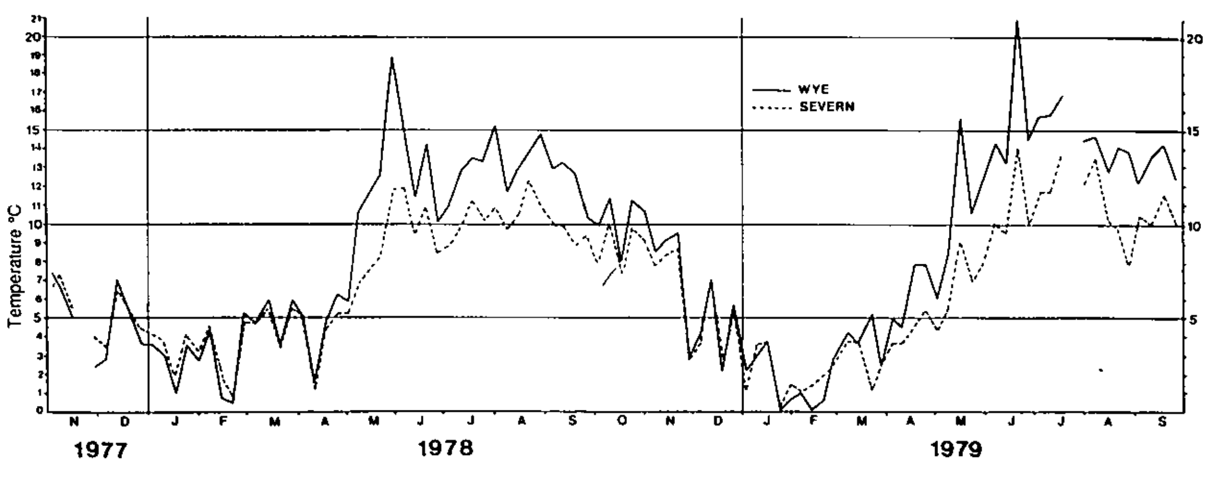


Figure 70 Mean daily water temperatures monitored at the outfalls of the two catchments

Bacterial water quality

The Ministry of Health's 1948 document on catchment land use paid "special attention to the consideration of recreational and agricultural areas as possible sources of pathogens", but concluded that "neither would, given adequate controls, constitute a threat; no pathogens were linked to a forestry source". Its publication followed public disquiet about a typhoid epidemic in Croydon in 1937-38. Since a major attraction in supplying the British lowlands with upland water, impounded and stored by reservoirs, was its bacterial purity, there was clearly concern that any organisms might escape the sterilisation process of chlorination, often the only purification process used needed for upland waters.

The commonly used indicator of bacteriological conditions in water used for supply is the species *Escherichia coli*. The University of Leeds and University College of Wales, Lampeter, have made a study of its concentrations in the Tanllwyth and Cyff tributaries.

Little field information is available describing the comparative bacterial water quality between the major catchment land uses of afforestation and sheep pasture. Data from the Plynlimon sub-catchments are presented by Kay and McDonald (1982) which show that upland sheep pasture produces a significantly higher coliform concentration in reservoir feeder streams. The importance of these results, which are limited in both spatial and temporal coverage, must be judged in relation to the 'limited' treatment provision and reservoir self-purification at Britain's older direct supply impoundments (Kay and McDonald, 1980; 1983).

Surveys of invertebrates and fish

Between January and August 1974, a group from the National Museum of Wales took samples of invertebrates from mid-stream riffles at several sites on the Severn. The effects of afforestation were difficult to discern because few of their sites were located outside the forest and, of those that were, some also differed in gradient or discharge. They concluded that there was evidence of a reduction in the density of individuals within the forest but there seemed little indication of a decrease in the number of taxa.

A different approach was adopted in July 1985 by a group from the Department of Biological Sciences at the University College of Wales, Aberystwyth. Samples were collected from a variety of habitats, including riffles, in two forested streams (Hore and Hafren, or upper Severn) and a moorland stream (Gwy, or upper Wye). As far as possible the streams were matched in abiotic characteristics; they differed principally in the extent of the conifer afforestation in their catchments. Sampling has been repeated each July since 1985 and also in October 1986. This period has included the clear-felling of 157 ha in the Hore catchment.

In general, there is no clear relationship between afforestation and the numbers of individuals. An exception is that the banks of the Gwy consistently yield more individuals than those of the Hore and Hafren. Equally, there is no clear effect of afforestation on the number of species. The most clearcut relationship between afforestation and invertebrates is the virtual absence of mayflies from the Hafren and Hore and their abundance in the Gwy. Removal of trees from the Hore resulted in the return of appreciable numbers of mayflies in less than two years from the commencement of felling. There was no comparable increase of mayflies in the Hafren, which acted as a control.

The reduction in invertebrates in streams of afforested catchments has been recorded elsewhere (Harriman and Morrison, 1982; Stoner *et al.*, 1984). It is often correlated with reduced pH and elevated concentrations of dissolved aluminium. The ranges and means of pH spot measurements differ very little between the Hafren, Hore and Gwy, but mean aluminium concentrations are higher by a factor of two or three in the forest streams (Reynolds *et al*, 1986). Experimental work suggests that mayflies are particularly sensitive to low pH and high aluminium concentrations (Ormerod *et al.*, 1987) but it remains to be seen whether changes in water chemistry can account for the apparent recolonisation of the Hore.

Electro-fishing in both the Severn and the Wye in 1979, carried out by a team from the Freshwater Biological Association (Crisp *et al.*, 1980), showed that there were far fewer trout in the Severn than in the Wye. Throughout the survey only one fish species, the Brown Trout, was found and trout were seen in all but one of the several sampling stations in the Severn.

The differences in fish populations between the Severn and Wye are very striking. Angling activity in the upper reaches of the Wye and Severn systems is slight, and possible differential effects of angling on fish populations in the two systems can be disregarded. Likewise, examination of some of the flumes suggests that they are not likely to be a serious barrier, at least to the upstream movement of larger trout.

Trees growing close to stream channels cause shade which modifies the temperature regime within the streams. The exact effect of such modifications can be assessed only by detailed analysis of local field data, because modifications may shift the annual temperature pattern either towards or away from the optimum for trout growth. Such changes will affect the growth rather than the survival of the fish. However, the tendency for afforestation to reduce average water temperatures and diurnal fluctuations during summer may also lead to a reduction in the frequency of occurrence of temperatures sufficiently high as to cause some distress to brown trout and this, in turn, could have some influence on both growth and survival.

Diverse effects upon trout are possible from the pesticides and fertilisers used in forestry and also from the solvents, carriers and other additives used with them. In addition, Huet (1951) has suggested that spruce may itself produce a toxin which can affect freshwater organisms.

Since the fish survey by FBA in 1979, the scarcity or complete absence of salmonids in forested streams in upland Wales has become very closely identified with the phenomenon of stream acidification (Stoner and Gee, 1985). The considerable research effort mounted at Plynlimon in respect of stream acidification has already been described in this chapter. Research continues into the precise mechanism of the forest effect but early results from sampling stemflow and throughfall in conjunction with rainfall above the forest canopy under different antecedent conditions suggest that dry deposition of pollutants may be of major importance.

Chapter 7 Conclusions and implications

This chapter summarises the principal findings from the Plynlimon experiment and considers their implications for our understanding of upland hydrology in the United Kingdom. Where possible, the Plynlimon results are placed alongside other work in this field, to bring out the complementary nature of localised long-term studies at a site such as Plynlimon, and more spatially extended exercises that can help to show regional variations.

7.1 The Plynlimon experiment

The Plynlimon experiment was set up to investigate the effects of a change in land use on the water yield of upland catchments used for water supply. Although rainfall, and consequently runoff, is high in the uplands of Britain, the seasonal pattern of water yield is opposite to that of its consumption. The full use of the upland water resource relies on storage in surface reservoirs, whose considerable cost is justified on the basis of the expected water yield of their catchments.

At the start of the Plynlimon study, large areas of the uplands of England and Wales were subject to afforestation or the prospect of it, and there were indications that the change of land use from grazing would reduce water yields. A plot-scale experiment carried out in the headwaters of the River Ribble by the water engineer Frank Law had shown that coniferous forests did indeed reduce water yields. To be really convincing, however, the work had to be repeated on a catchment scale.

In the first instance, then, Plynlimon was a paired catchment experiment aimed at comparing the water yield from mature forest and sheep grazing land, under conditions that were as closely controlled as was possible in the open air. With the passage of time it has become much more. In the early stages of the experiment the Institute of Hydrology premises at Dolydd Llwydion provided simple office accommodation for a small team of field workers, whose task was to service and maintain the data collection networks and to send the data for analysis at Wallingford.

The Plynlimon experiment was an ambitious undertaking, and the initial estimates of its timescale were optimistic, based on the expectation that new instruments and techniques would operate without hitches in the hostile upland environment.

In practice, the process of instrument development was to take far longer than planned, and the experiment would accrue new features aimed at bettering the precision of its conclusions and deriving the maximum benefit from the investment of time and resources. The Plynlimon station expanded as scientific staff were encouraged to take a closer interest in the experimental detail while the increasing importance of water quality considerations led to an expansion of data collection and to the instrumentation of other catchments.

The Institute's involvement with environmental problems in Wales is far from over: though the main catchment experiment has yielded enough results of a very high quality to settle the original question, the recognition of widespread man-induced changes in water quality and climate has raised new questions. In this context the value of the Plynlimon data set, covering 23 years of intensive monitoring of nearly 20 km^2 of land, and of the expertise and facilities of the Plynlimon station, are widely acknowledged. This report summarises research at Plynlimon up to 1985, with some pointers to work that has been going on since that date. The issues dealt with in this report are addressed at greater length in the many scientific papers which are listed in the Bibliography.

7.2 The catchments

Catchments for research have traditionally been of two types: representative catchments intended to typify climatic, physiographic or land use zones; and experimental catchments, where land use undergoes a planned change over the course of the investigation. The Plynlimon experiment in its original form comprised two representative catchments, the 10.55 km^2 grassland Wye catchment and the 8.70 km^2 largely forested Severn. Subsequent developments, for example the Hore clear-fell experiment, have adopted the experimental catchment approach. In any catchment experiment it is good practice to have a nearby control catchment where only the uncontrollable factors, such as climate, change. At Plynlimon this role has been filled by the Wye and its subcatchments, which have remained essentially unchanged over the period of the study.

The Plynlimon climate, as the backdrop to the study, has often been an important factor in the experiment: the catchments are a severe testing ground for instruments, and the spatial variability of the climate across the catchments is marked. In addition to short-term studies of soil temperature and wind speed, the major climatic variables have been measured at four automatic weather stations and one daily-read manual station.

Rainfall, originating mainly from depressional weather systems, is the major precipitation input to the catchments, with a maximum in autumn and winter. Field activities, particularly those involving electronic instrumentation and delicate operations, are difficult because of the large number of rain days in any year: on average two-thirds of days in winter record some precipitation. Snow averages about 5% of the total precipitation, but varies greatly from year to year.

Although the Plynlimon catchments were selected, among other factors, for the impermeability of their bedrock, it has been found that shallow groundwater plays an important part in sustaining low flows. In this respect the most significant groundwater body is in the periglacially-shattered grit underlying the peaty upper slopes of both the Wye and Severn catchments, but other minor aquifers may be involved in the seasonal storage of water and in the admixture of chemically distinct and well-buffered water to storm runoff.

7.3 Techniques of catchment research

The assessment of evaporative losses from a catchment by the water balance method requires precise measurement of all the elements of the balance. The length of the accounting period is open to choice, and the soil moisture storage in particular tends to return to a constant level of saturation, or "field capacity" once in most years, so that the water balance over a year may not need to take account of soil water storage. However, for the determination of losses over shorter periods soil moisture and groundwater are most important: the shorter the time interval the more significant becomes the precision of the estimate of storage.

The first stage of the Plynlimon experiment necessarily involved the refinement of techniques and instruments to achieve the required level of precision. Available methods for areal mean precipitation and flow gauging were inappropriate for use in upland catchments, and soil moisture could not be measured *in situ*.

Precipitation

Rainfall is known to vary with altitude and aspect and it had been established that slope was also an important independent variable. These three factors form the basis of the domain method of raingauge location in which the catchment is divided into subareas defined by selected ranges of altitude, aspect and slope. The advantage of the domain method over, for instance, a random spatial pattern is that the entire range of likely controlling variables is sampled. More recently, the domain method has been used to locate the network of raingauges in the Institute's Balquhidder catchments in the Scottish Highlands.

The combination of canopy level storage gauges, groundlevel storage gauges and a small number of recording gauges has been demonstrably effective in securing a consistent and uninterrupted sequence of rainfall measurements, whose precision is adequate for the purpose. The measurement of snow, however, demands a more intensive approach.

The raingauge network was primarily intended for the determination of areal mean precipitation, and the achievement of this objective depends on its effectiveness in sampling a complex spatial distribution. Tests of the network, for instance the installation of a duplicate network, have shown that areal mean is estimated well, but attempts to explain the variance of monthly rainfall using the three variables altitude, slope and aspect have demonstrated that non-local effects, for example the shadowing of slopes caused by macro-topography, are also important in controlling rainfall amounts in the uplands.

The measurement of snow, in a climate with an average of only 37 days of snow fall and a short lifespan of the snow pack, is inevitably labour-intensive. Various methods of estimation of snowfall and snowmelt have been tried at Plynlimon: the procedure used at present is to correct the estimates of precipitation given by the main raingauge network for "snow months" according to the readings of a reduced network of Meteorological Office standard raingauges in forest clearings.

Streamflow

Catchment experiments demand streamflow gauging of a high standard of accuracy and precision, but the combination of a wide range of flows, steep channel gradients and high sediment loads which typifies the British uplands imposes constraints on which type of gauging station can be used. Plynlimon has a range of different gauging structures: a Crump weir on the Wye, protected by a large stilling pool and sediment trap upstream, a trapezoidal flume on the Severn (also protected by a sediment trap), and seven novel steep stream flumes on the minor streams.

The history of flow gauging at Plynlimon is one of almost continuous checking, resurvey and maintenance of the gauging structures: only in this way can a consistently high standard be achieved and maintained. All the structures have been subject to field calibration by current metering and chemical dilution gauging, and, under conditions of extreme drought, the structures have even been checked volumetrically. As part of the routine operation of the catchment network, all structures are kept under surveillance to detect the early signs of bedload sediment intrusion and erosion which could change the calibration. With one exception, the minor structures have remained free of calibration problems due to sedimentation.

Evaporation

Given accurate measurements of rainfall and streamflow, the catchment water balance gives a good estimate of the actual evaporation over an annual timescale. However, to be of real application the annual catchment yield must be supplemented by a detailed understanding of the seasonal distribution of water losses. It is difficult to extract short-term evaporation estimates from the catchment data because of the difficulty in estimating the storage term in the water balance.

The Penman equation has been used widely for the estimation of short-term evaporation from meteorological variables: at Plynlimon a network of four automatic weather stations is used to collect the necessary data to provide daily estimates of potential evaporation.

Soil moisture

Appreciation of the importance of the storage term in the catchment water balance is growing: without knowledge of the storage of water in the catchment, detailed understanding, and hence prediction, of seasonal water yield is impossible.

An important aspect of water storage in catchments is the retention of water in the unsaturated zone of the soil. Though there are several methods for determining soil moisture, most are either destructive or involve disturbance of the soil profile. Only the neutron scattering method allows the determination of soil moisture in undisturbed soil surrounding a narrow vertical access tube.

Soil moisture access tubes were installed in an extensive network in the catchments and readings were taken monthly over five years. A reduced network was operated for a further ten years. It was found that local factors, including variability in soil properties and micro-topography, were more significant in controlling soil moisture variations than larger scale factors such as the position of the tube, the slope or the slope aspect. Soil moisture varies rapidly with time: water balances on a short timescale would require much more frequent readings which could only be taken by automated equipment.

Data precision

The success of the Plynlimon catchment experiment depends on the computation of differential evaporation rates from a range of measured variables. The precision of the final result is assured only if each of these measurements is made with a sufficiently high precision: it is important in this context to know the precision of the individual components of the water balance.

Areal precipitation is determined from a network of raingauges. Statistical analysis has shown that the Plynlimon network is capable of measuring mean monthly precipitation to a precision of slightly better than 5%.

The precision of streamflow gauging has been estimated by comparison of ratings of eight gauging structures, Cefn Brwyn weir on the Wye, the Severn trapezoidal flume and six subcatchment structures (the ninth structure, a steep stream flume on the upper Hore, has been in use since 1985). The calibrations were obtained by hydraulic theory, chemical dilution gauging and current metering. The dilution gauging rating for the Severn trapezoidal flume, extrapolated beyond the range of experimental points, gave a total discharge over a six-month period 5.4% greater than that calculated from the theoretical rating. In contrast a current metering rating, with a wider range of points, differed from the theoretical rating by 2.5%. It is concluded that the precision of stream gauging in the catchments is better than 2.5%.

7.4 The catchment water balance

Early results from the experiment, emerging from a study of the catchment water balance, indicated a larger water use by forested land than grassland but the growing emphasis on a more detailed understanding of the processes involved in runoff generation highlighted the need for the completion of the subcatchment networks. The instrumentation of nested subcatchments offered a number of additional advantages, not least the opportunity to explore spatial variation in the evaporation process, and to take account of practices such as felling and land improvement taking place in only part of the main catchment.

Within-catchment comparisons

Inevitably, the timescale of the experiment was lengthened by the expansion of its scope, and the necessary checks on the ratings of the subcatchment structures could not be completed until the early 1980s. Retrospective application of improved ratings of the minor structures and the Cefn Brwyn weir has increased confidence in the catchment data back to 1975, but earlier data is suspect because of progressive deterioration in the Severn trapezoidal flume, peak suppression in the Cefn Brwyn weir, and the lack of data for the application of a snow correction prior to 1977.

The installation of the subcatchment networks has more than repaid the investment: they provide an invaluable check on the internal consistency of the data, and the discovery of significant discrepancies in low flows in the Wye was entirely due to comparison work involving water balances for the Wye subcatchments.

In the Severn catchment, subcatchment water balances showed up significant hydraulic faults in the Hafren flume, subsequently circumvented by re-rating the flume.

Between-catchment comparisons

The catchment water balances for the Wye and Severn show a consistent difference: over the eleven year period 1975 to 1985, the catchment loss (difference between annual precipitation and annual runoff) for the Severn is between 99 mm and 267 mm greater than that for the Wye, with an average of 198 mm.

When a correction is applied for the non-forested area within the Severn, the loss for the Severn forested area, for the same eleven-year period, is between 145 mm and 390 mm more than that for the Wye, with an average of 287 mm. A completely forested catchment equivalent to the Severn would lose an additional 12% of precipitation, or 15% of runoff, in comparison with a grassland catchment.

Seasonal variations

The catchment loss, the difference between precipitation and runoff, is a rough indicator of the seasonal pattern of evaporation, but is complicated by the effect of soil moisture and groundwater storage. The catchment loss for the Severn is higher than the Wye throughout the year, larger losses in the late part of the year being due at least in part to higher soil moisture deficits in the forest.

The determination of the storage term in the water balance is more straightforward for the Wye than for the Severn, as the effect of interception by grassy vegetation can be assumed to be small. Although recent research on transpiration suppression from high altitude grassland will lead to modifications in the time distribution of actual evaporation, it has hitherto been assumed that the actual evaporation from grass is proportional to the potential evaporation, and hence the monthly actual evaporation from the Wye may be estimated fairly accurately. The total storage proves to exceed the soil moisture as determined by neutron probe measurements, by an amount which varies seasonally in a similar way to soil moisture storage. The size of this residual storage term, attributed to saturated groundwater in localised drift deposits, has important implications for summer base flow and for water chemistry.

When a similar analysis is applied to the Severn, allowing for the non-forested area at the head of the catchment, the monthly evaporation rate from the forest may be computed. Over a short period between 1977 and 1980 it was possible to separate out interception and transpiration components of evaporation, and it was found that transpiration from the forest, though an important component of the total evaporation in early summer, was actually less than that from grassland. The observed difference between total evaporation from forest and grassland is entirely due to the effectiveness of the interception process.

Actual evaporation from the grassland of the Wye catchment is between 15 and 17% of the precipitation, while the total evaporation from the forested part of the Severn catchment is between 29 and 32% of precipitation. Most of the loss from grassland is in the form of transpiration, while in the forest, about 25% of the rainfall is lost as interception, transpiration being suppressed to between 4 and 7% of rainfall, well below the potential evaporation.

The Plynlimon catchment experiment has provided data of a consistently high standard that demonstrates beyond reasonable doubt the partition of rainfall into evaporation and runoff both annually and seasonally. However, the climate is not steady, but changes on a number of timescales, ranging from the eleven year cycle associated with solar activity to longer term cyclic fluctuations and man-induced global warming. The Plynlimon catchment experiment has begun to show signs of trends in precipitation, runoff and evaporation, which appear to be associated with long-term changes in rainfall patterns. The long-running catchment experiment offers a unique opportunity to study changes as they occur, and a basis for predicting the response of the uplands to future change.

7.5 Hydrological extremes

Floods

Because of the high rainfall, steep channel gradients and the relatively low levels of soil moisture deficit that build up over the summer, the uplands are an important source of flood runoff. Yet the typical size of upland catchment represented by Plynlimon has not been much researched, even by the Flood Studies Report. This is mainly due to the lack of gauging stations in upland areas. On the River Severn, for example, full flood statistics are only available at Abermule, representing a catchment area of 580 km^2 or 68 times the size of the Severn above the trapezoidal flume. Although it has been demonstrated that afforestation reduces annual flows from British upland catchments, the intensive drainage and ploughing that is associated with the planting phase could, by increasing the drainage density, give rise to more rapid flood peaks, albeit with lower total flows. As with the elements of the annual water balance, the Plynlimon catchments offer a unique opportunity to examine the differences, if any, between grassland and mature forest.

The record of flows from the Plynlimon catchments is a little short for a full flood frequency analysis. In all 35 years of annual maxima can be amassed, by taking advantage of the data from stream gauging structures which pre-date the Plynlimon catchment experiment. For annual maximum flows, the difference between the flood frequency curves for the Wye and the Severn is not significant. More detailed analysis can be carried out on individual events. For a sample of 100 flood events, mostly smaller than the mean annual flood, a clear pattern emerges: for runoff rates of less than about 1 mmh^{-1}, peak flows from the Wye were consistently greater than those from the Severn. It is suggested that for small storms the effect of the more intensive forest drainage network, which tends to increase peak runoff and decrease response times, is more than compensated by the effect of interception by the forest canopy, which tends to decrease flood peaks, both by the reduction of total runoff and by delaying the arrival of water at the channel. At very high flows, interception is no longer of any significance, but conversely the artificial drainage network in the forest is no more intensive than the network of overland flow routes and natural pipes that become active in the grassland catchments. Upland floods in excess of the mean annual flood are scarcely affected by land use.

Low flows

If the uplands are regarded as a source for water supply, the significance of the reliability of low flows, especially during summer drought conditions, is clear. Although the filling of upland reservoirs in Britain takes place during autumn and winter, the rate of reduction of storage during the summer depends critically on base flow of the inflowing streams. The behaviour of streams under low flow conditions can be characterised by the base flow index, which is a measure of the proportion of total flow derived from groundwater or slow throughflow processes, the parameters of the recession curve, which can be used to predict the rate at which base flow decreases, and the flow duration curve, which indicates graphically the frequency distribution of flows. Within the UK, the range of base flow index is between 0.17 and 0.98. The base flow indices for the Plynlimon catchments and subcatchments are between 0.27 and 0.39, towards the less permeable end of the spectrum, but nevertheless demonstrating that groundwater and slow throughflow are important contributors to low flows.

Differences between subcatchments are consistent in base flow index, recession constant and low flows, e.g. Q95(1), the daily mean discharge exceeded for 95% of the time. However, these consistent distinctions between subcatchments are not associated with the vegetation differences, i.e. there is no tendency for forested catchments to have significantly different base flow characteristics. In extreme drought conditions, the most sustained flows have been from streams draining the central core of the Plynlimon anticline. This is also the area formerly mantled by blanket peat, now much eroded. Studies of groundwater in the blanket peat showed that spring flows towards the end of a long drought were fed by the weathered and fractured grit bedrock. The evidence from Plynlimon is that base flows are supplied by relatively deep sources, for instance the minor drift aquifers, which are unaffected by changes in vegetation. Low flow characteristics are available for a large number of catchments, and have been used to derive regional regression equations, which were presented in the Low Flow Studies Report (Institute of Hydrology 1980). The Plynlimon catchments compare well with published base flow index figures, and with low flow estimates predicted from the regression equations for Wales and south west England.

There have been two major droughts during the lifetime of the catchment experiment: the first, culminating in the summer of 1976, was brought about by two dry summers and an intervening dry winter, while during the second in 1984 there were six dry months starting in March. The detail of the catchments' response to such extremes is of interest. At times of extreme drought the runoff system is simplified and processes normally masked by others may be observed in isolation; such extremes also provide a model against which plans for water resource systems must be tested.

The 1976 drought consisted of a 16-month period over which the total precipitation was reduced by about 25%. During this time soil moisture measurements showed a deficit on forested slopes almost twice that on grassed slopes. In spite of this, and of reduced losses by interception, which is most significant in wet periods, the gross catchment loss from the Severn was much higher than that from the Wye.

The 1984 drought was more severe in the west of Britain than in the east, and the lowest flows in the catchments, which were the subject of repeated spot measurements as they had been in 1976, were even lower in some cases.

7.6 Hydrological processes

While the catchment water balance can answer the overall question of water use, the application of the results to other catchments, and particularly to the question of the effects of land use change on water quality, can be addressed only from a detailed understanding of the processes operating within the catchment. Process studies involve a different level of instrumentation: very intensive investigation of small plots within the catchment, often making good use of the background data provided on a more extensive scale by the catchment experiment.

Interception

The single most significant process contributing to the differences in the catchment water balance is interception of incoming rainfall by the intricate canopy structure of the trees, and its subsequent evaporation into the airstream. It had been shown by detailed hydrometeorological studies in the east of Britain that evaporation from the canopy was not limited by the available radiant energy, but could be supplied with energy by sensible heat transfer from the air itself.

To explain the phenomenon of interception, and to relate it to climatic variables, it was essential to develop a model of the process. This model had to simulate the process accurately, using easily measured parameters: a model whose parameters could be measured only by an intensive hydrometeorological study would be severely limited. The Analytical model used in the interpretation of results from the Plynlimon interception site relied only on hourly rainfall measurements. It treats incoming rainfall as discrete storm events, some of which will be insufficient to saturate the canopy.

The model was applied to data from four coniferous sites in the UK, and the most important parameter of the model, E, the mean evaporation rate under saturated conditions was found by optimisation. E was found to vary over a very small range, and it is concluded that the major cause of the variation in interception loss across the UK is not variation in the rate of evaporation, but the canopy capacity and the length of time over which the canopy is wet. The implication is that losses from interception are more closely related to the annual rainfall at a site and its time distribution than to the potential evaporation.

Another approach to the problem of evaporative losses from forest involved the isolation of a parcel of land to form a 'natural' lysimeter. The lysimeter, by excluding diffuse lateral throughflow and channelling both surface runoff and throughflow to a single gauged outfall, reduced the water balance equation to a balance of rainfall, evaporation, changes in soil moisture and lysimeter outflow. By measuring net rainfall at a nearby site, using a plastic sheet method that integrated both throughfall and stemflow, it was possible to measure evaporative losses from the canopy separately as interception and transpiration.

During the 1974 field season, losses from interception totalled twice the Penman estimate of transpiration. Transpiration rates were found to be matched by a form of the Penman-Monteith equation, with a canopy resistance that varied with vapour pressure deficit and with the time of year. No clear relation was found with soil moisture, even in 1976, when soil moisture deficits exceeded 200 mm.

Runoff processes on slopes

The mapped network of stream channels covers only a very small part of the catchment, and the importance of slope runoff processes in conveying excess rainfall to the channels is clear. Rainfall/runoff models that aim to simulate the effects of the spatial organisation of catchment elements, the distributed models, must take account of the processes of slope and channel runoff.

Runoff on the Plynlimon slopes is not generally dominated by Hortonian overland flow, as might be expected from a reading of hydrological texts. More recent research at Plynlimon and elsewhere has placed more emphasis on the consideration of subsurface flow processes, and on the partition of the catchment into contributing and non-contributing areas. The contributing areas extend up slope from the stream channels, taking advantage of micro-relief and channel-like features such as gullies and natural pipes.

The piping process is an intriguing demonstration of the significance of small and inconspicuous landscape features on the overall response of catchments. The lack of generalised overland flow in areas of the catchments between drainage channels and streams had been noted, as had the role of small declivities in focusing local surface flows, when it became apparent that very rapid downslope movement of water was taking place through subsurface pathways, which appeared to form a coherent network, but became really evident only when the flow was forced to the surface.

Natural pipes at Plynlimon are confined to slopes of between ten and twenty degrees, and are more common on south-facing slopes. They are generally absent in forested areas of the catchments: though it was still possible to trace pipe networks in the newly-planted Coalburn catchment in Cumbria, it is probable that the furrow pattern takes over some of the hydrological functions of the pipes, which cease to flow and finally collapse or fill.

Although the method of formation may differ in different soils, pipes always require a locally steep hydraulic gradient: they are often found in areas where such a gradient has been recently created or arises periodically, for instance in drained peat bogs, artificial embankments and salt marshes. In Plynlimon it is believed that the shallower ephemeral pipes are caused primarily by cycles of desiccation. It is certain that the summer of 1976 caused a disruption of the pipe networks, by opening up new cracks and changing the preferred directions of flow.

The deeper pipes have the appearance of peat-bridged streams, and appear to follow the lines of pre-glacial stream channels, presently filled with drift materials. It is the ephemeral pipe network that is of most interest in the modelling of runoff response: pipes provide a rapid response process akin to overland flow, generally beginning to flow after about 10 mm of rain, and carrying excess rainfall very quickly to the valley bottoms, where runoff finds its way to the stream by complex pathways through the valley bottom mires and marsh.

The initiation of pipe flow depends in a complex way on the soil moisture deficit: perhaps this is the least satisfactory result to come from the pipe flow studies, but it is clearly true of storm runoff in general. Soil shrinkage as a result of a high soil moisture deficit opens new pathways for storm runoff, and can lead to larger total flows and more rapid response times than would be expected by considering catchment-scale water balances. Response to summer storms is clearly a function of rainfall intensity as well as rainfall totals, and the piping process demonstrates how this may be due to processes operating on the micro-scale.

Other studies within the Wye catchment have shown up important spatial variations in runoff processes. The pipe flow studies were broadly in agreement with the results of a throughflow study on a south-facing slope which took account of flow through macropores in the podzol soil in addition to flow through the matrix of the soil. Blanket peat at the top of the slope acted as a slowly permeable storage reservoir, and the valley complex was the focus of overland flows as throughflow was forced to the surface. However, work on a gully in soliflucted material on a north-facing slope suggested that overland flow might have greater importance on this slope.

Contrasting results like this point to the need for a detailed spatial approach to modelling, particularly if models are to be used on other related but not identical catchments.

Intensive studies of the hydrology of blanket peat areas, in moorland around the source of the Severn and at a lower altitude within the forest, illustrated the relationship between water storage in the peat and flows in erosion channels and in forest ditches. It was concluded that the eroded blanket peat, though it does act as a store of water, has only minor significance on a catchment scale. In the forest, the drainage effect of proximity to ditches was less important than the lowering of the water table through interception of rainfall by the forest canopy.

Routing of runoff

Runoff generated by intense rainfall on the catchment flanks is modified and delayed by flow mechanisms on slopes and in the stream channels. Each process imposes its signature on the hydrograph: the practice of hydrograph separation, for example as carried out in the derivation of the base flow index, depends on the recognition of the contribution of each of a family of processes, from surface runoff to throughflow, in the shape of the hydrograph.

It is difficult to use inspection of the hydrograph to separate flow processes that have similar characteristics, for instance pipe flow and stream channel flow, but tracer methods lend themselves very well to the study of channelised flows, and can be used to derive quantitative results. A channelised flow has two main parameters, a mean velocity and a cross-sectional area. Each of these is related to the total discharge, in such a way that their product is equal to the discharge: usually both measures increase with discharge but in some cases the major component in increasing discharge is increasing velocity, while in others it is the depth or cross-sectional area of the flow.

Tracer studies at Plynlimon established that for overland flow, velocities are very low at low discharges, but increase very rapidly with depth. On the other hand, the rate of increase of velocity with flow in stream channels and natural pipes is less pronounced; the increase in discharge is due, roughly equally, to increased depth and increased velocity. Where form roughness is important, for example in steep, bedrock-controlled channels such as those at Plynlimon, increased discharge is sometimes almost entirely due to increased depth.

Modelling

Process investigations typify the analytical approach, in which the catchment is stripped down to its basic operating units, and processes must be separated and eliminated one by one. The ultimate aim is to derive results of general application, and to be able to predict the response of similar but not identical catchments to rainfall events, land use change or climatic causes, and this demands the assembly of what has been learnt about the individual processes operating on the micro-scale into a model of the behaviour of the complete catchment.

There are three main approaches to the modelling problem, with different domains of application:

(i) the distributed model seeks to incorporate detailed knowledge of the workings of the catchment and its spatial organisation. In a suitably modified form, taking into account measurements and mapped variables, the distributed model can be applied to another catchment.

(ii) the lumped catchment model is of most application to the prediction of future events in a known catchment, relying as it does on a sufficiently long record of catchment data. The parameters of a lumped model are integrals of field hydrological properties, and as such are not always easy to modify to apply to an unknown catchment.

(iii) stochastic models incorporate a random element, taking account of statistically distributed hydrological properties.

The distributed model starts with the intention of reaching a solution to the equations of flow on a catchment, both on the slopes and in the channels. Unfortunately these equations are non-linear and intractable in their pure form, and approximations have to be made to keep the model within the bounds of computer storage capacity and computer time. A number of distributed models, each using a slightly different approach to the simplification of the flow equations, have been developed and used on Plynlimon data.

The IH distributed model (IHDM)

The IHDM models the hillslope as a cascade, taking into account saturated and unsaturated throughflow and overland flow. The catchment is represented as a dendritic network of hillslope cascades and channel elements, and the simplified equations of surface and subsurface flow are solved by a finite element method.

Good results have been obtained using the IHDM, but there is some difficulty in establishing the appropriate values to use for the parameters: inevitably each parameter is defined for an area rather than a point, and some of the most important parameters, notably surface roughness and soil properties, have been optimised against measured catchment outflows. However, the model has proved robust enough, with the optimised parameters, to make accurate prediction of flood events outside the calibration period and on an adjacent subcatchment.

The SHE model

The SHE model's approach to the modelling problem differs from the IHDM: surface and saturated subsurface flows are modelled on a two-dimensional grid, whereas unsaturated subsurface flow is assumed to be vertical. The SHE model uses a finite difference method to solve the simplified equations. The model has been tested against catchment data from the Wye. Again certain parameters have been found to be particularly important: in this case the model is sensitive to soil properties such as the hydraulic conductivity and the initial soil moisture status.

7.7 Water quality

Upland water sources are valued for two attributes above all: the large quantities of runoff produced by high rainfall and low evaporation, and the quality of the water deriving from catchments with small human populations, little intensive agriculture and minimal industrial pollution. The water quality factor cannot be taken for granted: all regions of the UK are open to the possibility of changes in land use, and high leaching rates and the inherent instability of upland soils can exacerbate the effects of unwise alteration of the pattern of land use.

Sediment studies

Sediment studies at Plynlimon have helped to demonstrate that planted forests, far from controlling the rate of soil erosion as their natural counterparts do all over the world, actually contribute to enhanced erosion rates. The reason is that upland soils on steep slopes, often overlying deep drift deposits, are highly susceptible to erosion when flows are localised. The prerequisite of successful planting of trees in the uplands is good drainage, and traditionally this has been guaranteed by ploughing and ditching: both activities involve disturbance of the surface soil, and the channelling of drainage water provides ideal conditions for rapid and accelerating erosion.

Soil erosion has been studied widely in the UK and overseas: at Plynlimon it has been possible to adopt a whole-catchment approach, which takes into account not only the supply of sediment from the soil surface on the catchment slopes but also the sediment storage in and release from channel banks and bed features.

Sediment carried by streams is conveniently classified as bed and suspended load, according to its mode of transport by the water, and also according to available sampling technology. Suspended load, consisting of the finer particles, can be sampled by taking water samples or measuring the turbidity over a range of flows, while bedload is usually trapped, and the accumulated trapped load measured at low flows.

Bedload trapping at Plynlimon has shown that sediment yields from mature forested catchments are 3.5 times higher than those from similar grassland catchments. The increase in yield varies widely, and results from ditched moorland catchments, confirmed by field survey of drains in forested catchments, indicate that ditching, by exposing unstable subsoils to erosion in steep channels, is the major cause of increase in bedload yields.

Tracer methods have been used in ditches and stream channels to follow the downstream movement of bedload particles. In Plynlimon sediments, changes in magnetic susceptibility are easily induced, and altered sediment particles are identical in most other physical properties to the unaltered particles. The tracer studies confirmed one of the conclusions from trapping studies: that the capacity of the stream to transport bed sediment is less important in controlling the rate of transport than are the rate of supply of sediment and its storage in bed features.

Concentrations of suspended sediment in upland streams in mid-Wales are much lower than those in lowland reaches but their contribution to total sediment yields is still far from negligible. There are roughly equal amounts of suspended and bed-load yielded on a annual basis, although the relative proportions vary between subcatchments. In the course of a regional study commissioned by the Ministry of Agriculture, Fisheries and Food, it was possible to extend the study of sediment yields far outside the confines of the Plynlimon catchments. Measurements over five much larger catchments demonstrated the significance of the suspended load component.

Suspended load presents a formidable sampling problem in upland streams. Flood response is rapid and the period of high concentrations on any given flood flow is usually short-lived. A manual bulk sampling system was adopted in preference to the use of automatic samplers, which were found to give spurious results. Because of the limited depth range available in upland streams, a sample intake could also include bedload and saltating load. Flow velocities and the degree of disturbance to flow patterns at the intake nozzle also contributed to discrepancies between automatic and manual sampling. Manual sampling was supplemented by the installation of turbidity sensors. In the Plynlimon catchments the yields of suspended load followed broadly the same pattern as bedload: in subcatchments with mature forest cover, suspended loads were between 2 and 6 times those from the grassland Cyff subcatchment.

A joint study with the Environmental Safety Division of AEA Environment and Energy for the CEGB was completed in 1990. Caesium liberated in the Chernobyl incident has exhibited a strong attachment to particulate sediment. Monitoring of radio-caesium activity in the surface layers of the catchment soils has indicated zones of erosion and deposition on the surfaces of the Plynlimon experimental catchments. Chernobyl-derived ^{137}Cs was found to have contributed approximately 15% to the pre-existing radio-caesium inventory in the catchments. A network of specially designed bulk sediment samplers and bedload traps has been used to provide samples from streams at the lower ends of the catchments. Combination of caesium concentration data with estimates of catchment sediment outputs has permitted the calculation of the annual loss of Chernobyl-labelled caesium via stream outputs. Analysis has indicated that approximately 0.08% of the soil inventory of Chernobyl derived caesium has been removed per year from the Wye and Severn experimental catchments in 1988 and 1989. Suspended sediments accounted for 95.5% - 98% of this output. The other component of the output, highlighted by this study, was in the bed-load. During the study period, the University of Exeter analysed high flow samples for radio-caesium in dissolved form, but none was detected.

Sediment pollution is one of the most serious problems associated with upland forestry. This has been widely recognised in recent years, and sediment outputs are dealt with in a commendable new document "Forests and Water: Guidelines" (Forestry Commission 1988) and in the recent Nature Conservancy Council publication regarding impacts upon freshwater habitats (Maitland, Newson and Best 1990).

One of the interesting aspects of the Plynlimon results is the long term record of enhanced sediment yields associated with open drains. The implication for forest management is that where such erosion is perceived as a particulate pollution problem it is better to intervene to reduce sediment outputs than to assume that erosion rates will fall off with time, as often occurs with natural erosion inputs. The Plynlimon data have been used to indicate the impact of forest land use practice on sediment loads in streams throughout the forest rotation given conventional practice. These studies have also detailed, from survey of source areas and sediment tracer experiments, the delivery of sediment from the catchment surface, drains and tracks. With regard to the practical objective of an upland forested catchment with low sediment output, the need to isolate forestry track road embankments and drains from streams has been recognised and the value of modification of existing drain systems has been demonstrated. The beginning of the second rotation provides a good opportunity to get heavy plant into the felled forest areas to modify old badly eroding drain and road systems (Leeks 1990).

Serious sediment pollution associated with afforestation of 11.5% of the catchment of Cray Reservoir in the Brecon Beacons, South Wales, provided an opportunity to test the value of direct intervention to halt persistent erosion problems in existing forests. High inputs of suspended sediment immediately following afforestation in 1981 were reported by Stretton (1984). This problem persisted, resulting in reported additional operational costs of more than £350,000. By 1987 it was apparent that the dominant source was one spectacularly eroding drain which had contributed approximately 10,800 tonnes of sediment to the reservoir. This was found to be carrying a disproportionately large amount of the surface drainage, straddling two catchments, and was constructed with a long profile slope which was considerably steeper than FC guidelines. Following a joint site visit in 1987 by IH staff and C. Stretton from Welsh Water, modifications were carried out to the forest drain network, with the co-operation of Economic Forestry Ltd., leading to stabilisation of the eroding drain (Leeks 1990) and immediate reduction in sediment pollution back to acceptable levels for water supply.

Elsewhere, Robinson and Blyth (1982) and Burt *et al.* (1983) have also reported large quantities of sediment released by forest operations. Austin and Brown (1982) illustrated the costs of dealing with enhanced suspended sediment outputs following the excavation of forest drainage ditches above Holmestyles Reservoir in the Pennines: a new £78,000 water treatment works was required.

Major ions, pH and metals

The chemistry of most upland catchments represents a combination of natural chemical cycling and man-induced effects. The Plynlimon catchments are no exception to this, exhibiting few areas that have not been altered to some degree by man's activities. Large areas could be described as "semi-natural" because sufficient time has elapse since the land disturbance, for instance the iron-age clearances, for new equilibrium conditions to have been established.

The chemistry of streamflow from these semi-natural areas is dominated by precipitation chemistry, with a distinct sea salt bias, dominated mainly by Na, Mg and Cl. However, certain events have a chemical signature higher in industrial pollutants, SO_2, NO_x and metals. This effect is seasonal but not consistent as it depends on the direction of the prevailing winds; easterly winds associated with high pressure systems can occur in winter and summer. The precipitation is naturally acidic (mean pH 4.5) but can drop as low as 3.5 during some events, particularly during the winter when easterly winds bring snow. This form of precipitation appears to be especially efficient at collecting pollutants, which may form the nuclei that catalyse snowflake formation.

To maintain the ionic balance in solution, excess inputs of acid will remove Ca and Mg preferentially from the soil, but where soils do not have large buffering capacity, i.e when they are naturally low in calcium or magnesium carbonate, or where the buffering capacity has been exhausted by a long history of post-industrialisation pollution, then aluminium, yttrium and other related metals can be lost as substitutes. Streams susceptible to this type of pollution, which is increasingly linked to population failures in stream biota and fisheries, can be identified by their low calcium levels (<2 mgl^{-1}) and low hardness (<10 mgl^{-1} as $CaCO_3$). Many of these metals increase in concentration with flow, which suggests that the classic Hortonian model of overland flow is not the prime process at work. In such cases, the streamflow would be characterised by the low aluminium levels typical of rainfall. As the concentration is more reminiscent of Al levels in the lower inorganic soil horizons, this suggests that lateral piston or displacement flow is the dominant process at work.

At Plynlimon, the forested catchments all have low pH but, before laying blame completely at the door of the forestry industry, it should be remembered that these levels are nearly matched by flow from acidic "unlimed" catchments, as represented by the upper Wye. Areas of the Cyff and Iago on the other hand, which have received lime applications at varying intervals since the 1930s, when the first moves towards improving upland pastures started, have higher mean pH. High pH occurs mainly during baseflow although these limed catchments also exhibit reasonable buffering from the lower soil layers which prevents the persistence of acid conditions following an acid event that is common in forested streams and which can prove so detrimental to fisheries.

Nutrient cycling

What was once thought of as potentially the most serious water quality problem facing the uplands, that of increasing nutrient losses and the consequent eutrophication of upland lakes and reservoirs, has been held in abeyance by a number of factors. Firstly, the rivers and lakes in mid-Wales do not seem to be as susceptible to nitrate runoff as their lowland counterparts; the generally cooler climate precludes the worst cases of algal blooms found in the south and east England, some of which have been highly toxic. Phosphorus loss is thought to be more important in upland areas, with levels as low as 10 μgl^{-1} likely to result in eutrophication problems.

While intermittent high levels of P have been found in streams, particularly following land use disturbance such as moorland ploughing, clear felling or grassland improvement, the Plynlimon nutrient studies have shown that established forestry, which accounts for 40 years out of the 50-year forestry cycle, shows no greater levels of N and P than established grassland. Phosphorus, when mobilised, is very easily readsorbed, so that unless ploughing is carried out directly adjacent to a water body, the dominant physico-chemical processes will tend to prevent discharges to lakes in sufficient quantities to cause any long-term problems.

N and P applied to improved grassland can also cause local problems of pollution, as demonstrated by the lysimeter study conducted in the Iago subcatchment of the Wye, which recorded nitrate-N concentrations of up to 19 mgl^{-1}, or twice the World Health Organisation recommended upper level for drinking water, for a short period following tile drainage and fertiliser application. However, because hydrological processes in the catchments tend to act as cascades from one land unit to the next, nutrients released in one part of a catchment may well be locked up in another. In the case of N and P this could be the wet riparian mire typically found on glacial terraces at the foot of many slopes in mid-Wales and elsewhere.

The progress of grassland improvement has been piecemeal and on only small areas of catchments at one time, so that the effects have a chance to die down before the next phase of improvement. Add to this recent changes in agricultural grant schemes and general over-production in the EEC and the pace of improvement has slowed considerably. There is the possibility, however, that warmer conditions in the uplands and a lower demand for meat products could see arable agriculture move "up the hill" and that smaller amounts of nutrients in water bodies would be necessary to cause toxic algal blooms and associated problems for ecology, fisheries and potable water resources. Any deterioration of upland sources of water will also impair their currently effective role as a dilution agency for polluted lowland waters.

7.8 Land use implications of the Plynlimon study

An indication of the scale of the environmental impacts recorded at Plynlimon, both in time and spatial extent, is presented in Table 32. Some of the effects of land use change are limited in timescale, for instance it has been established that the effect of forest ditching in increasing flood flows is soon counteracted by the reduction in catchment yields as the forest matures. Sediment yields, increased by forest planting, are also increased by felling, so that in this case a repetitive cycle of increased yields might be expected, in step with the cycle of forest growth. Other effects will be sustained by repetitive operations, for instance upland grassland improvement has to be maintained by careful attention to drainage, regular application of fertilisers and lime, and periodic ploughing and reseeding.

The full relevance of the Plynlimon results can be appreciated only when they are set in a geographical context, and compared and contrasted with results from other upland hydrological research. As will be seen, this exercise is easier for quantity effects than for quality: catchment physics, controlled by the climate, landform, the current land use and simple physical properties of the soil, is more spatially uniform than catchment chemistry, which depends on all of these plus the more variable chemical constitution of the soil parent material and the past history of the land.

Water yield

The Stocks lysimeter

As a first step in establishing the wider geographical credentials of the Plynlimon results, Law's work in the catchment of the Stocks Reservoir must be considered in detail. When Law wrote his 1956 and 1957 papers, he made use of data for only one and a half years: in collaboration with the North West Water Authority, data for a further fifteen years have been recovered and processed by the Institute. The analysis has been carried out for annual, seasonal and shorter periods (Table 32).

Law challenged the policy of afforestation of water supply catchments with data from a 450 m^2 lysimeter, showing that over a 12-month period forested land was subject to 290 mm extra evaporative loss. He suggested that if the whole of the Stocks catchment were afforested the effect would be to reduce the water supply by 42%.

Rainfall and runoff data for the Stocks catchment have been analysed by the North West Water Authority using double-mass techniques. A significant break was identified in 1954 with an average increase in evaporation losses since that date of 37 mm $year^{-1}$ (Walsh 1977). A separate analysis of the data identified a trend towards increasing losses of 4.4 mm $year^{-1}$

TABLE 32 Summary of data from Stocks Reservoir (Units: mm)

	Calendar years															Averages	
	1956	1957	1958	1959	1960	1961	1962	1963	1964	1965	1966	1967	1968	1969	1970	All Years shown	6-years 1961-64 1966,67
Forest Lysimeter (450 m²)																	
1. Rainfall: mean of 3 outside gauges	1374	1557	1491	1245	1588	1615	1468	1367	1323	1552	1651	1915	1547	1184	1565	1498	1556
2. Throughfall: stemflow & plantation gauges	871	1003	1039	757	1001	993	902	836	828	955	1008	1062	1072	678	897	927	938
3. Interception: (1-2)	503	554	452	488	587	622	566	531	495	597	643	853	475	506	668	569	618
4. Lysimeter Runoff	411*	734	762	447	523	538	531	457	510	#	531	663	#	#	#	555	538
5. Gross Losses: (1-4)	963	823	729	798	1065	1077	937	910	813	-	1120	1252	-	-	-	953	1018
6. Nett (evapotranspiration) Losses: (2-4)	460	269	277	310	478	455	371	379	318	-	477	599	-	-	-	381	400
Stocks Reservoir Catchment (22% afforested) (37.5 km², including Bottoms Beck)																	
7. Estimated Area Rainfall	1471	1725	1665	1370	1785	1811	1640	1519	1412	1740	1841	2133	1737	1328	1750	1662	1726
8. Catchment Runoff	1038	1208	1200	907	1375	1439	1212	1143	979	1270	1355	1565	1289	881	1254	1208	1282
9. Losses: (7-8)	433	517	465	463	410	375	428	376	433	470	486	568	448	447	496	454	444
Bottoms Beck Catchment (70% afforested) (10.6 km²)																	
10. Estimated Areal Rainfall						1674	1458	1405	1269	1575	1684	2065	1593	1224	1494	1544	1592
11. Catchment Runoff						1250	1016	993	808	1092	1191	1341	1123	734	945	1049	1100
12. Losses (10-11)						414	442	412	460	483	493	724	470	490	549	495	492

Notes: 1.* Not recalculated from original field sheets.
2.# Runnoff data thought to be unreliable for all or major part of year.
3. 21 trees removed from lysimeter in March 1962 and a further 17 in December 1967 leaving 57 thereafter.
4. In May 1957 there was a severe loss of needles from trees in the lysimeter due to a aphid attack.

since afforestation began on 22% of the main catchment. The Plynlimon results have been applied to the Stocks catchment, assuming that the trees reach maturity at 25 to 30 years, and that the whole catchment was afforested. The average annual losses at Stocks were predicted to increase from around 400 mm year^{-1} to between 500 and 600 mm year^{-1} for the partly-forested catchment, which is equivalent to between 854 and 1309 mm year^{-1} from a completely forested catchment. This is consistent with an average interception loss of 569 mm year^{-1} measured by the lysimeter. Furthermore, measured net losses of transpiration plus evaporation from the ground surface of the lysimeter, 381 mm year^{-1}, are comparable with an average loss of 403 mm year^{-1} from the reservoir catchment prior to afforestation.

Interception is the 'new' process giving rise to the observed increase in evaporative losses from mature forest. The interception ratio, defined as the ratio between interception and annual rainfall, is 38% at Stocks, a similar value to Calder's lysimeter work at Plynlimon, but higher than the water balance results which suggest 25%. The chosen figure for forest cover in the Severn of 68% may account for the discrepancy, since many workers consider 60% a more reasonable estimate of 'active' forest.

Catchment experiments

There are very few other sources of data on the hydrological effects of afforestation in the UK at the catchment scale; there are no others in which small-scale process studies have been nested within a long-term conventional catchment framework. Green's paper on the initial effects of afforestation on the Brenig catchment (Green 1970) had the advantage of a long data base prior to the land use change (Lewis 1958) but reported on only the first few years of runoff after the catchment was ploughed and planted. At that stage the effect of the land use change was to increase water yield by 10% each year. Robinson (1980) also records an increased yield after ploughing and both papers relate the increase to the efficiency of drainage during the site preparation, i.e. catchment dewatering. Baty, Rodda and Templeman (1973) confirm that the change of albedo, by virtue of the fact that 80% of the ploughed area becomes bare earth, cannot of itself explain the enhanced yield. There is of course no transpiration from bare ground until revegetation occurs, a process which can take a few years. The same phenomenon has recently been seen at Balquhidder in the Monachyle catchment.

More recent analyses from the Brenig catchment, and the neighbouring Alwen catchment, both of which support reservoirs, show that losses have increased with the establishment of the forest cover. These losses are well correlated with precipitation in the winter season, an indication of the importance of interception, and are greater for the more heavily afforested Alwen (as reported by A. O. Lambert, Welsh Water).

In the early 1980s it was recognised that little was known about the water use of upland catchments in Scotland. The Balquhidder catchment experiment was set up by the Institute to investigate the effects of land use change in the Scottish glens, where altitude ranges, ground surface slopes and precipitation regimes are very different from those found in mid-Wales. Other important differences are the more frequent occurrence of snow and the change from intermediate height vegetation to forest. The Balquhidder project is partly funded by a consortium of bodies interested in land use, water supply and power generation. Like Plynlimon it has become the focus of detailed process studies set against the framework of the main catchment experiment.

The Balquhidder experiment consists of two instrumented catchments, the Monachyle which is primarily heather moorland, and the Kirkton which is 35% mature forest and 65% high altitude grassland. The results from the catchment experiment and process studies at Balquhidder (Blackie, 1987; Hall, 1987; Calder, 1986) show that heather moor has a high water use, related to a high interception, and that the high altitude grassland has a surprisingly low water use. This unexpected result suggests the limitation of transpiration at low temperatures, and the associated reduction in the length of the growing season.

With the above exceptions, the Plynlimon experiment is unique. It might be expected that the effects of reduced runoff from forested areas around reservoirs would have been detected within the water supply industry in due course, if the phenomenon did indeed pose a serious problem. However, this is doubtful in view of the relatively small proportions of upland reservoir catchments at present covered by trees (Calder and Newson 1979), and the lack of a sufficiently high standard or areal rainfall measurement and stream gauging in most reservoir catchments. There is now evidence that the effects of reduced runoff do emerge when the performance of reservoir catchments is examined closely. For example, Llyn Clywedog, whose catchment contains significant blocks of forest, including parts of the Hafren Forest, filled more slowly after the 1976 drought than did its more grass-covered neighbours Lake Vyrnwy and the Elan Valley reservoirs. Trentabank Reservoir in the North West Water Authority area, also forested, responded very slowly to the wet conditions which followed the drought.In Scotland there are indications that the losses from the Loch Grennoch catchment have increased following afforestation. Although the hydrometric data available here are far less comprehensive than at Plynlimon or the Stocks Reservoir, increased losses can be evaluated on the basis of the output of hydro-electricity. This is also the case at Loch Doon, where a fall in generator output can be translated into an increased loss of 41 mm year^{-1} over the period of forest establishment.

Robinson's (1980) study of the increased flood potential during forest establishment is, however, not unique: the success or failure of peat drainage has exercised many investigators, mainly motivated by the need to achieve suitable soil conditions for farming or forestry, or conversely by the suspicion that open ditching is environmentally harmful.

A widespread example of open drainage ditching for upland farming is the practice of "moor gripping". Conway and Miller (1960) using hydrographs, and Stewart and Lance (1983) using a literature review and botanical fieldwork, concluded that blanket peat of the type most often encountered by upland forestry and farming cannot be drained, and that the effect of open drainage ditches is merely to remove surface water. There is thus an obvious tendency towards quicker and higher flood response. Robinson (1985) confirms and extends this conclusion. Robinson has since shown how annual flood peaks were almost doubled, for a given return period, in the Brenig catchment following the period of ditching reported by Green (1970). Once again, however, there is a great shortage of gauge records to permit such analysis.

Acreman (1985) has indicated that on a larger scale, more relevant to flood protection works, the timing and location of forest drainage controls hydrograph response: whilst afforestation of the lower Ettrick, in Scotland, reduced flood flows, similar practices in the upper basin of the Ettrick increased peak flows by 37%.

At a much larger scale, the forest processes identified at Plynlimon as affecting water yield may be considered to apply worldwide. The review by Bosch and Hewlett (1982), whilst it was concerned with truly experimental catchments, where the crop was deliberately harvested, and therefore did not include Plynlimon within its purview, suggests that a 250 mm additional loss might be caused by coniferous trees covering a catchment to the same proportion as the Severn. For an annual precipitation in excess of 2000 mm, Bosch and Hewlett suggest an extra loss of more than 400 mm.

Their review is too wide in its scope to allow detailed comparisons, but there has been successful use of the hydrometeorological studies performed by the Institute in the management of forested catchments in New Zealand, under similar climatic conditions (Pearce and Rowe 1979).

Extrapolating the Plynlimon results

To apply the Plynlimon results to other regions of the UK is to undertake an extrapolation process, which must be based on similarities, but must also take realistic account of differences. The physical process studies in the Plynlimon catchments, together with others carried in Thetford Forest, East Anglia (Stewart 1977, Gash and Stewart 1977) and in Scotland (Gash *et al.* 1980, Calder *et al.* 1981) have demonstrated that high rates of evaporation from free water on the forest canopy during and after rainfall are the primary causes of the reduced streamflow observed from forested areas. Extrapolation of results on water yield to other regions must be based on our understanding of this process.

Climate and interception

The meteorological variables that determine evaporation associated with rainfall are the duration of the rainfall and the specific humidity deficit during rainfall, with wind speed, radiation and temperature playing only a secondary role. In the south and east of the UK the annual rainfall is less, and so is its duration: hence losses through interception are smaller than through transpiration. In the wetter north and west of the country, the difference in the transpiration between trees and grass has a smaller proportional effect on the total losses, and interception is by far the most important component of the total.

The climate of the British uplands is characterised by high rainfall and wind speed and low temperature, radiation input and evaporative demand: however, within this generalisation there is considerable variation, especially with respect to precipitation and temperature. The total annual rainfall varies from 600 mm in the south east of England to over 4000 mm in parts of Scotland, the Lake District and North Wales. Temperature shows a considerable decrease with altitude, typically 0.7 degrees per 100 m, as well as a latitudinal variation. Despite the large variability in total rainfall, intensities are relatively constant. Mean values quoted for England, Scotland and Wales range from 1.1 to 1.6 mmh^{-1} with no evidence of a systematic change across the country, although observations from Plynlimon show a small increase with altitude, from 1.2 to 1.6 mmh^{-1}. The rainfall duration (Figure 71a) is therefore proportional to the rainfall total, and this explains the very consistent relationship between the interception loss and total rainfall found in the UK (Figure 72; Calder *et al.*, 1981).

Measurements of the specific humidity deficit during rainfall are not widely available. In Plynlimon, where it can be calculated from the measurements made by the automatic weather stations, values range between 0.2 and 0.6 g kg^{-1}. This is very near to the accuracy of the measurements, and so the variability needs to be regarded with some caution. The lower values tend to be at the higher altitude stations. It was widely

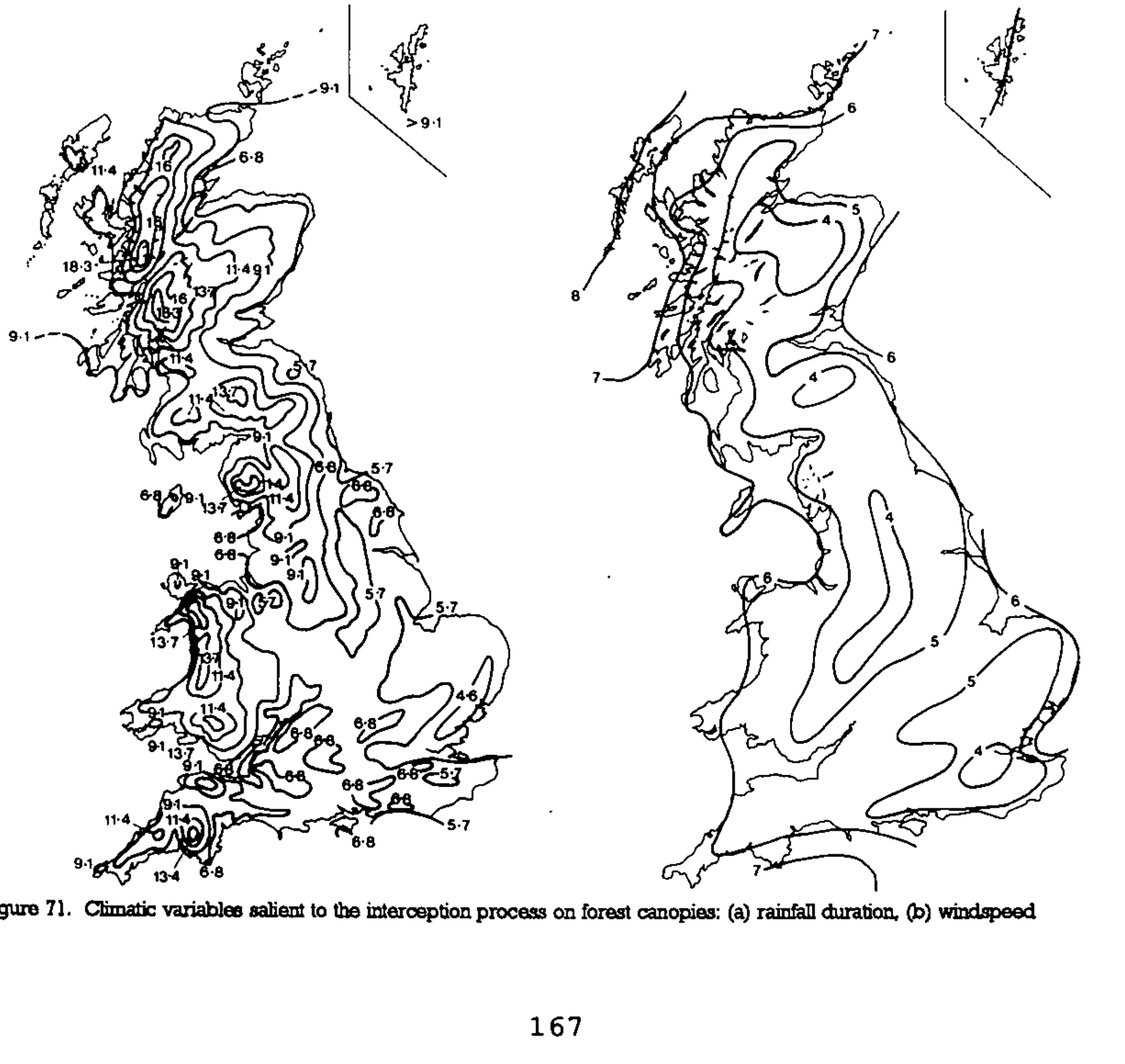


Figure 71. Climatic variables salient to the interception process on forest canopies: (a) rainfall duration, (b) windspeed

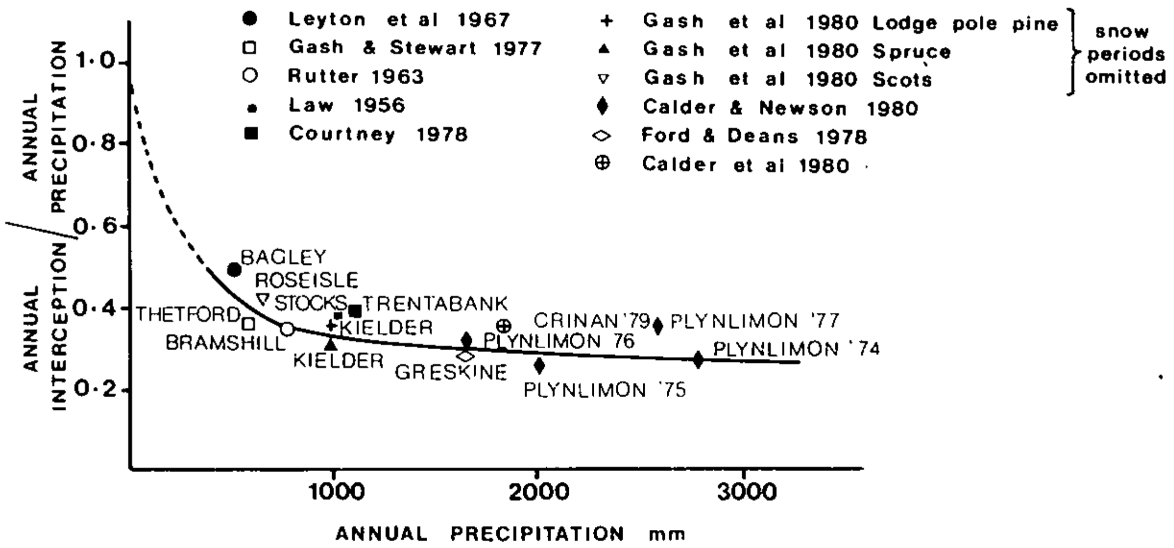


Figure 72. Plot of the interception ratio (Calder and Newson, 1979)

assumed that evaporation could not occur during rainfall, however the Plynlimon experiment has shown that considerable rates of interception occur with very small specific humidity deficits, these deficits being maintained by significant advection of relatively dry air. Deficits calculated at other automatic weather stations in the UK show a similar range to Plynlimon, typically 0.3 to 0.16 g kg^{-1} in the north and west of Britain, but greater, between 0.8 and 1.0 g kg^{-1} in lowland southern England.

Observed high rates of evaporation from a wet forest canopy would be expected to have both a cooling and moistening influence on the overlying atmosphere, leading to saturation. The high wind speeds (Figure 71b) associated with rain give rise to efficient vertical mixing, which will generally extend upwards to between 1 and 3 km. While a precise calculation of this depth of mixing and the consequent humidification of the atmosphere would be an extremely complex problem, an order of magnitude calculation can be made based on a mass and energy budget of the planetary boundary layer and order of magnitude estimates of the depth of mixing, surface fluxes and initial conditions. If a 2 km depth layer is considered, in 30 minutes a specific humidity deficit of 0.5 g kg^{-1} will be reduced by one half, with typical observed evaporation rates. In the frontal systems which give the majority of the rainfall in the west of the UK, the flow speeds in the lower atmosphere are typically 20 ms^{-1}: hence the air would have to travel over a forest for 36 km before its humidity deficit was halved.

Pearce *et al.* (1980) found that the specific humidity deficit measured over a wet forest at Thetford was 0.2 g kg^{-1} less than that over adjacent wet grassland; if the lower wind speeds in this area of the country are taken into account, this results agrees broadly with the calculation outlined above. It can be concluded that if a forest is larger than 30 km in the west or 15 km in the east, the feedback of high evaporation rates into the atmosphere will begin to have a significant effect. There are very few forests of this extent in the UK, but in other areas of the world, such as Amazonia, the USSR and Canada, these effects must have hydrological significance.

Temperature, while not of direct importance to the interception process, will determine whether precipitation falls as rain or snow.

Snow is a comparatively unimportant facet of the Plynlimon climate: there are on average 37 days per annum with snow falling. In parts of Scotland this is not so, and many stations report in excess of 60 days with falling snow. Studies from outside the UK give contradictory results, but it is evident that snow interception is appreciable in some climates. Detailed work in interception losses from snow started at Plynlimon using gamma attenuation techniques, which were then transferred to Scotland where more regular snow would be encountered. A site in the Queen's forest at Aviemore was chosen as more suitable logistically than the Balquhidder catchments.

Vegetation, interception and transpiration

A wide range of coniferous tree species is available for planting in the UK, and the choice of species is made on the basis of expected yield, given the soil type and climatic conditions of the site. Planting density and other aspects of crop management are also subject to variation, although during the first rotation these aspects of forestry practice have been standardised to a degree, and a pattern of close planting and later thinning has been adopted.

There is limited information on the influence of forest composition on interception losses. Table 33 gives a brief review of the UK literature on interception losses, broken down by species. Studies of interception on a range of forest trees have demonstrated that the range of values for interception losses is smaller than might be expected. Although the widely planted Sitka spruce has been extensively studied, less attention has been paid to the alternatives such as larch and Lodgepole pine. At Plynlimon, Lodgepole pine is a feature of the more recent plantations which have not yet grown to sufficient height to instrument. Larch (*Larix kaempferi*) was chosen, however, for one of the interception trough sites, and results indicate very little difference between interception losses of larch, Norway spruce and Sitka spruce. This suggests that the volume of storage on forest canopies is little altered by needle fall, or alternatively that the seasonal changes in storage occurring in deciduous trees are of less importance than the rate of evaporation from storage.

Roberts (1983) suggests that of the components of evaporation from forests, the interception process has been shown, in temperate regions at least, to be largely physically based, and the forest structure plays only a minor part (Rutter and Morton 1977; Gash and Morton 1978). Since the major influence is rainfall climate, models of the interception process can be easily extrapolated (Calder and Newson 1979).

Roberts goes on to address transpiration, which, as a partly biologically controlled process, might be expected to show more dependence on the composition of the vegetation community. Transpiration is influenced by many factors: climate, forest age, species and structure, and soil moisture conditions. In addition, as it is much more difficult to obtain sufficient information about forest transpiration, there is considerable doubt about the prospects of

TABLE 33 Interception ratios measured for conifers in upland Britain

	Interception %	Authors
Sitka spruce	38,30,39,32,27, 49	Law, 1957; Ford & Deans; Calder *et al.*; Gash, Wright & Lloyd, 1980
Norway spruce	34	Courtney; Pyatt
Lodge pole pine		
Scots pine	42,52	Gash, Wright & Lloyd, 1980; Courtney
Larch	20	Courtney

TABLE 34 Annual transpiration rates of various tree species

Species	Location	Transpiration (mm y^{-1})
Sitka Spruce	Slaidburn, Yorks, UK	340
Norway Spruce	Germany	362
Norway Spruce	Germany	279
Norway Spruce	Plynlimon, Powys, UK	290
	" " "	340
	" " "	330
Scots Pine	Germany	324
Scots Pine	Thetford, Norfolk, UK	353
Scots Pine	Crowthorne, Berks, UK	427
Oak (sessile)	Germany	327
Oak (sessile)		320
Beech	Belgium	344
	Mean	333

adequate modelling of the transpiration process. Roberts' paper examines information currently available on forestry transpiration from studies in European forests, and considers the importance of some processes which might tend to equalise transpiration between forests.

Forest transpiration was once regarded as very variable. However this assumption may be ill-founded, and could be a consequence of examining too closely the fine-scale processes operating in the tree crowns. This approach takes no account of other contributions to forest evapotranspiration, for example, from the understorey and the litter layer. Table 34 presents information derived from a number of studies carried out in continental Europe, but confined to trees which are used in UK forestry, including both deciduous and evergreen forests.

The transpiration totals presented in the Table are generally very similar. It can also be concluded that annual totals are low compared with annual potential evaporation obtained from formulae such as Penman (1963). However Roberts, Pitman and Wallace (1982) emphasised the role of understoreys in equalising transpiration between forest stands of differing structure. There is considerable scope for understoreys to exercise such an influence, for example when the lower transpiration rate of a tree species is a consequence of less dense foliage, permitting greater levels of radiation to reach the forest floor.

There is much less information about minimum surface resistances (Roberts 1979). These may differ between tree species and will influence transpiration rates. It is probable, for example, that Norway and Sitka spruces have a lower minimum surface resistance than Scots pine and so will transpire more under the same climatic conditions.

The influence of variations in soil moisture on transpiration would seem to be important at first sight. There is evidence however that soil moisture levels rarely limit transpiration from trees. It seems most probable that where forests exhibit a rather limited daily transpiration loss, perhaps because of feedback between atmospheric humidity and surface resistance, the control of transpiration by available soil water is negligible. Calder (1978) showed the surface resistance of Norway spruce to be independent of soil moisture potential over the range 0 to 0.06 kPa. In Thetford forest, small differences were observed in the stomatal resistance between irrigated and non-irrigated Scots pine trees in the dry summer of 1975. Only in the very dry summer of 1976 did leaf water potential exert a significant influence on stomatal resistance.

Table 36 shows the transpiration and interception losses for Thetford Forest and Plynlimon: the Thetford results are based on a micrometeorological study (Stewart 1977) and those from Plynlimon are based on data from the natural lysimeter in the Hore

TABLE 35. A comparison of evaporation between central Wales and East Anglia

			Rainfall	Intercepted rainfall	Transpiration	Total evaporation
(a)	Central Wales	Forest	2013 mm	529 mm	335 mm	864 mm
		Grass	2013 mm	-	-	413 mm
(b)	East Anglia	Forest	595 mm	214 mm	353 mm	567 mm
		Grass	595 mm	-	-	643 mm

Forest evaporation measurements are from (a) Calder (1977), and (b) Gash and Stewart (1977).

Total evaporation from grassland was calculated using the Penman (1948) formula for Thetford and is derived from the water balance of the Wye catchment.

subcatchment (Calder 1977). The forest transpiration losses are very similar at both sites but the much greater rainfall at the upland site results in a much increased interception loss. In contrast, the evaporation from grassland, estimated by the Penman method (Penman 1948) for the lowland site is larger by 230 mm than that observed in mid-Wales. Since the Penman potential evaporation exceeds the observed rainfall, actual transpiration from grass is likely to be restricted by soil moisture availability. Thus in the wetter parts of the UK the total evaporation from forest is much greater than that from grassland, whereas in the drier areas the losses from forest and grassland are comparable. In the drier areas the actual percentage difference between forest and grassland is more sensitive to differences in the transpiration losses between the two vegetation types. Hence the effects of afforestation in these areas depend much more critically on factors such as the soil moisture status and the meteorological conditions in dry periods rather than interception.

Practical estimation of upland forest evaporation in the UK

For regions of relatively high annual rainfall and low rainfall intensity, where snow is not a major component of the annual precipitation, it is possible to use a practical evaporation model based on a long-term semi-empirical approach. In these high rainfall areas interception losses dominate over transpiration, and it has been shown that for the UK at least, annual interception losses can be estimated quite accurately from rainfall and an estimate of the interception ratio (Calder and Newson, 1979).

Paradoxically, the very complexity of the plant stomatal response mechanisms facilitates the "broad brush" estimation of transpiration rates. The negative feedback responses brought about by increasing deficits in atmospheric vapour and soil moisture tend to make actual transpiration rates conservative in comparison with atmospheric demand. For the spruce forest at Plynlimon at least, transpiration losses are broadly in agreement with the long-term Penman potential transpiration values, when these values are reduced in accordance with the proportion of the time the canopy is wet. It is assumed that transpiration will not take place from a wet canopy.

A simple evaporation model for estimating the effects on water resources of afforestation in the uplands of the UK has been produced by Calder and Newson (1979, 1980). Annual losses from a catchment with a fractional canopy coverage f and an annual precipitation P are given by

$$\text{Annual loss} = E_t + f\,(P\alpha - w\,E_t)$$

where α is the interception ratio, w is the fraction of the year when the canopy is wet, and E_t is the Penman potential evaporation from grass.

It was suggested that by making use of the observation that at Plynlimon the forest is wet for about 50% longer than the duration of rainfall, w can be estimated from

$$w = 1.5 \times \frac{\text{number of rain hours per year}}{\text{number of hours in year}}$$

$$= 1.5 \times \frac{\text{annual precipitation}}{365 \times 24 \times \text{mean rainfall intensity}}$$

Within the limitations of the model, the method has three advantages over the Penman-Monteith approach:

(i) the data requirement is much more limited, annual data being more widely available than hourly

(ii) the model may be used with more confidence in a predictive mode to estimate losses from areas which may undergo afforestation, as it is essentially interpolating between measurements of evaporation loss from existing, typically-sized UK forests

(iii) model predictions are not unduly sensitive to measurement errors in the input data, whereas estimates obtained by the Penman-Monteith method, particularly in wet conditions, tend to be very sensitive to measurement errors of atmospheric humidity.

The simple model outlined above has been used quite extensively in the UK (see for example the Centre for Agricultural Strategy report, CAS 1980) to predict the effects of upland coniferous afforestation on the interests not only of water authorities, but also of bodies involved in hydroelectric power generation and canals.

There have been some interesting results from recent process studies which suggest that there may be a temperature limitation on the transpiration of upland grass. This effect is of most importance in cold regions, where the growing season is shortened by temperatures that lag behind solar radiation. It may explain why the water losses from the Wye catchment are approximately 80% of the Penman potential for this area. If this effect is confirmed by studies of actual evaporation rates from upland grassland currently being undertaken at Balquhidder, it seems likely that the predictions of Calder and Newson (1979, 1980) will need to be updated, to take into account the spatial variation of this additional factor.

7.9 The future

The Plynlimon experiment has now been in existence for over twenty years. Although the Institute's station at Dolydd Llwydion is no longer concerned exclusively with work within the framework of the main catchment experiment, the headwater catchments of the Severn and Wye still provide a valuable outdoor laboratory for a wide range of environmental studies, and the future promises an increasing return for the Institute's investment in this long-term study.

To some extent the main objective of the catchment experiment has been achieved, yet in the process the Plynlimon Station has become much more than just a centre for a paired catchment comparison of forest and grassland water use. The investigation of the differences between the Wye and Severn headwater catchments is only one important facet of the impact of land use on upland hydrology. Over the years that the Plynlimon experiment has been running, it has been realised that water quality is as important an issue as water quantity, both ecologically and in terms of the potability of water resources. It has also become evident that "maturity" is only one phase of the forestry cycle, and that the initial ploughing and planting of moorland, the canopy closure phase, remedial fertiliser application to stunted trees and eventual clear felling are all aspects of forestry which have unique impacts on the hydrology of upland catchments.

To complicate matters further, the results of the Plynlimon experiment, as with all experiments of this type, could be expected to be strictly applicable only to one small area on a particular range of hills in mid-Wales. Yet the framework of the experiment, and the scope of the measurements carried out on the catchments, was such as to enable confident extrapolation of the catchment results, and of the reasons for the variation in evaporation gleaned from parallel process studies, to other areas of upland England and Wales with broadly similar climates. Only when attempts are made to apply the results to areas of Scotland with climates approaching the continental, more frequent snowfall and a different indigenous vegetation, heather and rank grassland, being converted to forestry, does the Plynlimon model appear to suffer from the distance it has been transported. For this reason, the Plynlimon catchment study has been complemented by other Institute of Hydrology forestry studies at Coalburn and at Balquhidder. It is intended that this geographical diversity should be maintained by a continued Institute presence in future.

To extrapolate the findings of Plynlimon to future land use distributions, it has to be assumed firstly that the twenty year period covering the study so far has included much of the typical year-to-year variation in climatic and hydrological conditions, including any extreme wet and dry years that would be expected to fall within this return period. By the laws of statistics it is unlikely that any "normal" twenty year period would have included droughts as severe as those in 1976 or 1984, or floods as severe as those in both catchments in August 1973 and in the Severn alone in 1977. However, these occurrences tell us one of two things: either the twenty year period has been an extreme within the normal long-term random variation, or that there is a recent climatic trend to conditions in which these droughts and floods are not so extreme as historical data would suggest. Either way, to get a true picture of the nature of variability in a climatic response system, requires that the study period is extended into the foreseeable future so that the maximum return is obtained from the considerable investment already made in the project. To interrupt the continuity of data collection and then to invest all over again, perhaps elsewhere, when the impacts of man-induced climatic change start to become apparent, would be a waste of the accumulated knowledge, expertise and background data.

If the Plynlimon experiment alone was the original *raison d'être* for the setting up of the Plynlimon Station, it has since developed to cover many other aspects of upland hydrology. The remit now includes water quality, fluvial geomorphology, wetland and river engineering consultancy and other environmental impact assessments. This divergence of interest started in the 1970s with the nutrient studies described earlier, with studies of geochemical cycling begun by ITE in 1979 and augmented by IH in 1983, with studies of stream temperature and with ongoing censuses of stream biota and fish populations. Nearby, and run from Plynlimon, the Llanbrynmair afforestation study was started in 1982 to look at many aspects of moorland ploughing, the various techniques of tree planting and their impacts on downstream ecology and water resources. This study is now approaching the canopy closure phase and represents the most comprehensively monitored environmental study covering the initial stages of forest growth. Its new role is to improve our quantitative knowledge of the changes in water use, streamflow response, nutrient outputs, acidification processes, fish populations and sediment transport that are expected to accompany canopy closure. The study is considered as complementary to Plynlimon and as such receives funding from the same source; it also gains in value for being run in parallel with Plynlimon.

In spite of a nationwide search for suitable catchments on which to conduct a hydrochemical study of deforestation by clear felling, the timely cooperation of the Forestry Commission in agreeing to fell the lower half of the Hore subcatchment at Plynlimon earlier than planned, persuaded the upland water quality consortium funded by DoE, Welsh Office, WRC and NERC to take advantage of the Plynlimon catchments as a primary research site. The felling took four years, from 1985-1989, and although the initial effects are dying down, e.g. increased suspended sediment concentrations, the continued monitoring of streamflow, chemistry and sediment is picking up those effects which lag behind the felling operations. These include: movements of bedload held back by debris dams, the temporary storage of mobile phosphorus associated with sediment in drainage ditches, the increase in nitrate peaks associated with brash decay, the change in water use because of the reduced interception from the rough canopy and a commensurate decrease in acidity resulting from smaller inputs of NO_x and SO_2. In addition, the environmental impact of the second rotation is liable to be very different from that of the first, partly because of the different starting point, in that the drainage network and plough lines are already in place from the earlier crop, and partly because many of the lessons from the Plynlimon experiment and others have been painfully learnt by the forestry industry, who are now starting to put into practice new, environmentally sensitive techniques of site preparation and planting, the efficacy of which has not yet been tested in practice.

Many of the alternative forestry practices are already being studied at sites maintained from the Plynlimon Station. At Llanbrynmair for example, one of the major aims of the original afforestation study was a comparison between the traditional downslope ploughing technique used on the upper parts of the catchment and contour ploughing used in the more sheltered valley bottom, specifically to reduce the losses of nutrients and sediment that would otherwise have caused problems at a water intake lower down the catchment. Initial impressions suggest that this approach has been a success, marred initially by increased erosion from forestry roads, with significant losses of N, P and sediment from the downslope plough lines, but little change attributable to the contour ploughing. The study at Llanbrynmair is also confirming the findings of early work at Plynlimon, in the Cyff catchment, which indicated an important role for wet riparian areas in controlling stream chemistry and sediment outputs. The addition of lime to wet riparian areas appears to be a potential solution to acidification on some catchments, but by no means all. Work currently being carried out at Llyn Brianne, supported by IH, shows that carefully-placed lime of the correct grade can have beneficial and long lasting effects; this feature is mirrored by long term monitoring, by ITE and IH, of previously limed grassland at Plynlimon, where mean pH values are significantly higher than in streams draining acidic (unlimed) grassland or forests and do not respond so adversely to acidic precipitation events. There is clear potential for further work on liming, and a start has been made at Gesail Ddu, also on Llanbrynmair Moor, in conjunction with Economic Forestry Ltd. and the National Rivers Authority, who are concerned about the potential effects of acidification and sediment losses on a tributary of the River Banwy (itself a tributary of the Severn) and on important salmonid fisheries, particularly their spawning grounds. The study also gives an ideal opportunity to look at the potential benefits of using ripping (mole drainage) as an alternative ground preparation technique to the disruptive ploughing, both on sediment losses and hydrochemistry.

The sediment studies in the Plynlimon catchments are becoming increasingly concerned with the association of sediments with other substances such as the Chernobyl fall-out and the interaction with the solute chemistry of upland streams. The results are being extended to provide a scientific background to the amelioration of sediment pollution problems elsewhere in upland Britain. Another aspect of this work, which may acquire more importance as the sediment released in upland areas starts to appear in greater quantities in downstream alluvial reaches, is the identification of forestry impacts translated to lower reaches. Finally, in complementary studies to those of dissolved load, the effects of forest practices such as the use of ripping techniques are being investigated, to quantify the value of some of the new approaches to forest ground preparation.

A continued role for the Plynlimon site as a centre for basic hydrological research into the changing face of upland land use is assured. However, even if the quantities of the major fluxes in upland catchments are now known to a considerable degree of accuracy, the physics and chemistry behind many of the processes are still not well understood: yet it is important that they are, so that mathematical models based on the processes of translation of precipitation to runoff, and the routes by which pollutants reach streams, can be used for predictive purposes on other catchments. In this way, realistic solutions can be found to some of the important environmental problems now coming to the attention of an ever more aware public. Some of the outstanding work in the process of being tackled at Plynlimon includes:

(i) Investigation of the reasons for the difference between annual estimates of actual evaporation and potential for short grassland. This work is complementary to an intensive lysimeter and micrometeorological study recently completed at Balquhidder, and aims to look at the impact of temperatures and short growing seasons on evaporative demand, together with the importance of soil moisture stress conditions in reducing transpiration from shallow soils. Related to this topic is the suppression of transpiration in forests subject to high interception rates and the implications of this for forest productivity.

(ii) Further investigation of the differences between short term estimates of evaporation from the water balance and Penman evaporation. Considerable differences exist between these even when soil moisture storage change is included in the equation, giving rise to much speculation about the role of superficial and hardrock aquifers in maintaining baseflow during dry weather. The inability of conventional, near-surface models of chemical reactions and mixing processes to explain the observed streamflow chemistry adds further weight to the argument for the existence of active aquifers in the catchment which provide considerable baseflow buffering. A programme of geophysical survey, borehole drilling, groundwater level monitoring and chemical sampling has been proposed, to aid understanding of the deep hydrological and hydrochemical pathways in the catchments.

(iii) All of these processes have a major impact on the framework of hydrological and chemical models and give further clues regarding the internal processes which need to be included in lumped and distributed models of the Plynlimon catchments. Sensitivity analyses indicate that many of the most commonly used models are dependent on accurate estimates of hydraulic conductivity and its spatial variability, together with potential gradients in the saturated zone. The discovery of chemical evidence for piston flow rather than near-piezometric surface flow may change the way modellers view the behaviour of the Plynlimon catchments, and the relative importance of the various parameters to be optimised. In terms of spatially distributed models, further work on the factors controlling the distribution of precipitation (and snow melt) across the catchments to aid better interpolation of the inputs to ungauged grid elements, will also improve model optimisation, as will improved hydraulic models of flow routing in upland catchments whose steep, windy, rough and irregular channels are not best suited to treatment by conventional flow equations. The inclusion of a sensible hydraulic treatment of pipe flow, hitherto largely ignored, to replace interflow on some parts of the catchments, will be a major step forward in catchment modelling.

(iv) Perhaps most importantly, the Plynlimon results need to be packaged into a format which allows easier extrapolation of water use models to other catchments and other regions with potential water resource problems caused by forestry activities. The models also need to take into account predicted changes in the climate, as well as land use, and must therefore be based on climatic indices. The most commonly used model of forest evaporation is that of Calder and Newson (1979), which relies on the Penman equation to calculate forest transpiration when canopies are dry and an interception ratio, relating annual interception to annual precipitation when canopies are wet. Justification for the model was made by the strong relationship between the calculated interception ratio and early Plynlimon results (for 1974-6) at the high rainfall end of the model. These years are now known with hindsight to be extreme examples, and this useful model should now be recalibrated to take into account the better knowledge of upland evaporation that has been gained at Plynlimon and elsewhere in the intervening years.

Finally, the results reported in this document for the years up to 1985 were starting to indicate significant downward trends in evaporation rates from both forests and grassland. More recent data, though not reported here, show that these trends have continued and added weight to the hypothesis that evaporation is perhaps not such a conservative process that it can use positive feedback mechanisms to equilibrate annual rates from year to year, as was once thought. The next major challenge for the Plynlimon experiment will be to identify the causes of these trends which are likely to be climatic. It remains to be seen whether the decline in evaporation continues or whether it is part of a natural long-term cycle, a description of which the Plynlimon experiment is only just starting to offer.

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