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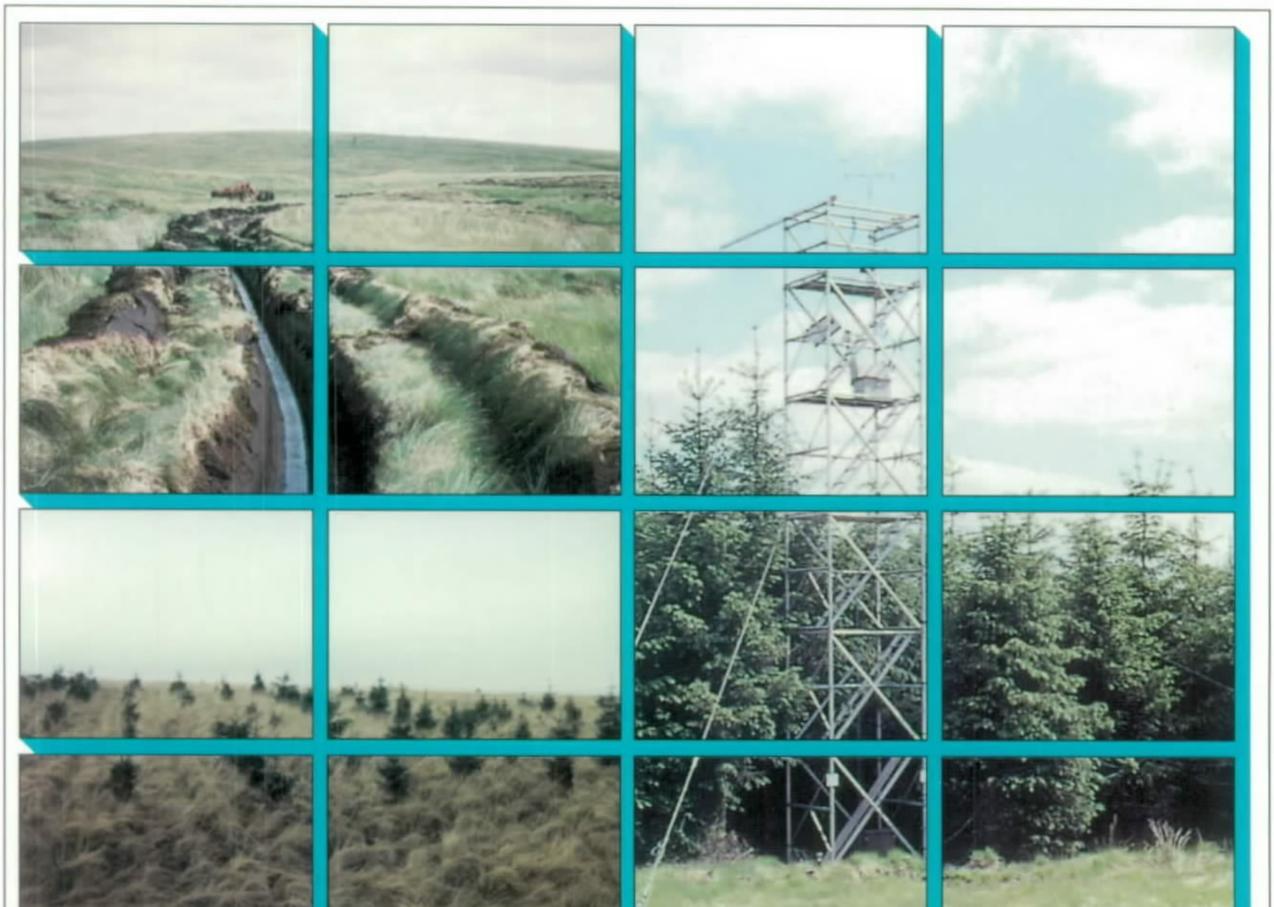

Natural Environment Research Council

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From moorland to forest: the Coalburn catchment experiment

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Cover photographs (anti-clockwise from top left):

a Catchment plough drainage in 1972, prior to tree planting

b Young trees in 1978

c Closed canopy forest in 1994

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Contents

Acronyms and abbreviations

AOD	above Ordnance Datum
AWS	automatic weather station(s)
BFI	Baseflow Index
CRA	Cumberland River Authority
DBH	diameter at breast height
DOC	dissolved organic carbon
EU	European Union
GIS	Geographical Information Systems
IAHS	International Association of Hydrological Sciences
IH	Institute of Hydrology
Met. Office	Meteorological Office
Mld	megalitres or million litres of water per day
MORECS	Met. Office Rainfall and Evaporation Calculation System
NRA	National Rivers Authority
NWW	North West Water Limited
NWWA	North West Water Authority
SHE	Système Hydrologique Européen
THMs	trihalomethanes
UNECE	United Nations Economic Commission for Europe

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Executive summary

The uplands of Britain are crucially important for water supply; although they comprise only approximately 20% of the country's land area they provide about 50% of the water. They also contain the bulk of the nation's plantation forestry and the impact of this land use on water resources has been a cause of major concern. It is well known that water yields are lower from forested catchments than from other vegetation types. Whilst the majority of land-use studies on forest hydrology have concentrated on well-established mature trees, the extensive conifer plantation forests in upland Britain are managed on a crop cycle of about 50 years, and the relatively slow growth rates in this environment ensure that a significant proportion of the cropping cycle (and therefore the total area under forest) is occupied by immature trees.

The Coalburn research catchment provides unique information on the long-term effects of forest establishment and growth on upland water supplies. Established in late 1966, Coalburn is now Britain's longest-running experimental catchment, with over 30 years of observations from open moorland, through tree establishment, in 1973, to canopy closure. It is situated in the Kielder Forest, Britain's largest forest, which provides 5% of the nation's home-produced timber. The tree species planted, the peaty soil types in the catchment, and the need for extensive ground cultivation and drainage to aid tree establishment are typical of many upland forests.

As in any long-term environmental study, the consistency of data collection and analysis is crucial. The data have been subject to rigorous checks, for internal consistency and, where possible, by comparison with independent measurements. For example, precipitation is measured at gauges sited in the middle of large unplanted areas; comparisons with independent gauges confirm that their catch has not been affected by the growing tree crop. Similarly, the consistency of potential evaporation estimates by automatic weather stations on the catchment was confirmed by correlation with values at a nearby Meteorological Office climate station. Streamflow measurements have been corroborated by current metering.

This report covers the period 1967–96. The work to date has highlighted some important points regarding the hydrological impacts of plantation forestry:

- **Effects of different forestry activities differ substantially.** Ground preparation ploughing increased annual total flows (especially by augmenting low flows) and enhanced peak storm flows (although shortening their duration). In contrast, the growth of the trees reduced water yields and peak flows, and base flows declined. The overall effect of mature forests on extreme flows is still the subject of considerable debate.

- **Effects of forestry vary with time.** In the early years of afforestation, the cultivation and drainage system will exert the dominant hydrological influence, whilst in later years the trees will become progressively more important hydrologically. At present, with the forest reaching canopy closure, Coalburn appears to be in a 'transitional' state. Compared to the original moorland, the total water yields are now lower, storm flow peaks have returned to similar levels and baseflows, although slowly declining, still remain higher than the pre-drainage pattern.

- **Effects of forestry ploughing are very long lasting.** Forestry drainage continues to exert an important hydrological role after half of the forest cropping cycle has elapsed. This suggests that a similar proportion of the area of upland forests may exert environmental impacts at variance with commonly held views of forest effects. The study underlines the great value of long-term observations if we are to understand properly the changes and interactions of a land use with a rotation length of half a century. The long-term extent of the enhanced low flows may be due, in part, to the depth of the drains and furrows. Recent moves by foresters to adopt shallower cultivation techniques may result in a smaller and shorter-lived enhancement of base flows; research into this is currently being carried out at Coalburn.

- **Young forest interception losses are low and variable.** Although the young forest has now reached canopy closure, the measured interception losses are somewhat lower than the values observed in other studies of more mature trees; losses appear to be increasing each year and further measurements are continuing.

- **Forest transpiration is limited by environmental conditions.** Catchment water balance estimates suggest that annual forest transpiration is only about 150 mm — much less than many published studies — and direct measurements of the transpiration of individual trees are being made to investigate environmental controls.

- **Forest cloud water deposition is much lower than previously assumed.** The duration of mist and the magnitude of cloud deposition to the forest canopy are both much less than values given in the literature for the Kielder Forest. Cloud deposition rates are probably less than 5% of the annual precipitation, but because of the much higher concentrations of solutes, may provide 30% of the total wet deposition load.

- **Streamwater quality varies greatly both in time and across the catchment.** The upper peaty soil layers create potential problems for water treatment (colour, trihalomethanes) whilst at the same time reducing aluminium toxicity by organic complexing. The base-rich geology mitigates acidity but, nevertheless, pronounced acidic pulses occur in the stream water at the catchment outlet during storm events. In addition, streams within the catchment show marked differences in water chemistry which are related to soil parent material; this may provide a way to manipulate the catchment to improve the poor water quality conditions.

- **The findings show the benefits of a mixed aged forest structure.** The impact downstream of areas undergoing the most marked environmental disturbance — such as cultivation and drainage resulting in locally increased sediment yields or peak flows, or long-established trees reducing annual streamflow through high interception losses — will be attenuated by contributions from other areas of managed forest at a different stage of development.

- **There is a continuing need for catchment studies.** A physically based hydrological model (SHE) was used to simulate catchment flow from moorland and then to test if it could predict the consequences of land-use change. It correctly predicted the direction of changes in low flows after forest drainage although not the amount, nor the direction of peak flow changes This result underlines the value of catchment studies, especially in situations where conditions have changed and are changing.

Future work will investigate the distribution of forest evaporation losses between interception (greatest in winter) and transpiration (confined to the growing season, April to October), detailed studies of the spatial variability of streamwater chemistry in relation to soils and geology; further work on time trends in water quantity and quality following canopy closure, leading eventually, it is hoped, to the study of the impacts of forest felling and second rotation planting.

1 Background

The uplands are major gathering grounds for the water supply industry. Although comprising only about 20% of the land area, they supply approximately half of Britain's water. They are also important for timber production and salmonid fisheries, and are of intrinsically high conservation and amenity value.

The purpose of the Coalburn catchment study is to determine in detail the hydrological effects of upland conifer afforestation. Unlike many forestry studies which deal only with mature forests, this project encompasses the ground preparation and planting phase, as well as a substantial pre-forestry 'baseline' period. Following a five-year calibration under rough grazing, the catchment was plough drained and planted with conifer species, predominantly Sitka spruce. This report reviews the results of the monitoring programme to date; it covers the effects on both water quantity and quality of the site preparation, planting and the growth of the trees to 25 years of age. Over half of the planted area now has a closed canopy.

Coalburn lies within the Kielder Forest which, at approximately 600 km^2, is Britain's largest forest, and currently produces 400 000 m^3 of timber per year. Kielder Forest also contains Kielder Water, northern Europe's largest man-made lake, with a capacity of nearly 200 million m^3 and a reliable yield of 900 Mld (megalitres or million litres of water per day).

The Coalburn catchment was established in 1966 as a combined venture by water engineers (Cumberland River Authority, later to become part of North West Water Authority), the forest industry (Forestry Commission) and researchers (Hydrological Research Unit, the precursor of the Institute of Hydrology). The establishment of Coalburn was part of the broad strategy by the Institute of Hydrology (IH) to study different land uses and physical characteristics in a number of catchments (Painter *et al.*, 1972). These included the lowland rivers Ray (clay) and Cam (chalk) as well as upland catchments. The Coalburn study of forest establishment complemented the Plynlimon experiment in Wales which compared grassland to a plantation forest already some 20–30 years old.

In 1977, day-to-day responsibility for Coalburn was handed over to the North West Water Authority (NWWA) and the Forestry Commission. The data for 1967–77, including the first five years after ploughing and planting, were analysed by IH (Robinson, 1980).

Monitoring continued during the 1980s, interrupted only by gaps in the flow record due to maintenance work on the weir. The initial effects of forestry ploughing on streamflow at Coalburn were referred to in a parliamentary debate in on upland flooding (Hansard, 1982), but further data analysis awaited growth of the trees in the harsh upland environment. In 1989 when the National Rivers Authority (NRA) and the private Water Companies (including North West Water Ltd) were created there was renewed interest in the project. This was due to increasing public concern about the environment in general and an increasing reluctance by central Government to give financial support to agriculture, resulting in the need to encourage alternative land uses, particularly forestry. Some of the early findings at Coalburn have been incorporated into the forest industry's *Forests and Water Guidelines* (Forestry Commission, 1993).

The strategic importance of Coalburn was quickly recognised by NRA: only 15 months after its creation, it approved the funding of a thorough analysis of the data, the replacement of the aged instruments and the incorporation of new topics of interest, and the production of a 25-year review of the findings (Robinson *et al.*, 1994). This effort was supported financially by North West Water Ltd (NWW) and the Forestry Commission. IH continues to support the catchment study, and the University of Newcastle upon Tyne has active research programmes. In 1996 the NRA's crucial role in running the catchment was taken over by the Environment Agency.

1.1 History of the study[1]

The origins of the Coalburn study were very specific. In the 1960s the Hydrological Research Unit was establishing a network of catchments, principally to investigate the hydrological impacts of land-use change in the uplands; in particular to

[1] J S G McCulloch, Founder Director, Institute of Hydrology

quantify the potential loss of water yield following the afforestation of acid moorland. As a result of the stimulus of the International Hydrological Decade (1965–74), there were numerous studies, at this time, of the hydrological consequences of land-use change in various parts of the world. The main effort in the UK was to set up paired catchments at Plynlimon in mid-Wales, where grassland and established forest were to be compared. Coalburn was seen as complementary to that study since it was recognised that the forest establishment stage (already long past at Plynlimon) might be important.

The 1963 Water Resources Act had led to centralised assessment of the water resources of England and Wales, with forecasts of population and economic growth indicating a possible shortage in water supply. The Water Resources Board was investigating a number of sites in Cumberland and Northumberland for a major new reservoir to supply water to the then growing industries of north-east England, this led to the construction of the Kielder Reservoir on the North Tyne. The Forestry Commission began afforesting parts of northern Cumberland; this provided an opportunity to conduct a valuable hydrological experiment by following the changes in the hydrological regime consequent on ploughing and planting according to current Forestry Commission practice. This was also of direct practical concern to the Cumberland River Authority (CRA) because it needed evidence to show whether the Forestry Commission was altering the frequency and magnitude of floods, because of the concerns of local farmers and landowners.

A joint project was established at Coalburn, initially for five years, providing a two-year calibration of the grassland catchment, followed by site preparation drainage and tree planting, and a similar two-year study period afterwards. Subsequently, it was decided to extend both periods from two to five years to take better account of weather variability. Ploughing began in 1972, and the research programme and IH involvement were due to end in 1977 when NWW, assisted by the Forestry Commission, were to take over responsibility for the catchment data collection.

The catchment research programme might have ended then, like so many studies of the International Hydrological Decade. Fortunately, the data were analysed by Dr Mark Robinson, then at the University of Leeds, and publication of the results in 1980 stimulated renewed interest in the experiment and ensured the continuation of data collection at this isolated site. However, the original instruments were showing their age, and the second 'salvation' of the project was the award of NRA research and development funds in 1991 to upgrade the whole site under the control of Ray Moore.

Coalburn was established at around the same time as the Plynlimon catchments in mid-Wales, but the particular problems of flow measurement at Plynlimon, with its steep streams and high sediment loads, resulted in few data being collected before 1970, thus Coalburn is the longest-running UK research catchment.

Research catchments are costly and at times unfashionable ventures. The achievement of Coalburn reflects its continuing relevance to practical issues and its success in the generation of new scientific findings and insights. To adapt Pliny's famous statement regarding discoveries in Africa:

"New findings are always coming from Coalburn".

2 Introduction

Although the forest cover in Britain remains limited compared with other European countries (10% of the total area against the EU's average of 36%) it has grown rapidly in the last 70 years as a matter of government policy and is the largest single land-use change. Before the First World War, little attention was given to home-produced timber due to the ease of supply from the British Empire, particularly Canada Problems of supply during the war highlighted the strategic need for secure supplies from within Britain.

Large-scale planting for timber production in Britain began in earnest after the formation of the state-run Forestry Commission in 1919 (Mather, 1993). Private forestry (accounting for nearly half of the forested land) was also encouraged by the Government. The UK currently imports over £6000 million worth of timber and wood products, private forestry is supported by the Government through a grant system (principally the Woodland Grant Scheme) and woodland ownership is largely outside the British tax system (with exemption from Income, Corporation, Capital Gains and Inheritance taxes). The plantations created are predominantly conifer species, and are mostly situated in upland areas because of their low agricultural productivity (Forestry Commission, 1993).

This increase in forest cover is likely to continue. International conferences at Strasbourg (1990) and Helsinki (1993) set general guidelines for the sustainable management of forests in Europe, and agreed to promote forest conservation, reforestation and further afforestation. In 1995 the British Government produced three Rural White Papers which called for an expansion of the forested area over the next 50 years: a doubling in England (from 7% to 14%), a 50% increase for Wales and "continued expansion" for Scotland. While new planting is being encouraged outside the traditional upland areas, and forestry on agricultural and semi-urban lowland areas has been widely publicised (e.g. Smith, 1997), for economic reasons, it is likely that the marginal upland areas of southern Scotland and northern and western England will remain important for future afforestation. Most of these areas are of poor quality land; better quality agricultural land is too expensive for forestry unless generous grants are available. The land planted is often infertile, poorly drained and with peaty soils, where cultivation and drainage are essential components of site preparation for successful tree establishment.

Quantification of the hydrological effects of upland afforestation practices was the original objective of the research at the Coalburn catchment (Painter *et al.*, 1972). This interest stemmed from concern that forest ploughing and drainage could increase downstream flooding. As the study progressed and developed, the aims of the monitoring were extended to assess the timescale over which the ploughing effects persisted, as well as the impact of the growth of the forest itself upon extreme flows, catchment water yield and aspects of water quality. In recent years the data have been used to address topics of public concern, such as the impact of forest development on low flows (arising from fears that summer baseflows may be reduced because of the greater evaporative loss associated with upland forests), and the effects of afforestation on water quality.

2.1 Changing perceptions of the hydrological impact of forestry

When the Forestry Commission was created, concepts of forest hydrology were based largely on experiences in the British colonies in Asia and Africa, where the clearance of native forests for agriculture often resulted in soil erosion and increased flooding. Water engineers consequently assumed that planting forests in Britain would have beneficial effects: forests would bind the soil and prevent erosion, and produce a deep litter layer that would encourage infiltration. This would help to even out the pattern of streamflow by reducing flooding and increasing dry-weather flows. Furthermore, since forests support a smaller human and animal population than farmland, they would reduce any chemical and biological pollution to surface water reservoirs (Ministry of Health, 1948)

Few people challenged such ideas. It was generally accepted amongst engineers to be a self-evident truth that a forest gave more streamflow than a grass cover. The Board of Agriculture and Fisheries (BOAF, 1918) stated quite categorically that "long continued observations have shown that more water drains from a wooded area than from one devoid of trees". There was inadequate scientific understanding of the processes involved in evaporation losses from a catchment. Many engineers simply used a standard loss of 14 inches (approximately 355 mm) (Lewis, 1957). Others, in the absence of any direct measurements of evaporation or soil moisture, assumed that water use by vegetation was a percentage of precipitation.

The situation changed somewhat when, in a series of very influential papers, the British physicist Penman (1948; 1963) provided a means of estimating the potential evaporation from open water and from short grass. This was the first physically based equation for estimating evaporation from meteorological measurements over a natural surface. It was a fundamental advance in the understanding and quantification of the evaporation process. Penman showed how the evaporative demand could be calculated from meteorological observations, by combining consideration of both the available radiative energy (for the latent heat of vaporisation) and the ability of the air to absorb water vapour (determined by its humidity and the wind speed).

In the 20th century a growing number of catchment studies in Europe and, particularly, in the USA indicated that forest could reduce total streamflow relative to grassland (Engler, 1919; Bates and Henry, 1928; Keller 1988; Swank and Crossley, 1988). At first, it was assumed that these results were not relevant to UK conditions because of physical differences, particularly climate. It was argued, for example, that many of the study areas were drier than the UK uplands. Thus, any higher water use of their forests than grass could be attributed to the greater rooting depth of trees. In contrast, in the British uplands the often peaty soils remain wet in all but the most exceptional droughts. Under such conditions it was argued that for streamflow yield it would make "very little difference whether the area was all forest or all grass" (Schofield, 1948).

Bosch and Hewlett (1982) summarised the results of 94 catchment experiments worldwide into the effects of forest on annual water yield. Most of these studies were concerned with deforestation rather than afforestation, and the average catchment size was about 0.8 km². There was a consistent pattern of increased annual flow following deforestation, but a large variation in amount between basins. Much of the difference in response was due to different climatic conditions, but there were also systematic differences in the magnitude of flow changes when the studies were subdivided into coniferous forest, deciduous woodland and scrub.

Surprisingly perhaps, Bosch and Hewlett did not include any studies from the UK, or indeed Europe. Work into forest effects on streamflow in this country was largely prompted by the finding of Law (1958), at Stocks Reservoir in north-west England, of much higher water losses from conifers than from grass. This was attributed to the greater rate of evaporation from aerodynamically rougher forest than from short grass (Rutter, 1967) although the source of the extra energy required was unclear, and the result was not generally accepted. It was argued, for example, that the small forested area studied yielded atypical results. Even Penman at first doubted the results, saying that increased interception losses would be offset by reduced forest transpiration, since both processes depend on the same energy (Penman, 1963). Subsequent work has, however, vindicated Law's results. Micro-meteorological studies have shown that the additional energy required could be supplied by large-scale advection (Shuttleworth and Calder, 1979).

As a direct result of Law's work, the Plynlimon catchment study in central Wales (Kirby *et al.*, 1991) was established to compare the water balance of two adjacent catchments: one mostly under mature forest, the other under grass. The two catchments are each approximately 10 km² and have high precipitation (about 2400 mm year^{-1}) and impermeable bedrock of mudstones and shales. The soils are blanket peats on level areas and podsols on the freer draining slopes. Very importantly, numerous field-based investigations were embedded into the catchment study to provide the understanding and quantification necessary to model the different processes within the two land uses.

Annual evaporation losses were consistently higher from the forested catchment; the most significant process accounting for this increase was the interception of precipitation by the tree canopy and its evaporation at a faster rate than from the aerodynamically smoother grassland surfaces (Calder, 1990). Flood peaks from the forested catchment were lower than from the grassland for small events: for large events there was no significant difference. Dry-weather baseflows were dominated by the geology, and no differences arising from surface vegetation cover were detected.

Following the Plynlimon experiment, which both demonstrated and explained the different water use of forest and grass, a similar study was conducted on two catchments at Balquhidder with contrasting land cover: grass/heather and grass/coniferous forest (Whitehead and Calder, 1993). The vegetation is aerodynamically rougher than the short-cropped grass found at Plynlimon and the precipitation includes more snow. This study showed the need to consider the complete vegetation mosaic, with high-altitude grass in the upper parts of the forested catchment using so little water that it counterbalanced the higher losses from the forested areas.

However, none of these British studies dealt with the impacts of transforming a catchment from grassland to different stages of plantation forestry. The Coalburn study is unique in Britain in providing a detailed long-term hydrological record of the impacts of afforestation, covering five years prior to forestry and 25 years of forest growth with which to quantify such hydrological effects.

Recognition of the significance and relevance of the Coalburn study for water engineers, forest managers and environmental agencies concerned with forestry and water issues, and the importance of the study in the international context, is summarised in Sections 2.2–2.5, written by representatives of these sectors.

2.2 Water industry interests[2]

North West Water Limited (NWW) is the regulated water service company for north-west England and is part of United Utilities PLC, a multi-utility group formed in 1996. The company supplies some seven million customers in an area comprising Cumbria, Lancashire, Greater Manchester, Merseyside and most of Cheshire. The major sources of supply are:

- Lake District supply system (Haweswater and Thirlmere reservoirs and lakes Windermere and Ullswater);
- Lancashire Conjunctive Use Scheme (Stocks and Barnacre reservoirs, Rivers Lune and Wyre, Fylde sandstone boreholes);
- River Dee (regulated by Bala Lake and Celyn and Brenig reservoirs in North Wales);
- Vyrnwy Reservoir (mid Wales).

All these sources supply water via aqueducts and pipeline connections to most of the population centres of north-west England. The regional aqueduct system is highly integrated with the local sources of supply, primarily upland reservoirs in Cumbria, Lancashire and Greater Manchester and boreholes in the Permo-Triassic sandstone in Cheshire and Merseyside. This integration provides a high security of supply. Overall, 65% of NWW's water supplies are derived from reservoirs (168), 25% from river or stream intakes (55) and 10% from groundwater (240 boreholes and adits).

Over the past five years (i.e. since the 25-Year Review), NWW has continued to fund research at Coalburn in collaboration with the other research partners. The research is significant, given the company's ownership of substantial upland reservoir catchments, many of which contain some coniferous afforestation. Indeed, the coniferous and broadleaved forest in major reservoir catchments, such as Thirlmere (Lake District) and Rivington (west Pennines), is owned and managed by NWW Forestry, which manages some 3000 hectares of forest — of which around 65% is coniferous — on water supply catchments. NWW also owns the Stocks Reservoir catchment where Frank Law carried out his research on the impact of coniferous afforestation; its interest in the effects of afforestation on water supplies continues through the Coalburn Catchment Study.

With its own forestry enterprise and the recent expansion in forestry plantation plans stimulated by Government and EU grants, the Coalburn research will help NWW to make informed decisions when assessing afforestation plans affecting water supply catchments.

Of major interest to NWW is the continuing research on catchment evaporation losses, given the limited understanding of the processes involved and the general lack of data on evaporation rates. Evaporation from reservoir catchments is a critical variable in calculating reservoir yields and, with over 150 reservoirs, NWW is keen to obtain more accurate estimates of catchment losses. NWW is concerned to continue investigations into evaporation processes and rates as the forest canopy begins to close, and as the initial felling programme proceeds. The company also requires improvements in estimates of evaporation losses so that the potential impact on water supplies of the various climate change scenarios can be assessed.

The company supplies some 2200 Mld; the loss of just 1% of the total water yield would cost NWW in the order of £15–20 million for capital works to obtain new sources of supply (boreholes, reservoir pumped refill or aquifer artificial recharge). To transfer the water from a more distant source may incur additional pumping costs of £0.5–1 million per year.

North West Water is also interested in the processes affecting upland raw water quality because this determines the treatment processes required to supply potable water which meets EU standards. Understanding these processes has been assisted by greater monitoring of water quality within the Coalburn catchment over the last five years. This has included the installation of an automatic water quality sampler to study water quality during runoff events (i.e. on the rising and falling limb of the flow hydrograph, at peak flow and at normal baseflow).

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[2] J. Sanders, Hydrology Manager, Water Management Department, NWW Operations

2.3 Forest industry interests[3]

The Coalburn catchment lies within Kielder Forest, the largest man-made forest in northern Europe. Kielder Forest straddles the boundary between Cumbria and Northumberland, immediately south of the Scottish border, and extends to 62 000 ha; over 95% of it is planted with conifer species.

Apart from its size, Kielder is typical of many upland forests, created in the post-war years as strategic reserves of timber. These upland areas comprise infertile, poorly drained and often peaty soils, of little value for productive agriculture, but with cultivation and drainage, it has been possible to establish highly productive conifer forests. The principal species is Sitka spruce, a relatively fast-growing softwood, originating in the wet western mountains of North America, which is more productive than other species on cold, wet and wind-exposed upland areas.

Most of Kielder Forest was created between 1925 and 1970, with the most rapid period of expansion between 1945 and 1960, when half of the current forest area was planted, and government policy was to concentrate forestry on land of least agricultural value in the uplands where rural employment was most needed. The 1963 statement of Forestry Policy confirmed the desire for continued forest expansion and added that greater attention would be given to providing public access and recreation, and increasing the beauty of the landscape. Environmental outputs continued to acquire increasing importance within forestry policy, so that today, objectives such as landscape, recreation, wildlife and water rank alongside timber production as integral parts of sustainable multipurpose forestry.

As long ago as 1925, foresters would have been aware that the creation of new forests in the uplands would have an impact on water balance, streamflow and erosion. In European forestry, the concept of protection forests as a means of regulating runoff and reducing erosion has a long history. Basic forestry textbooks described how forests reduce flood peaks, and the incidence of low flows and erosion. When forests such as Kielder were being planted, there would have been little concern about the long-term impacts on water resources. Water yields from upland catchments exceeded any downstream demand, and the few downstream users would not have had demanding water quality specifications. If the long-term impact on water resources were considered at all, the effect of forests would generally have been thought to be beneficial.

[3] G. Gill, Forest Manager, Kielder Forest, Forest Enterprise

One short-term impact was given great attention because of the need to provide a raised, well-drained planting position to establish trees successfully on wet upland soils. Advancing efficiency in land drainage necessitated rapid planning for the disposal of surplus water which would be draining away at a greatly accelerated rate. In South Wales the drainage of a large blanket peat plateau was completed at the same time as the construction of the Vale of Neath racecourse. The eve of the first day's race was wet, and at sunrise next morning, the sun glittered across a beautiful new lake, with the grandstand a forlorn island in its centre. There was no racing that season but a legal battle started which lasted for years. Improved methodologies for forestry drainage were quickly developed.

As the early forests approached maturity in the 1960s and 1970s, other water-related issues began to emerge. Unnoticed in the dense thicket-stage forests, shading of bankside vegetation had allowed streambanks to erode, resulting in wide, shallow streams unable to support fish populations. In the 1970s, this led to the practice of keeping conifer planting back from streamsides; a minimum distance of five metres became a condition of a planting grant. In 1980, the first comprehensive guidance to foresters on watercourse management was published as Forestry Commission Leaflet No. 78 *The Management of Forest Streams* (Mills, 1980). This established the concept of riparian buffer zones, and gave guidance on safeguarding water quality, and on conserving and improving aquatic habitats, particularly for salmonids.

Much of the information on forest hydrology at this time came from studies of felled forest catchments in the United States. The need for information about the effects of afforestation in Britain generally, coupled with the proposal to create the largest reservoir in Europe to supply the industrial needs of Tyneside, led to the establishment of the Coalburn Study in 1966.

With increasing use being made of water resources from upland catchments, stricter water quality specifications and higher environmental awareness, the potential impacts of afforestation on water quantity and quality were becoming increasingly important. Results from the Coalburn study and from many other areas of research were to inform a 'Forestry and Water Industry Workshop', organised jointly by the Forestry Commission and the Water Research Centre, and held at York in 1986. The main outcome of the workshop was the publication in 1988 of *Forests and Water Guidelines*; this provided the best guidance available to forest managers, while also informing the water industry about forest operations that affected their responsibilities. Whereas Leaflet No. 78 had been only advisory, the Guidelines became a Code of Practice for the forest industry, compliance being mandatory for the state Forest Enterprise and as a condition of planting grants for private forests.

Since publication of the first edition, *Forests and Water Guidelines* has been revised twice, in 1991 and 1993. the later editions contain greatly expanded sections on acidification. The third edition (Forestry Commission, 1993) draws on recent and continuing studies of the various effects of land use, pollutant inputs and forest operations and, significantly, now gives as much attention to the management of existing forests as to the creation of new ones.

The introduction of these Guidelines has had a major impact on the design and management of forests. At Kielder, extensive riparian buffer zones have been created along all major watercourses. When felling and restocking, the opportunity is being taken to hold back conifers and introduce broadleaves along minor streams. Harvesting is planned to minimise ground damage and to prevent sediment from entering streams. All harvesting teams carry anti-pollution equipment and have been trained to use it. Restocking sites are prepared by mounding rather than by ploughing and, in most cases, without any cultivation at all. Drains are installed at shallow gradients and terminated at the edge of riparian buffer zones. The process of forest restructuring through forest design planning ensures that logging of catchments is phased so that neither water quantity nor quality is subject to sudden change.

In its first 30 years, Coalburn has provided valuable information on the effect of afforestation on water yield and, increasingly, is providing information on water quality. In the longer term, it will supply equally valuable information on the effects of felling and restocking — information which will be vital in informing future forest management decisions.

The Forestry Commission will continue to support the Coalburn study through its Research Agency, whose staff have made a major contribution to the study by assisting with routine recording of site measurements and collection of water samples. The Research Agency has also organised and chaired the Coalburn Catchment Study Group since its formation in 1988, and has provided direct funding to maintain the instrumentation network and to support the recent process studies

2.4 Environment Agency interests[4]

The Environment Agency, created in England and Wales by the Environment Act 1995, started to operate in 1996. It is an 'executive non-departmental government body' sponsored by the Department of the Environment, Transport and the Regions, and has a statutory responsibility for pollution control, flood defence, water resources, fisheries, conservation, recreation and navigation. Its principal aim is to "protect or enhance the environment taken as a whole" and to advise the Government.

The impacts of land use such as forestry are of concern to the Agency, not just because they affect water resources and extremes of flow, but also because of their impact upon water quality, erosion and stream ecology. Like the NRA before it, the Agency recognises that Coalburn will provide vital information on how forestry practices can influence water quality and the amount of water available for streamflow. The Agency is supporting the long-term study at Coalburn by monitoring river and rainfall quantities and water quality, coupled with the sponsorship of a member of staff who is analysing the water quality data as part of a PhD. The Agency has also funded weir and instrument refurbishment to improve the quality of the data, which are validated, archived and disseminated to other interested parties. It recognises the need to demonstrate forest impacts and for process studies to explain the differences, and has also supported an investigation into forest interception losses.

This unique project, with some 30 years' data, will greatly improve our understanding of the effects of forestry on water quality and the amount of water available for streamflow at the different stages of the cropping cycle. This work is of increased importance now, given the Government's stated intention in the Rural White Papers to increase substantially the area under forestry.

Like most good ideas, part of the strength of Coalburn lies in its simplicity of concept: to monitor the changes accompanying forest growth for the same catchment properties (soils, topography, etc.). The Agency has a long-term commitment to Coalburn and aims to see the study through to the cropping of the forest — funds permitting Data analyses have demonstrated the need for reliable, long-term data sets to enable sound judgements to be made on the changes taking place

The Agency's aim is to improve the quality of the environment through informed decisions made on how forestry can be undertaken with minimum adverse effect on both quality and quantity of waters in our catchments. The Coalburn project should help greatly in this endeavour.

[4] P Kerr, Water Resources Manager, North Area of North West Region, Environment Agency

2.5 International perspective[5]

The purpose of this Section is to consider monitoring at Coalburn in a broader context, particularly in terms of the wider academic and international treatment of land-use issues. The river basin, watershed or catchment is central to many of the concepts in hydrology, and the drainage basin has been widely recognised as a fundamental geographic unit of study. Hydrological investigations of river basins date back some 300 years to the work of Perrault in a headwater catchment of the River Seine in central France. There have been many other studies since then, largely as a result of the International Hydrological Decade (1965–74).

One of the first reasons for establishing basin studies was to demonstrate land-use impacts upon streamflow as an objective way to settle arguments, often between vested interests, e.g. whether forests offered greater protection against erosion and silting of rivers and lakes than agricultural use. The concept of employing complete catchments, usually small ones, to monitor and demonstrate the effects of manipulating land use gained widespread acceptance. Other people saw catchments as a means of advancing hydrology as a whole: the better the instrumentation and the more precise the knowledge of each component of the hydrological cycle, the more complete the studies became. Establishing a water budget is a primary method for revealing undetected errors in estimates of the individual components.

Whilst catchment studies were at first deemed to be highly successful, it later became apparent that each basin had provided a unique set of properties (climate, topography, geology etc.); in other areas, a land-use change might yield different relationships between the elements of the water balance. Many catchment studies did not actually increase our understanding. Knowing that forests influenced streamflow was not sufficient in itself: it was necessary to quantify the differences and to know the causes, so that findings from one study could be used with confidence in other areas.

Recognising the limitations of the early catchment studies, as well as the large commitment of money and time, led to their falling out of favour in the late 1970s and 1980s. This was a time of great advances in computer power and the development of increasingly powerful mathematical models, which seem to offer a suitable alternative to catchment studies. They could produce quick results — in months rather than the years required for data collection — and often gave remarkably impressive 'fits' to the observed data. Models also have apparent generality, especially when their computations incorporate physically based flux equations, such as the Richards equation for subsurface flow or the Penman Monteith equation for potential evaporation, and their parameters appear to be based on measurable catchment characteristics. Furthermore, office-based managers found computer modellers' presentations easier to relate to than visits to distant catchments — and the constant preoccupation with data collection problems.

However, from the late 1980s, the limitations of models began to become apparent. Impressive fits were often obtained by tuning many parameters to match one output variable (usually streamflow at the basin outlet) to observed data. Fits to subsequent data were much poorer, and fits to internal variables (such as soil moisture and sub-catchment flows) were often extremely poor. There remain fundamental theoretical limitations when essentially point processes or parameters are applied to areas or regions, as well as practical problems because the level of spatial data required is often impossible to achieve. Furthermore, it became apparent that equally good fits could often be obtained by quite simple models.

It is now recognised that a combination of approaches is necessary to advance hydrological understanding and predictive capability. There is a need for long-term basin studies for land-use changes and for climate change. Process studies are required within these catchments to explain the observed effects. These process relations must be incorporated in mathematical models to understand the scale effects and the overall impact of patchwork landscapes with mixed land use, and to extrapolate results to other areas — and, importantly, to know those areas where they will not apply. There has also been a welcome recognition of the importance of water quality, both in its own right and as a valuable indicator of flow sources, pathways and storages.

With its multidisciplinary approach and the input of both academic and more practically based organisations, Coalburn combines many of the best features of a successful catchment study, and can serve as an example to many others aspiring to establish research basins. It meets the two main objectives of basin research: to gain a better understanding of the hydrological processes, and to provide quantitative data for application in land and water management practices.

[5] J.C. Rodda, President, International Association of Hydrological Sciences

3 Study catchment

The Coalburn catchment (Figure 1) is a headwater tributary of the River Irthing and lies about 40 km to the north-east of Carlisle. It comprises a 1.5 km^2 upland area of fairly smooth topography, varying in altitude from 270–330 m AOD and with a main channel gradient of about 25 m km^{-1}. The mean annual precipitation (1967–96) of about 1350 mm is distributed fairly evenly through the year. The driest year in the study period (1973) received 990 mm, and the wettest (1985) 1685 mm. There is snow most winters, and although no measurements of snow cover are available at Coalburn, the long-term records at Eskdalemuir — 30 km to the north and at a similar altitude — show snow lying for an average of 31 days per year in 1967–96. The average annual Penman potential evaporation (grass) is 445 mm, with a range from about 390 mm (1993) to 500 mm (1977). The highest recorded discharge is 6 m^3 s^{-1} and flow may cease during dry summer weather.

The solid geology of Coalburn comprises calcareous mudstones, sandstones and shales with some thin limestone bands and coals, belonging to the Upper Border Group of the Lower Carboniferous Period (Day, 1970; Frost and Holliday, 1980). The area is covered by glacial boulder clay deposits up to five metres thick, which are derived from Carboniferous sediments. Due to the cold, wet climate and the generally low slopes, much of the catchment has a surface layer of blanket peat, generally 0.5–3 m thick (although the maximum recorded depth is 10 m). About 75% of the catchment is covered by peat bog, and the remaining 25% by peaty gley soils (peat <45 cm thick) which usually occur on the steeper slopes (>5°) and are found mainly in the south-east of the catchment. Three types of soils (Clayden and Hollis, 1984) may be distinguished: Longmoss, Winter Hill and Wilcocks (Figure 1). The Longmoss series and Winter Hill series are both oligo-fibrous peats; the former is predominantly sphagnum peat and occurs chiefly in raised mires: the latter contains sphagnum and eriophorum remains and is generally found as blanket peat. The Wilcocks 1 series is a cambic stagnohumic gley soil, comprising a strongly gleyed clay loam with a humified peat topsoil (typically 20–30 cm thick).

Before this study started in 1966, the land was used as rough grazing for sheep, and the vegetation comprised *Molinia* grassland and peat bog species (including *Eriophorum, Sphagnum, Juncus* and *Plantago*). There were some 'sheep drains' comprising shallow ditches about 20 m apart that would originally have been about 40 cm deep and

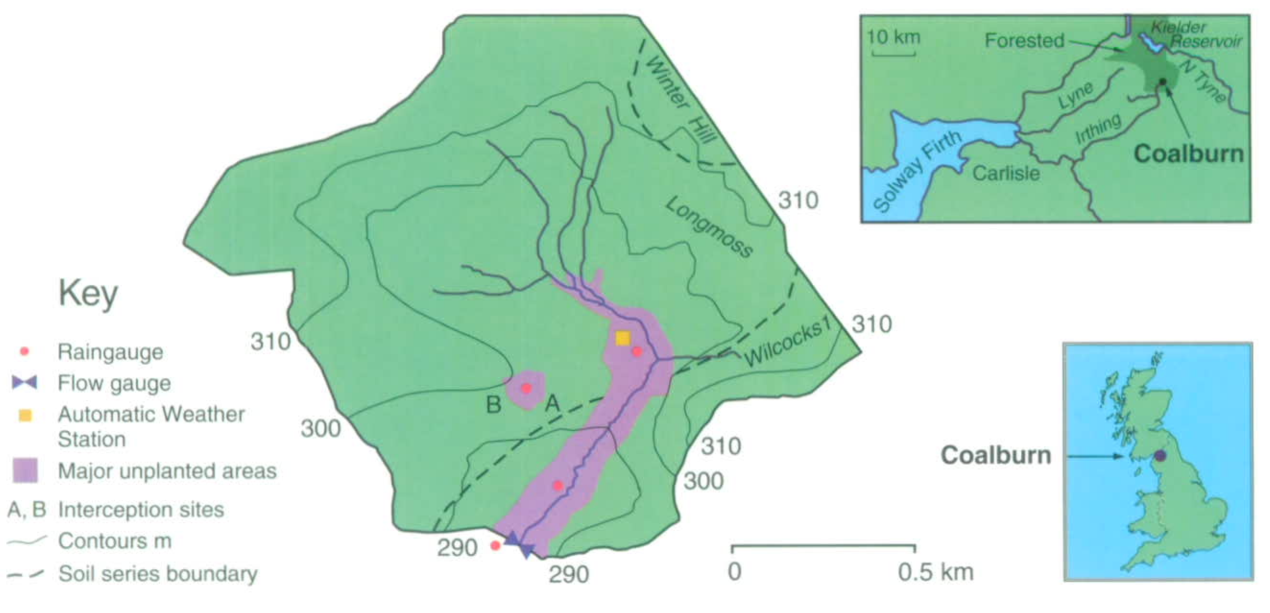


Figure 1 *The Coalburn catchment, showing the current instrumentation, main soil types and planted areas*

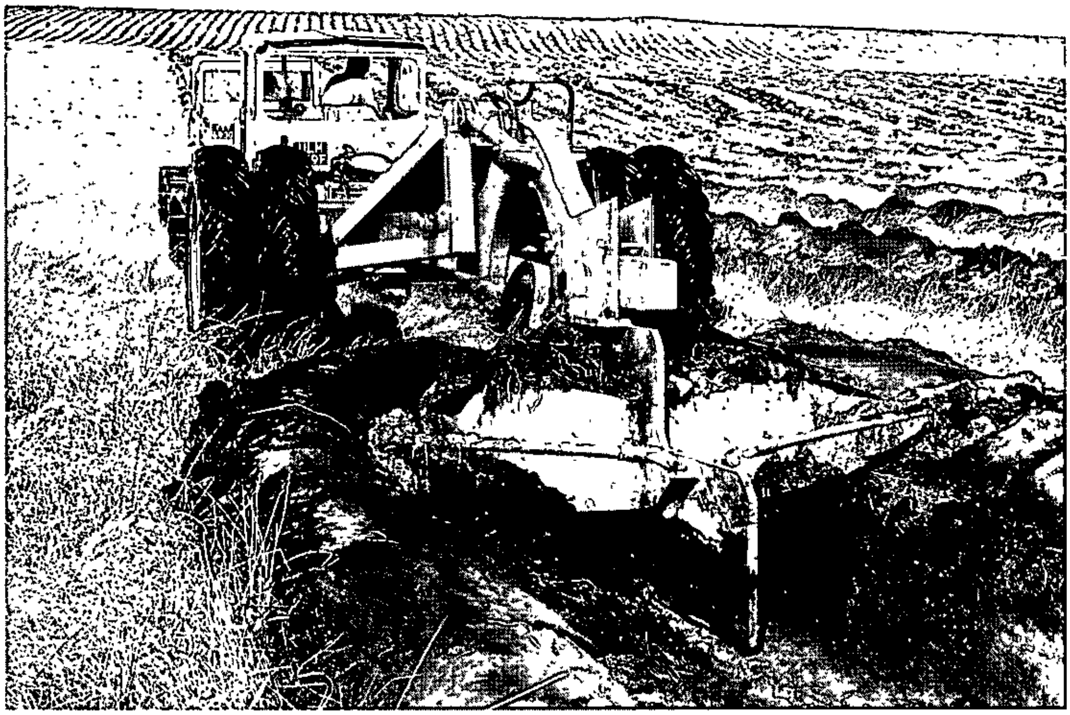
were intended to improve the grazing capacity of the land. Aerial photography and government agricultural advisers' records indicate that they date from the 1940s and 1950s, and a field survey at the start of the study showed that they were overgrown and inoperative. The ground was saturated for long periods in winter, but the catchment did not contain any significant areas of standing water.

Given the difficulty of defining the watershed of a small catchment on gentle topography, two parallel boundary ditches were cut in early 1967 (Table 1). This enabled the area of moorland draining to the weir to be known and, more importantly, ensured that it was not subsequently altered by cutting the drains for forestry in 1972. The boundary ditch followed the natural topographic divide as closely as possible, with allowances being made for any existing ditches, such as that on the edge of a plantation immediately to the north-east of the catchment.

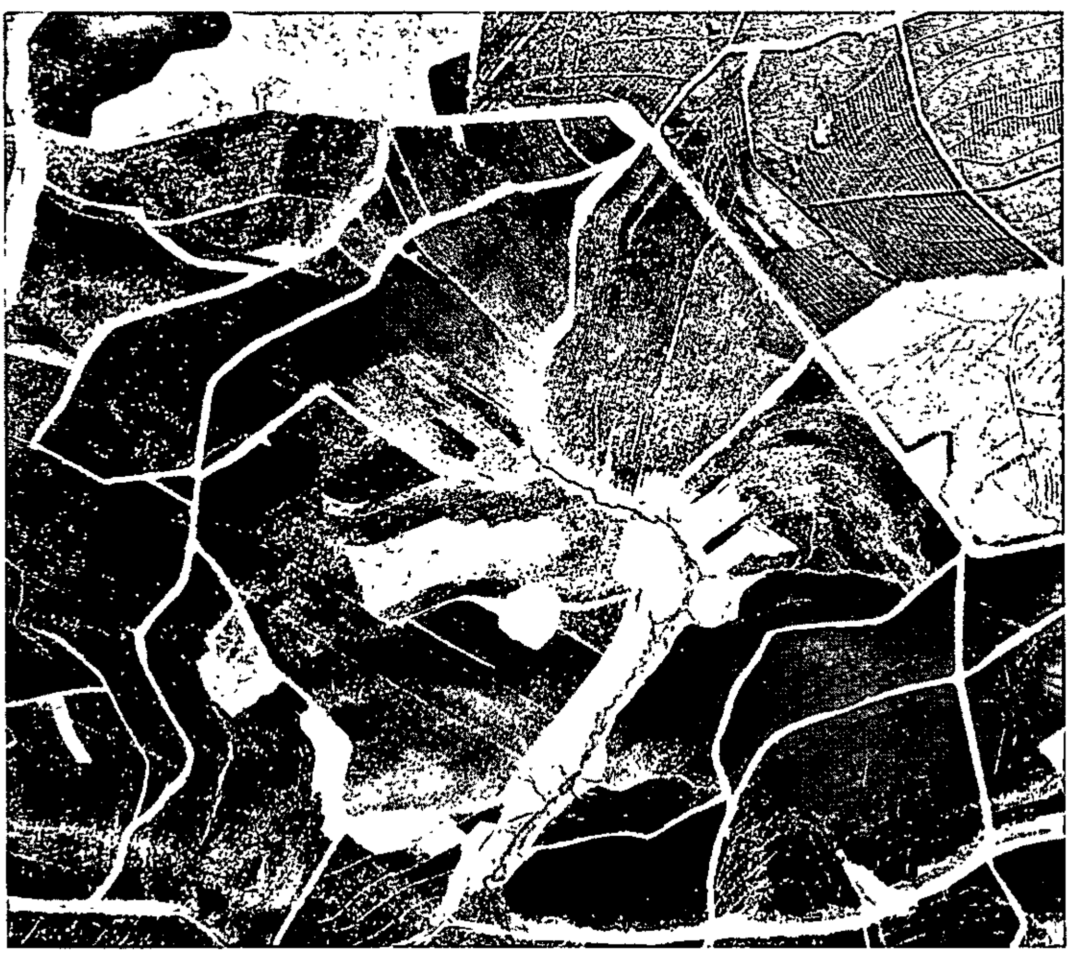
About five years of hydrological data were collected before the Forestry Commission ploughed and drained the entire catchment in the summer of 1972. Furrows (open ditches) were cut to 80–90 cm depth with a D90 deep double-mouldboard plough (Thompson, 1976; 1984). Over time, these channels reduced to about 50 cm depth due to soil infill, vegetation colonisation and peat shrinkage. According to forest terminology, plough 'furrows' comprise the site 'cultivation', and the excavated material provides turf ridges as elevated drier sites for planting (Thompson, 1984). Water from the furrows is intercepted by deeper 'drains' or is allowed to run directly into the stream system. In practice these furrows facilitate drainage and act hydrologically as extensions of the drainage network, so the terms 'ploughing' and 'drainage' are justifiably often used interchangeably in the literature by non-foresters.

Table 1 *Summary of the major activities and changes during the Coalburn Catchment Study*

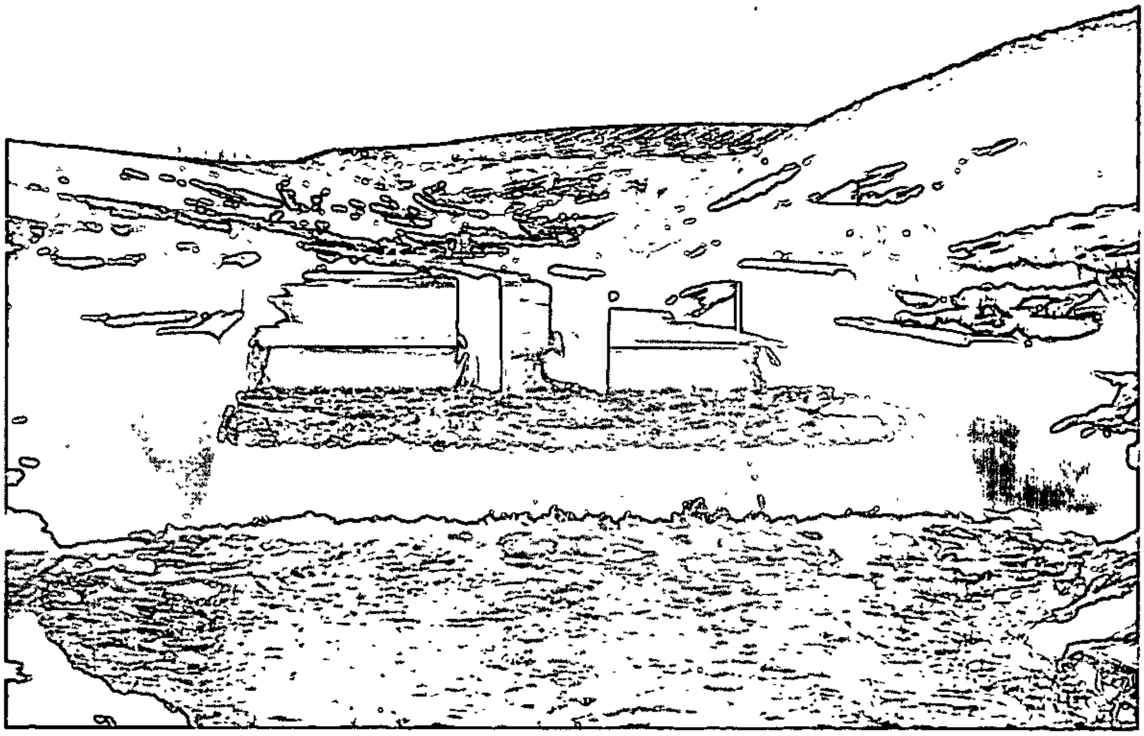
Year	Instrumentation and activities	Year	Instrumentation and activities
1966	Geological and soil surveys of catchment; first storage raingauges installed in October; weir operational in December.	1980	Publication of Institute of Hydrology (IH) Report 73, summarising results to date, stimulated renewed interest in the catchment study.
1967	Start of first full year of observations; catchment boundary ditches cut; completion of remaining minor work to weir in spring; standard raingauge network expanded during year: 9 gauges by May and full network of 13 gauges in September.	1981	Maintenance work on weir.
		1982	Effects of forestry drainage at Coalburn described in *New Scientist;* reference to Coalburn study in House of Commons debate on upland flooding.
1968	Access road to weir and centre of catchment completed; commenced installation of ground-level raingauges.	1983	Tipping bucket raingauge replaced chart recorder in September.
		1984	Maintenance work on weir; second application of phosphate
1969	Decision to delay ploughing until 1972 to extend baseline period to 5 years.	1985	Soil survey (Forestry Commission) in November; repairs to weir.
1970	Comparison of catches of ground-level and standard raingauges.	1989	IH rainfall event recorder replaced by National Rivers Authority (NRA) gauge.
1971	Installation of 2 Automatic Weather Stations (AWS) in August, producing daily Penman potential evaporation values.	1990	Telegen installed for river level measurement in mid-June; soil moisture measurements on peaty gley site.
		1991	Temporary weir from end May until new weir completed in August.
1972	Stream sediment monitoring began in March; precipitation network reduced to 4 sites in February. Site drained using D90 peat plough (July–September). Boundary drain checked in November. Break in flow data from October 1972 until June 1973 for weir repair and sediment removal. Rock phosphate applied in May, and stream concentrations monitored from April–October.	1992	Forest cover survey (mean height 7 m); catchment boundary ditch checked; soil moisture measurements on deep peat site; monthly water chemistry sampling commenced. Installation of British Telecom line and portable weather station in August.
		1993	NRA AWS records began in March; soil moisture measurements on peat site under closed canopy forest; continuous monitoring of stream pH, conductivity and temperature.
1973	Trees (about 20 cm tall) planted in spring; suspended sediment monitoring ended in October.		
1975	Largest recorded discharge (peak flow of 6 $m^3 s^{-1}$).	1994	Weir on adjacent Howan Burn installed in March. Forest interception study began in June. Cloud deposition gauges installed at the meteorological site. Streamwater sampler installed near catchment outlet.
1976	Catchment boundary ditch checked.		
1977	Transfer of catchment to Forestry Commission and North West Water Authority (NWWA); backup AWS removed and remaining AWS began to supply hourly meteorological data.	1995	Cloud deposition gauge installed above the forest canopy. Forest health plots installed by the Forestry Commission.
1978	Suspended sediment monitoring; tree heights generally <1 m.	1996	Flow measurements started on four forest drains. First measurements of forest transpiration.



Ploughing using a double-mouldboard plough



Aerial view of the Coalburn catchment, 1989: the trees have begun to grow strongly, as can be seen from the dark areas of forest growth



The weir at Coalburn in 1973. The forestry furrows can be seen on the hillside in the background.

At Coalburn the furrows are at about 4.5–5 m spacing, generally aligned with the ground slope and without regular cross-drains. This type of ploughing was used on deep peats in some areas in the 1970s (Forestry Commission, 1972); it was later stopped because of technical problems (Thompson, 1976). It may be distinguished from the more widespread use of a shallower D60 plough (resulting in 60 cm deep channels with a tine slot beneath), at 2 m or 4 m spacing with a regular system of deeper cross-drains at, say, 90 cm depth and 40 m apart (Thompson, 1984). The hydrological effects of these two techniques are likely to be broadly similar, although possible differences are noted later in this report, particularly the impact of the plough drains' depth on dry-weather streamflow, and the effect of spacing on high flows.

The benefits of ploughing for forestry include removal of excess soil water and improvement of aeration, mobilisation of nutrients and reduction of competition from natural vegetation. The density of this network of artificial channels is about 200 km km^{-2} (60 times greater than the original stream network). Following the common forestry practice of leaving the soil to dry for up to a year after drainage, Sitka spruce (*Picea sitchensis*) with some Lodgepole pine (*Pinus contorta*) were planted in the spring of 1973 at about 2 m spacings along the turf ridges. As a result of the severe site conditions with repeated frosting, their growth has been relatively slow: after five years their height was typically 1 m, and after 12 years, about 3 m. The height in 1996 was 7–12 m and corresponds to a forest yield class of 10–12 (i.e. 10–12 m^3 ha^{-1} $year^{-1}$ timber growth), which is considered good for that altitude. Areas were left unplanted around the four raingauge sites (to reduce the effect of tree growth on raingauge catch) and on the steepest areas adjacent to the main stream channel, so that 136 ha were planted — 90% of the catchment. According to a forestry ground survey at the end of 1992, about 60% of the forest (i.e. 54% of the whole catchment) had reached the canopy closure stage.

4 Instrumentation and analysis

For any study spanning several decades it is essential to be confident that the data collected are consistent and homogeneous. We outline here the types of instrumentation used and significant changes that took place, as well as describing the methods used to calculate (and where necessary to infill or extend) the basic hydrological data for the components of the catchment water balance (precipitation, streamflow and the weather variables for potential evaporation), together with water chemistry. As much of the basic instrumentation has been renewed since 1990, a detailed record is given of the key changes.

4.1 Precipitation

Precipitation is measured by a network of storage raingauges across the catchment, the average rainfall is calculated using the Thiessen method. The gauges were emptied and read each week in 1966–77 and at two-week intervals thereafter.

The installation of standard height (30.5 cm) storage raingauges began in October 1966. The full network of 13 gauges across the catchment was completed by September 1967 (Table 1) and operated until just before the pre-planting drainage in 1972, when it was reduced to the four sites (Figure 2, see also Figure 1) This was to limit their interference with the ploughing and planting programme, since a large area around each raingauge was left unplanted to ensure that the raingauge catches were not affected.

Catches at the 13 sites are given in Table 2 for the four calendar years 1968–71, excluding periods of snowfall. Variation between the gauges is small, which is to be expected for an area of relatively subdued relief, and the average difference of individual gauge catches from the catchment average (computed by the Thiessen polygon method) was <3.5%. However, mapping these deviations indicates a pattern of lower catches in the eastern part of the catchment (Figure 2). These apparent 'undercatches' are probably caused by topography, since it is well known that wind turbulence around raingauges with their rims at some height above the ground surface causes them to undercatch relative to the 'true' catch of gauges with their rims flush with the ground (Sevruck,

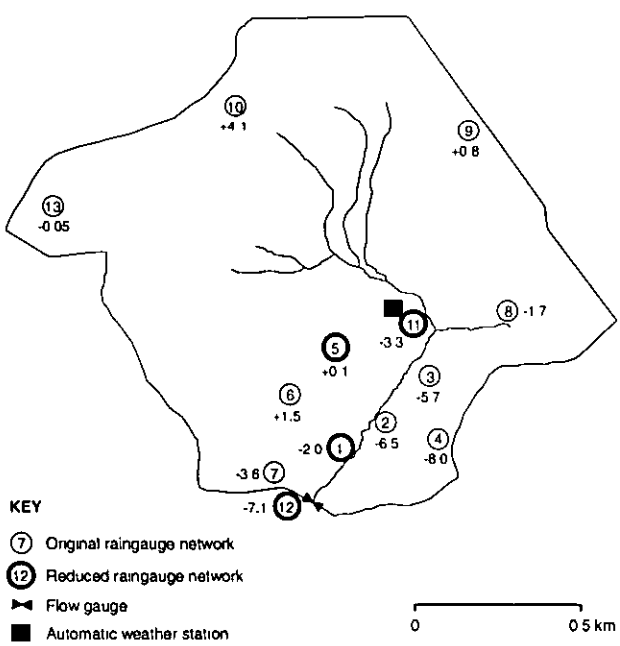


Figure 2 *Original network of 13 storage raingauges, showing their individual deviations (%) from the catchment average, 1968–71*

Table 2 *Comparison of raingauge catches, 1968–71, excluding periods with snow, showing the difference in the period total from the Thiessen weighted catchment average*

Raingauge site	Total rain *(mm)*	Difference from full network *(%)*	SD weekly differences *(mm)*
1*	3927.5	-2.05	7 35
2	3748.6	-6.51	8.26
3	3782.2	-5.67	9.18
4	3683.1	-8.14	11.67
5*	4010.1	0.14	5.98
6	4069.1	1.48	6.70
7	3866.7	-3.57	7.50
8	3940.9	-1.71	7.79
9	4042.3	0.81	7.64
10	4174.6	4.11	9.51
11*	3878.0	-3.28	6.67
12*	3723.9	-7.13	6 09
13	4007.6	-0.05	8.61
Full network (13) (average)	4009.7	–	–
Subset*(4)	3937.7	-1 8	0.04

*Gauges used since 1972 in the reduced network of 4 gauges

1982). Analysis of wind direction data indicates prevailing south westerly winds; and gauge sites 2, 3 and 4 all lie on slopes exposed to these winds. Evidence of a windward slope 'rain shadow' and a leeward 'fallout' effect on raingauge catch has also been detected under the steeper topographic conditions of IH catchments at Plynlimon in Wales (Kirby *et al.*, 1991) and at Balquhidder in Highland Scotland (Blackie *et al.*, 1986).

The sites selected for the reduced gauge network (from 1972) excluded those gauges most prone to this effect The total depths and standard deviations of the differences between individual sites (read every week) were compared with the catchment average depth for that period: this confirmed that the choice of sites for the reduced network was reasonable. At first sight, the inclusion of gauge site 12 appears to be unnecessary: it is just outside the catchment and contributes little to the Thiessen weighted catchment average. Occasionally, however, in exceptional periods of heavy snow it was the only gauge that could be reached and read.

Catchment average period totals (using Thiessen polygons) were compared for the full network of 13 standard gauges and for the subset of four standard gauges (Table 2). For the years 1968–71 inclusive (excluding periods affected by snow), the difference was very small; the reduced network total was within 2% of the full network. This difference is probably well within the measurement error of any of the gauges, although this value was fairly consistent between the individual reading periods. Accordingly, it was decided, for consistency and to ensure a homogeneous time series of data, to use the catchment average based on these four raingauges throughout the whole study. It may be argued that, even in the pre-forestry period when the additional gauges were available, it would be better to avoid using those gauges suspected of being vulnerable to the greatest problems of exposure.

An independent check on the homogeneity of the long-term precipitation estimates (including periods with snow) was obtained by comparison with the records of daily read gauges in the vicinity, operated as part of the Meteorological Office's National Raingauge Network, which do not include any of the gauges at Coalburn. The areal rainfall for Coalburn was estimated from the Met. Office gauges by D.G. Morris, of the Institute of Hydrology, using Voronoi interpolation (British Standards, 1996).

There was good correlation between the monthly catchment rainfall (mm) measured at Coalburn and estimates based on the Met. Office gauges:

$$P_{\text{Coalburn}} = 4.0 + 1.11\ P_{\text{Met Office}} \quad (R^2 = 88\%) \qquad (1)$$

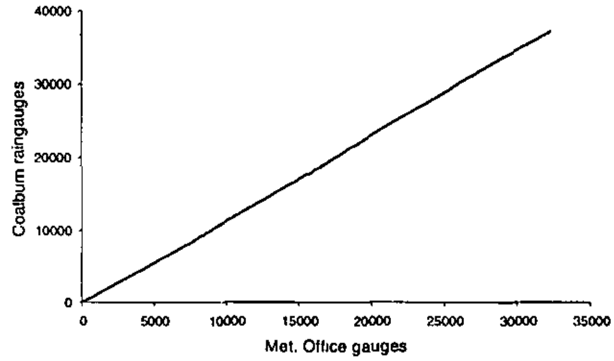


Figure 3 *Comparison of cumulative measured catchment precipitation (depth in mm), 1967–96, with an independent estimate using nearby gauges from the Met. Office's national raingauge network*

The cumulative totals (1967–96) in Figure 3 show the consistency over the whole period. Both sets of rainfall data were obtained from standard rim height storage raingauges. The Met. Office estimates confirm and validate the homogeneity of the Coalburn raingauge records, but by themselves they would not have provided an adequate measure of the absolute precipitation inputs, since they under-estimate Coalburn's true rainfall by about 14%. This may be because the Met. Office national network of raingauge sites is constrained by the availability of suitable meteorological observers, and in the British uplands people generally live in valleys, where rainfall will be somewhat lower. This validation of the homogeneity of the raingauge series is very important since it confirms that the unplanted area around each gauge has been adequate to avoid any changes in exposure and catch with the growth of the forest.

To study the precipitation inputs to the catchment in more detail, some raingauge sites were also equipped with ground-level gauges (Rodda, 1970). Comparisons between the two types of gauges (Table 3) show the tendency for the 'true' ground-level catch to be a few percent greater than in a standard raingauge. The difference varies between sites: gauges 2, 3 and 4 show the greatest undercatch. This is consistent with the above suggestion that, because of their aspect, they are most prone to wind effects. The anomalous overcatch at site 8 was noted by Rodda but could not be explained. The difference between the ground-level and standard raingauge catch at each site also varies with the time period considered. This reflects the prevailing weather conditions (particularly the wind speed and the raindrop size). Consequently, there is no unique correction value to be applied in all circumstances, although in practice, information on wind and raindrop size are not generally available and an average value is, therefore, normally adopted.

Table 3 Comparison of standard and ground-level gauges, excluding periods with snow

Raingauge site[1]	Standard raingauge undercatches[2] (%) June–Nov1969[3]	1968–71	1975–92[4]
1	–	–	4
2	5	9	–
3	6	6	–
4	4	7	–
5	3	3	4
6	0	0	–
8	-6	-11	–
10	2	1	–
11	5	6	6

[1] Sites 1, 7, 12 & 13 did not have a ground-level gauge in the first two periods.
[2] Undercatches are calculated as (ground-standard)/ground.
[3] Rodda (1970).
[4] Robinson *et al.* (1994). Only sites 1, 5, 11 & 12 remained after 1972; site 12 does not have a ground-level gauge.

A long-term comparison of the gauges at site 11 (1968–78) showed that the standard level gauge underestimated by 9% (Rodda and Smith, 1986). This is greater than the values shown in Table 3, and may be explained by the fact that Rodda and Smith included periods of snowfall in their analysis. It is well known that precipitation measurement problems are much greater for snowfall than for rain. Standard gauges undercatch falling snow because wind turbulence deflects snowflakes across the rim of a gauge, and unmelted snow is blown out of the raingauge funnel. Furthermore, ground-level gauges are also prone to substantial errors, and may produce spurious high precipitation values caused by drifting snow, since the pit and its raingauge may fill up with snow to the same elevation as the surrounding land. Thus in 1968–71 the difference between the two gauges at site 11 was 6% for snow-free periods, but increased to 10% when snow periods were included.

The pairs of standard and ground-level gauges currently operating at sites 1, 5 and 11 indicate an average of 4–6% greater catch for the ground-level gauge in snow-free periods (Table 3 and see footnote). Therefore it was decided that a global correction value of 5% to all the standard gauge catches would be appropriate. In the absence of satisfactory instrumentation for measuring snow at Coalburn, this correction value was applied to snow periods and rainfall periods to obtain rainfall depths for the water balance studies. This is justified by the fact that, although imperfect, the standard gauges provide a somewhat better measure of snowfall than the ground-level gauges, which may be completely buried. In addition, the use of a consistent correction value eliminates the need for subjective assessment of the proportion of precipitation in each measurement period that fell in liquid or in solid forms

4.2 Streamflow

Streamflow from the catchment is measured by a weir at a site where bedrock outcrops near the surface to ensure sound foundations and minimise the possibility of flow under the weir. Upstream, there is a large stilling pool to encourage deposition of stream sediment away from the weir. When the structure was designed there was no road into the catchment and pre-cast concrete blocks were used to make its construction easier. The crests were capped with machined steel sections. The weir was originally intended for only a few years' service and, when the decision was later taken to extend the experiment, a more permanent replacement had to be considered. Deterioration of the structure resulted in an increasing number of breaks in the records while repair work was carried out (for example in July 1981, November and December 1984, April 1985, October and November 1985). Although the check gaugings showed that flows were still measured accurately, it is known that there were extremely small leaks (measured in August 1990 as 0.0003 $m^3 s^{-1}$), and the weir had to be replaced in 1991.

The original structure (operating from 1967–91) was a compound Crump weir (Ackers *et al*, 1978), designed to contain all flows up to 8.4 $m^3 s^{-1}$ (19.8 mm h^{-1}). A theoretical rating was used over the whole period. There were 25 check gaugings between August 1985 and May 1991, made by current meter, usually in 0.1 m wide panels, or volumetrically by stopwatch and container for very low flows. These gaugings encompassed flows up to 0.46 $m^3 s^{-1}$ (a flow exceeded for only 1% of the time). There was generally good agreement between the gauged and theoretical flows (R^2 = 99.2%). Until its final year of operation there was no evidence of any time trend in the residuals with approximately equal numbers of positive and negative residuals in each year. Then for the final 11-month period from July 1990 until May 1991 (when the old weir was demolished), the gauged flows were generally *lower* than the theoretical rating. The reason for this apparent overestimation of flows is not clear, but could be largely accounted for by a hypothetical 0.5 cm error in the water level datum following the installation of a Telegen system in mid-June 1990. There is no direct evidence of this, however, and the flow records have not been altered.

A new, compound, broad-crested weir (with low-flow V-notch section) was built on the same site, and began operation in August 1991. Up to the end of 1996, 43 check gaugings were made by current meter for the whole range of the V-notch (which contains flow for 98% of the time), with excellent agreement between the gauged and theoretical flows (R^2 = 99.5%). Of these, 20 gaugings had negative residuals and 23 were positive. Insufficient data are yet available to confirm the stage-discharge relation for the highest flows over the broad crest.

4.3 Potential evaporation

When the catchment was established there were no on-site meteorological readings and records were obtained from a manually read climate station at Spadeadam, about 8 km away. In 1971 two automatic weather stations (AWS) were installed near the centre of the catchment. The data collected comprise solar and net radiation, air temperature and wet bulb depression, wind run and direction, and are used to estimate Penman (1963) short grass potential evaporation.

This was one of the earliest operational AWS sites in the country — and certainly one of the most remote. The early weather station sensors and logger were not considered reliable enough for shorter than daily values to be archived; when individual sensors failed, records at other climate stations (e.g. sunshine hours at Carlisle) were used to obtain estimates of the daily Penman values. By 1977, however, the reliability of the on-site AWS measurements had increased sufficiently for hourly data to be archived, and the second, backup AWS was removed. The previously published average value for Penman, of about 460 mm year^{-1} at Coalburn over the period 1967–76 (Clarke and Newson, 1978), should be treated as only a broad initial estimate for a period when the data quality was not good; before 1971 no on-site measurements were available.

A six-month comparison of the daily estimates of Penman at Coalburn with those made at the Spadeadam climate station (which closed in 1973) indicated that the Spadeadam values were approximately 17.5% lower (IH, 1973). However, no radiation measurements were made at Spadeadam and, consequently, values from the Met. Office's long-term climate station at Eskdalemuir were used. More recently, comparisons have been made between the Coalburn AWS estimates of potential evaporation and monthly totals obtained at Eskdalemuir. Preliminary results for 1988 and 1989 (Hughes, 1990) showed a strong correlation between the monthly potential evaporation E (mm) of the two stations:

$$E_{\text{Coalburn}} = 1.67 + 0.958\, E_{\text{Eskdalemuir}} \quad (R^2 = 98.6;\ n = 21) \quad (2)$$

The hourly AWS data at Coalburn for the 15 years 1978–92 were then re-examined and subjected to detailed quality control (Robinson *et al.*, 1994). In some cases the raw data were reprocessed and some apparent gaps in the archive were correctly filled. Examining all the available monthly AWS data from Coalburn for this period enabled a much larger set of monthly Penman estimates to be compared with Eskdalemuir. This also provided an independent check on the operation of the AWS for quality control of periods of suspect data. Care was taken not to reject periods of AWS data solely because of apparent discrepancies with the Eskdalemuir values. Good quality data for 104 individual complete months were identified and yielded the linear equation:

$$E_{\text{Coalburn}} = 2.71 + 0.956\, E_{\text{Eskdalemuir}} \quad (R^2 = 97.7;\ n = 104) \quad (3)$$

Alternatively, since the intercept term is not statistically significantly different to zero, an equation fitted to the data may be forced through the origin:

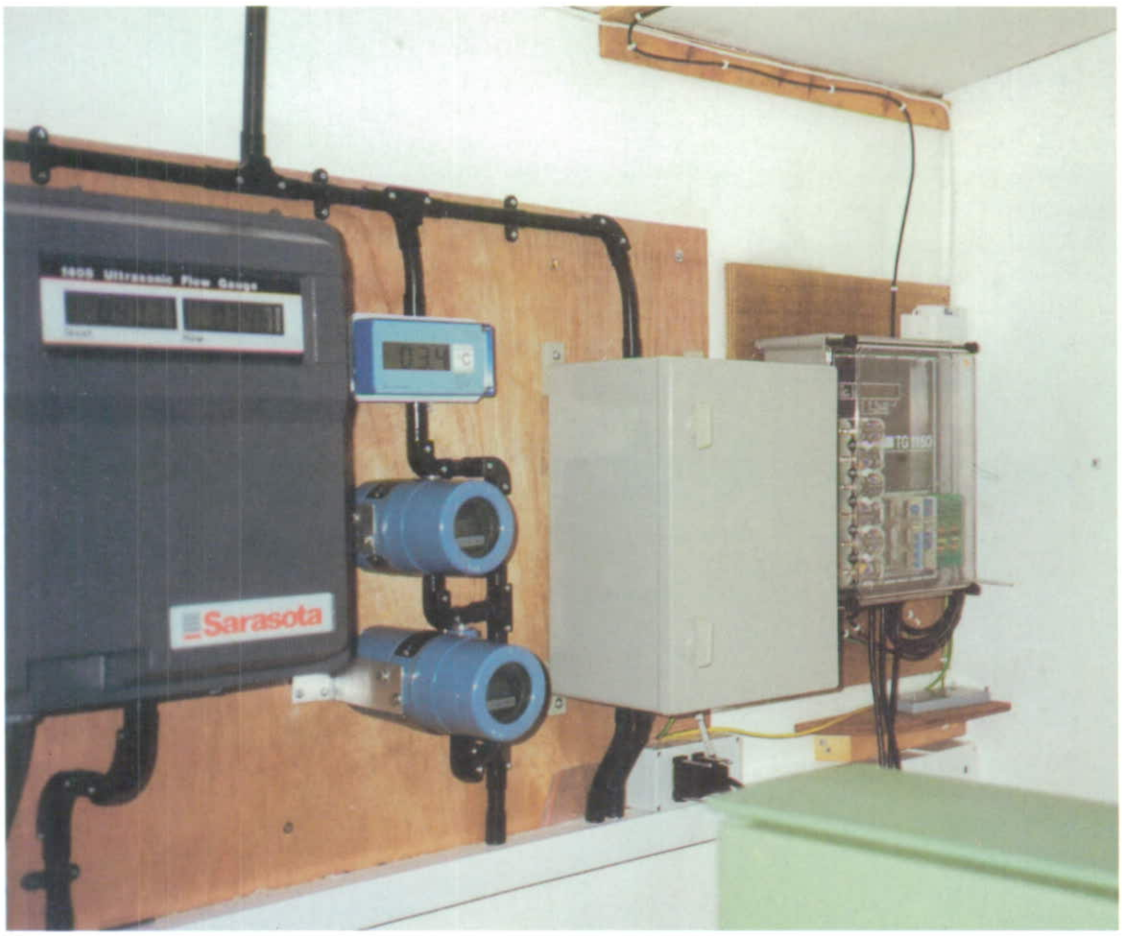
$$E_{\text{Coalburn}} = 1.022\, E_{\text{Eskdalemuir}} \quad (R^2 = 96.3;\ n = 104) \quad (4)$$

This indicates that the potential evaporation at Eskdalemuir was, on average, 2% lower than at Coalburn, which is considerably closer than the 17% difference found in the short-term comparison of Coalburn with Spadeadam (IH, 1973). The Eskdalemuir data thus offer the potential for obtaining a homogeneous time series of data for the whole period of the Coalburn study. The relationship was used to fill in periods of missing data at Coalburn and to extend the potential evaporation estimates back to the start of the catchment study, before there were any on-site meteorological measurements.

The Eskdalemuir data were examined to ensure that this 'baseline' station had a consistent series of data; a number of features of this investigation raised doubts that are relevant to this study. In the early years of the Coalburn catchment study (1967–73), the Eskdalemuir potential evaporation data had surprisingly constant annual totals, averaging 404 mm year^{-1} with a standard deviation of only 8.5 mm. Then there was an apparent increase of nearly 10% with much greater variability; in the subsequent period 1974–80, the estimated potential evaporation averaged about 441 mm year^{-1} (SD = 25.6 mm).

The reason for this variation (whether climatic or instrumental) is clearly of great importance for the interpretation of the water balance, especially since the change in the Eskdalemuir data occurred at a similar time to the land-use change at Coalburn. As a check, early AWS data, obtained before trees were planted at Coalburn, were compared to the values

The automatic weather station near the centre of the Coalburn catchment



Instruments in the weir hut, showing (from left to right) ultrasonic gauge level and flow, stream-water quality parameters of temperature, conductivity and pH, and the TG1150 telegen that stores data and transmits them via a land line obtained at Eskdalemuir. Penman evaporation values for Coalburn were 8% higher than Eskdalemuir in 1971–72, compared with just 2% higher in 1978–92. This is an annual difference of 30 mm, and the apparent change corresponds in sign and magnitude with the increase in the Eskdalemuir totals around 1974. It was then learned from the Met. Office that in January 1974 there was a change in the calculation of the Penman values for Eskdalemuir. This included an increase — from 4 observations per day to 24 per day — in the number of hourly meteorological readings (temperature, vapour pressure and wind speed) used in the calculation of potential evaporation. Unfortunately, the Met. Office documentation is incomplete and, although this change coincides with the increase in potential evaporation values and their variability, the precise details are unclear.

The consistency of the Eskdalemuir weather data has also been subject to doubts because the recorded wind speeds have decreased from 1970–90. It had been suggested that this could be the result of forest growth around the climate station. A study of the wind speed records, measured at 10 m above the ground, showed a statistically significant reduction over this period. However, this was not due to a consistent trend, but to an apparent 16% reduction after replacement of the anemometer, its tower and data processing system in March 1981 (Wilson, 1993). Dividing the data into two periods, before and after this date, removed most of the apparent time trend. It appears that the instrument change, and not forest growth, was the cause of the apparent drop in wind speed at Eskdalemuir. This conclusion enabled a correction to be applied to the later data (because the earlier data were believed to be correct) to provide a homogeneous record of wind speed. The data processing system used at Eskdalemuir has now been changed by the Met. Office to rectify the problem.

The implication of this apparent error in the wind speed values for Eskdalemuir was assessed by recalculating the Penman estimates with the revised data. This altered the Penman potential evaporation estimates by an average of only 3.2% (i.e. about 12 mm year^{-1}). The relatively small effect is because the vapour pressure deficits are generally small, thus restricting the impact of the changes in wind speed on evaporation rates. There was a fairly constant effect on evaporation rates throughout the year, with the greater windiness in winter balanced by the larger vapour pressure deficits in summer.

Since publication of Robinson *et al.* (1994) the Met. Office has recalculated the potential evaporation data for the whole period of record at Eskdalemuir as part of a general review and updating of the MORECS system (Met. Office Rainfall and Evaporation Calculation System). These data became available as this report was being prepared. Comparison of these new values with the original ones highlighted large discrepancies (>10% higher for some annual totals), particularly the early data in the 1960s and 1970s. However, because of the 8% correction previously applied to the pre-1974 Eskdalemuir values for application to Coalburn, the effect of these changes on estimates for the catchment over the study period was relatively small.

The reasons for the changes to the Eskdalemuir estimates on recalculation are not known with certainty, although the Met. Office now recognises that the original Penman data for Eskdalemuir were calculated at the end of each year, and that over time, there were changes in the formulation used, as well as in the number of readings per day that were used. Records of these changes in procedures were not rigorously recorded. In the present recalculations, however, the original archived hourly data at Eskdalemuir were used in a completely consistent manner throughout the whole period of record (R. Tabony, personal communication).

Over the 30-year period corresponding to the Coalburn study, the revised Eskdalemuir values were generally about 5% higher than those previously used. Whereas potential evaporation at Eskdalemuir was formerly estimated as being on average 2% lower than Coalburn, this is now revised to being about 3% higher. This 5% change amounts to only about 22 mm year^{-1}, which is equivalent to only 1.6% of the average annual precipitation. The impact of this new data set on the interpretation of the long-term average catchment water balance is thus very small, but we now have much greater confidence in the consistency of the long-term potential evaporation series; this is of great importance for investigations of water balance trends over time. The newly recalculated figures have accordingly been adopted in the subsequent analyses in Section 5.

4.4 Water quality

When the catchment study began there were no measurements of water quality but the situation is different today. Initial interest in water quality arose in connection with the effects of the pre-planting forestry ploughing on erosion and stream sediment, and on the loss of aerially applied rock phosphate fertiliser in the streamflow. These were studied by short-period sampling programmes using an automatic water sampler installed near the basin outlet during 1972 and 1973. Further water samples were collected by Leeds University in 1978.

Beginning in early 1992, a regular programme of manual sampling of stream water at the weir and of rainfall has been carried out by the Environment Agency (formerly the National Rivers Authority) and the Forestry Commission for the analysis of major cations, anions and nutrients. An automatic sampler was installed by NWW in June 1994 specifically to take samples during storm events, since the flashy hydrograph response of the catchment means that few manual samples would be taken during high flows. These samples are analysed for a range of water quality parameters. Since October 1993, continuous (15-minute) measurements of stream-water quality have been made at the weir using Rosemount pH, temperature and conductivity sensors.

In addition to these studies at the catchment outlet, a programme of manual sampling within the catchment has been conducted since 1988 by University of Newcastle Department of Geography (Hind, 1992).

4.5 New instrumentation initiatives

In the late 1980s, with the project nearing 25 years of monitoring, problems began to arise because of the age of the instrumentation and the deteriorating state of the weir. A large injection of capital was needed for it to continue; Research and Development funding (1991–94) from the NRA was its lifeline. This covered the replacement of ageing instrumentation, the adoption of new techniques, and contributed to a thorough review and reappraisal of the existing data (Robinson *et al.*, 1994).

The first priority was to demolish and rebuild the weir. There were two choices for its design: a flat V Crump weir or a non-standard broad-crested weir with a central V-notch installed. Maximum sensitivity was required to enable small changes occurring within the catchment to be monitored. In addition, there had to be simple construction techniques to reduce time and transport costs to this remote site, coupled with possible poor weather conditions during construction. Future ease of maintenance of the structure over the next 25 years was also an important consideration.

Bearing these points in mind, the non-standard weir was considered the better option. The central 90° V-notch was constructed with a depth of 0.6 m containing flows up to 0.38 $m^3 s^{-1}$. Consideration of the flow duration relations for the catchment indicates that this notch contains 80% of the total flow (which occurs for 98% of the time). The top 20% of the flows will be contained within the wing walls, with the maximum recorded flow of 6 $m^3 s^{-1}$ (30 August 1975) still leaving 150 mm freeboard.

A temporary, compound thin-plate weir was sited upstream of the construction site, with a Newlog logger and shaft encoder to provide flow measurements during the construction period, 31 May to 21 August 1991. Demolition of the old weir and the building of the new compound weir were completed by 16 August 1991, and the old instrumentation within the flow/level measuring station was replaced. All instrumentation in stations within the NRA North West Region had been standardised and Coalburn was equipped accordingly. The primary data source was a Delta Technical Services TG1150 fed from a shaft encoder positioned on a table over the stilling well. Backup was provided by an Ott R20 autographic recorder. A staff gauge was fastened to the wing walls and zeroed to the centre V-notch. A datum plate was fitted within the station to enable probing of well water levels for accurate instrument setting and checking.

A tipping bucket raingauge at site 12, near the catchment outlet, was replaced with a Didcot Instruments gauge and a Celia Logger to conform to standardisation within NRA-NW. This allows it to be programmed for calibration checks which are carried out at Area workshops.

All data collection with validation and first line maintenance on site is carried out by Area Hydrometric Staff. The data are transferred to the Carlisle Office for downloading onto PCs for final validation checks and archiving. Hydrometric Officers carry out both aspects, using their knowledge of stations and catchments, to ensure best possible data quality on Archive.

The installation of a British Telecom line in August 1992 enabled monitoring of levels and flows in remote sites. Difficulty in obtaining a clear signal to allow downloading due to the length of the service line (one of the longest in the country) was overcome by the use of boosters to amplify the signal.

A Didcot Instruments portable weather station was installed in August 1992 and, initially, was run in parallel with the IH weather station, until the latter was removed in November 1993, following a comparison study which showed close agreement (Robinson, 1993). The weather station is sited within a large open area around raingauge site 11, and is near the centre of the catchment. The meteorological parameters measured are: wind speed and direction, solar and net radiation, dry and wet bulb air temperature, together with rainfall.

With streamflow, weather and rainfall already being monitored, the measurement of water quality needed to be addressed. Spot-sampling of rainfall and stream water by NRA and Forestry Commission staff had been under way since 1992. In October 1993 a Rosemount water quality monitor was installed on the stream; its pH, temperature and conductivity sensors feed 15-minute data values remotely via the TG1150 to Carlisle and to Richard Fairclough House at Warrington. There are particular problems with the measurement of pH in low ionic strength water such as Coalburn, because an insufficient flux of ions to the probe head causes most pH probes to underestimate the true pH (Davison and Woof, 1985). A special low-ionic-strength probe with double-junction KCl gel-filled reference cell was selected; the internal solution provided free ions for pH determination. The performance of the electrode is checked each month using special low conductivity standards at pH 4, 7 and 9.

Even with this special electrode, water movement during measurement (such as by stirring in a container, or flowing water in a stream) exacerbates the error. For this reason, the continuous pH data were checked against the twice-monthly analyses of streamwater samples conducted by the Environment Agency laboratory. This indicated a consistent linear bias. Over the lifetime of the first probe (18/10/93–31/5/95) for a range of pH from 4.4–7.6 the relationship was:

$$pH_{sample} = 1.51 + 0.815\ pH_{cont} \quad (R^2 = 97.6\%,\ n = 23) \quad (5)$$

Over this period there was no evidence of a time trend, or of flow dependence. The probe was replaced in May 1995 as a precaution, and the new relationship for this second probe is yielding pH values generally within 0.1 units of the old relationship.

To obtain water samples at varying flow rates, particularly during short-lived flow peaks, a Rock and Taylor automatic water sampler capable of taking 48 samples was installed at the weir in July 1994. Sampling is triggered when measured flows reach a pre-determined level, and water samples are taken every 30 minutes. Each sample can be linked to a time and instantaneous flow.

5 Results and discussion

The data in this report cover the period from the instrumentation of the original moorland catchment in late 1966, through its drainage in 1972 and planting in 1973, up to the end of 1996, by which time the trees had reached canopy closure over much of the catchment

This Section deals firstly with the water balance results, then with process studies to understand better the storages and fluxes of water within the catchment; water chemistry is discussed and finally some of the ecological effects are briefly described.

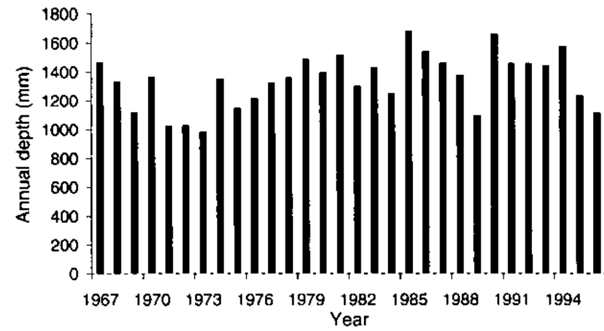


Figure 4 *Catchment annual precipitation, 1967–96, based on the current network of four storage gauges with a +5% ground-level correction*

5.1 Catchment water balance

The individual components of the catchment water balance are summarised below, followed by the construction of the water balance and discussion of its variations over time

5.1.1 Precipitation

Catchment average monthly precipitation totals (1967–96) have been computed from the network of four standard gauges using Thiessen polygon weightings, and indicate an average value of 1350 mm $year^{-1}$ (including a +5% ground level correction). Figure 4 shows a slight increase in annual rainfall over this study period. When the data are broken down by season, it can be seen that there has been a tendency for a greater proportion of the annual precipitation to occur in winter months (September to February inclusive), particularly in the late 1970s and early 1980s (Figure 5).

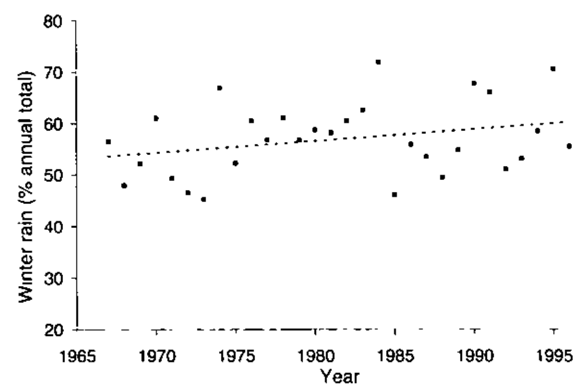


Figure 5 *Winter (September–February) component of annual precipitation, 1967–96*

5.1.2 Potential evaporation

As indicated in Section 4.3, the on-site AWS may be used with the long-term Eskdalemuir station records to provide Penman estimates for the whole period of study at Coalburn. The Eskdalemuir estimates have recently been revised, yielding an average annual figure for Coalburn (1967–96) of about 440 mm; there is no indication of a systematic time trend (Figure 6).

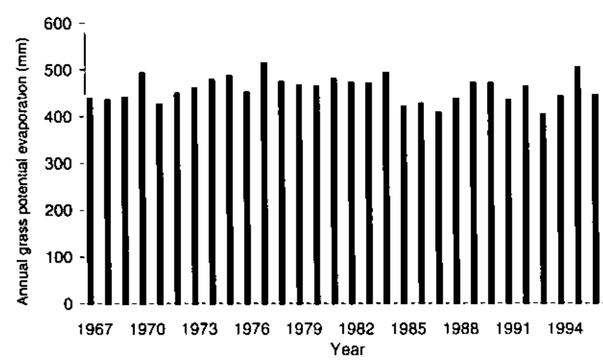


Figure 6 *Annual Penman short grass potential evaporation, 1967–96, based on correlations between on-site automatic weather station (AWS) and the long-term records at the Met. Office Eskdalemuir climate station*

5.1.3 Streamflow

Streamflow is the component of catchment water balance that was most prone to breaks in the record due to the lack of replication (compared with the duplication of raingauges) and its site-specific nature (preventing inter-site correlations such as that for the Penman evaporation estimates). The age of the weir led to reductions in its accuracy in the late 1980s and to breaks in the record while repair work was carried out and flow was diverted through a bypass channel. For the calculation of overall water balance it was necessary to make estimates for periods of missing data. For short gaps, particularly during dry-weather periods, data were infilled based on analyses of streamflow recession patterns; at other times when this was not possible, the monthly rainfall/runoff relations were used. The flow data were examined carefully and compared to the precipitation in the month. An average runoff coefficient for that particular calendar month, based on the whole 30-year period of record, was assumed. In months where there was much greater flow than precipitation, but no indication of 'carry over' from rain at the end of the previous month, the same approach was adopted. Such infilled periods were used only to complete the water balance, and were not included in the short period analyses of flow extremes. The average annual runoff (1967–96) was approximately 910 mm.

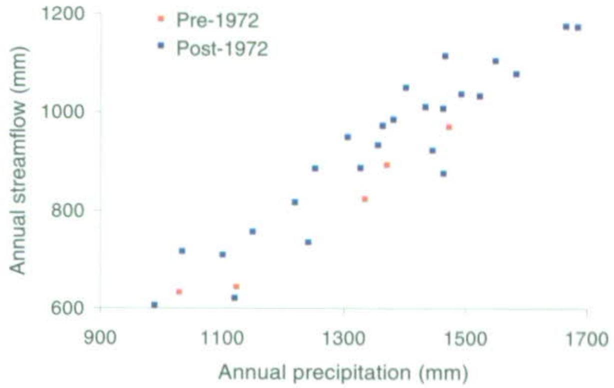


Figure 7 *Coalburn annual precipitation and streamflow, 1967–96*

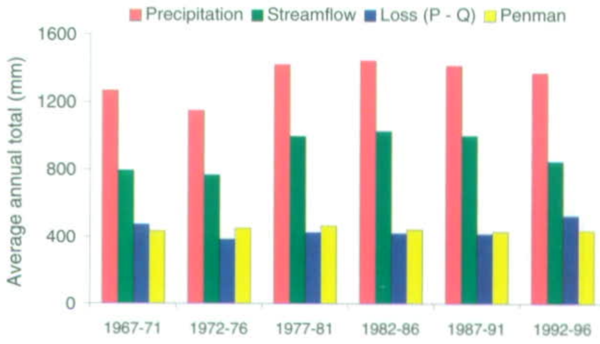


Figure 8 *Water balance — 5-year average precipitation, flow and evaporation losses*

5.1.4 Water balance changes

The annual totals are presented in Figure 7. In general after ploughing (in 1972) there was about 70 mm year^{-1} greater streamflow for an equivalent annual rainfall. Since only limited data are available for catchment storages and because of year-to-year climatic variability, the data are also presented as average values for successive five-year periods (Figure 8). Five-year mean annual totals of precipitation, streamflow, losses (precipitation minus streamflow) and estimates of potential evaporation are also presented (Table 4).

Table 4 clearly shows the influence on streamflow amounts of the variability in the precipitation in addition to any land-use effect. There was a broad increase in precipitation, particularly in streamflow, in the 1980s, although higher rainfall and river flows have been noted over this period, further north in western Scotland (Curran and Robertson, 1991;

Table 4 *Water balance of the Coalburn catchment — values are five-year average annual depths (mm)*

Period	Precipitation (rainfall) *(P)*	Measured discharge (streamflow) *(Q)*	Losses (evaporation) *(P-Q)*	Winter rain (Sept–Feb) *(% annual)*	Penman potential evaporation *(PE)*	Penman minus losses *(PE-[P-Q])*
Before ploughing						
1967–71	1266	793	472	54	433	-39
After ploughing						
1972–76	1149	766*	383	55	435	52
1977–81	1421	995	426	58	437	11
1982–86	1445	1025	420	59	442	22
1987–91	1415	998	416	59	439	23
1992–96	1370	846	524	58	454	-70

* Flows in winter 1972–73 were estimated since the weir was inoperative due to the deposition of sediment released by the forestry ploughing.

Mansell, 1997). A number of features of recent weather conditions may be seen in this table, e.g. there was a drought in the period 1972–73 and again in 1976, although the latter was much less severe in NW Britain than in the south of the country. The period 1977–86 was probably one of the wettest decades in the last 100 years for western regions of Britain. In contrast, in the most recent period, 1995–96, there was a very severe drought in the western Pennines/Cheviots, with an estimated return interval for the rainfall over north-west England, between April and October 1995, of between 80 and 120 years (Marsh, 1996).

The impact of weather variations may be reduced by considering the catchment losses in relation to potential evaporation Before planting, the annual losses for the ungrazed grassland were about 9% greater than the Penman estimates for short grass, and it is known that the Penman equation under-estimates evaporation at windy sites (Thom and Oliver, 1977). In the early periods after afforestation, the actual losses were lower than the potential rate, although they have been progressively increasing relative to the Penman values, and currently exceed them To many people, aware of the general consensus that mature forestry increases evaporation losses, it may seem surprising that afforestation at Coalburn resulted at first in a decrease in evaporation losses (Figure 8). This apparent conflict may be explained when it is understood that this initial effect was the result of the extensive pre-planting drainage.

An increase in annual flows following artificial drainage has been noted in a number of studies (e.g. Green, 1970, Seuna, 1980) due to a short-term dewatering of the peat soil, suppression of transpiration from the bare soil of the plough furrows and the overturned ridges, and to reduced evaporation resulting from the drains maintaining lower water-tables. Higher evaporation losses in contrast will occur with the growth of the trees.

There has been an *increase* in the annual losses (from 380 mm to over 500 mm) since plough drainage took place, despite the fairly steady level in the estimated potential evaporative demand (Table 4). The reduction in the annual deficit of actual losses to potential rates in successive five-year periods was marked: from 52 mm (1972–76), through to the most recent period (1992–96) when actual losses exceeded potential rates by about 70 mm $year^{-1}$. Annual losses exceeded the potential rate in each year from 1990 onwards: this occurred in only two of the previous 18 years since the forestry ploughing.

The changing water balance at Coalburn demonstrates the relative hydrological importance of drainage and vegetation, together with natural variations in the weather conditions. Prior to the ploughing, when the catchment was still used as rough grazing, flow accounted for about two-thirds of the precipitation, and evaporation for about one-third. In the first five-year period after ploughing, despite lower precipitation, streamflow was similar and the annual losses were about 100 mm lower (Table 4). In the second period after ploughing (1977–81), rainfall was about 20% higher, resulting in much higher flows and an annual percentage runoff averaging 70%. The greater runoff was also partly due to a shift in the seasonal occurrence of rainfall from summer (when potential evaporation is greatest) to winter months. An increase in the annual rainfall and a tendency to drier summers and wetter winters over this period has been noted elsewhere in Britain. In the decade following 1977, annual rainfall over England and Wales was about 10% higher than average, and flows 10–20% higher (Marsh and Lees, 1986). In the third and fourth periods after drainage, average annual rainfall and streamflow were similar to 1977–81 and the losses had increased slightly. In the fifth period (1992–96) evaporation losses exceeded Penman estimates for the first time; this occurred when substantial areas of the forest reached canopy closure and interception losses exerted a significant impact on the water balance. The rating of the new flow gauge has been checked recently and it has been confirmed that flows are exceeded for less than 5% of the time without serious error, although it is possible that further peak flow gaugings may change the total flow estimates slightly.

The changing pattern of water use in Figure 9 shows the difference between actual evaporation (precipitation minus streamflow) and Penman short grass potential evaporation, the index value of atmospheric demand. Annual differences are shown

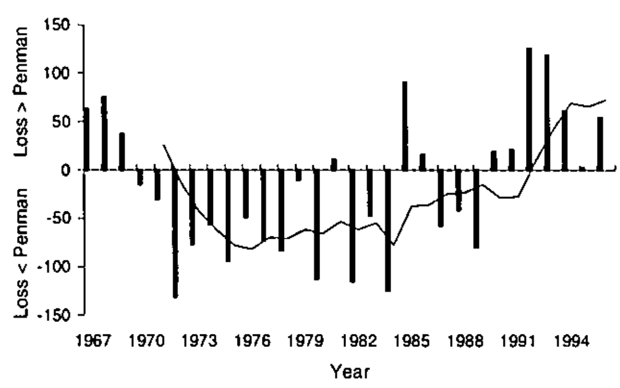


Figure 9 *Comparison of annual actual evaporation loss (P–Q) and Penman potential evaporation (mm), 1967–96. Evaporation initially fell after the ploughing, followed by a slow but steady increase with the forest growth and present losses exceed the Penman rate.*

(vertical bars) together with a five-year moving average (line). It is apparent that the immediate reduction in actual evaporation was followed by a steady increase and, since about 1990, it has exceeded the Penman value — and is still rising.

5.2 Interception losses

Higher interception loss from forest, i.e. water retained on the forest canopy and evaporated, is the principal reason for its greater water use than shorter vegetation (Calder, 1979). An interception study was established at Coalburn in summer 1994 to measure net rainfall (throughfall and stemflow) beneath the tree canopy. The difference between the quantity of rainfall reaching the ground beneath the forest canopy and the total rainfall (measured by a ground-level raingauge in an unplanted area) is the amount of water intercepted by the tree canopy and then evaporated.

Studies of rainfall interception date back to the nineteenth century, and some were listed by Horton (1919), who measured stemflow and throughfall. He noted that interception losses from forests may amount to one third or more of the precipitation, and that losses were higher from conifers than from broadleaved species. However, the significance of this, and subsequent work, for water resources was not realised for nearly half a century, because it was widely believed that evaporation of this water suppressed an equivalent amount of transpiration with no net effect on the total evaporative loss.

A ground survey of the forest growth across the catchment was carried out in December 1992 (R.J. Bell, personal communication) and provided information on tree height, species and yield class, together with estimates of the percentage canopy closure based on aerial photographs. This information was used as the first stage in the selection of suitable study areas; the final locations were identified in site visits. Areas with the smallest trees, where many had failed to become established, had to be rejected, since they were spatially too variable and too exposed, making the plastic sheets (see 5.2.1) liable to wind damage. Two sites were chosen (A and B, both under Sitka spruce) with contrasting forest growth: one with 7 m high trees and a second site, further west, with 9 m high trees (Figure 1). Both sites were at least 50 m from the nearest forest edge in order to provide representative conditions, not unduly influenced by forest 'edge' effects.

From examination of the top leader shoots, it was estimated that the growth of the trees is currently about one metre per year. Over the study period, the trees have grown from 7 m to 9 m at the first site and from 9 m to 11 m at the second site, thus providing information on losses from trees over a total range of heights of 7–11 m. Interception losses may be expected to increase with tree growth since the trees extend horizontally towards each other, reducing the direct throughfall through gaps in the canopy; the canopy density and vertical thickness also increase, and the forest aerodynamic roughness becomes larger with tree height.

5.2.1 Field measurements[6]

Over the years a range of techniques has been used to measure net rainfall: the most common method is to use networks of rain or throughfall gauges under the forest canopy and collars of different materials fitted on tree trunks to measure stemflow (e.g. Horton, 1919; Law, 1957; Gash *et al.*, 1980; Lloyd and Marques, 1988). Calder (1976) used large, plastic sheet net-rainfall gauges, collecting both throughfall and stemflow, to determine the water losses from mature Sitka spruce.

The choice of technique for any interception experiment will depend upon a number of factors. With immature trees there is much greater spatial variability in the tree canopy — and hence net rainfall — than for a mature fully closed canopy forest. It is therefore particularly important to sample the net rainfall adequately to obtain a representative average areal value. Consequently it was decided to use large, plastic sheet net-rainfall gauges capable of collecting all the stemflow and throughfall over areas of 20–50 m^2. Flows from the sheets were recorded using large (1-litre capacity) tipping buckets. Since the study was intended to determine not just the interception loss at one stage of forest growth, but also (for the first time in the UK) the changes over time with forest growth, it was important to be able to separate out the impact of differences in weather conditions. For this reason, the site was also equipped with a weather station installed on a tower over the forest canopy to enable modelling of the evaporation of the intercepted water. Both wind speed and net radiation will be higher over the forest (due to elevation and albedo). Gross rainfall was measured by a ground-level recording raingauge sited in the middle of an unplanted area adjacent to storage raingauge site number 5 (see Figure 2).

Four sheet interception gauges (Calder and Rosier, 1976) were installed: two at each site. This was to replicate measurements under each size of tree, in order to help determine whether differences were due to the different size of the trees or simply due to random errors. In addition, the two sheets at each

[6] P T W Rosier, Institute of Hydrology

Interception sheets in the forest collect stemflow and throughfall.

Water from the interception sheets is recorded using large tipping buckets.

site were constructed in different sizes to ensure that the full range of potential flows would be measured accurately: the larger sheet would yield more accurate measurements of low and medium flow rates, whilst peak flows from the smaller sheet would be less likely to overwhelm the tipping bucket system.

Site A, nearest to the tower upon which the canopy AWS is mounted, contains the shorter trees at a stem density of about 2100 ha^{-1} and is the location for gauges 2 and 4 (Table 5). Gauges 1 and 3 are located at site B, about 100 m to the west, and contain the taller trees with a stem density of 2800 ha^{-1}.

Despite the 2 m difference in height between the two sites there was no statistically significant difference in the mean diameter at breast height (DBH) between the four plots. This was also reflected in the measurements of tree and row spacings at both sites:

Mean spacing (cm)	*Site A*	*Site B*
Between trees	167.8±11.4	158.2±28.6
Between rows	272.0±24.5	243.3±49.9

The lower branches, up to a height of about 1.5 m from the ground, were removed to allow access during the installation. No live branches were removed from any of the trees enclosed by the gauges. The design of the gauges was modified because of the limited natural slope at both sites. Ideally a sheet gauge should have a slope of approximately 5% to allow water to run off freely in response to any rain event and to minimise ponding. The shallow general slope and the many localised depressions and mounds resulting from the site cultivation meant that substantial ground levelling would be required to create a sufficiently smooth surface before the gauges could be installed. The turf ridges contain many live tree roots and disturbance to these could have damaged the trees. Because of these concerns, an artificial slope was constructed using sheets of plywood laid on a wooden wedge-shaped framework. The plastic sheets were then laid on this slope and gathered and sealed around the tree stems. The net rainfall onto the sheets (stemflow and throughfall) drains from the bottom edge of the slope into a plastic gutter, and then into a large tipping bucket flow-meter. Water flows through these flowmeters are recorded as pulses from a magnetically operated reed switch each time the bucket tips, in exactly the same way as a tipping bucket raingauge. Each bucket also has an incremental mechanical counter as a backup which is read each time that the field observer visits the site (approximately every two weeks).

5.2.2 Interception amounts

Data from the gauges are available from May 1994 to December 1996 inclusive (Figure 10a). The gross rainfall for the measurement periods was obtained from the ground-level recording raingauge at site 5. This was checked with the standard storage rain-gauge (corrected by +5% to ground level) and there was good agreement between the two (cumulative totals over the period were within 1%).

There was also close agreement in the net rainfall at all four plots, both in their totals and in their pattern of response to individual rainfall events. Looking in more detail it may be seen that the flows from the two plots at each site — A (gauges 2 and 4) and B (gauges 1 and 3) — are very similar. This gives confidence that the results are accurate and representative. Comparing the two sites, there was greater net rainfall at A (shorter trees) than at B. This reflects the greater interception loss from the taller trees, and is also in accord with interception losses at both sites increasing from year to year with the growth of the trees.

Over the whole period (May 1994 to December 1996) the interception loss averaged over all plots was approximately 28% of the gross rainfall. This interception ratio is lower than has generally been found from studies within the UK for similar climatic conditions (Calder and Newson, 1979; Calder, 1990). Higher values, of about 35%, have been found in other studies (Figure 10b), where measurements have usually been made on much

Table 5 *Details of interception plots at time of installation in 1974 at Site A (7 m high trees) and Site B (9 m high trees)*

Site	Sheet area (m^2)	Tip bucket volume (litres)	Tip bucket depth (mm)	Number of valleys	Number of tree stems	Mean DBH (cm)	Gauge number
A (shorter)	44 58	1.266	0.0284	4	15	14.9±3.3	2
	25.08	1.248	0.0498	2	7	16.0±2.8	4
B (taller)	44.07	1.245	0.0283	3	14	15.5±5.0	1
	28.04	1.258	0.0449	2	7	14.8±3.1	3

DBH = diameter at breast height

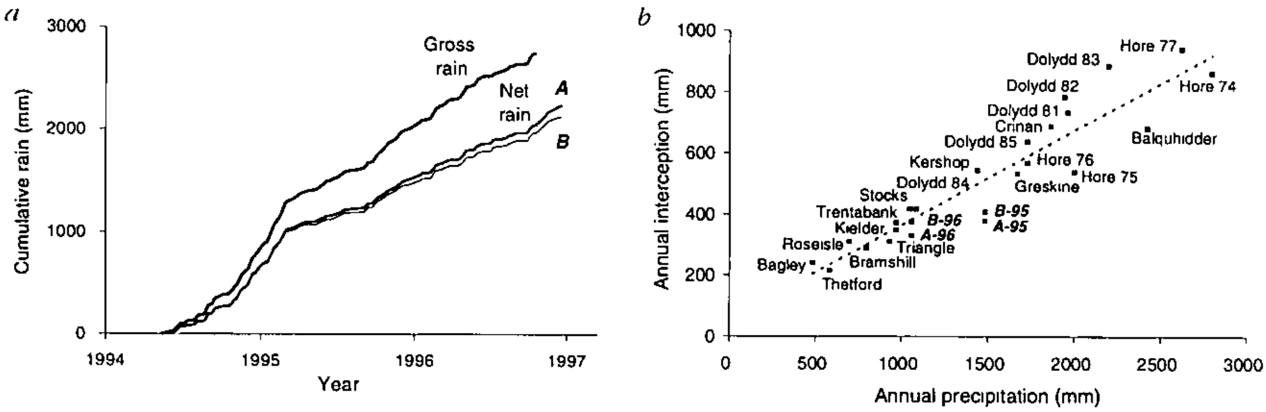


Figure 10 *Comparison of (a) gross rainfall and net rainfall under the forest canopy 1994–96 (average for two plots each for* ***A*** *shorter trees and* ***B*** *taller trees) and (b) interception loss at Coalburn (two years — 1995 and 1996 — data from sites* ***A*** *and* ***B****) with other published studies in UK*

older trees. The interception losses noted here amount to 100 mm year^{-1} less than expected for a mature forest. Such losses are comparable to those reported by Johnson (1990) for wider-spaced and thinned older trees, and may reflect the restricted height of the young trees limiting their canopy storage and aerodynamic roughness.

For the first year of observations (13 May 1994–16 May 1995) interception losses from the taller trees (gauges 1 and 3) amounted to 21% and 23.6% of the annual rainfall, and for the shorter trees (gauges 2 and 4) 19.6% and 21.8%. The interception varied through the year, with highest losses in summer and the lowest in winter. In the second year (1995–96), these losses had increased to 33% and 34.3% from the taller trees, and to 30 8% and 28.9% from the shorter trees. Direct comparison of the losses in these two years needs to be treated with some caution, however, because the amount and distribution of rainfall in the two periods were different. The second year had 40% lower rainfall, and even without any changes to the forest, it would be expected that interception losses would have contributed to a higher proportion of rainfall.

An independent, less sophisticated measure of interception is available from estimates of net throughfall collected as part of the Forestry Commission's Health Study (Section 5.9.2). This uses 10 storage raingauges (150 mm diameter) permanently placed at randomly sited positions beneath the forest canopy. Over an 18-month period, from April 1995 to October 1996, catches in the throughfall collectors equalled 83% of the site A and 79% of site B values (D. Durrant, personal communication). If there were no other site differences and the raingauges collected an areally representative catch, this would suggest that the difference, 17–21% of net precipitation, could be attributed to stemflow. This would be in good agreement with the published value of 18% Sitka spruce of similar age at Kielder (Anderson and Pyatt, 1986). It should be noted, however, that the forest canopy at the Forest Health site is significantly thicker than at the two interception sites. Stemflow gauges installed at the interception sites in 1997 will provide a direct measure of this component, and to enable its water chemistry to be sampled.

To attempt to distinguish the effects of climate variability from those of forest growth, it was decided to use a model to simulate the interception losses under different conditions, and to look for systematic changes over time in the model parameter values that might be related to growth of the tree canopy.

5.2.3 Modelling the interception loss[7]

The most widely used physically based model of interception loss is the Rutter model (Rutter *et al*, 1971; Rutter *et al.*, 1975; Rutter and Morton, 1977). This model has been used for interception loss from temperate coniferous and broadleaved forests (Rutter, 1975, Calder, 1977; Gash *et al.*, 1980). The purpose of this exercise was to establish whether the Rutter model can be applied successfully to model interception loss from immature coniferous forest and thereby gain insights into the interception process occurring in such plantations. The interception loss (gross minus net rainfall) at the Coalburn site (~35%) is below what would be expected (Calder, 1990) from mature coniferous forest in the rainfall climate of Coalburn.

For the initial model calibration, a seven-day period was selected (5–11 January 1995) and parameter values were obtained using an optimisation procedure described below. This period contained approximately 34 mm of rainfall distributed in six

[7] R.L. Hall, Institute of Hydrology

rainstorms. Data from the following two-month period (12 January–11 March 1995) were used to validate the model, which was then used to estimate interception losses in successive periods following the 1995 and the 1996 growing seasons to investigate the effect of forest growth.

The Rutter model

The Rutter model calculates a running balance of water storage C on the forest canopy using the continuity equation:

$$\frac{dC}{dt} = (1 - p)R - D - I \qquad (6)$$

where $(1-p)R$ is the addition of intercepted water on the canopy; D is the drainage rate, and I is the evaporation rate from the wet canopy.

The input of water is given by the gross rainfall R and the throughfall coefficient p (the proportion of 'gaps' in the canopy that do not intercept water). The evaporation loss rate of the intercepted water I is given by $E_w CS^{-1}$, where E_w is the evaporation rate from a completely wetted canopy, estimated by the Penman-Monteith equation (Monteith, 1965) from hourly meteorological variables. It is dependent on net radiation, specific humidity, wind speed and the aerodynamic resistance of the vegetation canopy. The canopy storage capacity S is the plan depth of water when the canopy is completely wetted, so that evaporation of intercepted water is assumed to take place at the potential rate when the canopy is fully wet ($C = S$) and to decrease proportionately with decrease in the canopy storage.

In addition to the canopy capacity, throughfall coefficient and the vapour transfer terms (ζ is the product of aerodynamic resistance r_a and wind-speed u), the Rutter model contains two parameters, k and b, for the drip drainage D from the wet canopy $D = k\,[\exp(bC) - 1]$.

The model was run on a five-minute time step using five-minute gross and net rainfall, and hourly mean values of net radiation, windspeed, air temperature and air humidity. Five-minute values of the components of the canopy water balance, including the predicted net rainfall, were calculated by the model.

Measurement of the variation of the net rainfall on a short timescale is limited by the response time of the net-rainfall gauges. This response time is a function of surface tension effects, the size and slope of the plastic sheets, debris on the sheets and the capacity of the tipping buckets. It is therefore necessary to allow for this response time when comparing the observed and model-predicted net rainfall. This was achieved by including a drainage function for the net-rainfall gauges derived previously for a net-rainfall gauge beneath a leafless canopy of ash trees in Northamptonshire. The effect of the leafless trees on the drainage characteristics of the sheet had been assumed to be minimal. To allow for the response time, net rainfall, predicted by the interception model, was used with this drainage function to give the predicted net rainfall corrected for the time response of the sheet gauge.

Model parameters

Following Leyton *et al.* (1967) and Rutter *et al.* (1971) the canopy capacity S was estimated using the measured net rainfall plotted against gross rainfall for the individual storms in June 1994 to March 1995 (Figure 11). Only those storms preceded by at least 12 hours without rain were used to ensure that the canopy was dry at the start of the storm; S can then be taken as equal to the magnitude of the negative intercept of the line regressed through the upper envelope of points. This gave a value for S of 0.85 (±0.2) mm and a slope of 0.994 (R^2 = 0.9977), indicating that there was virtually no evaporation during the 12 storms used in the regression. The slope from another regression, using data from 67 small storms, with gross rainfall less than the value at which the upper envelope of points steepens, gave an estimate for the free throughfall coefficient p of 0.09 (±0.01) with R^2 = 0.458. This method of estimating S and p is rather subjective and is limited by the accuracy of the gross-rainfall measurements. The net-rainfall measurements have a much greater resolution and, by using the average of the gauges, the accuracy is improved further. Nevertheless these gross figures can be used as base values for parameter evaluation through optimisation. The final values of the parameters together with limits considered to be realistic, based upon considerations of the physical processes, are given in Table 6.

Obtaining the parameter values through optimisation is made difficult by strong interdependence between the aerodynamic resistance parameter ζ and the

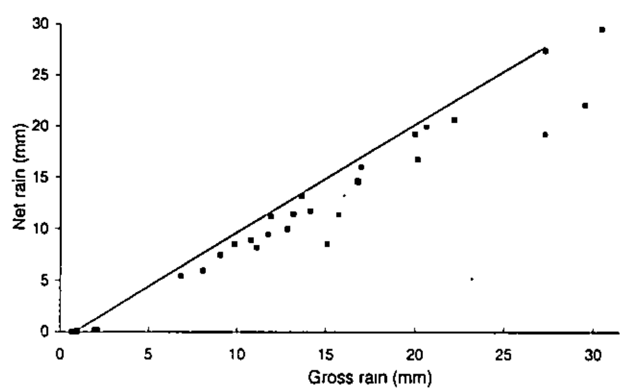


Figure 11 *Estimation of canopy storage capacity for individual storms, 1994–95*

Table 6 *Optimised interception parameter values for the calibration period 5–11 January 1995*

Parameter	Symbol	Upper and lower limit	Optimised value
Vapour transfer*	ζ	5–50	37.9
Open canopy	p	0–0.15	0.1
Canopy capacity (mm)	S	0.79–0.9	0.83
Canopy drainage	k	0.0001–1	0.07
parameters (mm h^{-1})	b	0.1–10	3.20

* The aerodynamic resistance coefficient was optimised separately using the difference between the predicted and observed *total* net rainfall in the objective function.

drainage parameters. Final selection of the aerodynamic resistance coefficient was achieved by using the fact that the total predicted and observed net rainfall should agree. The value of ζ was therefore optimised by minimising the sum of squares of the differences between the cumulative predicted and cumulative observed net rainfall.

The model is able to simulate well the net rainfall recorded during the calibration period with the optimised parameters. It produces net-rainfall increments in good agreement with the observed net-rainfall increments (explained variance of 91%). The mean absolute error of 0 021 mm is equivalent to one tip of the tipping bucket flowmeters on the net-rainfall gauges.

The model was then validated using the January–March 1995 data. The agreement between the predicted and observed net rainfall over the validation period, completely independent of the calibration period, is good (cumulative plot in Figure 12); it is less than the variation in the net rainfall measured between the different gauges.

This modelling has shown that the Rutter model is able to predict well the interception loss from the

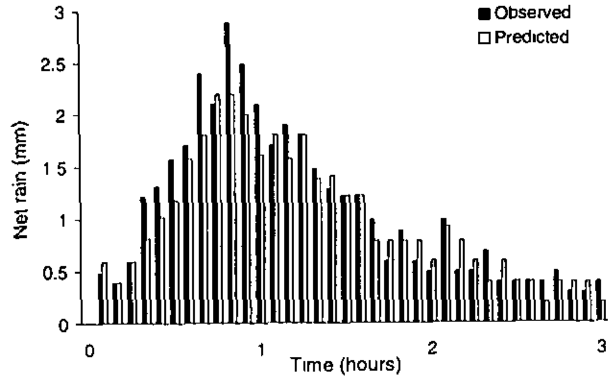


Figure 12 *Modelled and observed net rainfall under the forest canopy*

coniferous forest at Coalburn when the appropriate parameter values are used. The values of $p = 0.1$ and $S = 0.83$ are reasonable for this immature forest canopy. The value of S is lower than some published values for coniferous forest, most of which are for mature canopies, but is for example within experimental uncertainty of the figure of 0.80 mm reported by Gash and Morton (1978). The low recorded interception losses are partly the result of this relatively small S, but also the result of relatively high aerodynamic resistance. The optimised aerodynamic resistance parameter yields an aerodynamic resistance of about 8.5 s m^{-1} for the mean windspeed recorded at the site (January–March 1995) which compares with values of 3.5–5 s m^{-1} usually associated with mature coniferous forest canopies. A high value of aerodynamic resistance (i.e. low aerodynamic roughness) is reasonable, given the shorter height of the young trees; and the more rapid drainage indicated by the high values of the parameters may reflect the less developed stage of the tree canopy. The high aerodynamic resistance results in little evaporation of intercepted water during rainfall, and the relatively small S and high drainage rates result in only small quantities of water being present on the canopy and available for evaporation after rainfall.

The model was then run with data at the end of the 1995 and 1996 growing seasons, keeping the same parameter values, and the agreement between the simulated and observed net rainfall was poor. This could reflect the growth of the trees which would be likely to influence mainly three parameters: canopy storage S, aerodynamic resistance to vapour transfer r_a and the open canopy proportion p In the absence of direct field measurements, unequivocal values cannot be assigned to these parameters. They are to some extent interdependent and, to determine the size of the changes necessary to provide good agreement, it was decided to fix the values of r_a and p, and to optimise the value of S The canopy drainage parameters k and b were assigned values published by Rutter *et al.* (1971) for Sitka spruce, scaled by the ratio of our optimised values of S to the values of S used by Rutter, following the relationships given by Rutter and Morton (1977).

After the first growing season, the optimised value of S for the period 4–15 October 1995 had increased from 0.83 mm to 2.40 mm, and after the second growing season the optimised value for the period from 4 September–16 October 1996 had changed to 1.8 mm. This three-fold variation in the size of S is unrealistically large, particularly considering that the forest is already 25 years old; this indicates inter-dependence of the three model parameters. A more detailed analysis will aim to establish which of the three parameters has the greatest effect. These changes coincided with an increase in the observed interception fraction, and since the model used the measured rainfall pattern, this suggests that forest canopy growth was responsible for at least part of the increasing interception loss.

Measurements continued in 1997 to study further increase in the interception fraction. The modelling analysis will be developed to determine whether linking net-rainfall rates to windspeed improves the simulation results. Relationships relating r_a, S and the drainage parameters to the leaf area index and tree height will be investigated to determine if a unified model is able to simulate the interception process accurately.

5.2.4 Cloud water deposition

The interception study assumes that the difference between the rainfall measured in open areas and the net rainfall underneath the forest canopy is a direct measure of the water lost to canopy interception and evaporation. There could be an under-estimate of total interception losses if there was an additional input to the forest in the form of cloud or mist droplets that are not measured in conventional raingauges.

Instrumentation was installed to estimate cloud water deposition to the vegetation. This occurs when airborne water droplets in fog or mist are deposited on vegetation or other surfaces, generally as a result of turbulent diffusion processes and, like canopy interception losses, will potentially be much greater for tall, aerodynamically rougher forests than for shorter vegetation. This direct capture of droplets by the vegetation is not to be confused with condensation which is dewfall. The deposited water may drip to the ground, run down stems or alternatively be re-evaporated as intercepted water. Fowler *et al.* (1989) have suggested that it is an important contributor to total pollutant deposition in upland areas, particularly within forested sites. It may also represent a potentially significant gain to the precipitation input to the catchment. In areas of frequent fog and mist it has been claimed that cloud water deposition may more than offset forest interception losses, resulting in higher annual runoff and baseflows from forested basins (Harr, 1982).

The following approach considers only one-dimensional vertical cloud water deposition to the top surface of the forest canopy, and assumes that because of the extremely small size of droplets (generally <20 μm in diameter) the fog and mist will follow the movement of the air and can be described by the process of eddy diffusion (Shuttleworth, 1977) It ignores forest edge effects since water droplets blown into the edge of the stand are intercepted quickly — generally within <20 m — so that the flux of water droplets to the forest canopy is predominantly vertical. In this study, the cloud water content was measured first, and the likely deposition rates were estimated for the particular vegetation characteristics from knowledge of the aerodynamic resistance to the turbulent transfer of entities (water vapour and energy) from the vegetation surface to the atmosphere.

The cloud water content was measured using the standard passive cloud water collector gauge developed by the Institute of Terrestrial Ecology (Milne *et al.*, 1988). This consists of a vertical, inverted cone of polypropylene filaments stretched over a metal frame coated in low-density polyethylene. Cloud water droplets impact on the filaments and drain down a pyrex glass funnel. A 1.2 m diameter lid of marine plywood, with its lower surface sheathed in plastic, is supported above the collector by a tubular steel frame. This is designed to exclude raindrops >0.5 mm diameter from the collector when windspeeds are <5 m s^{-1}. The collector is positioned 2 m above the ground and the cone has a vertical cross-sectional area A_f of 0.033 m^2.

The cloud water content of the air C_w (kg m^{-3}) at the height of the gauge can be calculated from $C_w = G(\eta\ u\ A_f)^{-1}$, where G is the catch rate ($m^3\ s^{-1}$), u is the wind velocity and η (dimensionless) is the catch efficiency of the gauge. The vertical deposition onto the forest canopy can then be determined by inverting the turbulent diffusion equation used for the evaporation of intercepted water on the canopy, i.e. deposition is $C_w\ r_a^{-1}$.

Two cloud water collectors were installed at the meteorological site in September 1994. One was connected to a tipping bucket raingauge to record volume: the other drained into a polypropylene bottle to provide a fortnightly sample for chemical analysis. The calculated cloud water content averaged about 0.2 g m^{-3} which, although high, is within the expected range observed in meteorological studies (Pruppacher and Klett, 1997). Cloud water deposition was recorded for about 6% of the time, amounting to around 500 hours per year; this may be an overestimate as no attempt was made to exclude periods when rain was falling and wind speeds were >5 m s^{-1} and there is the possibility of the inclusion of some blowing rain. At present there is no rigorous way to make such a separation.

Assuming standard values of aerodynamic resistance r_a of 50 s m^{-1} for grass and 3.5 s m^{-1} for forest yields, deposition rates were about 0.01 mm h^{-1} and 0.19 mm h^{-1}, respectively. Using the higher r_a of 8.5 s m^{-1} obtained in the interception modelling study would have yielded a lower deposition rate to the forest of 0.085 mm h^{-1}.

View of the forest canopy showing roughness and the large rate of growth, with long leader shoots

The standard passive cloud water collector gauge

Over the course of a year it is estimated that there would be about 5 mm deposition to grass (under 1% of the recorded rainfall) and higher deposition to forest amounting to about 50–90 mm. This is the estimated additional input to the forest and, because of the practical problems of excluding rainfall, may probably be taken to represent an upper estimate of deposition. This would have no direct effect upon the overall water or energy balances of the catchment as the net interception (the balance between deposition and canopy evaporation) is already known from the below-canopy measurements of throughfall The cloud water deposition is matched by an equivalent underestimate in the interception losses. However, depending upon when the deposition occurs, it might reduce forest transpiration. This additional cycling of water between the atmosphere and the forest canopy is potentially very significant for water chemistry, since the small mist droplets have much higher chemical concentrations than rainfall (see Section 5.6).

There is considerable uncertainty in these calculations. Small changes in r_a will affect the computed deposition rates, and there is the likelihood of rainfall entering the gauge during windy periods, despite the lid. Although only preliminary, and likely to be overestimates rather than underestimates, these results suggest that earlier estimates for Kielder Forest that assumed an annual 1000 hours of deposition (i.e. 11% of the time) were a significant overestimate (Fowler *et al.*, 1989). That figure was based on a national study using 20-year average cloud base observations by the Met Office and the Royal Air Force to obtain large-scale patterns (Weston, 1992). As such, the estimates are not necessarily accurate at a particular point, and in any case a low cloud will not necessarily generate deposition as it requires sufficient cloud water content (K.J. Weston, personal communication). Additional evidence, to support the conclusion that the cloud water deposition is relatively small, comes from the absence of flow from the large interception sheets at times when there was no rainfall. Thus, any deposition during periods with low cloud, but no rainfall, did not exceed the forest storage capacity estimated to be about 0 8 mm

5.3 Transpiration

Transpiration is another important component evaporative process It is the loss of water vapour from plants to the surrounding air and occurs through stomatal openings in the leaves. Transpiration may be regulated by controlling the size of the stomatal openings to balance the evaporative demand of the atmosphere (which may be represented by the Penman-Monteith equation) and the supply of water to the plant roots (which depends upon the soil water content and on the soil permeability). When the leaves are covered with intercepted water, this will be evaporated first and transpiration will temporarily cease until this water has been removed.

Consideration of the catchment water balance (Table 4) indicates that over the most recent five-year period, with 1370 mm precipitation and 846 mm streamflow plus interception loss of 25–30% (say 350 mm), there is only limited water loss (about 150 mm year^{-1}) that may be attributable to forest transpiration. Studies over a wide range of tree species, soils and climatic conditions have reported values within the range 300–350 mm (Roberts, 1983), although of course water loss will be lower in wetter and colder climates. Currently, the trees at Coalburn appear to be healthy and growing strongly, by about 0.75–1 m year^{-1}, and there is no indication that they are 'checked'.

In order to address this apparent anomaly, it was decided to make direct measurements of transpiration losses. The aim is to determine to what extent transpiration losses from conifers may be estimated from standard Penman rates (there is no forest understorey vegetation) and whether transpiration is suppressed, for example, by soil water conditions during dry-weather periods (Coalburn is in an upland area of more moderate precipitation than the extremes of the other UK catchment studies at Plynlimon and Balquhidder — both >2000 mm year^{-1})

The transpiration of a whole tree may be measured as sap flow movement up the tree stem (Smith and Allen, 1996). One technique for measuring this is the heat pulse velocity method. An extremely fine heating element is inserted into a hole drilled in the sapwood, with heat sensing probes inserted above (downstream) and below (upstream). An electric current is briefly applied to the heater and the time taken for a corresponding temperature pulse to reach the upper probe yields an estimate of the sap flow velocity. The actual quantity of flow may be calculated if the cross-sectional area of the conducting xylem is known. The lower probe provides a correction for heat conduction which is independent of flow velocity.

In a preliminary study, two Sitka spruce trees close to interception site A were instrumented in August 1996: four sets of heaters and temperature probes were inserted to different depths into the xylem. This study of how the sapflow velocity profile varies with depth indicated that sapflow is concentrated in the outer 20–30 mm of the sapwood. Figure 13 shows transpiration from a single tree with net

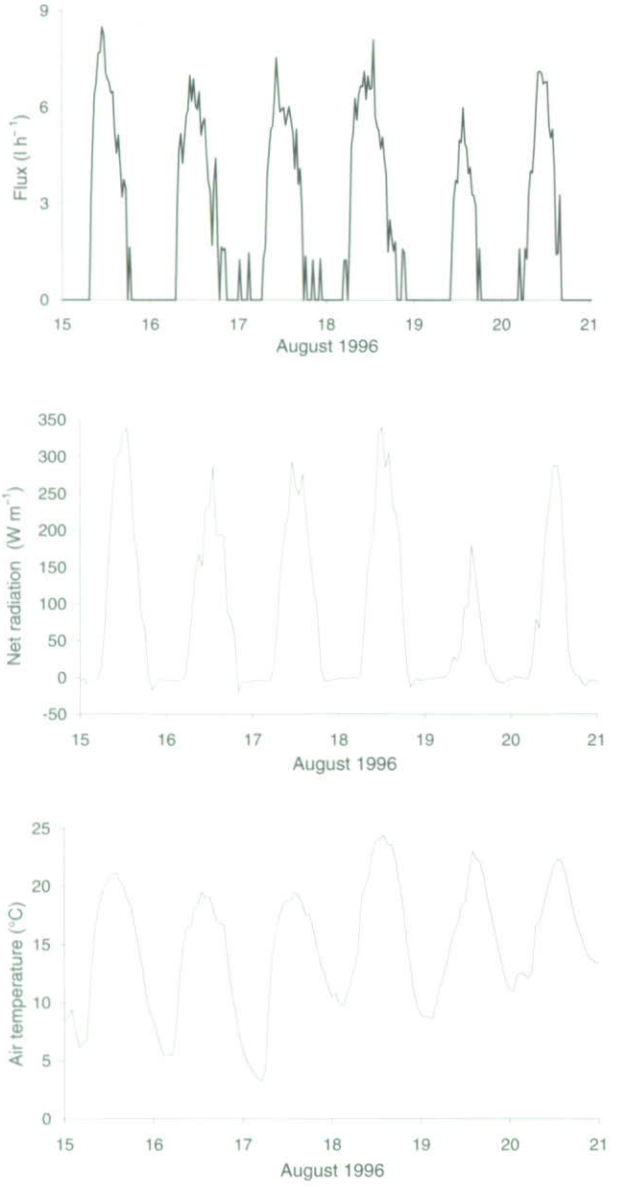


Figure 13 Hourly transpiration flux, net radiation and air temperature, 15–21 August 1996

radiation and air temperature. From spring 1997 transpiration was measured over the course of the growing season with the aim of eventually estimating rates over the catchment.

5.4 Soil water studies

Soil water monitoring began in the early 1980s with readings of water levels in dip wells. Since the early 1990s, water content has been measured regularly at a number of sites using a neutron probe. Short-term soil water dynamics have also been studied using recording tensiometers.

5.4.1 Water levels in dip wells

Given the importance of plough furrows to the catchment hydrology, water levels have been measured since January 1983 in a transect of seven perforated pipes installed between two plough furrows (Figure 14). The transect is in an open area without significant tree cover, and provides a direct indication of the local effect of the plough furrows. The vertical pipes are sited in an area of deep peat and reach to approximately one metre below the ground surface. Water levels are read twice monthly.

Figure 14 shows the mean water level in the dip wells and indicates the movement of soil water towards the plough drain. The greatest effect of the drain is confined to the zone immediately adjacent to the drain edge, with only a small water-table gradient beyond one metre distance. Nevertheless, the water-table gradient towards the drain is consistent in direction throughout the year and, with a channel density of 200 km km^{-2}, provides 400 km km^{-2} of drain-side seepage faces, helping to sustain streamflow of both dry-weather baseflow and annual totals.

a *b*

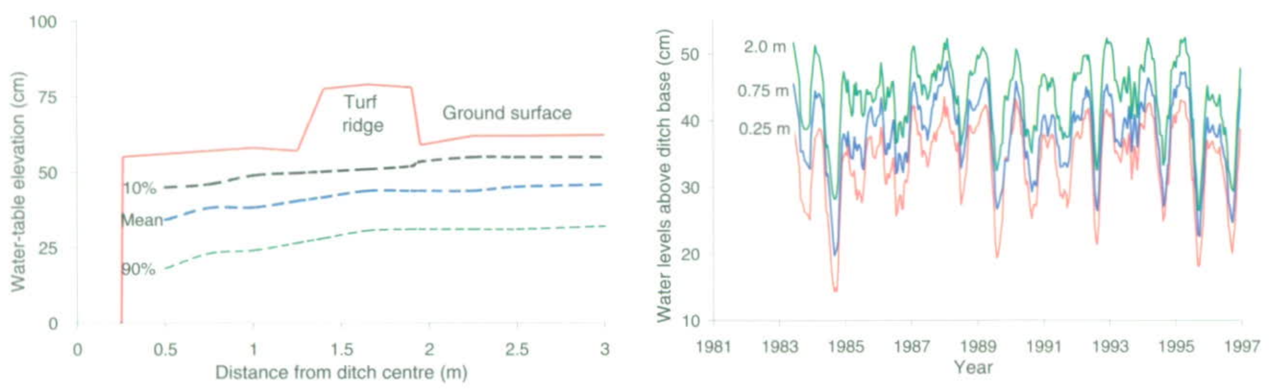


Figure 14 Water levels (1983–96) in the transect of dip wells in an unplanted area showing (a) mean values and 10% and 90% exceedance levels, and (b) time series of levels at different distances from the drain edge

Transects of dip wells were installed across a further four drains in autumn 1996: two are under forest and two are under grass. Although only limited data are available they already show consistently lower water-tables under the forest than at the two grass sites.

5.4.2 Soil water contents[8]

From spring 1992, the Geography Department of Newcastle University has made regular measurements of soil water content within the catchment using a neutron probe. Measurements were made over the soil profile to a depth of 1.1 m where there was no change in water content at three sites with different soil types and vegetation combinations. Readings were taken at all sites, which have the same site drainage (depth and spacing), on the same days and with the same neutron probe.

Although the data interval (approximately monthly) is too crude to show all but seasonal variations, and the sites are not replicated, there are clear systematic differences between the sites (Figure 15). The peaty gley site is drier than the two deep peat sites; and the peat soils are drier under the forest — an observation that is not surprising given the higher measured forest interception losses. There are apparently no site factors except vegetation that can explain these site differences. Significantly, the seasonal range of water contents (10% and 90% exceedances) for the two peat soil sites is greater under the closed canopy forest (~130 mm) than under grasses (~100 mm). This indicates the greater total water use of the forest (combined interception losses and transpiration).

The lower soil water content under the forest represents an additional water loss (through a change in catchment storage) that is not shown explicitly in the catchment water balance (Section 5.1.4). To look for evidence of time trends and remove the impact of climate variations, the profile water contents for the two forested sites were standardised against the unplanted grassland site value for each set of measurements. There is a weak, but not statistically significant, downward trend over time, suggesting that the forest soils are becoming progressively drier with the growth of the trees. However, the period of comparison is too short to reach any definite conclusions; further measurements are needed over a much longer period.

[8] W. Stelling, Department of Geography, University of Newcastle upon Tyne

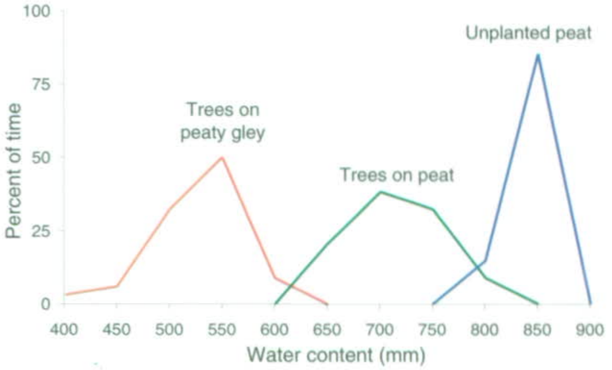


Figure 15 *Range of observed soil water contents using a neutron probe, under different soil and vegetation conditions*

5.4.3 Soil water potentials

From October 1990 to November 1993 recording tensiometers were installed in the catchment to provide more information about soil water conditions, particularly during storm events. This is important for a better understanding of flow processes, which will be relevant to studies of streamflow quantities and streamwater chemistry. The same three sites were used as for the neutron probe access tubes (Section 5.4.2) and the recording tensiometers were logged at 30-minute intervals. Figure 16 shows the very rapid response of soil water to rainfall, particularly in the upper peat layers, which can be transmitted quickly to the catchment outlet when it reaches the extensive network of plough drains. No point in the catchment is further than 2.5 m from one of these channels, although water may not necessarily travel direct to a drain, particularly where they are aligned with the ground slope.

The continuous record of soil water potentials also provided a more complete picture of the differences

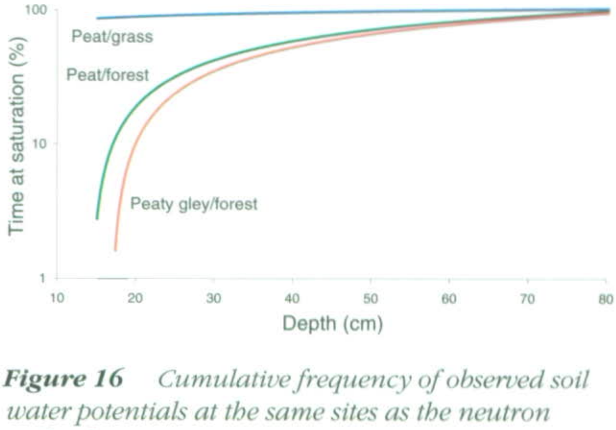


Figure 16 *Cumulative frequency of observed soil water potentials at the same sites as the neutron probe data*

between the sites than the monthly neutron probe readings. Thus, for the peat site under grass at mid-drain spacing, the water-table was within 50 cm of the ground surface throughout the year. In contrast, unsaturated conditions persisted at that depth under forest for about 20% and 25% of the time for peat and peaty gley, respectively. At a shallower depth (20 cm), the unplanted grass site peat was saturated for over 50% of the time compared to the forested sites — only 5% and 10% of the time for peat and peaty gley, respectively. At the grassland peat, only the elevated turf ridge provided consistently unsaturated conditions — for over 95% of the time at a depth of 20 cm below the ridge crest.

5.5 Flow regimes

5.5.1 Low flows

The low-flow characteristics of a river may be described by a number of different parameters. The flow duration is often quoted but is known to be highly sensitive to climatic variability, and is not ideally suited to a study of changes over time. The proportion of annual flow occurring as 'baseflow' defined by a Baseflow Index (BFI) has been widely used, and has been found to be a more stable parameter (Gustard *et al.*, 1993). It was calculated for Coalburn and for three nearby catchments known to have little or no forestry drainage, using data from the UK National Flow Archive (IH/BGS 1996). To aid comparisons between the catchments, their annual BFI values were standardised by the mean value for the catchment in the period of record prior to 1972. Comparison of the BFI for successive five-year periods (excluding gaps in the flow record) suggests that forestry drainage at Coalburn increased the baseflow proportion by as much as 0.1–0.15 of the annual flow (Figure 17).

For the three control catchments BFI values were generally within ±15% of their pre-1972 mean value, whilst those for Coalburn ranged from +225% (1972–76) to +160% (1987–91) and were significantly different at the a = 0.005 level (Mann Whitney Rank Test). Whilst this increase is incontrovertible, it should not be taken to indicate that a doubling of the BFI would occur at other sites. The large relative increases in BFI at Coalburn reflect the very low pre-forestry value against which they are compared. In common with many headwater upland catchments, Coalburn is small and impermeable, with little baseflow and does occasionally cease to flow in summer; its pre-1972 BFI of 0.108 was one of the lowest values examined in a national low-flow study of nearly 1000 gauged catchments (Gustard *et al.*, 1993). These catchments were typically several hundred times larger than Coalburn, with perennial flow, and would not be expected to show such a large proportional change as Coalburn.

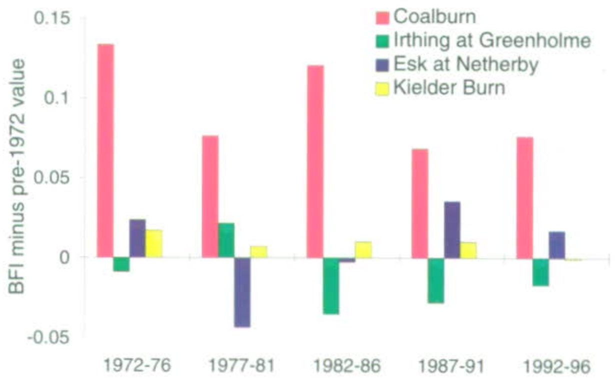


Figure 17 *Comparison of 5-year average Baseflow Index (BFI) values for Coalburn and nearby catchments standardised by their average value prior to 1972*

There is evidence of a slight decline in BFI values at Coalburn since the early 1980s, but no time trend is seen at the other catchments. Whilst it may perhaps be attributed to the effects of deterioration and infilling of the ditches, together with the increasing hydrological effect of the growing tree crop, the present rate of decline is so slow that the increase of low flows following drainage would extend for the whole duration of the plantation cycle. The rate of decline is of the order of only 1–2% $year^{-1}$ (Figure 18) and if it continued at present rates, pre-drainage BFI levels would be reached in about the year 2030 (some 15 years after felling is scheduled).

This conclusion of an increase in low flows after ploughing (in 1972), followed by a gradual decline is also supported by general changes in the flow duration curves. There was an apparent increase in the magnitude of low flows, with a doubling of the 90 percentile flow between the periods 1967–71 and

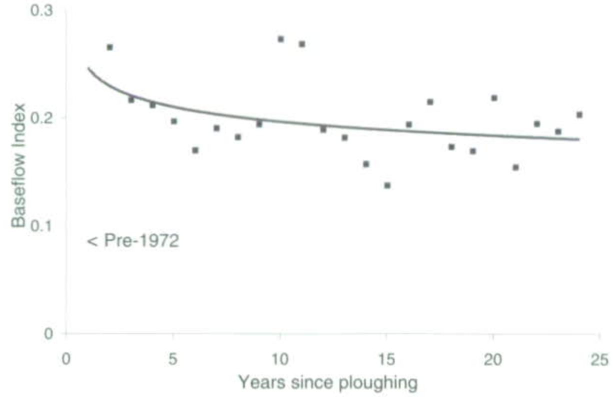


Figure 18 *Decline in annual Baseflow Index since the ploughing*

Table 7 *Average annual number of storm peaks above specified flow thresholds ($m^3 s^{-1}$), before drainage in 1972 and afterwards*

Periods	Threshold flow				Mean annual
	>0.9	>1.0	>1.2	>1.5	flood peak
1967–71	4.6	3.0	2.4	1.6	1.97
1974–83	6.9*	5 7*	3.8*	1.7	2.33
1984–90	7.0*	4 7	2.7	1.3	2.20
1990–96	5.3	4.2	3.2	1.2	1.87

* Significantly different from pre-drainage period at a = 0.1 level

1979–83, which was attributed to the ploughing and to weather variations (Robinson, 1986). Since then the low-flow percentiles have decreased to near to their 1967–71 levels, but this is at least partly in response to weather fluctuations (Table 4).

5.5.2 Peak flows[9]

Maximum flows in the five years before ploughing (1967–71) were compared with those in the ten years afterwards (1974–83), and in the following 13 years (1984–96). Longer periods were used for this comparison than for water yields and low flows, due to the much greater year-to-year variability in peak flows. The number of independent peaks in each year above a range of thresholds from 0.9 $m^3 s^{-1}$ to 1.5 $m^3 s^{-1}$ was counted (Table 7).

Following the drainage, there was an apparent increase in the number of stormflow peaks, particularly the 'smaller' ones. This indicates that the open drains were providing routes for the rapid evacuation of stormflow (compared with surface and near surface runoff), a finding observed elsewhere in upland Britain (Nicholson *et al.*, 1989). There was no change in the seasonal occurrence of storm peaks, with approximately 70% falling in winter months (October–March).

If it is assumed that the number of exceedances is governed by a Poisson process, then the statistical significance of the difference in the rates of occurrence between the two periods may be tested (Cox and Lewis, 1966). For thresholds up to 1.2 $m^3 s^{-1}$ the number of peaks in the periods 1967–71 and 1974–33 was significantly different at least at the a = 0.10 level. The mean annual maximum flow was about 15% greater after drainage but was not significantly different. The second and third periods after drainage, 1984–96, showed a reduction in the number of peak flows, which would accord with a decline in the drain efficiency resulting from infilling with sediment and vegetation, and to the growth of the tree crop. However, it is difficult to draw definite conclusions because the occurrence of flood peaks is highly sensitive to the number and magnitude of rainstorms.

5.5.3 Storm hydrographs

To confirm that the artificial drainage had altered the pattern of storm discharge response, it is necessary to remove the effect of differences in storm rainfall profiles upon the storm hydrograph response. Storm events giving high discharge peaks were identified and, after excluding events with a snowmelt component, about 70 events were used to derive unit hydrographs (NERC, 1975). For each storm the shape of the unit hydrograph was summarised by its peak value and rise time (Figure 19). Average parameter values are given in Table 8; the data after drainage have been subdivided to look for changes in response over time as a result of vegetation growth.

In the period 1973–77 the peak of the half-hour unit hydrograph was about 40% greater than the original moorland response whilst the time to peak and the width at half peak were both shortened by about 20% (both these differences were statistically significant at the a = 0.005 level). This change to a more flashy pattern of storm response resulted from

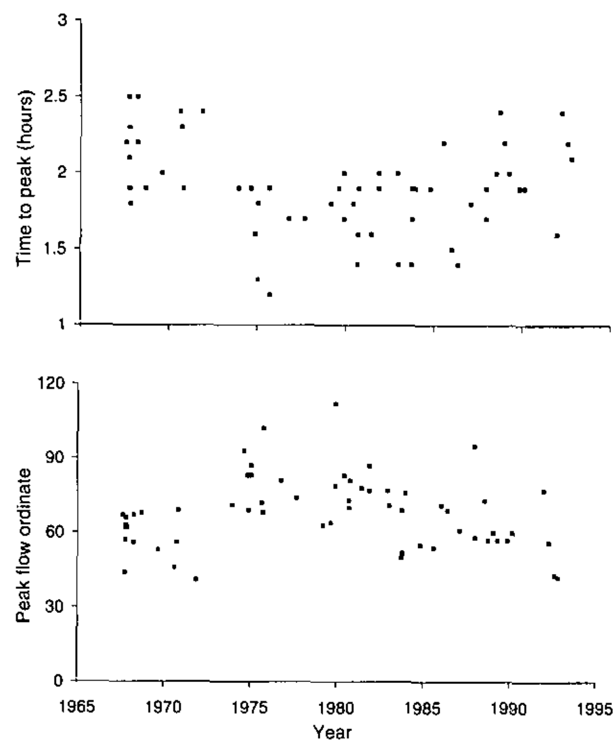


Figure 19 *Changes in individual storm unit hydrograph parameters: time to peak and peak flow ordinate*

[9] H.N. Davies, Institute of Hydrology

Table 8 *Average parameter values of the half-hour unit hydrographs, together with the observed storm hydrographs used to derive them, before drainage in 1972 and afterwards*

	Derived unit hydrograph parameters		Observed storm hydrographs analysed	
Period	**Time to peak** *(hours)*	**Peak ordinate** *(% volume)*	**Observed peak** *($m^3 s^{-1}$)*	**Observed discharge** *(% rainfall)*
1967–71	2.15	10.5	1.34	70
1973–77	1.68*	14.4*	1.80	64
1979–81	1.76*	13.3*	1.45	68
1981–83	1.76§	12.3	1.38	69
1984–88	1.87§	11.8	1.36	62
1989–	2.04	10.0	1.14	59

Note: Significantly different from pre-planting value at * α = 0.005, or § α = 0.05 level; single-tail Mann-Whitney Rank Test.

the greater density of drainage channels considerably reducing surface flow travel distances. These changes reduced over time as the unit hydrographs became more attenuated, and by 1990 were no longer statistically different from the pre-drainage response. A diminution of the effects of the ploughing over time accords with the observation that many of the furrow drains became colonised by grass and mosses which would reduce their hydraulic efficiency. Subsequent tree growth shaded out this vegetation but provided large quantities of litter from needle fall.

The magnitude of a stream hydrograph peak depends upon the total volume of storm runoff as well as its time distribution. For the storm events used in the unit hydrograph study there was no significant difference between the observed percentage runoff from winter storms in the periods before and after drainage. These findings indicate that the effect of drainage on soil storage capacity and, hence, runoff quantities was relatively small. Its main role was to remove overland and surface water more quickly from the catchment. A similar conclusion was reached in other studies of draining moorland by open ditches for pasture improvement (e.g. Robinson, 1985; Nicholson *et al.*, 1989) and is supported by measurements of soil water around a plough furrow (Section 5.4). This is not to say that subsequent tree growth with higher interception losses and drier ground will not lead to a reduction in hydrograph volumes, at least for smaller and summer period storms.

These results have been presented for the somewhat abstract concept of a half-hour storm hydrograph. In attempting to quantify the 'increase' in peak flows due to drainage, it must be emphasised that the 40% increase applies only to flows resulting from a half-hour duration rainstorm. It cannot be applied directly to flow hydrograph peaks from longer storms since the unit hydrograph must be convoluted with successive half-hourly ordinates of the storm rainfall. The increase in the flow peak is not a constant amount; for a particular storm it will depend upon both the duration and shape of the rainfall profile. In the UK a standard rainfall profile often used for engineering design is a symmetrical bell-shaped profile, which is peakier than 75% of the winter storms observed (Keers and Wescott, 1977). Using this design profile for a six-hour storm (equivalent to the time base of the unit hydrographs, and providing for stormflow contributions from all of the catchment) indicates that, for a given volume of storm runoff, the artificial drainage increased peak flows by about 15–20% in the first five years, reducing to about 10% after 15 years, and about 5% after 20 years (Figure 20)

This is not, however, to say that the increases indicated here would be the same for extreme events: the unit hydrograph analysis was based on events that were generally smaller than the mean annual peak (Tables 7 and 8). In extreme (and rare) events, system thresholds may be surpassed. For

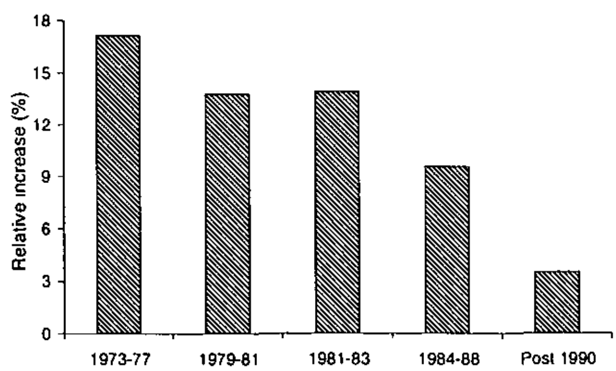


Figure 20 *Change in predicted design flood peaks, based on observed variations in unit hydrograph parameters and the NERC Flood Studies Report (NERC, 1975) procedures*

instance, if a storm exceeded the interception capacity of the vegetation and the available depression storage capacity of the many partly infilled and blocked drains, then the extensive artificial channel network could potentially produce much higher peak outflows than the original moorland. That is the direct consequence of the much greater velocities of open channel flow than subsurface or overland flow.

5.5.4 Model simulations of streamflow[10]

Once a catchment study, such as Coalburn, has demonstrated the impact of a change in land use on the streamflow from that area, it is desirable to apply that knowledge to other areas The most common approach is through mathematical models — especially those that incorporate a representation of some of the key hydrological processes identified in field studies — which may be considered 'physically based' and therefore better able to cope with changing catchment conditions. Recent advances in computer technology have led to highly sophisticated models such as the Système Hydrologique Européen (SHE) (Abbott *et al.*, 1986). These may be used to scale up hydrological processes for integrated catchment management and may be applied to whole river basin management such as the 2000 km² of the Tyne Basin (Dunn, 1995). They are, however, dependent upon the accuracy of their representation of hydrological processes within the limits of present computing capability and data availability.

One such issue relates to how small-scale topography and drainage affects the runoff process. Over much of the UK, the natural drainage network has been augmented by artificial agricultural drainage (Robinson and Armstrong, 1988), and in areas which have been afforested, such as Coalburn, this has created a drainage network up to 60 times denser than the natural system. At the present stage of development of large catchment models, which may have a grid resolution of 1 km², it is not yet possible to represent these small-scale features directly, although it is known that their effect on hydrological flow paths may be significant. To investigate these effects, SHETRAN (a model derived from SHE) was applied to a small-scale hillslope model and the effect of different intensities of drainage on the hillslope runoff was analysed. These model simulations led to the development of a technique for calculating 'effective' parameter values to represent the characteristic effects of drainage in a simplified manner for a coarse-resolution large-scale model (Dunn and Mackay, 1996). Application of the effective parameters to a sub-catchment of the South Tyne at Alston showed that the technique could successfully improve predictions of subsurface flow dynamics. This involves adjusting the channel routing roughness parameter and the saturated hydraulic conductivity of the soil to reduce soil saturation and hence lower the water-table in a similar manner to artificial drainage.

Coalburn provided an ideal data set to validate this approach, and to investigate how forest drainage changes the hydrological response of a catchment. Two SHETRAN models of the Coalburn catchment were developed: one to describe the catchment in its undrained state prior to 1972, and the other to describe the catchment in its drained state using effective parameters.

A 50 m grid resolution was used and effective drainage parameters, based on a ditch separation of 4.5 m and depth of 0.5 m, were derived. Flow simulations were performed on an hourly time step for two six-month time periods: July–December 1967 (pre-drainage) and July–December 1982 (post-drainage) The simulations were as follows (and see Table 9):

(a) **Grassland** with original stream network from Ordnance Survey maps, and parameter values taken from the literature

(b) **Grassland** with original stream network, and parameter values (saturated soil hydraulic conductivity and Manning's channel roughness coefficient) adjusted to fit the simulated outflows to the observed flows

(c) **Forest** with original streams, and parameters calibrated in (b) plus modifications to the model to represent the drains altering soil flow pathways and for the young trees altering evaporation

(d) **Forest** with original stream network, parameters calibrated in (b) and no allowance for drainage or young trees

(e) **Grassland** with post-drainage representation derived in (c) and no allowance for trees.

The purpose of simulation (b) was to eliminate as much uncertainty as possible in the basic model parameters, such that changes effected by the drainage could be distinguished from model error. After calibration of parameters to the 1967 flow record, simulations for the 1982 data (c and d) were performed 'blind'. The R^2 fit between the predicted and observed daily flows in each six-month period is shown in Table 9.

[10] S. Dunn, Department of Civil Engineering, University of Newcastle upon Tyne (present address: Macaulay Land Use Research Institute, Aberdeen)

Table 9 Results of flow model simulations based on different levels of artificial drainage

Simulation period		Description	R^2 (%)
1967	(a) Grassland	Undrained, no calibration	84
1967	(b) Grassland	Undrained, calibrated	93
1982	(c) Forest	Drained	94
1982	(d) Forest	Undrained	91
1967	(e) Grassland	Drained	92

In general, once the model parameters for sub-surface flow and channel flow had been calibrated (simulation b), all the simulations (b to e) achieved an acceptable prediction of flow, regardless of whether the forestry drainage was accounted for. This implies that the drainage has little effect on flows, yet it is known that this was not the case. Closer examination of the hydrographs shows that there were significant differences between the simulations in the characteristics of the flow regime, particularly the low-flow component.

The low-flow simulations for 1967 were slightly over-predicted by both the undrained and drained models (b and e), but the undrained model produced the slightly better prediction (93 vs. 92%). Conversely, for 1982, the low flows were slightly underestimated by both the drained and undrained models (c and d), but the drained model (c) produced the better prediction over all flows (94 vs. 91%). Thus, the drainage representation in the model does at least have the correct direction of effect on the flow predictions, and is consistent with the observation that the initial effect of the forest (drainage and planting) was to increase baseflow in the streams substantially.

The simulations for high flows were less satisfactory: the predicted effect of the drainage was to reduce the hourly peak flows, whereas the site observations showed that the opposite occurred. Nevertheless, it was felt that overall, the SHETRAN simulations support the procedure of effective parameterisation of drainage derived in Dunn and Mackay (1996).

As well as being used as management tools at the catchment scale, models may also provide insights into the flow dynamics that can then be used to design field experiments. Thus, following on from the soil water studies and the modelling results presented here, in autumn 1996, the Forestry Commission began a study of soil water conditions around a number of ditches, with and without trees. The aim is to study the effect of imposing differences in drain depths, thus distinguishing 'technical' from 'biological' drainage of the soil.

5.6 Water chemistry

At the start of the Coalburn study there was little interest in the effects of forestry on water quality — extreme flows and water yield were the main concerns. Over the last decade, in common with the general trend in hydrology, there has been a growing awareness of the importance of water quality. Consequently, water chemistry studies now form a major part of the research effort. These include 'traditional' studies of major cations and anions in the stream water, acidification resulting from air pollution from industry and enhanced by the scavenging of these atmospheric pollutants by deposition to trees, and concerns over naturally occurring potential carcinogens in peatland waters for drinking water supply.

5.6.1 Sampling at the catchment outlet[11]

Samples of stream water, taken in the period covering the ploughing of the catchment in 1972, and in winter 1978–79, were analysed for major cations and total dissolved solids (Robinson, 1980). These showed a small change in solutes as a result of the exposure of the mineral subsoil to chemical denudation, and comparison of waters from streams draining peaty gley soils with those from areas of deep peat indicated clear differences within even this small catchment.

With the recent growing concern about the role of conifers on stream acidification, detailed studies of water chemistry began in March 1992. Manual samples were taken for a range of chemical parameters, initially at monthly intervals and from April 1994 twice monthly. Bulk sampling of rainfall in open plastic containers and 'grab' samples of stream water were taken immediately upstream of the stilling basin of the weir. Arithmetic means and the range of the values are given in Table 10. The mean pH values are computed as the mean of the hydrogen ion concentrations. The main findings are:

- The rainfall is slightly acidic and solute concentrations similarly show evidence of moderate pollution. Rainfall at Coalburn is derived from a variety of sources, which is clear from the variability of its chemical composition. The dominant ions are chloride and sodium but high concentrations of sulphate and ammonia can occur occasionally Generally, south and westerly winds are of low acidity (Davies *et al.*, 1991) and are associated with marine ions, including sodium, chloride, magnesium and sulphate. In contrast, winds from the north, east and south-east, which have passed over agricultural land and industrial

[11] S. Mounsey, Environment Agency

Table 10 *Summary of the water sample chemistry data 2 March 1992–17 December 1996 (all units are mg l^{-1} except Al, Mn and Fe which are μg l^{-1}, and pH is dimensionless; for clarity the number of decimal places shown has been limited)*

	pH	Al	Ca	Mg	Na	K	SO_4	Cl	NO_3-N	NH_3-N	DOC	Mn	Fe
Rainfall													
Mean	5.4	21.1	1.1	0.5	2.4	0.4	3.2	4.9	0.52	0.68	3.3	13.8	23
Max.	7.5	45.2	8.5	6.3	10.7	4.9	20.9	13.0	1.84	3.80	23.6	47.7	67
Min.	4.4	11.2	0.1	0.1	0.1	0.02	0.5	1.0	0.01	0.08	1.0	4.0	10
Cloud water deposition*													
Mean	4.4	400.1	7.9	8.7	70.0	3.3	37.9	126.9	10.13	6.86	7.2	48.1	606
Max.	7.2	757.0	33.2	34.9	301.0	12.4	130.0	508 0	36.10	24.10	30.6	113.0	1060
Min.	3.6	87.6	1.3	0.7	4.2	0.1	6.0	16.5	0.73	0.84	1.1	23.2	91
Stream water													
Mean	4.8	134.1	7.4	1.1	4.6	0.2	9.7	8.8	0.045	0.03	18.2	24.9	634
Max.	7.9	225.0	33.1	4.0	7.6	0.9	19.8	14.5	0.49	0.08	30.2	65.3	1960
Min.	3.8	8.3	1.8	0.2	1.6	0.04	3.3	4.0	0.002	0.004	7.4	10.9	67
Baseflow and stormflow§													
High flow	4.5	146.1	2.4	0.5	4.0	0.27	n/a	8.7	n/a	0.044	11.7	29.4	410
Low flow	7.3	40.6	27.6	3.3	4.8	0.33	10.0	7.1	0.04	0.026	15.9	34.8	1109

* From 20 October 1994.
§ Calculated from the five lowest and five highest flows when samples were taken.
DOC = dissolved organic carbon.

areas, yield rainfall with relatively low pH and they are enriched by lithogenic and pollutant components.

- Although the estimated quantity of cloud water deposition is <5% of the annual precipitation, it contains much higher concentrations of solutes (including sulphate and nitrate, as well as the dissolved metals aluminium, manganese and iron) than rainfall, typically greater by an order of magnitude. It may make significant contributions to the catchment inputs, with loads about half as much as in rainfall.

- Streamwater chemistry shows generally higher concentrations of solutes than the rainfall — and differences in their relative magnitudes. This reflects the chemical and biological reactions occurring in the catchment as well as cloud water and dry deposition inputs. Given the rapidity of the streamflow response to rainfall, it might have been expected that streamwater chemistry would have mirrored rainfall variations at high flows. However, generally this is not the case, even for unreactive components such as chloride (Robinson *et al.*, 1994; Hind, 1992). This implies that the catchment is able to smooth the rainfall signal; terrestrial processes are rapidly modifying the rainfall to produce the observed stream chemistry. Most solute concentrations vary weakly with flow (typically by only one order of magnitude whilst flow may vary by four) so that twice-monthly samples may be adequate to describe catchment fluxes.

- The major changes in streamwater concentrations occur at relatively low flows: at intermediate and high flows, concentrations remain constant or decline as flow increases. However, consistent patterns have emerged in baseflow and stormflow chemistry. During prolonged periods of baseflow, the stream pH typically rises above 7 as shallow groundwater sources and throughflow from the deeper horizons dominate. Weathering processes and long residence times enable the acidity within the soils to be neutralised. As this water passes to the stream, carbon dioxide degasses to produce low acidity, higher pH baseflow waters that are enriched in base cations (especially calcium) and depleted in aluminium (Neal *et al.*, 1992; Robson, 1993).

- Storm events exhibit acid episodes which come from the increasing volumes of water derived from near-surface and surface flow paths through organic peat horizons. This water overwhelms the acid buffering capacity of deeper water contributions, dilutes base cation concentrations and reduces colour, whilst aluminium and hydrogen ion concentrations increase (Mounsey and Newson, 1995). During high flows there may be a slight decrease in the hydrogen and aluminium concentrations, suggesting either that a component of rain water is reaching the stream at such times or that a soil-driven mechanism is operating. A similar decrease in aluminium observed at Plynlimon by Neal *et al.* (1992) was ascribed to lower aluminium concentrations in the upper soil horizons.

These results are consistent with the two-component mixing regime first proposed for the Hubbard Brook in eastern USA (Likens and Bormann, 1995) and later adopted by Neal *et al.* (1992) and Robson (1993) for British upland catchments with a substrate of high buffering capacity and organic-rich peat surface horizons. This chemical 'fingerprinting' of water also helps to identify flow routing pathways and contributing source areas to the stream

5.6.2 Sampling during storm hydrographs[12]

The manual sampling interval is too coarse to provide detail of the short-term changes in response to storm rainfall; this was partially addressed by the continuous recording of a limited number of water quality parameters (Section 5.6.3). North West Water Ltd (NWW) also has a direct interest in the processes affecting upland raw water quality, since this determines the treatment processes required to supply potable water. For this purpose an automatic water sampler, triggered by rising river level, was installed to take samples through storm hydrograph events for analyses of a wider range of determinands

The NWW supplies some seven million customers with 2200 Mld of potable water, all of which must meet the extremely high standards stipulated in the 1980 EC Drinking Water Directive and the 1989 Water Supply (Water Quality) Regulations. Of particular concern for water supplies from peat covered catchments are the levels of trihalomethanes (THMs) in treated water supplies. These are a class of chemicals often formed by reactions between chlorine and organic compounds in the water. During the past 20 years, concern has been rising that THMs may be toxic, carcinogenic or mutagenic when ingested at low concentrations over a prolonged period of time (termed subchronic exposure).

A substantial proportion of NWW's raw water supplies is derived from upland surface water catchments in the Lake District, Pennines and Peak District. Many of these catchments are peaty and consequently the raw water often has a high organic content, low pH and is highly coloured. The use of chlorine, a highly effective means of disinfection, has long been part of the water treatment process in the UK, and there is a propensity for THMs to be formed during treatment of these upland waters with chlorine. Alternative methods of disinfection, such as the use of ultraviolet light, do not provide the 'persistent' protection of chlorine — against contamination by ingress — as water supplies move through the distribution network.

Because of these concerns, the 1980 EC Drinking Water Directive required that the concentrations of haloforms (including THMs) in drinking water must be as low as possible. In England and Wales, this requirement has been implemented through the 1989 Water Supply (Water Quality) Regulations with a standard of 100 $\mu g\ l^{-1}$ set for total THMs. Many other developed countries have also set this standard for total THMs, but it is likely that this maximum concentration level will be reduced over the coming years.

Securing the microbiological safety of water supplies by disinfection is the most important part of water treatment, and there is a need for greater understanding of how THMs are formed during the treatment process and how their formation can be minimised. As part of NWW's increasing research in this area, it was recognised that there was a need to investigate the concentrations of THM precursor material (organics) in upland raw water and how they varied with season, catchment and hydro-meteorological characteristics. It is generally believed that the highest concentrations of THM precursors occur following 'flushing' events in upland catchments, which entrain significant amounts of organic material and produce highly coloured raw water. As the Coalburn catchment has extensive areas of peat and highly coloured waters, and because detailed catchment and hydrometric data are available, it was decided to investigate these aspects at Coalburn.

The trigger level to start the automatic sampler has been varied several times in order to sample at different flow conditions (such as flow events following periods of dry weather or with wet antecedent conditions), as well as at different times of the year. A selection of samples was chosen to reflect the various stages of the flow event which triggered the sampling. They are then dispatched to the Environment Agency's National Laboratory Service at Nottingham for THM precursor analysis. The routine fortnightly water samples of the Coalburn river are also sent to the Laboratory for THM precursor analysis and can be linked to an instantaneous flow rate. In addition, from the continuous monitoring at the weir, values of pH, temperature and conductivity can be associated with each sample: this is extremely beneficial since these parameters are believed to influence THM formation.

Analysis of the Coalburn samples shows the concentration of THMs formed in the water after chlorination with an excess of free chlorine, and storage at 25°C for seven days to allow the reaction to approach completion. Although this does not

[12] J. Sanders, North West Water Ltd

exactly simulate the water treatment process, it is considered useful in providing an estimate of THM precursors within the raw water. Furthermore, the types and concentrations of THMs in the raw water are provided, as well as details of pH, conductivity and colour.

Water discoloration is caused by the leaching of dissolved organic matter (particularly fulvic and humic acids) and is expensive to treat. It is a problem in peat-covered catchments and may be exacerbated by drying in periods of drought, by artificial drainage or by afforestation. The colour of water is also of interest since it is readily determined and is frequently used as a substitute for determining the THM formation potential of raw water supplies (assuming high colour = high THM potential). Unfortunately, a consistent positive correlation with colour does not hold for all source waters. Thus, some of NWW's upland sources which are low in colour still demonstrate significant THM formation potential.

The first samples were taken with the automatic water quality sampler in August 1994. Given the dry weather conditions that have prevailed in north-west England since April 1995, the number of flow events has been much lower than expected. As a consequence, the THM data set from the automatic water quality sampling remains relatively small. Further samples triggered by flow events were sent for analysis during the remainder of 1996 to produce a larger data set.

Individual THM values of up to 2300 μg l^{-1} have been recorded, underlying the potential significance of this study for water supplies from upland peat-covered catchments. There is a wide range of values at all times of the year, but there is an underlying seasonal pattern, with highest values tending to occur in autumn and early winter, and the lowest values between January and March. This indicates that there may be a link to soil moisture (and possibly temperature). No clear patterns have emerged, although there is often an increase of total THMs on the rising limb of a storm hydrograph; an example of the relationship between flow and raw water quality determined from the automatic sampling is given in Figure 21.

These data will be examined in more detail by a multidisciplinary team at NWW comprising water resources, water quality and water treatment specialists, and staff involved in upland catchment management. It is hoped that they will begin to identify the main factors influencing THM formation potential in upland raw waters.

If the initial results from the THM sampling programme prove beneficial to the understanding of

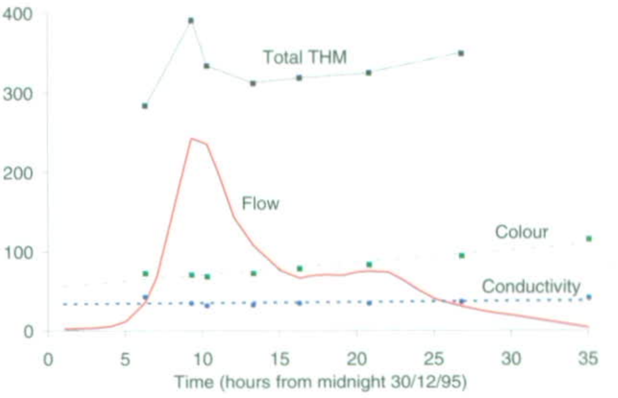


Figure 21 *Typical pattern of trihalomethane (THM) concentrations (μg l^{-1}) during a storm event showing early peak, but little correlation to other water quality parameters, colour (Hazen units) and conductivity (μS cm^{-1})* or flow *($l\ s^{-1}$)*

THM formation potential, it is likely that the automatic sampling will continue. This initial analysis may indicate whether particular hydrological events and antecedent catchment conditions should be targeted. Since THM formation is closely linked to the concentration of organic material present in the raw water, a more detailed soil survey of the Coalburn catchment — planned for summer 1997 — may assist in the analysis of the water quality data.

5.6.3 Continuous data at the catchment outlet[13]

Hind (1992) and Robinson *et al.* (1994) showed that acid episodes occurred during hydrological events at Coalburn, but the manual sample data alone were insufficient to capture the short-term dynamics in hydrochemistry at Coalburn. This problem was tackled by installing Rosemount pH, conductivity and temperature probes at the catchment outlet with readings taken every 15 minutes.

The continuous pH data for the period of record may be summarised as the percentage of the total time that the mean daily values were within particular class ranges. Thus pH was >5.5 for 31% of the time, in the range 5.5–5.0 for 39%, 5.0–4.0 for 26%, and <4.0 for 4% of the time. In broad terms, the pH can be related to the health of fish (e.g. Alabaster and Lloyd, 1980). The impact of acid episodes on, say fish populations, depends on a number of factors. In addition to the pH itself consideration should be given to factors, such as aluminium concentration, since lower pH increases the solubility of soil metals, particularly aluminium, and both mobilised aluminium and hydrogen ions

[13] S. Mounsey, Environment Agency

are toxic to fish. Additional factors include calcium concentration, the age and species of fish as well as the severity and frequency of the acid episodes. Nevertheless, whilst recognising its simplifications and limitations, it is useful to be aware of the broad pattern of acidity in relation to salmonid fish health. Values of pH <4.0 are likely to be lethal; values of 4.0–5.0 are likely to be harmful to salmonids that have not previously been acclimatised to low pH conditions and harmful to eggs and fry; and for values >5.5 harmful effects are unlikely.

The observed stream pH values exhibit two maxima at approximately pH 4.5–5.0 and 6.5–7 0, which reflect the seasonality in the catchment's water-tables. In winter, as the soils gradually become saturated, lateral flows predominate through the more acidic surface horizons and the streamwater pH falls to about 4.5; in the summer, as low flows are associated with well-buffered deep throughflow and shallow groundwater, the pH rises to approximately 7.0.

The basic form of the pH response to a storm event is surprisingly uniform (Figure 22), with an initially rapid fall in pH mirroring the increase in flow, followed by a more gentle recovery towards the pre-storm level as flow recedes. The magnitude of the initial increase in pH appears to depend upon event conditions, with the pulse possibly derived from piston flow of water stored in the bankside and near channel sources, or from the flushing of well-buffered water standing in the drainage channels cut into the mineral subsoil (cf. Harriman *et al.*, 1990). The subsequent pH fall then results from the near-surface soil water component dominating the hydrograph.

The rapid increase in flow is accompanied by a corresponding decrease in pH (Figure 23), which reflects the distinct chemical gradients within the peaty soil profile and the network of drains that rapidly delivers acid runoff to the main channel with little residence time for buffering. This phase of the hydrograph is likely to represent the soil water overwhelming the buffering capacity of the deep water component. The rapidity of the pH change is critical with regard to the biological impact of an event (Ormerod and Jenkins, 1994)

The minimum pH usually lags behind the occurrence of the peak flow which suggests that the most acidic flow paths do not contribute until after peak flow. This may be a result of the catchment shape, the distribution of different soil types or the dominance of pre-storm soil water during a hydrograph (Soulsby, 1995). However, during extremely large hydrological events the minimum pH occurs sooner, either before or with the peak flow. Because of the predominance of peat soils in the catchment, low pH waters continue to contribute to streamflow well after an event. As a result, the acid episodes are often prolonged and the recovery is curtailed by the next storm event, causing a progressive decline in stream pH.

Similar relationships between pH and flow, and the consistent characteristics of the pH response to a storm event have been observed in other catchments (e.g. Davies *et al.*, 1992, Robson, 1993).

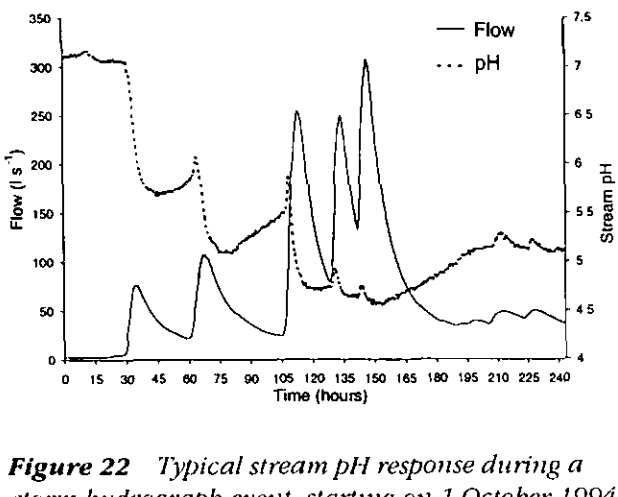


Figure 22 *Typical stream pH response during a storm hydrograph event, starting on 1 October 1994*

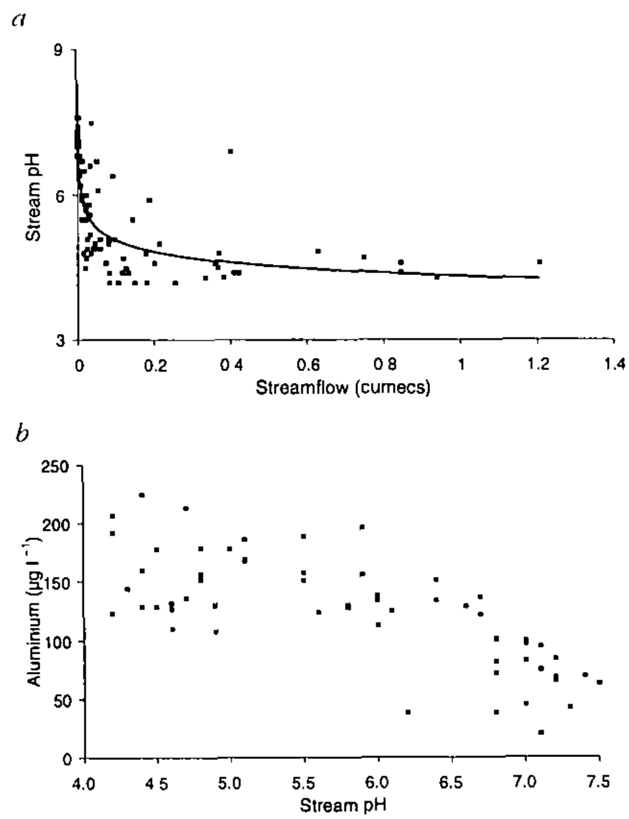


Figure 23 *Streamwater acidity showing (a) evidence of baseflow buffering and (b) relationship of dissolved aluminium concentration to stream pH*

However, whilst the general form appears consistent, the exact relationship is event-specific. This variation may reflect the dynamic nature of the catchment stores and soils as well as the residence times of water.

Stream conductivity and flow exhibit an exponential relationship, with the conductivity decreasing as flow increases, and the most rapid changes in conductivity are at low to medium flow. The baseflow conductivity is high and falls rapidly as flow increases, reflecting the change in flow paths to shallower horizons and dilution. The conductivity reaches a minimum at intermediate flows and thereafter exhibits a positive relationship with flow, which may in part be attributed to the corresponding increase in the hydrogen ion concentration with peak flows. During very high flows this relationship breaks down and conductivity decreases again; this may result from a direct channel component of rainfall causing dilution.

Changes in stream conductivity can be related to pH since, at a low pH, the increased hydrogen ion concentrations bring about an increase in conductivity, whilst a similar effect can be seen at high pH as a result of the enhanced concentrations of weathered products. A minimum in the conductivity occurs at intermediate pH.

Conductivity demonstrates seasonality which appears intrinsically linked to the dominant flow path. During summer baseflow conditions, the high conductivity reflects the dominant deep flow paths associated with long residence times, in or near to the boulder clay, and elevated concentrations of weathered products. In contrast, the dominant flow paths in winter are derived from the soil horizons associated with acidic base-poor waters, which results in lower conductivity.

5.6.4 Small-scale studies within the catchment[14]

Since 1986 the Geography Department of the University of Newcastle has been studying water movement and chemistry at points within the catchment which contribute to the overall understanding of the catchment behaviour.

From November 1988 to July 1989 spatial variations in surface water quality were investigated within the catchment (Hind, 1992). Surface water samples were collected each week at 16 sites, including the weir outfall: 10 were located on natural channels and 6 on forestry drains, and this network covered the main geological and pedological variations in the catchment.

The data showed differences in water quality within the catchment (Robinson and Hind, 1991). To the eastern side of the main stream, waters are characterised by high values of pH, conductivity, and concentrations of sodium and calcium; there is no discoloration of these waters. The western-side waters are the converse of this, which is thought to be due to differences in geochemical processes relating to variations in pedology; the eastern area has peaty gley soils and the other sites drain predominantly deep peat.

To investigate this further, two small sub-catchments were selected: one lying entirely on deep peat and the other on peaty gley. The mean pH of 6.8 for the peaty gley sub-catchment is surprisingly high, but is corroborated by the high calcium ion concentrations (Table 11); this is thought to be caused by the calcareous boulder clay under the shallow surface peat.

Collectors for canopy throughfall, stemflow and soil solutions were also installed at random locations within the two plots (Table 12). There was no significant difference in solutes between the two sub-catchments until the water reached the ground, the peaty gley area having soil water and streamflow with higher pH and conductivity than the deep peat. Stemflow amounts vary considerably from tree to tree, being greater for trees with multiple stems. On an areal basis, throughfall amounts far exceed stemflow. Chemically, stemflow and throughfall have higher concentrations of cations than the bulk deposition samples, and stemflow has a lower pH.

Following the work of Hind (1992), further work on throughfall chemistry beneath the forest canopy has revealed some differences which may be related to the nutrition of the tree, with lower pH for trees

Table 11 *Mean solute concentrations (mg l^{-1}) and pH of rainfall and outflows from the two sub-catchments (November 1988–July 1989)*

	Precipitation	Peat site	Peaty gley site
Na	2.9	5.1	4.8
K	1.1	0.3	0.2
Ca	3.1	3.9	12.8
Mg	0.8	0.3	1.1
Fe	0.3	1.3	0.2
Al	0.8	1.8	1.2
Cl	4.8	22.5	22.1
pH	4.8	3.9	6.8

[14] M D. Newson, Department of Geography, University of Newcastle upon Tyne

Table 12 *Comparison of mean pH and conductivity of precipitation, soil water and streamflow in the sub-catchments and streamflow at the main weir*

		pH	Conductivity (*µS cm⁻¹*)
Precipitation		4.8	33
Throughfall		4.8	160
Stemflow		4.2	320
Peat	**soil**	4.0	71
	stream	3.9	83
Peaty gley	**soil**	6.8	155
	stream	6.8	120
Main weir	**stream**	5.9	74

growing on deep peat. Washed (eluted) samples from dry spruce needles indicated nearly double the hydrogen ion concentration from trees growing on peat than on peaty gley. Differences in tree canopy density were also found to account for differences in throughfall volumes collected at individual collecting gauges.

Studies of soil profiles have confirmed the difference between the highly acidic surface peaty layers and the base-rich mineral layers at depth, with calcium contents rising from zero near the surface to 2000 mg l^{-1}. Measurements of saturated hydraulic conductivity using piezometers have also confirmed the very slow rate of water movement, with underlying clays having values of the order of only 10^{-10} m d^{-1}. This suggests, for example, that the unplanted 'buffer zone' along the main channel will have a limited ability to conduct sufficiently large volumes of water at depth to improve their chemistry (i.e. to buffer acid pulses) before reaching the stream.

To understand further the role of different zones of the catchment to storm runoff processes and to the overall streamwater chemistry, spatial surveys have begun of waters taken from eight small tributaries or large drains before they discharged into the main stream. Initial results indicate enormous differences in stream chemistry, demonstrating that extremely small parts of a catchment may have a disproportionate impact upon the overall water quality of the main stream. This has potentially important implications for the role of management to mitigate adverse impacts of land use.

5.7 Fertiliser losses

Upland soils are generally poor in nutrients and the addition of phosphate and potash fertilisers, generally applied as rock phosphate, has become almost the rule on peat soils (McIntosh, 1981). Phosphate is of particular concern because it is the principal nutrient limiting biological productivity in upland lakes and reservoirs. Fertiliser may result in changes to biota and, in extreme cases, lead to algal blooms which may collapse causing deoxygenation and fish kills. There may also be water treatment problems including taste and colour

Ground rock phosphate was applied from the air to the entire catchment in May 1972, some nine weeks before the ploughing. Laboratory analyses of phosphate concentrations in the stream runoff were carried out in accordance with DOE (1972); particulate and dissolved orthophosphates were determined by colorimetry using a molybdate reagent. Organic phosphates and polyphosphates were converted to orthophosphates by acid hydrolysis.

Measurements of phosphate concentrations in the stream water began in April 1972, about a month before the application of fertiliser, to determine the natural levels as a base for comparisons. Phosphate concentrations were generally low, with values ranging from 0.01 mg l^{-1} to 0.06 mg l^{-1} (mean 0.016 mg l^{-1}). Concentrations were not apparently related to discharge levels, but this may be because they were of a similar magnitude to the accuracy of the techniques used (about 0.01 mg l^{-1}).

Within a few hours of the aerial application of the fertiliser, phosphate levels in the stream increased from 0.01 mg l^{-1} to about 0.27 mg l^{-1}, probably resulting from rock phosphate that had fallen directly into the natural stream channel network. In succeeding storms, more phosphate was washed down the stream network and concentrations rose as high as 1.5 mg l^{-1}. Levels between storms remained at about 0 25–0.35 mg l^{-1}, about 15–20 times the previous natural level (Robinson, 1980).

Concentrations increased further during the ploughing operations, with values recorded of up to 2.1 mg l^{-1}. Unfortunately the analyses were only continued for a few weeks after the end of the drainage and, as discussed earlier, this was a generally dry period with very low streamflow. Nevertheless phosphate concentrations were an order of magnitude greater than prior to fertilising, and much higher concentrations would probably have been recorded in the following wet winter if measurements had continued. Fertiliser application was repeated in the early 1980s; present phosphate concentrations in the stream are about 0.01–0.05 mg l^{-1}, which is similar to the original pre-forestry levels.

Recent Forestry Guidelines (Forestry Commission, 1993) avoid treating watercourses and streamside buffer zones, and limit the application to part of a catchment in each year.

An eroding drain in 1977, five years after ploughing. This has since been stabilised by vegetation growth

5.8 Stream sediment

Erosion represents a loss of the soil resource and sediment entering river systems may cause problems downstream. Sediment deposition may damage habitats and smother salmonid eggs, while high sediment concentrations may have an important effect on water treatment works (Austin and Brown, 1982). Moreover, finer sediment particles may carry adsorbed chemicals, particularly phosphorus, most metals and pesticide residues. Erosion and stream sediment loads from forested catchments are generally assumed to be low, but can be increased by forestry operations.

Streamwater samples were taken between March 1972 and October 1973 for suspended sediment analysis to look for short-term changes when the catchment was drained, and further samples were taken in the winter of 1978–79 to investigate the longer-term impact. Water samples were collected by a vacuum sampler, installed on a straight section of the main channel some 10 m upstream of the stilling basin of the weir. Samples were first taken at 12 points in the channel cross-section to identify a representative point. A sampling interval of eight hours was adopted which, although much longer than the ideal, represented a necessary compromise with the immense difficulties involved in collecting records from such an isolated site, over an extended period. Suspended sediment concentrations were then determined in accordance with the procedure given by DOE (1972).

The excessive quantities of sediment released into the stream by the forestry ploughing had to be removed from the approach channel and stilling basin of the weir in 1973.

In the four months before the forestry drainage, suspended sediment concentrations were very low, averaging under 4 mg l^{-1}, despite samples being taken over a wide range of discharge. The annual sediment load was estimated to be about 3 t km^{-2} — generally, higher annual yields are recorded at other upland sites. Factors limiting sediment yields at Coalburn included the generally gentle slopes and armouring of the channel bed by cobbles (Robinson and Blyth, 1982).

During ploughing, the average suspended sediment concentrations ranged from 30 mg l^{-1} in dry periods to 150 mg l^{-1} in rainy periods when flow washed loose sediment out of the newly cut drains. Even higher concentrations were recorded when blocked plough drains were cleared by hand (with maximum recorded values of >7000 mg l^{-1} and average values of 300–1700 mg l^{-1}). This increase in concentrations occurred despite the unusually low rainfall: July–September 1972 had under half the average rainfall for that time of the year. Nevertheless it was estimated that about 20 t of sediment (approximately four years' pre-drainage yield) was carried from the catchment during ploughing work in these three months. In contrast, there was no change in sediment concentrations when the trees were planted in spring 1973, demonstrating that it was the drainage work associated with forestry, rather than the afforestation itself that caused the high sediment losses In the months following ploughing, concentrations remained at least an order of magnitude higher than before. Large quantities of loose sediment in the drains were available for transport, and in subsequent storms concentrations of up to 400 mg l^{-1} were recorded (compared with 28 mg l^{-1} maximum before drainage) The importance of storms for transporting sediment was increased as a result of the ploughing, both in absolute terms and in relation to the overall long-term yield. Bed-load movement in the stream was also measured, but was insignificant in comparison to the quantities of suspended sediment.

Suspended sediment sampling continued until October 1973, a year after the plough drainage was completed Figure 24 shows a double mass curve of cumulative streamflow and sediment loss. This form of presentation was chosen since it gives more weight to the wet periods when most sediment was being carried, and reduces the effect of differences in weather conditions (the period immediately after ploughing was, as noted, unusually dry). The slope of this curve represents the quantity of sediment carried per unit of discharge (i.e. the discharge-weighted mean concentration). The increased importance of storms as transporters of sediment after drainage can be seen from the more irregular form of the curve, compared with the almost constant relationship before drainage. The double mass curve was smoothed by eye to remove the remaining irregularities, and the slope plotted to show the underlying trend of sediment concentration during the study period (Figure 25). This indicates a rapid rise during the draining with a subsequent steady decline, which appeared to be tending towards an average suspended sediment concentration somewhat higher than that before drainage.

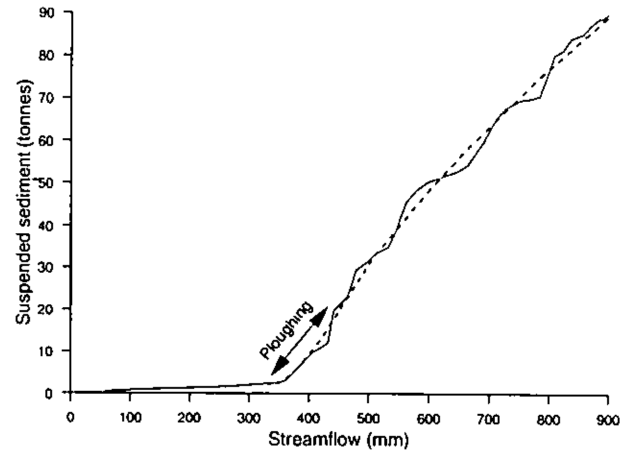


Figure 24 *Double mass curve of streamflow and suspended sediment over the period March 1972 to October 1973*

The peak of the smoothed concentration curve was about 250 mg l^{-1} and resulted from the high rate of sediment loss during drain clearance operations. The rise occurred essentially within the period of drainage, although the peak is plotted somewhat later because of the numerical smoothing. Since an even higher peak might be expected for catchments with steeper slopes and more erodible soils (and

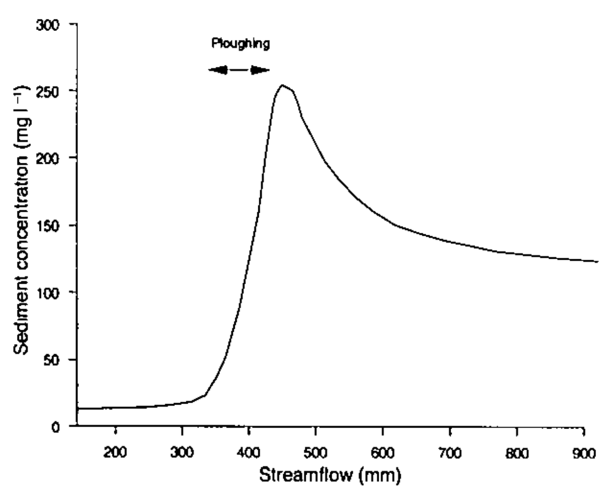


Figure 25 *Smoothed curve of suspended sediment loss from the catchment*

thus probably higher 'natural' sediment losses), it may perhaps be most meaningfully expressed as approximately 60 times the average pre-drainage level. This multiple is coincidentally the same as the increase in the drainage density but many other factors, such as ground slope and drain dimensions, may also be important. Where drains cut into a substratum of different material, widely different values could result. Field observations at Coalburn indicated that erosion of the drains was generally limited, and the major source of sediment following drainage was loose material left by the plough in the newly cut drains.

Sediment losses were still declining when the sampling programme ended in 1973 and consequently the total sediment yield from the ploughing is unknown. To try to estimate this loss, and to put the findings of this study in a more generalised form, which could be relevant to other catchments, a simple mathematical description of the decline in sediment concentration after ploughing was used. An exponential decay function was proposed since it has the same general form as that observed and has the advantage of a physical interpretation since the output of loose material might be expected to depend upon the quantity still remaining. This function was fitted to the middle section of the declining limb (avoiding both the immediate effects of the drain clearance and the uncertainties of the latter part of the curve arising from numerical smoothing to the end of the data). The loss of sediment following ploughing may then be represented by:

$$C = a \exp(-bQ) + K \qquad (7)$$

where C is the sediment concentration (mg l^{-1}) and Q is the cumulative discharge (mm $\times$ 10^{3}) since ploughing. Coefficient a (168) represents the peak concentration and is less than the value of 250 mg l^{-1} given in Figure 25, to exclude the brief period of exceptionally high concentrations when blocked drains were dug out. Coefficient b (1.605) describes the rate of decline of the supply of loose sediment flushed out of the drainage network. For a typical annual runoff of about 900 mm, this indicates a general 'half-life' for sediment concentrations of about five years. The discharge weighted average sediment concentrations will halve every five years after the drainage work, and will reduce to 25% after 10 years. Individual samples may, of course, vary considerably from this predicted value. The third coefficient K represents the erosion of new material, and was assumed to be 15 mg l^{-1} on the basis of further sampling in 1978/79, which indicated an annual yield of about 12 t km^{-2}. In reality this term will also be expected to decline somewhat over time as vegetation grows over the exposed soil surfaces.

Extrapolation of this curve after the main sampling programme ended, together with the estimated 20 t lost during the drainage operations, would mean that over approximately a five-year period about 120 t km^{-2} of loose material was lost from the 1.5 km^2 catchment, representing the load of nearly half a century at the estimated pre-drainage natural rate of erosion (Robinson and Blyth, 1982).

Such an extrapolation must be treated with caution. It is possible, for instance, that sediment concentrations increased in the wet winter following the ending of sampling in October 1973. However an independent, though crude, estimate of total loss was obtained by surveys of sediment deposition in the stilling basin of the weir. This provides a lower bound to sediment yield, since some material may be carried over the weir. The accumulated sediment was measured in 1973 and 1979 and accounted for about 70% and 60%, respectively, of the predicted loss for the corresponding periods. Manual samples in the catchment at the weir since 1993 (W. Stelling, personal communication) indicate that suspended sediment concentrations are currently very low (<5 mg l^{-1}), although still higher than those measured before drainage.

This generalised model of sediment release has been found to be applicable to other upland catchments (Burt *et al.*, 1984; Francis and Taylor, 1989). The subsequent decline in sediment loads will depend upon the site conditions (slopes, soil types and weather) and the drainage layout. Longer-term sediment yields may remain high if new sources of erodible material are exposed by ditches that are too steep or too deep (Newson, 1980). Techniques to reduce erosion and sediment transport to receiving watercourses include avoiding ploughing where possible, limiting furrow gradients to <2°, limiting furrow lengths (by using cross-drains), installing furrow end buffer strips and sediment traps, and keeping unploughed buffer zones along the stream channels (Carling *et al.*, 1993). Such buffer zones may act as effective sediment filters as long as the surface flow across them occurs as generalised sheet flow rather than as concentrated rivulets. Guidance on these aspects is given in *Forests and Water Guidelines* (Forestry Commission, 1993). Additional ideas include the 'seeding' of bare drainage channels to accelerate the growth of vegetation.

5.9 Biology

In addition to the hydrological effects of upland afforestation there are other environmental considerations which may have a significant bearing upon the options open to forest and water managers. The 1985 Wildlife and Countryside Act placed a duty on the Forestry Commission to achieve a balance between the management of forestry for timber production and sustaining valuable wildlife habitats. Central to this is the attention to biodiversity, visual impact and conservation inherent in current forest design plans. All new planting over 100 ha within a designated area requires an Environmental Assessment, including the provision of open areas and some broadleaf planting, particularly along streams. Felling and restocking should be in coupes of typically 5–50 ha to provide diversity in forest age and species structure (Forestry Authority, 1998).

5.9.1 Conservation and wildlife

Coalburn is fairly typical of the southern part of Kielder Forest which is flatter and lower than the northern portion The original grassland was grazed and there was little diversity in the species present — mainly purple moor-grass and some heather. The lack of grazing immediately prior to tree planting would not have increased species diversity. Mammals supported by this moorland habitat include short-tailed field voles which provide a rich food source for predators such as foxes, stoats, weasels, kestrels and tawny owls.

As the trees grew and spread out towards each other, the underlying ground vegetation began to die off, but the remaining open areas (such as the unplanted areas along the main watercourse and around the raingauges) provided an ideal habitat for roe-deer. In winter when food is scarce the deer will browse on young trees, causing serious damage which stunts their future growth and seriously affects the subsequent value of the timber.

As a habitat for wildlife, the present 'thicket stage' of the forest at Coalburn is generally poor compared to the original moor or to later stages of growth. The habitat value can be expected to increase after felling when, under current guidelines, more broadleaved trees would be included in the replanting. Once the conifers start to produce cones, specialist seed-eating birds such as crossbills and siskins become established. These in turn are preyed upon by sparrowhawks and goshawks. Red squirrels, which are becoming increasingly rare in Britain, are still present in numbers in Kielder Forest, and depend heavily on supplies of conifer seed. Ironically their number may reduce with the encouragement of broadleaved trees which favour the spread of grey squirrels, although this depends upon the forest design.

Once the forest develops a closed canopy very little light reaches the forest floor and, together with the thick covering of conifer needles, plant life is severely restricted to a few mosses and ferns, as well as some fungi in damp areas. Reptiles and amphibians in the forest include adders, frogs and toads.

Black grouse are now increasingly rare in northern England, partly because of afforestation, but they use a lek at Coalburn for their courtship display. In addition, merlin, which are also quite rare, breed nearby. Both of these are birds of the forest edge and prey on creatures in the moorland and nesting in the trees.

Within the Kielder Forest area there are a number of unplanted blanket mires that were considered too wet for timber production. These are now recognised as being of conservation value, and some concern has been expressed about documented alterations over time in their plant communities (Smith and Charman, 1988). It is possible that these changes have in some way been caused by the ground drying because of the growth of the surrounding forest, although a direct link for this has not been found. Another possibility is that the change in vegetation is a result of the cessation of grazing and periodic burning. These hypotheses are not, or course, mutually exclusive and both may operate. In addition, some changes may have resulted from recent spells of dry weather.

5.9.2 Forest health studies[15]

Trees 'capture' greater quantities of air pollutants than shorter vegetation. As well as the acidifying effect of these pollutants as they wash off the tree canopy to the ground and thence to watercourses, there may be direct damage to the trees themselves.

In the early 1980s, widespread concern about the effects of atmospheric pollution on forest health led to a number of European countries establishing national surveys to assess the condition of their forests. The Forestry Commission embarked on its first annual survey of tree health in 1984, looking at the condition of Sitka spruce, Norway spruce and Scots pine within 99 plots distributed throughout Britain. Oak and Beech were added to the list of species surveyed in 1987, when the age range of trees was also extended to include older crops, and additional plots were selected in private woodlands to achieve better coverage of the country. In 1987 the British plots were incorporated into a Europe-wide large-scale survey of forest health for the United Nations Economic Commission for Europe (UNECE).

The key indicator used to assess forest health is the density or transparency of the forest crown. An

[15] D. Durrant, Forestry Commission

index of tree condition is obtained by comparing trees within each plot to a standard set of photographs of 'ideal' trees. Crown density may depend upon a number of site factors, and for this reason some people consider that a better name for this indicator would be 'tree condition'.

While the forest health surveys can help to establish whether the condition of different tree species is improving or deteriorating over time, they provide only weak evidence of the causal factors involved. Therefore, to improve our understanding of the factors and processes affecting tree health, particularly the impact of air pollution, a network of 10 permanent forest observation plots was established around Britain in 1994. These form part of a wider network of 400 plots distributed throughout the European Union (under Regulation (EC) No. 1091/94 and its amendments), with additional plots in some adjacent States. One of the 10 British plots is in the Coalburn catchment and involves the intensive and continuous monitoring of forest condition over a period of 20 years.

It was the existence of a such large body of research data for Coalburn that led to its selection as one of the permanent British monitoring sites. The programme of work which began in March 1995 involves sampling and chemical analysis of rainfall and throughfall at two-week intervals, of foliage every two years and soils every 10 years. In addition, crown condition is assessed annually and tree growth measured every five years. All measurements are carried out within a central observation plot, which is in a stand of Sitka spruce, close to the interception site A.

A forest health survey plot was established at Coalburn in autumn 1994 to compare the assessment of forest condition with the more intensive measurements made in the permanent observation plot. Crown density of Sitka spruce at Coalburn and in the Kielder Forest (the nearest site in the original network) for 1993–96, when compared against an 'ideal' tree, is shown in Table 13. The condition of Sitka spruce in both areas is very good, with trees exhibiting only a modest reduction in crown density compared to an ideal tree. This small degree of reduction from the ideal probably represents trees with full foliage under local physical conditions. Of the 72 Sitka spruce forest health plots distributed across Britain, Coalburn lies in the upper quartile in terms of crown density. This implies that the relatively high altitude of the site and the moderately high pollution climate (e.g. 1986–88 total non-marine sulphur deposition of 1.1 keq H^+ ha^{-1} $year^{-1}$) have little effect on tree health. The between-year differences are very small and not statistically significant.

Table 13 *Percentage deficiency in crown density of Sitka spruce at Coalburn and Kielder forest compared against an 'ideal' tree*

	Coalburn	Kielder
1993	n/a	10.0
1994	12.7	13.8
1995	9.6	10.2
1996	11.5	12.3

5.9.3 Watercourses[16]

As a consequence of the discovery of highly acidic episodes in the main stream during hydrological events, it was decided to conduct a baseline biological investigation to investigate the possible impact on the stream biota of this acidic water chemistry regime. Biological assessments integrate environmental conditions over time and, as such, complement chemical data which are instantaneous in nature. Fish and invertebrate sampling were undertaken on 4 November 1993 and basic data are contained in Prigg (1994).

Sampling methods

Fish sampling was by electric fishing, using an Electracatch WFC911 portable battery-operated electric fishing unit, set for smooth DC, high volts. The 70 m reach (from 100 m to 170 m upstream of the flow gauging station) was stop-netted at either end and sampled by a three-catch removal method. The fish were measured and, at the completion of the sampling, returned unharmed to the survey reach.

The fish catch data were used to estimate the population in the stop-netted reach by the Zippin method. Field measurements of the wetted channel width of the stream in the sample area enabled the data to be expressed as fish density in terms of number per unit area. Assuming a grossly oversimplified relationship between fish length and weight — *weight* (g) = *length* (cm) /100 — crude estimates of biomass density could also be derived. These biomass density estimates of juvenile salmonid population in hill streams are likely to underestimate actual values, from local experience, but they are a reasonable indication of biomass for comparative purposes, in the absence of field weighing. The results of the fish sampling were stored on a computerised fish survey archive.

Macro-invertebrates are present in most aquatic habitats, and the communities are differentially sensitive to various types of pollutants. Macro-

[16] R. Prigg, Environment Agency

invertebrates were sampled at two locations, just beyond the upstream and downstream limits of the electric-fished reach, using a three-minute kick sample. Invertebrates dislodged by kicking into the substratum were caught in a 1 mm mesh hand-net. The kick sampling was supplemented by a one-minute hand collection from stones to sample those groups less vulnerable to capture by kick sampling. These samples were preserved and the organisms identified in the laboratory; the species lists of invertebrates were also archived. In addition to the fish and invertebrate sampling, general field notes were made on the physical habitat characteristics of the sites and the aquatic flora.

Aquatic findings

The only fish species present in the sample reach was brown trout (*Salmo trutta*). From the Environment Agency's considerable data on salmonid populations of hill streams — including acidified sites in Cumbria — the density recorded in this instance was moderate in terms of 1+ and older. This is comparable with other streams surveyed as part of a wider network of sites, and certainly not pathologically low, as found in many acidified hill streams in the poorly buffered Upper Esk and Duddon catchments and some nearby catchments (Prigg, 1983).

Fish scales were not taken for age determination, but from previous experience of growth rates of trout in local hill streams and inspection of their length/frequency distribution, it was apparent that only one 0+ fish was captured, a specimen 57 mm long. During the electric fishing sampling one similar-sized trout escaped capture.

The presence of at least one fish from the current year's hatching of ova signifies some successful recruitment in the current year. The fact that the population in the sampled reach was dominated by 1+ and older fish, with a low contribution from 0+ fish, is not necessarily a reflection of poor recruitment. The stream is small and narrow, and although offering considerable cover by virtue of undercut banks, it is likely that under low-flow conditions the fish distribution would be restricted largely to residual pools. In such a restricted habitat the fry of the year would be likely to suffer high predation by older trout.

Although not systematically sampled as part of the survey reach, a large natural deep pool upstream, with a maximum depth in excess of one metre, was informally electric fished from its margins to see if older, larger trout were present. Only fish of comparable size to those taken in the survey reach were noted, though it is likely that the equipment was not very effective, given the depth and awkward site conditions.

The gauging weir downstream of the sample reach would undoubtedly act as a barrier to upstream migrants, and on the day of the survey several medium-sized adult trout, about 200 mm long, were seen immediately below the structure.

Turning to the invertebrate sampling results, an immediately striking observation is the relative lack of mayflies (Ephemeroptera) in the sample, particularly the common and widely distributed Baetidae and Heptageniidae: the only mayfly present was *Paraleptophebia submarginata*. In our experience the Leptophlebidae are relatively acid-tolerant Mollusca and crustaceans are also lacking. Acidic stress in upland streams can be detected by an indicator system, developed by the Catchment Research Group at Cardiff in 1989 (Rutt *et al*, 1990), from a knowledge of the macro-invertebrate fauna. Strictly, this method is recommended for sampling carried out between January and mid-May, as the system was based on kick samples taken in winter and spring, when the faunal relationship with acidity is most pronounced. The samples were taken in November, but would be expected to approximate reasonably to a faunal list for the recommended seasonal period.

The acid-sensitive families Baetidae, Heptageniidae and Hydropsychidae were absent, so the samples both fall into Groups 3 or 4. Both include Taeniopterygidae, Elminthidae and Perlodidae, and the final diagnosis is Group 3 Group 3 was characterised in the national data set (derived from Welsh, Scottish and North West Region data) as acidic stream: 71% with mean pH <6 0, 87% with filterable aluminium >50 mg l^{-1}, 53% with aluminium >100 mg l^{-1}. They were poorly buffered: 76% with total hardness <10 mg l^{-1}, 95% with hardness <15 mg l^{-1}. The faunas were described as impoverished, and the streams were thought to be vulnerable to enhanced acidification by conifer forestry.

The Environment Agency's routine biological quality monitoring of the Upper Irthing catchment, which for obvious strategic reasons concentrates on main river and major tributary sites, rather than smaller headwater streams, gives no general cause for concern in these larger watercourses. Invertebrate data from the two nearest routine sites on the Irthing, upstream and downstream of the Coalburn confluence, were compared. The greater diversity at the upstream (Churnsike) site is likely to be a reflection of physical differences between the two sites, with clay exposures at Churnsike encouraging a diverse and abundant macroflora. In terms of the presence of potentially acidification sensitive taxa, however, it is worth noting the abundance of *Gammarus* spp. and sensitive Ephemeroptera at both sites.

Data were also gathered between 1987 and 1990 from four Upper Irthing tributaries, which are no longer included as routine monitoring sites. Inspection of the species lists shows expected seasonal fluctuations, but the lack of Baetidae in spring 1990, other than at Foulbog Sike, is striking. Foulbog Sike is also the only tributary of the four with *Gammarus* present. The Padda Burn site appears, on the basis of acid sensitive taxa, to be the most acidified with winter/spring samples more often than not assigning it to Group 3 of the classification of Rutt *et al.* (1990), the same group to which Coalburn was assigned by our sampling.

Water chemistry

In considering these generalisations against the chemical regime in Coalburn, reference is made to the streamwater chemistry data at the main weir in Table 10. Clearly Coalburn conforms to the typical mean pH grouping of Group 3 sites. Data on calcium, magnesium, and total and unacidified filtered aluminium were also examined using the monthly samples. There was a close relationship between pH and calcium and magnesium levels; a low pH was associated with high discharge conditions in which the calcium and magnesium levels were diluted, the catchment rather than rainfall being the prime source of these ions. The calcium and magnesium levels covered a wide range: mean calcium was 7.4 mg l^{-1} (range 1.76–33.1 mg l^{-1}); mean magnesium was 1.1 mg l^{-1} (range 0.21–4 mg l^{-1}). Converting these mean values to total hardness yielded a mean total hardness of about 25 mg l^{-1} as calcium carbonate. This value is significantly in excess of the typical hardness of Group 3 streams of which 95% have a hardness <15 mg l^{-1} as calcium carbonate. The aluminium records (unacidified, filtered) averaged 134 mg l^{-1} and appear to fall within the aluminium concentration range criteria of Group 3 sites.

The Coalburn water chemistry has two redeeming characteristics in terms of the impact of acidification on fish:

- The first is the moderate calcium level. The Upper Irthing catchment, an area of underlying Carboniferous rocks with boulder clay deposits, is generally not of particular geological sensitivity. This is in marked contrast to the central Lake District streams where there have been significant restrictions of salmonid populations. These streams have low calcium levels and the impact on the fish can be attributed to the toxicity of elevated levels of soluble monomeric aluminium at pH values around 5 in the presence of low calcium concentrations. Furthermore, the fishless sites in the Upper Esk and Duddon catchment and adjacent systems were also in areas of high rainfall (mostly well in excess of 2200 mm $year^{-1}$), compared with the annual mean of about 1350 mm for Coalburn.
- The second significant factor likely to ameliorate any aluminium-based toxic impacts on fish in Coalburn is the peat staining of the waters: the presence of humic materials gives the potential for organic complexing of aluminium, resulting in reduced toxicity.

Although the fish stock is currently not showing any gross indications of acidification impact, the existence of significant rapid drops to very low pH episodes, albeit in a water that is not dramatically low in calcium, would be of interest for further investigation. This is particularly relevant in the context of work by Brown and Lynam (1982) on the survival of freshly fertilised eggs of brown trout which showed some mortality during eight days' exposure at some combinations of calcium and pH levels which have been recorded in the Coalburn monthly sampling programme. For example, the sample taken on 3 November 1992 had pH 4.2 and calcium 3.5 mg l^{-1} Such extremes are probably of relatively short duration, and unlikely to equate to the eight days' exposure results quoted, which at this pH and calcium level would result in <60% survival after eight days by interpolation from the results in Brown and Lynam (1982). Nevertheless, the rapid onset of potentially lethal conditions is clearly worthy of further consideration, and egg-box experiments on trout ova in the catchment seem to be justified.

6 Comparisons with other studies

In interpreting the significance of the results at Coalburn, it is necessary to put them into a wider context, in terms of the international literature on forest hydrology, the representativeness of the site conditions and forest management at Coalburn to other areas of the UK, and the relevance and importance of the findings for the management of forest and water resources.

6.1 Catchment studies

There is a long tradition of catchment studies in hydrology (Whitehead and Robinson, 1993). The first modern basin study began in 1902 when two catchments in the Emmental region of Switzerland, one mainly forested and the other mostly pasture, were instrumented (Engler, 1919). Flood flows and annual yields were lower from the forested catchment, and baseflows were higher.

Soon afterwards two catchments were studied near Wagon Wheel Gap in southern Colorado, USA. Initially, both basins were under forest and, after a calibration period, the forest in one basin was cut down; the subsequent changes in its streamflow, relative to that of the untouched control catchment, were ascribed to the removal of the trees (Bates and Henry, 1928). It was concluded that forest removal increased annual streamflow, mostly as higher spring flood discharge but also as a small increase in summer low flows.

Many basin studies followed; it was reasonably argued that further investigations were necessary, since under different site conditions (including climate, topography and soils) different hydrological effects could well result from land-use change.

The following is a brief review of some of the catchment studies which have had the most impact on the development of our understanding of forest hydrology.

- The Coweeta catchment in North Carolina, USA, has been used since the early 1930s for forest impact studies (Swank and Crossley, 1988). Experiments on over 20 individual sub-catchments have included clearfelling and replanting. The work showed that clearcutting increased mean stormflow and peak flow rates, and there was a strong dependence of streamflow volumes on forest type; for example, hardwood to pine conversion reduced runoff. The Coweeta results clearly demonstrated that forest management can affect evaporation, and hence streamflow.

- In the 1950s attention was given to those developing countries where the impacts of land-use changes were most significant. A series of experiments in East Africa (Kenya, Tanzania and Uganda) studied the effects, on water yield and on stormflow, of replacing native forest by tea estates, pine plantations, grassland and cultivated crops (Edwards and Blackie, 1981).

- The Hubbard Brook catchment study in New Hampshire, USA, was established to determine the impact of forest land management on streamflow in an area where much of the annual runoff occurs as spring snowmelt. These experiments showed that cutting forest increased annual streamflow.

Much of this research is reported in major publications, most recently summarised by Likens and Bormann (1995). A broad summary of the main conclusions of a number of the more important catchment studies is given in Table 14. However, since many complex factors and interrelationships may be involved, no attempt has been made here to quantify these results: just the direction of change is shown — care must be taken in its interpretation. Despite its limitations, Table 14 indicates a broad degree of uniformity under a wide range of climatic and topographic conditions and alternative land uses.

6.1.1 Annual flows

The studies in Table 14 showed a general reduction in annual discharge under forestry. This was also the conclusion of an international review by Bosch and Hewlett (1982) who concluded that forest cover typically reduced runoff by approximately 400 mm year^{-1}. The conflicting result for the early data at Coalburn can be explained by the immature growth stage of the plantation trees: streamflow was still dominated by the extensive pre-planting artificial drainage (enhancing baseflows) and not by the growing trees. Once the trees became more

Table 14 *Simplified summary of main hydrological effects of forestry from selected key basin experiments worldwide*

Catchment	Streamflow changes due to forestry Annual	Peaks	Baseflow	References
Emmental, Switzerland	↓	↓	↑	Engler, 1919
Wagon Wheel Gap, USA	↓	↓	↓	Bates and Henry, 1928
Coweeta, USA	↓	↓	↓	Swank and Crossley, 1988
Hubbard Brook, USA	↓	↓	↓	Likens and Bormann, 1995
Plynlimon, UK	↓	–	–	Kirby *et al.*, 1991
Jonkershoek, South Africa	↓	↓	↓	van Wyke, 1987
East Africa	↓	↓	↓	Edwards and Blackie, 1981
H.L. Andrews, USA	↓	↓	↓	Rothacher, 1970
Coalburn				
Drainage impacts	↑	↑	↑	This study – early years
Forest growth impacts	↓	↓	(↓)	This study – later years

established and interception losses increased, then evaporation rates became higher than for the original grassland — but only some 20 years after planting, showing the hitherto largely unrecognised importance of the early stages of tree establishment.

6.1.2 High flows

Forestry is generally associated with reduced flood peaks and this was the predominant pattern from the studies in Table 14. In most studies it was reported that peak flows are lowered by forest. However, what applies to 'normal' or 'common' magnitude floods, may not apply to extreme floods. Robinson and Newson (1986) showed that although small/moderate flood events were lower from the mature forested catchment at Plynlimon, in very large events there was no apparent difference between peak flows from forest and grassland catchments. The increase in peak flows at Coalburn is the direct result of the extensive plough drainage, and is representative of conditions in immature upland plantations.

6.1.3 Low flows

Table 14 reveals far more variability between studies in the impacts of forestry on low flows. Impacts may be highly dependent upon factors such as local geology influencing the storage capacity of a basin. Furthermore, the majority of the catchment experiments shown here dealt with the short-term effects of felling an existing forest, rather than the much longer and therefore more expensive procedure of afforestation. Research has indicated the critical importance of the *type* of logging method adopted and the nature of the soil; severe ground compaction can significantly lower soil infiltration capacities and, hence, reduce soil water recharge and the ability to sustain dry-weather flows. Infiltration may also be reduced by the replacement land use, perhaps involving overgrazing or the construction of roads and villages (Bruijnzeel, 1990). Consequently it is often very difficult to separate the effect of the tree cover from that of ground disturbance. With afforestation studies (such as Coalburn), the picture may be complicated by the need to install artificial drainage channels. Such drainage is generally deeper and denser than the previous natural network of channels and, even accounting for any dewatering of wet soils, tends to enhance dry-weather baseflows. The extent to which this effect balances the tendency of the growing trees to decrease low flows and the manner in which this changes over time is not well known.

Given the higher annual evaporation losses from forests, it might be concluded that forestry must necessarily reduce baseflows as a consequence of the higher evaporation losses drying the soil and so lessening the opportunity for groundwater recharge. Conversely, there are arguments that baseflows will be higher under forestry as a result of the generally higher soil infiltration capacities under forest cover (Pereira, 1992).

In interpreting the effects of a change in forest cover on catchment outflows it is also necessary to consider the impacts of the associated site disturbance, including possible soil compaction and road construction and any artificial drainage prior to tree planting.

6.1.4 Water quality

In common with a number of other studies at British upland sites, the work at Coalburn has shown the importance of different flow sources and pathways for streamwater quality. At times of low flows when subsurface sources from within the mineral material dominate the hydrograph, the pH may be as high as 7.7. In contrast, when the catchment soils are wet, the stream pH may fall to below 4 once water movement through the surface peats becomes predominant. This distinction may also be seen in the spatial differences in streamwater chemistry from areas of different soil types.

The acid flushes during storm events have significance for stream ecology, although the buffering capacity of the underlying material helps to limit the impact.

6.2 Forest management at Coalburn

The predominant tree species at Coalburn, Sitka spruce, is the most common species planted in the British uplands, and the General Yield Class of 10/12 for the site is also typical of upland Britain (Crowther *et al.*, 1991). In common with peaty soils in general, the site preparation at Coalburn involved drainage Ploughing to 90 cm was deeper than usual practice, both at the present time and in the past, and may have resulted in an enhanced augmentation of the baseflows because of the greater thickness of the soil profile that was exposed and available for gravity drainage to the plough furrows. A shallower ploughing depth of 60 cm, with widely spaced cross-drains of 90 cm depth, was more common at the time, and currently a plough depth of 30–45 cm is preferred. Deeper ploughing may expose erodible mineral subsoils and also restrict root extension, which may lead to tree instability in exposed windy conditions. The original furrow depth would be maintained only in the short term because of 'slumping' of the sides, peat shrinkage and sphagnum growth on the base. Currently many furrows are only about 40 cm deep.

A drain deepening experiment will investigate the impact of depth on low flows and channel roughness and infill on high flows. The plough spacing of approximately 4.5–5 m is at the wide end of current forestry practice (generally 2–4 m). Computer modelling produced higher baseflows when allowance was made for the plough furrows (Dunn, 1996). Simulations of flow rates, based on the Dupuit-Forchheimer assumptions, indicate that reducing drain spacing (of a given depth) generally lowers baseflows, whilst deeper drain depths (for a given spacing) enhance low flows (Robinson and Rycroft, 1998). Although the hydraulic conductivity of the lower peat is believed to be very low, approximately 300 km of plough furrows were cut across the catchment, providing very extensive areas of channel sides for subsurface seepage.

If much of the storm flow from newly ploughed areas is generated by direct precipitation onto channels, the wide plough furrow spacing adopted at Coalburn may have tended to reduce the increase in peak flows in comparison with the more common situation of narrower spacing today (Binns, 1979; David and Ledger, 1988). Studies at Llanbrynmair in mid-Wales (Hudson *et al.*, 1997) are investigating the magnitude and duration of such effects at a site where drainage practices differ considerably from those at Coalburn.

The sediment losses following ploughing at Coalburn were extremely high. Recent forestry guidance (Forestry Commission, 1993) emphasises the need for shallower cultivation and for uncultivated buffer zones to be left on either side of streams, with drains terminating some distance upslope. These steps are intended to reduce the potential for erosion and to encourage water to spill out and flow across the buffer strip, allowing the vegetation to filter out and retain any mobilised sediment. Other studies at Llanbrynmair, in which forest plough lines were stopped short of the main channels, have helped in keeping sediment concentrations to low levels (Francis and Taylor, 1989). Although the low-lying land along the main stream at Coalburn was ploughed and planted, it has no trees because of frost damage. Together with the unplanted zone acting to prevent excessive shade, these procedures limit the impacts on stream flora and fauna (e.g. Ormerod *et al.*, 1993).

The planted ground received two applications of rock phosphate and potash fertiliser — at the time of the cultivation and in 1981 — to correct the expected deficiencies of these nutrients in the peaty soils in order to aid tree establishment and growth. A combination of the wide plant spacing, frost damage and nutrient competition by the existing moorland vegetation was probably responsible for the early checked growth and delayed canopy closure of a significant part of the forest. Recent measurements, however, show that the trees are growing well following canopy closure, and phosphate and potassium concentrations in the tree foliage are at optimum levels. Although nitrogen levels are below optimum they do not appear to be restricting growth.

7 Conclusions

The Coalburn study has produced some surprises as regards the *type* and *direction* of forestry effects and also the *timing* and *duration* of the changes. Most of the early hydrological effects noted at the site were in the opposite direction to those generally described in the literature for forestry (McCulloch and Robinson, 1993). It has been shown that this is not because the site is untypical, but is due to the relatively young stage of tree growth studied and to the effects of the site preparation. Most previous published studies dealt only with the effects of economically mature forest.

One of the major achievements of the Coalburn study to date has been to show the great difference in the local impact of different stages of the forest cycle. Initially the effects of afforestation at Coalburn were dominated by the site preparation. The pre-planting ploughing and drainage increased total flows and low flows; peak flows also increased but shortened in duration. Erosion and sediment losses increased substantially and continued at enhanced levels for many years. Over the 25 years of forest growth, and with colonisation of many plough furrows by vegetation, annual water yields have recently fallen below the pre-afforestation level, peak flows are now similar, and low flows, although gradually reducing, are still higher (Figure 26a).

The long-lasting effects of the ploughing, extending over half of the planned forest cropping cycle, are quite unexpected. If these are representative of other areas, this would indicate that half of the coverage of British upland forests may have hydrological effects that are the opposite to what has previously been thought. These results have great significance for future forestry policy. Forestry effects are not simply cumulative — increasing with forest age — but vary in direction and magnitude through the cropping cycle. This gives support to judicious mixed-age forest planning in the future, in which the hydrological effects of plantations of different ages within a catchment may tend to balance out (Robinson, 1980). Indeed a patchwork forest landscape is now part of Forestry Commission policy for economic, landscape and ecological reasons and fits in with the requirements to reduce the impact on water resources and extreme flows. The current trees at Coalburn were all planted in the same year (except for a few small areas where the trees died and new trees had to be planted), whilst in contrast the felling and second rotation planting of the forest at Coalburn is planned to take place in three stages, over approximately a 15-year period.

Comparisons of short-term records from forested and non-forested catchments, or from catchments with trees of different ages, could not have brought out the subtle interrelations between the effects of the deep ploughing and the trees that have been revealed in this long-term strategic study. Valuable

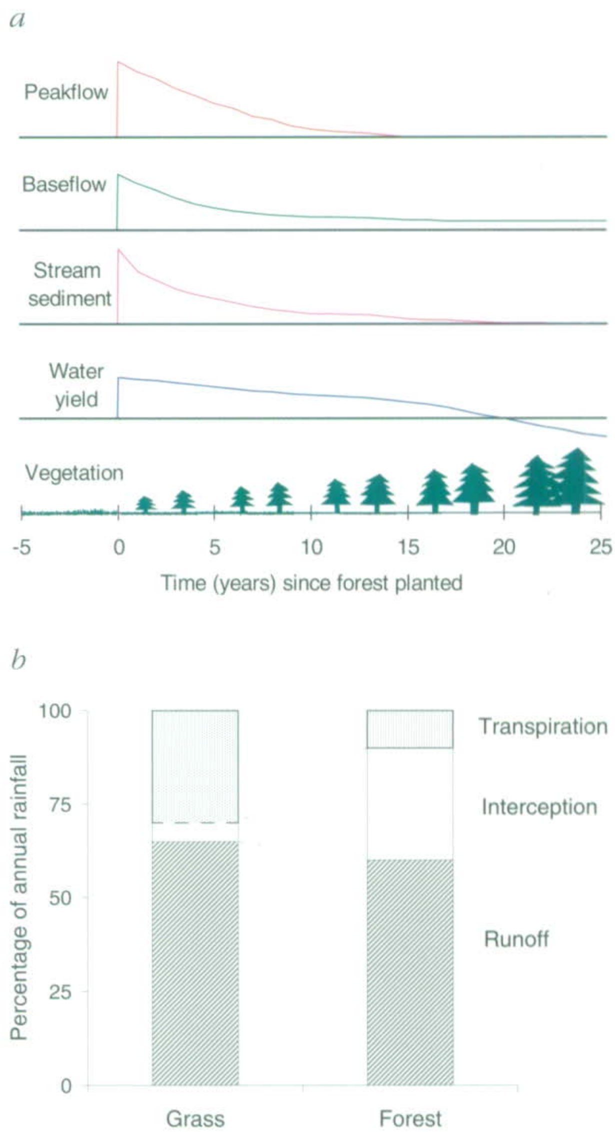


Figure 26 *Summary of main hydrological changes at Coalburn: (a) over time, (b) water balance before forestry and at current time*

though such short-term and regional studies may be, they will always be subject to uncertainties arising from spatial and temporal variability in soils, topography and weather conditions. Catchments are never identical in all respects other than land use.

Figure 26b shows, in a generalised form, the water balance of the grass before afforestation and of the forest at the present time. It uses the measured catchment rainfall and runoff, with the actual evaporation computed as the difference. For the grass evaporation, a widely-used ratio of 1:9 between interception and transpiration has been assumed, although because of the high winds and frequent light rainfall, the grass interception component may be even greater than its transpiration at this site. For the forest, the measured interception losses were used, with the proportion of unplanted land being used to estimate the forest transpiration as the residual amount. This indicates a smaller forest transpiration (~150 mm year^{-1}) than has been reported widely in the literature

The results from the water chemistry studies demonstrate the crucial importance of soil type in determining streamwater acidity, with the drift deposits providing good buffering capacity in contrast to the upper peats. This finding may also provide a basis for better design and management of 'patchwork' forests. A detailed soil survey and sampling programme of water chemistry in the major tributaries was started in 1997.

Results from Coalburn and elsewhere have influenced forestry operations via the *Forests and Water Guidelines* (Forestry Commission, 1993). These guidelines describe the working methods and measures that should be employed to minimise the impact of forestry operations on the freshwater environment. They apply equally to the state and private forestry sectors, and both planting grant approvals and felling licences are subject to the required standards.

8 Continuing studies and forward look

With its extensive archive of baseline data, the Coalburn catchment experiment should continue to yield many more results of both practical and academic interest in the years to come. The trees are at present 7–12 m in height, and will grow to a final height of some 18–20 m before felling (scheduled for the year 2012 and beyond). There are many important and unresolved questions about the effects of upland forestry which this study will help to answer over the remaining years of the cropping cycle. These include a test of the predictions that evaporation losses under a complete cover of mature forest at Coalburn will be about 320 mm year^{-1} higher, almost double those from the original moorland (Calder, 1979), or a more modest 130 mm year^{-1} greater (Newson, 1992). The difference between such estimates is clearly very important for the water industry. Further data will also help to clarify and quantify the effect of mature forestry on low flows and whether peak flows under a mature (drained) forest are higher (Robinson and Newson, 1986) or lower (Binns, 1979) than from the original (substantially undrained) moorland.

Process studies are needed to understand the controls on evaporation losses at different stages of forest growth. Up to now, studies of interception losses from upland forests have largely concentrated on mature forests (Calder, 1990), and there is relatively little information on losses from young trees, although they account for a significant proportion of the area of upland plantations. The interception study at Coalburn, using large, plastic sheet net-rainfall gauges under the tree canopy, provides further information on this aspect as the trees are currently in their period of maximum rate of growth, extending in height by approximately one metre per year. Furthermore, the transpiration measurements will yield valuable information on that component of evaporation rates, particularly with regard to the impacts of forestry during dry-weather periods, when due to their extensive rooting systems they may be less limited by soil water deficits than shorter moorland vegetation.

Up to now, estimates of transpiration for Coalburn have had to be made indirectly by comparison of the other elements of the water balance. From considering measured precipitation, interception loss and streamflow, it seems that transpiration from those parts of the catchment that have attained a closed canopy is only about 150 mm year^{-1}. This is at variance with other studies: values of 300–350 mm year^{-1} have been widely reported in the literature (Roberts, 1983). Calder (1978) for example, reported values of about 300 mm for 12 m high Norway spruce at Plynlimon, with no evidence of suppression during summer drought, even though soil moisture deficits of 200 mm were recorded. The trees were approximately 40 years old at the time of study and probably had a more extensive rooting system than those at Coalburn. Milne (1979) reported transpiration rates of 3 mm d^{-1} from 14-year-old Sitka spruce growing on peaty gley soil during the dry summer of 1976. Nevertheless, there is evidence from the water balances of other upland catchments of apparently low transpiration losses. At Plynlimon (Kirby *et al.*, 1991) the water balance suggests that forest transpiration is suppressed to "well below the potential rate", and at Balquhidder in Scotland, the predicted loss from the partly forested Kirkton catchment was systematically lower than that predicted in each of the five years studied (Hall and Harding, 1993).

Resolving the transpiration losses at Coalburn may, therefore, have wide implications for upland catchments. Detailed transpiration measurements commencing in 1997 will investigate whether transpiration is suppressed and, if so, try to identify the physical factors responsible. There are many factors that might be involved, including low temperatures and soil water stress, and it is clear that more research is needed before definite conclusions can be reached.

There is also much that is still unclear regarding forest impacts on low flows at a particular site. The long-term enhancement of the low flows resulting from plough drainage may be due to the depth of the ploughing, and it is anticipated that by monitoring the impact on outflows of deepening a number of furrows, this effect may be studied directly.

When the Coalburn catchment was established in the 1960s, there was little interest amongst hydrologists or engineers in water quality considerations (McCulloch and Robinson, 1993). Since then, the importance of water quality has increasingly been recognised, and this is reflected in recent water quality studies at Coalburn. With regular manual sampling for the determination of major ions, and continuous water quality monitoring, the catchment study will help to answer concerns about the effect of forestry on surface water acidification. As the data set grows it will be possible to identify time trends. Changes in water chemistry which have been linked with forest growth elsewhere include lower pH and higher metal concentrations, particularly aluminium. It is recognised that conifer forests have a 'natural' acidifying action, but the primary cause of surface water acidification is air pollution: forests exhibit enhanced scavenging of pollutants because of their taller vegetation and greater aerodynamic roughness. Coalburn is ideally placed to test the effectiveness of recent international agreements for significant reductions in sulphur and nitrogen emissions in improving streamwater chemistry within areas previously subject to high pollutant loadings. Further work may enable chemical mass balances to be determined. The data on water colour and trihalomethanes (THMs) will also allow the impact of soil drying under the forest to be determined, since both aspects are of concern for public drinking water supplies.

Further work is needed to improve our understanding of the mechanisms of water movement to the catchment outlet, and the ways in which the water chemistry is altered. Better knowledge of this might offer the possibility of manipulating conditions in forested catchments in order to enhance the degree of buffering by encouraging water flow through the deeper, less acid, soil layers.

With many British plantation forests now reaching commercial maturity, there is an increasing interest in the impact of felling. The trees at Coalburn are due to be felled around 2012–26. A nearby small catchment, Howan Burn, due to be felled some 15 years earlier, has been instrumented to give some indication of the likely changes and of the impact of different site practices. Comparison of streamwater chemistry at the two catchments, before Howan Burn is clearfelled, will enable water chemistry changes to be predicted at Coalburn, and allow models to be tested.

The combination of a long-term catchment study, to observe and quantify overall changes and budgets, with shorter-term process studies, to understand cause and effect relationships, provides a sound basis for the extrapolation of results This should help decisions to be made about how best to plan and manage forests for the whole range of their uses. It is anticipated that future work will use Geographical Information Systems (GIS) to manage, process and link together spatial information such as climate, soils and vegetation cover (e g Calder, 1996). This will produce large-scale catchment outputs, scaling up from small plot studies as well as combining the contributions of different sub-areas, which may have different land uses or be at different stages of the forest cycle.

Coalburn has produced many important findings regarding the impacts of forestry on both water quantity and quality, and will undoubtedly continue to do so as we follow the forestry cycle through to its completion.

References

Abbott, M.B., Bathurst, J.C., Cunge, J A , O'Connell, P.E. & Rasmussen, J. 1986. An introduction to the European Hydrological System, 1: History and philosophy of a physically based distributed modelling system. *J. Hydrology,* **87**, 45–59.

Ackers, P., White, W.R., Perkins, J.A. & Harrison, A.J.M. 1978. *Weirs and flumes in flow measurement.* John Wiley & Sons, Chichester.

Alabaster, J.S. & Lloyd, R 1980. *Water quality criteria for freshwater fisheries.* Butterworths, London.

Anderson, A R & Pyatt, D.G. 1986. Interception of precipitation by pole-stage Sitka spruce and lodgepole pine and mature Sitka spruce at Kielder Forest, Northumberland. *Forestry,* **59**, 29–38.

Austin, R. & Brown, D. 1981. Solids contamination resulting from drainage works in an upland catchment and its removal by flotation. *J. Institution of Water Engineers and Scientists,* **36**, 281–288.

Bates, C.G. & Henry, A.J. 1928. Forest and streamflow experiment at Wagon Wheel Gap, Colorado. *Monthly Weather Review,* Supplement No. 30, 1–79.

Binns, W.O. 1979. The hydrological impact of afforestation in Great Britain. In. Hollis, G.E. (Ed.) *Man's impact on the hydrological cycle in the United Kingdom.* 55–69. Geo Books, Norwich.

Blackie, J.R., Hudson, J.A. & Johnson, R.C. 1986. Upland afforestation and water resources — preliminary analysis of Phase I of the Balquhidder catchment studies. Unpublished report, Institute of Hydrology, Wallingford, UK.

BOAF 1918. Relationship of woods to domestic water supplies. Board of Agriculture and Fisheries Leaflet No. 99. HMSO, London.

Bosch, J.M. & Hewlett, J.A. 1982. A review of catchment experiments to determine the effect of vegetation changes on water yield and evapotranspiration. *J. Hydrology,* **55**, 3–23.

Brown, D.J.A. & Lynam, S. 1982. The effect of calcium and aluminium concentrations on the survival of brown trout (*Salmo trutta*) at low pH. Central Electricity Generating Board Report TARD/L/2347/N82 December, 1982.

Bruijnzeel, L.A. 1990. *Hydrology of moist tropical forests and effects of conversion: a state of knowledge review.* UNESCO Humid Tropics Programme Publication, Free University, Amsterdam.

Burt, T.P., Donohoe, M.A. & Vann, A.R. 1984. A comparison of suspended sediment yields from two small upland catchments following open ditching for forestry drainage. *Zeitschrift für Geomorphologie,* **51**, 51–66.

Calder, I.R. 1976. The measurement of water losses from a forested area using a 'natural' lysimeter. *J. Hydrology,* **30**, 311–325.

Calder, I.R. 1977. A model of transpiration and interception loss from a spruce forest in Plynlimon, Central Wales. *J. Hydrology,* **33**, 247–265.

Calder, I.R. 1978. Transpiration observations from a spruce forest and comparisons with predictions from an evaporation model. *J. Hydrology,* **38**, 33–47.

Calder, I.R. 1979. Do trees use more water than grass? *Water Services,* **83**, 11–14.

Calder, I.R. 1990. *Evaporation in the uplands.* John Wiley & Sons, Chichester.

Calder, I.R. 1996. Water use by forests at the plot and catchment scale. *Commonwealth Forestry Review,* **75**, 19–30.

Calder, I.R. & Newson, M.D. 1979. Land use and water resources in Britain – a strategic look. *Water Resources Bulletin,* **15**, 1628–1639.

Calder, I.R. & Rosier, P.T.W. 1976. The design of large plastic-sheet net-rainfall gauges. *J. Hydrology,* **30**, 403–405.

Calder, I.R. & Wright, I.R. 1986. Gamma ray attenuation studies of interception from Sitka spruce: some evidence for an additional transport mechanism. *Water Resources Research,* **22**, 409–417.

Clayden, B. & Hollis, J.M. 1984. Criteria for differentiating soil series. Soil Survey Technical Monograph No. 17, Soil Survey of England and Wales, Harpenden, UK

Clarke, R.T. & Newson, M.D. 1978. Some detailed water balance studies of research catchments. *Philosophical Transactions of the Royal Society, London,* **B363**, 21–42.

Cox, D.R. & Lewis, P.A.W. 1966. *The statistical analysis of series of events.* Methuen & Co., London.

Crowther, R.E., Low, A.J. & Tabbush, P.M. 1991. Establishment and tending. Chapter 5. In: Hibberd, B.G. (Ed.) *Forestry practice.* 41–80. Forestry Commission Handbook No. 6. HMSO, London.

Curran, J.C. & Robertson, M. 1991. Water quality implications of an observed trend of rainfall and runoff. *J. Institution of Water Engineers and Managers*, **5**, 419–424.

David, J.S. & Ledger, D.C. 1988. Runoff generation in a plough drained peat bog in southern Scotland. *J. Hydrology*, **99**, 187–199.

Davies, T.D., Dorling, S.R., Pierce, C.E., Barthelmie, R.J. & Farmer, G. 1991. The meteorological control on the anthropogenic ion control of precipitation at three sites in the UK: the utility of Lamb weather types. *International J. Climatology*, **11**, 795–807.

Davies, T.D. Tranter, M., Wigington, P.J. & Eshleman, K.N. 1992. Acid episodes in surface waters in Europe. *J. Hydrology*, **132**, 25–69.

Davison, W. & Woof, C. 1985. Performance tests for the measurement of pH with glass electrodes in low ionic strength solutions including natural waters. *Analytical Chemistry*, **57**, 2567–2570.

Day, J.B W. 1970. Geology of the country around Newcastle. Geological Survey of Great Britain Memoir No. 12. HMSO, London.

DOE 1972 Analysis of raw, potable and waste waters. Department of the Environment HMSO, London.

Dunn, S.M. 1995, Modelling the effects of land-use change in a large UK river basin. PhD Thesis, Department of Civil Engineering, University of Newcastle upon Tyne.

Dunn S.M. & Mackay, R. 1996. Modelling the hydrological impacts of open ditch drainage. *J. Hydrology*, **179**, 37–66.

Edwards, K.A. & Blackie, J.R. 1981. Results of the East African catchment experiments, 1958–74. In: Lal, R. & Russell, E.W. (Eds.) *Tropical agricultural hydrology*. 163–188. John Wiley & Sons, Chichester.

Engler, A. 1919. Untersuchungen über den Einfluss des Waldes auf den Stand der Gewässer. *Mitteilungen der Schweiz. Eidg. Anst. für das Forstliche Versuchswesen*, **12**, 1–626.

Forestry Authority. 1998 The UK Forestry Standard. Forestry Commission, Edinburgh.

Forestry Commission. 1972. Record of forest research. Forestry Commission, Edinburgh.

Forestry Commission. 1992. Annual report. Appendix 6. HMSO, London

Forestry Commission. 1993. Forests and water guidelines. 3rd edition. Forestry Commission, Edinburgh.

Fowler, D., Cape, J.N. & Unsworth, M.H. 1989. Deposition of atmospheric pollutants on forests *Philosophical Transactions of the Royal Society, London*, **B324**, 247–265.

Francis, I.S. & Taylor, J A. 1989. The effect of forestry drainage operations on upland sediment yields: a study of two peat-covered catchments. *Earth Surface Processes and Landforms*, **14**, 73–83.

Frost, D.V. & Holliday, D W. 1980 Geology of the country around Bellingham. Geological Survey of Great Britain. Memoir No. 13. HMSO, London.

Gash, J.H.C. & Morton, A.J. 1978. An application of the Rutter model to the estimation of the interception loss from the Thetford Forest. *J. Hydrology*, **38**, 49–58.

Gash, J.H.C., Wright, I.R. & Lloyd, C.R. 1980. Comparative estimates of interception loss from three coniferous forests in Great Britain. *J. Hydrology*, **48**, 89–105.

Green, M.J. 1970. Calibration of the Brenig Catchment and the initial effects of afforestation. *IAHS Publication No. 96*, 329–45

Gustard, A., Bullock, A. & Dixon, J.M 1993. Low flow estimation in the UK. *Institute of Hydrology Report No. 108*, Wallingford, UK.

Hall, R.L & Harding, R.J. 1993 The water use of the Balquhidder catchments: a processes approach. *J. Hydrology*, **145**, 285–314.

Hansard 1982. York (flooding) House of Commons parliamentary debates. Weekly Hansard (5–11 February) **17** (1231), 1089–1094.

Harr, R.D. 1982. Fog drip in the Bull Run municipal watershed, Oregon. *Water Resources Bulletin*, **18**, 785–789.

Harriman, R. Gillespie, E., King D., Watt, A.W., Christie, A E G., Cowan, A.A. & Edwards, T. 1990. Short-term ionic responses as indicators of hydrochemical processes in the Allt A' Mharcaidh catchment, W. Cairngorms, Scotland. *J. Hydrology*, **116**, 267–285.

Hind, P.D 1992. The Coalburn experimental catchment study: an evaluation of process hydrology at canopy closure using solute chemistries. Department of Geography, University of Newcastle upon Tyne.

Horton, R.E. 1919. Rainfall interception. *Monthly Weather Review*, **47**, 603–623

Hudson, J.A., Crane, S.B. & Robinson, M. 1997. The impact of the growth of new plantation forestry on evaporation and streamflow in the Llanbrynmair catchments, mid Wales. *Hydrology and Earth System Sciences*, **1**, 463–475.

Hughes, C. 1990. A correlation study of the Penman evaporation from the Coalburn automatic weather station, MORECS data and Eskdalemuir observatory during 1988 and 1989. Applied Hydrology Note CH/112. Unpublished report, Institute of Hydrology, Wallingford, UK.

IH/BGS 1996. *Hydrological data: UK series*. Institute of Hydrology/British Geological Survey, Wallingford, UK.

IH 1973. Record of research, 1972–73. Institute of Hydrology, Wallingford, UK.

Johnson, R.C. 1990. The interception, throughfall and stemflow in a forest in Highland Scotland and the comparison with other upland forests in the UK. *J. Hydrology*, **118**, 281–287.

Keers, J.F. & Wescott, P. 1977. A computer-based model for design rainfall in the UK. Meteorological Office Scientific Paper No. 36. HMSO, London.

Keller, H.M. 1988. European experiences in long-term forest hydrology research. In: Swank, W.T & Crossley, D.A. (Eds.) *Forest hydrology and ecology at Coweeta*. 407–459. Ecological Studies No. 66. Springer Verlag, New York.

Kellıher, F.M , Leuning, R. & Schulze, E.-D 1993. Evaporation and canopy characteristics of coniferous forests and grasslands. *Oecologia*, **95**, 153–163.

Kirby, C., Newson, M D. & Gilman, K (Eds.) 1991. Plynlimon research: The first two decades. *Institute of Hydrology Report No. 109*, Wallıngford, UK.

Law, F. 1958 Measurement of rainfall, ınterception and evaporation losses in a plantation of Sitka spruce trees. *IUGG/IASH, General Assembly of Toronto*, **2**, 397–411.

Lewis, W.K. 1957. Investigation of rainfall, runoff and yield on the Alwen and Brenıg catchments *Proceedings of the Institute of Civil Engineers*, **8**, 17–51.

Leyton, L., Reynolds, E.R.C. & Thompson, F B 1967. Rainfall interception in forest and moorland. In: Sopper, W.E. & Lull, H.W. (Eds.) *International symposium on forest hydrology*. 163–178. Pergamon Press, Oxford. .

Likens, G.E. & Bormann, F.H. 1995. *Biogeochemistry of a forested ecosystem*. 2nd edition. Springer Verlag, New York.

Lloyd, C.R. & Marques, A. de O. 1988. Spatial variability of throughfall and stemflow measurements in Amazonian rainforest *Agriculture and Forest Meteorology*, **42**, 63–73.

Mansell, M.G. 1997. The effect of climate change on rainfall trends and flood risk in the west of Scotland. *Nordic Hydrology*, **28**, 37–50.

Marsh, T.J. 1996. The 1995 drought — a water resources review in the context of the recent hydrological instability. In: *Hydrological data: UK: The 1995 yearbook*. 25–33. Institute of Hydrology, Wallingford, UK.

Marsh, T.J. & Lees, M.L. 1986. The 1984 drought: A historical review. *Hydrological data: UK series*. Institute of Hydrology, Wallingford, UK.

Mather, A. 1993. *Afforestation — policies, planning and progress*. Belhaven, London.

McCulloch, J.S G. & Robinson, M. 1993. History of forest hydrology *J Hydrology*, **150**, 189–216

McIntosh, R. 1981. Fertiliser treatment of Sitka spruce in the establishment phase ın upland Britain. *Scottish Forestry*, **35**, 3–13.

Mills, D. 1980. *The Management of Forest Streams*. Forestry Commission Leaflet No. 78. HMSO, London.

Mılne, R. 1979, Water loss and canopy resistance of a young Sitka spruce plantation. *Boundary Layer Meteorology*, **16**, 67–81.

Milne, R., Crossley, A., & Unsworth, M.H. 1988. Physics of cloudwater deposition and evaporation at Castlelaw, SE Scotland. In: Unsworth, M.H. & Fowler, D. (Eds.) *Acid deposition processes at high elevation sites*. 299–307. Kluwer Academic Publishers, The Netherlands.

Ministry of Health, 1948. Gathering grounds, public access to gathering grounds, afforestation and agriculture on gathering grounds. Report of the Gathering Grounds Committee. HMSO, London.

Monteith, J.L. 1965. Evaporation and the environment. In: *The state and movement of water in living organisms. Proceedings of the 19th Symposium of the Society of Experimental Biology, Swansea, 1964*. 205–234. Cambridge University Press, Cambridge.

Mounsey, S.C, & Newson, M.D. 1995. Acid episodes in the Coalburn Catchment. In: *BHS 5th National Hydrology Symposium, Edinburgh*. 5.17–5.27. British Hydrological Society, London.

Neal, C., Smith, C J., & Hill, S. 1992. Forestry impact on upland water quality. *Institute of Hydrology Report No. 119*, Wallingford, UK.

NERC 1975. *Flood studies report*. (5 Vols) Natural Environment Research Council, London. Reprinted 1993

Newson, M.D. 1980. The erosıon of drainage dıtches and its effect on bedload yields ın mid-Wales. *Earth Surface Processes and Landforms*, **5**, 275–290.

Newson, M.D. 1992. Kielder Water, Kielder Forest and the N Tyne valley. In: Whitby, M.C. (Ed.) *Land-use change: the cause and consequences*. 159–165. Institute of Terrestrial Ecology Symposium No. 27. HMSO, London.

Nıcholson, I.A., Robertson, R.A. & Robinson, M. 1989. The effects of drainage in the hydrology of a peat bog. *International Peat Journal*, **3**, 59–83.

Ormerod, S.J & Jenkins, A 1994. The biological effects of acid episodes. Chapter 18. In: Steinberg, C.E.W. & Wright, R.E. (Eds.) *Acidification of freshwater ecosystems. implications for the future*. John Wiley & Sons, Chichester.

Ormerod, S.J., Rundle, S.D., Lloyd, C.E. & Douglas, A.A. 1993. The influence of riparian management on the habitat structure and macroinvertebrate communıties of upland streams draınıng plantation forests. *J. Applied Ecology*, **30**, 13–24.

Paınter, R.B., Rodda, J.C. & Smart, J.D.G. 1972. Hydrological research and the planner. *Surveyor*, 1 December 22–25.

Penman, H.L. 1948. Natural evaporation from open water, bare soil and grass. *Proceedings of the Royal Society Series, London*, **A193**, 120–146.

Penman, H.L. 1963. Vegetation and hydrology. Technical Communication No. 53.

Commonwealth Bureau of Soils, Harpenden, UK.
Pereira, H.C. 1992. The role of forestry in the management of tropical watersheds. Keynote paper at 10th World Forestry Conference, Paris. 139–150. Revue Forestière Francais Hors Series 3.
Prigg, R.F. 1983. Juvenile salmonid populations and biological quality of upland streams in Cumbria with particular reference to low pH effects. North West Water Rivers Division Report BN77-2-83 February, 1983.
Prigg, R.F. 1994. Fish and macroinvertebrate populations of Coalburn and their interpretation in an acidification context. National Rivers Authority, Northern Area Biology Laboratory Report NB 276.
Pruppacher, H.R. & Klett, J.D. 1997. *Microphysics of clouds and precipitation*. Kluwer Academic Publishers, The Netherlands.
Roberts, J.R. 1983. Forest transpiration: a conservative process? *J. Hydrology,* **66**, 133–141.
Robinson, M. 1980. The effect of pre-afforestation drainage on the streamflow and water quality of a small upland catchment. *Institute of Hydrology Report No. 73,* Wallingford, UK.
Robinson, M. 1985. The hydrological effects of moorland gripping: a re-appraisal of the Moor House research. *J. Environmental Management,* **21**, 205–211.
Robinson, M. 1986. Changes in catchment runoff following drainage and afforestation. *J. Hydrology,* **86**, 71–84.
Robinson, M. 1993. Intercomparison of automatic weather stations at Coalburn. Report to National Rivers Authority. Institute of Hydrology, Wallingford, UK.
Robinson, M. & Armstrong, A.C. 1988. The extent of agricultural field drainage in England and Wales, 1971–80. *Transactions of the Institute of British Geographers,* **13**, 19–28.
Robinson, M. & Blyth, K. 1982.The effect of forestry drainage operations on upland sediment yields: a case study. *Earth Surface Processes and Landforms,* **7**, 85–90.
Robinson, M. & Hind, P.D. 1991. The Coalburn catchment experiment *N. England Soils Discussion Group Proceedings,* **26**, 9–26.
Robinson, M., Jones, T.K. & Blackie, J. R. 1994. The Coalburn catchment experiment — 25-year review. R & D Note 270. National Rivers Authority, Bristol, UK.
Robinson, M. & Newson, M.D. 1986. Comparison of forest and moorland hydrology in an upland area with peat soils. *International Peat Journal,* **1**, 49–68.
Robinson, M. & Rycroft, D.W. 1998. The impact of drainage on streamflow. Chapter 23 In: van Schilfgaarde, J. & Skaggs, R.W. (Eds.) *Agricultural drainage.* American Society of Agronomy, Madison, Wisconsin, USA.
Robson, M.A. 1993. The use of continuous measurement in understanding and modelling the hydrochemistry of the uplands. PhD Thesis Lancaster University
Rodda, J C 1970. On the questions of rainfall measurement and representativeness. *IAHS Publication No. 92,* 174–186.
Rodda, J.C. & Smith, S W. 1986. The significance of the systematic error in rainfall measurement for assessing atmospheric deposition. *Atmospheric Environment,* **20**, 1059–1064.
Rothacher, J. 1970. Increases in water yield following clear cut logging in the Pacific Northwest. *Water Resources Research,* **6**, 653–658.
Rutt, G.P., Weatherley, N.S. & Ormerod, S.J. 1990. Relationships between the physicochemistry and macro-invertebrates of British upland streams: the development of modelling and indicator systems for predicting fauna and detecting acidity. *Freshwater Biology,* **24**, 463–448.
Rutter, A.J. 1967. An analysis of evaporation from a stand of Scots pine. In: Sopper, W.E. & Lull, H.W. (Eds) *International symposium on forest hydrology.* 403–417. Pergamon Press, Oxford.
Rutter, A.J., Kershaw, K.A., Robins, P.C. & Morton, A.J. 1971. A predictive model of rainfall interception in forests. 1. Derivation of the model from observations in a plantation of Corsican pine. *Agricultural Meteorology,* **9**, 367–384.
Rutter, A.J. & Morton, A.J 1977. A predictive model of rainfall interception in forests. 3. Sensitivity of the model to stand parameters and meteorological variables. *J. Applied Ecology,* **14**, 567–588.
Rutter, A.J., Morton, A.J. & Robins, P.C. 1975. A predictive model of rainfall interception in forests. 2. Generalization of the model and comparison with observations in some coniferous and hardwood stands. *J. Applied Ecology,* **12**, 367–380.
Schofield, R.K. 1948. Discussion of biology and civil engineering. *Proceedings of the Institute of Civil Engineers,* 90.
Seuna, P. 1980. Long-term influence of forestry drainage on the hydrology of an open bog in Finland. *IAHS Publication No. 130,* 141–149
Sevruck, B, 1982. Methods for correction of systematic error in point precipitation measurements for operational use. Operational Hydrology Report No. 21, World Meteorological Organization, Geneva.
Shuttleworth, W.J. 1977. The exchange of wind-driven fog and mist between vegetation and the atmosphere. *Boundary Layer Meteorology,* **12**, 463–489.
Shuttleworth, W.J. & Calder, I.R. 1979. Has the Priestley-Taylor equation any relevance to forest evaporation? *J. Applied Meteorology,* **18**, 639–646.
Smith, C. 1997. Community forests — the first years. *Quarterly J. Forestry,* **91**, 21–26.

Smith, D.M. & Allen, S.J. 1996. Measurements of sap flow in plant stems. *J. Experimental Botany*, **47**, 1833–1844.

Smith, R.S. & Charman, D.J. 1988. The vegetation of upland mires with conifer plantations in Northumberland, N. England. *J. Applied Ecology*, **25**, 579–594.

Soulsby, C. 1995. Contrasts in storm event hydrochemistry in acidic afforested catchment in upland Wales. *J. Hydrology*, **170**, 159–179.

Swank, W.T. & Crossley, D.A. (Eds.) 1988. *Forest hydrology and ecology at Coweeta*. Ecological Studies No. 66. Springer Verlag, New York.

Thom, A.S. & Oliver, H.R. 1977. On Penman's equation for estimating regional evaporation. *Quarterly J. Royal Meteorological Society*, **103**, 345–357.

Thompson, D.A. 1976. Double-mouldboard ploughing in deep peat. Forestry Commission Research Information Note 14, Forestry Commission, Edinburgh.

Thompson, D.A. 1984. Ploughing of forest soils. Forestry Commission Leaflet No. 71, HMSO, London.

van Wyke, D.B. 1987. Some effects of afforestation on streamflow in the Western Cape Province, South Africa. *Water South Africa*, **13**, 31–36.

Weston, K.J. 1992. Objectively analysed cloud immersion frequencies for the UK. *Meteorological Magazine*, **121**, 108–111.

Whitehead, P.G. & Calder, I.R. (Eds.) 1993. The Balquhidder experimental catchments. Special issue. *J. Hydrology*, **145**, 215–480.

Whitehead, P.G. & Robinson, M. 1993. Experimental basin studies — an international and historical perspective of forest impacts. *J. Hydrology*, **145**, 217–230.

Wilson, D. 1993. Investigation of wind speed data, Eskdalemuir 1970–90. Unpublished report. Institute of Hydrology. Wallingford, UK.