Institute of Hydrology

Report No. 116

Effects of upland afforestation on water resources

The Balquhidder Experiment 1981-1991

Natural Environment Research Council

Report No. 116

Second edition

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The Balquhidder Experiment 1981-1991

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May 1995

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ISBN 0 948540 49 4 (revised edition)
(Original 1991 edition ISBN 0 948540 29 X)

IH Report No. 116

published by the Institute of Hydrology

May 1995

British Library Cataloguing-in-Publication Data

A catalogue record for this book is available from the British Library

Foreword

This report on the results of the research carried out in the Balquhidder catchments is an updated version of the original *Institute of Hydrology Report No. 116* produced in 1991. Further analysis was carried out following the original publication and, although no results have changed, more detail is included in this second edition. The section on water quality has been omitted from this edition, because that analysis has been greatly expanded and is published separately in a report to the Scottish Office (Harriman & Miller, 1994).

Abstract

The effects of upland afforestation on water resources have been studied in two upland catchments, Kirkton and Monachyle, at Balquhidder in Highland Scotland. These catchments are similar in orientation, area and altitude range, but differ in detailed topography, precipitation amount and land use. The initial objectives were:

1. To replicate and extend the Plynlimon study on the effects of upland afforestation on water resources into Highland Scotland where the indigenous vegetation, typically coarse grasses and heather, is aerodynamically rougher than the short cropped grass found in Wales and the distribution and type of precipitation is also different;

2. To develop and improve applied evaporation models for upland areas;

3. To determine the seasonal differences in evaporation rates, including snow conditions, between forest, heather and grass, and the spatial variability of upland meteorological parameters which control evaporation rates;

4. To determine, in typical Scottish Highland conditions of climate, topography and soils, the integrated effects of two different forms of land use:
   a. plantation forest
   b. rough grazing

   on streamflow, sediment and nutrient loadings, thereby determining the effects of afforestation on the quantity and quality of upland water resources.

Results of the catchment monitoring and site process studies are reported. The land-use changes — afforestation in the Monachyle and clearfelling in the Kirkton — are assessed in terms of their impacts on catchment water yields, stream flows and sediment loads. Analysis is carried out using standard techniques and existing models, and a model is developed of the effects of land-use change on streamflow.

Acknowledgements

Local cooperation from the community at Balquhidder has been invaluable. Particular thanks must be given to the private landowners and the local Forestry Commission officers who have assisted with our research. Their names are listed below in acknowledgement.

Monachyle west: Mr R. Gauld, Mr R. Lewis.
Upper Monachyle: Mrs J. Bowser.
Monachyle east: Mr R. Gauld, Mr G. Cummins.
Kirkton west: Mr D. McDiarmid, Mr R. Brown.
Kirkton east: Mr P. Ferguson, Mr C. Methven.
Forestry Commission District Managers:
Mr D. McAskill, Mr B. Roebuck, Mr D. Howat, Mr K. Wilkinson.

The Balquhidder experiment is funded by a consortium of interested bodies. The Institute of Hydrology would like to thank the members of this consortium, who have included the Scottish Development Department, Department of the Environment, Natural Environment Research Council, Forestry Commission, Water Research Centre and the North of Scotland Hydro-Electric Board.

The support of Strathclyde Regional Council, Central Regional Council, British Waterways Board, Forth River Purification Board and the Meteorological Office is also acknowledged.

Contents

Executive Summary

This report summarises work on the effects of upland afforestation on water resources, carried out by the Institute of Hydrology in the two Balquhidder catchments between 1981 and 1991. The project has been managed by a consortium of interested bodies, including the Scottish Office Environment Department, Department of the Environment, Natural Environment Research Council, Forestry Commission, Water Research Centre, Scottish Hydro-Electric and Strathclyde and Central Regional Councils.

Objectives of the Research

The initial objectives were:

1. To replicate and extend in Highland Scotland the study begun at Plynlimon in Mid-Wales into the effects of upland afforestation on water resources — the indigenous vegetation, typically coarse grasses and heather, is aerodynamically rougher than the short-cropped grass found in Wales and the distribution and type of precipitation is also different;

2. To develop and improve applied evaporation models for upland areas;

3. To determine the seasonal differences in evaporation rates, including snow conditions, between forest, heather and grass, and the spatial variability of upland meteorological parameters which control evaporation rates;

4. To determine, in typical Scottish Highland conditions of climate, topography and soils, the integrated effects of two different forms of land use:
   a. plantation forest
   b. rough grazing

   on streamflow, sediment and nutrient loadings, thereby determining the effects of afforestation on the quantity and quality of upland water resources.

The Balquhidder catchments

1. The two catchments, Monachyle and Kirkton, are in the Balquhidder Glen, 60 km north of Glasgow. They are similar in orientation, area and altitude range, but differ in their detailed topography, precipitation and land use. Monachyle, the more westerly catchment, is the wetter (it receives some 18% more precipitation than Kirkton). It was initially under heather/grass moorland, but 14% of the Monachyle catchment has now been planted with trees. Kirkton started with a 40% cover of mature forest, with the upper slopes under rough grazing and small areas of heather. Half of the forest cover has now been clearfelled.

2. These catchments were chosen because access is easy, they provide an opportunity to study differences between afforested and non-afforested catchments in Highland Scotland and they receive a high proportion of snow in the winter precipitation.

3. Instrumentation in the catchments comprises networks of precipitation gauges, three stream gauging structures, six automatic weather stations and sites for studying forest interception, upland grass evaporation and snow and soil moisture storage. There are also sites for monitoring water quality (streamwater solutes, invertebrate communities, fish populations and sediments).

Site process studies

1. An upland grass site was instrumented with two lysimeters, soil moisture access tubes and micro-meteorological equipment to record continuously the water use of grass freely supplied with water and to provide estimates of the Penman potential evaporation, E_t. Results have been developed into a seasonal grass water use model. The main conclusions were that the grass becomes dormant in the winter and water use increases from 0.5 of E_t in late spring to E_t in summer, giving an annual grass evaporation of around 0.75 of the E_t value.

2. Results from a forest interception site showed that the mean interception loss from the trees was 28% of the precipitation. The throughfall and stemflow components of the net precipitation were 97% and 3% respectively. A comparison with other studies in the UK suggested that these proportions vary with age, throughfall increasing and stemflow decreasing from around an age of 10 to 15 years.

3. Analysis and intercomparisons of the data from the individual automatic weather stations showed that the Penman potential evaporation

(E_t) values from the high altitude, exposed sites were significantly greater than those from the valley bottom sites. The higher radiation and wind speed values at the high altitude sites were the major factors responsible for increasing the E_t values outweighing the effects of lower temperatures and humidity deficits.

Catchment water use

1. The water balance results showed that mean annual water use (1983-89) from the predominantly heather and grass Monachyle catchment, was 621 mm (22% of the precipitation), higher than the Penman potential evaporation estimate, E_t (551 mm), whilst the mean annual value for the predominantly forest and grass Kirkton catchment, 423 mm (17% of the precipitation), was lower than the E_t estimate (484 mm). Use of simple annual evaporation models suggested that the differences in evaporation measured between the catchments could be explained primarily by (a) the different vegetation types, (b) the higher precipitation in the Monachyle, and (c) the different altitudinal distributions of vegetation types in the two catchments. In the Kirkton, grass (low evaporation) dominates the upper, wetter altitudes with forest (high evaporation) at the lower, drier altitudes. In the Monachyle grass dominates at the lower altitudes with heather (high evaporation) dominating at the upper altitudes. Any changes in the water use resulting from the planting of 14% of the Monachyle and the progressive felling of half of the forest area in the Kirkton are not yet detectable from the annual water balance data.

2. A suite of sophisticated water use models (THISTLE) was developed from process studies carried out at Balquhidder and at other sites in Scotland. Application of these models to the Balquhidder catchments indicated a mean annual water use of the Monachyle (1984-89) of 521 mm, exceeding E_t for the same period (474 mm) but some 16% lower than the water balance estimate (622 mm). For the Kirkton the models estimated the water use as 562 mm, higher than E_t (474 mm), but some 40% higher than the catchment water balance estimate (404 mm). These apparent discrepancies must be viewed against the uncertainties associated with each approach: the possible errors in the measurements of precipitation and streamflow, and any errors in the assumptions incorporated in the models and in the E_t values on which they operate. The estimated error bands for both approaches overlapped in each case, but the differences were in the opposite direction in the two catchments.

Streamflow effects

1. To convert the water use estimates into predictions of streamflow patterns, the THISTLE model parameters were incorporated into a version of the IH Land-use Model. This lumped conceptual model was calibrated on data from the 1985 period, prior to the land-use changes, with the Monachyle volume flows reproduced to within 0.7%, and daily flows with an explained variance of 90%. The model was then used to predict flows from the catchments over the period 1986-89 assuming that no changes had taken place. Comparison of these predicted flows with the observed flows suggested that no significant changes in total flow occurred in the Monachyle catchment in the immediate aftermath of the planting of 14% of it in 1986, but that there was a small increase in flow from the Kirkton as a result of felling some 50% of the forest during the period.

2. Two models developed elsewhere (TOPMODEL and IHACRES) were applied to the catchments to investigate their streamflow response characteristics. Both suggested that the catchments had significantly different responses to precipitation inputs, with the Monachyle being the 'flashier' of the two, but neither model could detect any significant change in response characteristics in the Kirkton immediately after the felling operations. IHACRES detected no change in the Monachyle response after the planting operation, whilst TOPMODEL identified some change in the transmissivity profile but no overall change in the ratio of subsurface to rapid response flow.

Forestry and water resources

The effects of the different land-use evaporative regimes on low flows and catchment yield was investigated by using standard modelling and flow analysis procedures. The IH Land-use Model described above was applied to a simulated 25-year rainfall series to give daily flow sequences for each catchment, each sequence representing the response of a forest cover ranging from 0% to 100%.

2. The simulation runs of the calibrated model indicated that with increasing afforestation in both catchments: (a) the mean flow will decrease, (b) the flow duration curves will shift down, and (c) the annual minimum flows will be reduced.

3. Reservoir storage yield curves computed from the simulated streamflow sequences indicated a decease in yield from each catch-

ment as the forest area, and therefore the evaporation, increases. The size of reservoir needed to sustain a given yield from a catchment increases as the area of mature forest cover increases.

Water quality

1. Stream water chemistry and aquatic biota have been monitored in both catchments throughout the period of land-use change. The results are presented in a separate report: the significant results are

a. The Monachyle stream supports a healthy population of fish and invertebrates, including low numbers of some acid-sensitive species. Chemical studies indicate that the stream is likely to be sensitive to any further acidification. To date there have been no obvious chemical and biological changes following ploughing and planting of the catchment.

b. The Kirkton catchment has a small outcrop of limestone in the headwater region, providing a source of relatively alkaline water. Chemical monitoring in the main stream has shown that no changes have occurred since the start of the clearfelling although monitoring in one clearfelled tributary has indicated a doubling of nitrate concentrations and a significant reduction in chloride levels since clearfelling started. Fish populations have been unaffected below the clearfelling but have declined significantly in an upper reach. This decline is considered to be due to forest debris blocking the narrower upper reach and preventing the movement of fry from elsewhere.

2. Sediment discharge increased in both catchments since 1986 when the land use changed and the annual precipitation increased. Most of the load was in suspension; concentrations in the low flows increased proportionally more than in the high flows. Sediment yields increased to 312% of former levels in the Monachyle and 818% in the Kirkton. The increases resulting solely from the land-use changes were estimated to be 121% for the Monachyle catchment (pre-afforestation ditching) and 595% for the Kirkton (road maintenance and use). The increases in suspended sediment load did not appear to have had any effect on streamwater biology or chemistry.

1 Introduction

The Balquhidder catchments study was established in 1981 by the Institute of Hydrology to study the effects of forestry on water resources in the central Highlands of Scotland. Ten years of research have achieved a number of important results which are of significance to the forestry, hydroelectric and water resources industries as well as to hill farming, nature conservation and the general sustainability of the UK uplands. This report summarises the results from the analysis of the first ten years of the catchment data, from the process studies and from comparison with results from other UK studies. It complements the selection of papers on the Balquhidder study published in the May 1993 Special Issue of the Journal of Hydrology.

The demand on water resources in Britain increased from early in the 19th century as a result of industrial development and rising standards of living. This continued into the 20th century, but in the late 1970s the increase in demand slowed down, mainly because of reduced industrial requirements associated with a national economic recession. Expansion of forestry in Britain had been taking place since the inception of the Forestry Commission in 1919. Much planting was carried out after the First World War to make good the reduction in the timber stocks and to reduce the country's dependence on imported timber, although it was not until after the Second World War that large-scale plantation forestry really expanded in upland Britain.

Arguments can be put forward that afforestation will eventually return the countryside to its natural wooded state (although mainly with exotic species) and that imports of timber must be reduced for the sake of the national economy. Over the past 40 years however, research in British upland catchments has increasingly demonstrated that evaporation rates from conifers are greater than for shorter vegetation types (Calder, 1990; Blackie & Newson, 1986). This results in a reduction of the water resource in a forested catchment. Conifer plantations also affect the quality of the water, with increases in sediment loads (Soutar, 1989), increasing acidification of the surface waters (Hornung *et al.*, 1987) and reductions in fish populations (Harriman *et al.*, 1987) all being observed. The forestry industry is aware of these potential problems and is prepared to compromise in the interest of the water resource. What once looked like a conflict between foresters and water engineers has become a constructive working situation: this is illustrated by the development of jointly produced documents such as the *Forests and Water Guidelines* (Forestry Commission, 1988).

Of paramount importance is the need to maintain a plentiful supply of good, clean water to domestic and industrial consumers. The uplands form the main source of water in Britain and provide high-quality supplies to the major consumers in the lowlands. The impacts of any potential changes in land use in the uplands must be fully understood and evaluated before they are implemented. This is the main purpose of the research at Balquhidder, in the headwater catchments of the River Forth, where afforestation has been widespread and where there are still more demands for future forestry development.

1.1 Development of research into the effects of forests

Much of the early research into the effects of forests concentrated on changes in the annual water yield resulting from deforestation (Bosch & Hewlett, 1982). In Europe and the USA small catchment studies were carried out in a range of climatic conditions. Even though the different precipitation regimes resulted in some large variations between the catchments, there was a consistent pattern of increased annual streamflow after deforestation. At Wagon Wheel Gap in southern Colorado, USA, clearfelling of one catchment resulted in an increased streamflow of 30 mm year^{-1} which is 6% of the precipitation (Bates & Henry, 1928) and at Coweeta in North Carolina, USA, clearfelling increased the mean stormflow and peak flows by some 15% (Swank & Crossley, 1988).

The numerous catchment studies which have been undertaken were considered necessary because of the range of climates, catchment characteristics (geology, soils, topography, etc.) and the range of forest management being applied. Although these catchment studies proved invaluable the results could only be fully interpreted and applied following the addition of further studies to look at the processes taking place within the catchments. This also enabled new forestry techniques to be studied such as the strip harvesting at Hubbard Brook in New Hampshire, USA (Hornbeck, 1975).

In the UK the water gathering grounds were often in remote areas where sheep farming was the traditional land use. These areas were the major source of water for the more densely populated and industrial lowlands. Water supplies were reliable, with high rainfall and streamflows. There were few sources of pollution and reservoir construction was often a feasible way to regulate the supply of water for consumption and hydroelectricity generation.

Early research efforts in the UK into the impacts of plantation forestry concentrated on the changes in runoff from upland catchments. The pioneering work of Frank Law at Stocks Reservoir in Lancashire (Law, 1956) first showed that there was an increased water use by trees compared to grassland. The result was obtained from a lysimeter experiment in the catchment and showed that the conifer forest had an additional evaporation loss of 290 mm per year compared to the grassland. Law estimated this to represent an annual loss in revenue to the water company of some £500 ha^{-1}. This result was sufficiently convincing to initiate further studies into the physical processes of evaporation from vegetation and the assessment of water balances in catchments with different climates, topography and land uses.

In 1966 the Coalburn catchment study was established in northern England where the hydrology of a single catchment was monitored for five years before any pre-planting drainage and afforestation were carried out (Robinson *et al.*, 1993). Results from this study have shown that there was an initial increase in runoff following the drainage. As the trees developed, streamflow decreased, but even after 20 years it remained at or above the pre-planting levels. The drainage also resulted in large initial sediment yields and storm peaks.

In 1968 two catchments on Plynlimon in central Wales were selected for detailed catchment research. One catchment, the Wye, was sheep pasture; the other, the Severn, was 62% covered with forest. Early results from Plynlimon (Calder & Newson, 1979) confirmed those of Law with the water use of the Severn catchment (adjusted to 100% forest cover) being 21% of the rainfall greater than the Wye catchment. Previous studies demonstrated that it is rainfall interception and transpiration by the trees which leads to the increased water use in forested catchments and so to reductions in streamflow.

The Plynlimon study also showed significant differences between the catchments in the stream responses. Flood peaks in the forested catchment were lower than the grassland catchment for small events but similar for the larger events. The baseflows, controlled by catchment geology, did not vary with different surface vegetation cover.

1.2 Forestry in Scotland and the need for research catchments

Recently published figures illustrate the relative positions of forestry and water resources in Scotland: of the 915,000 ha of land in Britain which is afforested, 60% is in Scotland (Forestry Commission, 1989), while in the Strathclyde Region alone there are 75 (52%) water supply catchments containing some forestry (Greene & Taylor, 1989).

Opinion in Scotland up until the 1970s was that water was in plentiful supply, with higher precipitation and lower evaporation than in England and Wales. However, as Calder & Newson (1980) pointed out, an increase in evaporation because of afforestation would result in a greater volumetric loss of water from Scottish supply catchments. The water suppliers and hydroelectricity generators were concerned not only about the annual water balance but also about seasonal effects, especially in years of summer drought. Clarke & Newson (1978) illustrated this using hypothetical reservoir storage and streamflows, simulating the effects of afforestation, to indicate the possible effects of an extreme (1000-year) drought on reservoir water levels if land-use changes were not considered in the management of the resource.

The concern in the late 1970s was about how to continue expanding the forestry industry in Scotland without detriment to water resources, and whether the water balance results from the Plynlimon research catchments in mid-Wales could be applied to Scotland. To answer these questions it was decided that a major research study was required in Scotland with the following objectives:

1. To replicate and extend the Plynlimon study on the effects of upland afforestation on water resources into Highland Scotland where the indigenous vegetation, typically coarse grasses and heather, is aerodynamically rougher than the short cropped grass found in Wales and the distribution and type of precipitation is also different;

2. To develop and improve applied evaporation models for upland areas;

3. To determine the seasonal differences in evaporation rates, including snow conditions,

between forest, heather and grass, and the spatial variability of upland meteorological parameters which control evaporation rates;

4. To determine, in typical Scottish Highland conditions of climate, topography and soils, the integrated effects of two different forms of land use — (a) plantation forest, and (b) rough grazing — on streamflow, sediment and nutrient loadings, thereby determining the effects of afforestation on the quantity and quality of upland water resources.

Two catchments at Balquhidder in Central Scotland were selected which had physical similarities but supported different land uses: one was a moorland catchment, the other was partially (42%) forested. With the cooperation of the private landowners, as well as the agreement of the Forestry Commission to delay any planting and clearfelling for five years, and the backing of a funding consortium (Blackie, 1987), fieldwork began in 1981.

2 The Balquhidder catchments, instrument networks and data base

2.1 The physical characteristics of the Balquhidder catchments

The Balquhidder catchments, Kirkton and Monachyle, lie 60 km north of Glasgow in the Grampian Mountain range, also referred to as the southern or central Highlands of Scotland (Johnson & Law, 1992). The two catchments (see Figure 1) are on the north side of the main Balquhidder glen (OS Grid Reference NN5020), a deeply glaciated valley which contains the two lochs, Voil and Doine. A small catchment, Glen Crotha, separates the Kirkton and Monachyle catchments by 2 km.

The catchments are south facing, with an area of 6.85 km² for the Kirkton and 7.70 km² for the Monachyle (Table 1). The Upper Monachyle, a sub-catchment in the Monachyle, has an area of 2.24 km² and forms a northern lobe of the main catchment. The altitude of the catchment outfalls is 242 m (Kirkton) and 292 m (Monachyle); the maximum altitude is 852 m and 906 m respectively. The Kirkton has the greater proportion of higher altitude land, with a median altitude of 540 m; the Monachyle's median altitude is 470 m. The Kirkton is also the steeper

Table 1 *Catchment dimensions*

	Monachyle	Kirkton
Length, km	3.71	3.32
Width, km	2.82	2.72
Orientation, degrees	006	343
Area, km² - plan	7.70	6.85
surface	8.08	7.34
Altitude, m - median	470	540
maximum	906	852
minimum	292	242
Mean slope, degrees	15.8	19.9
Drainage density, km km⁻²	3.8	5.1

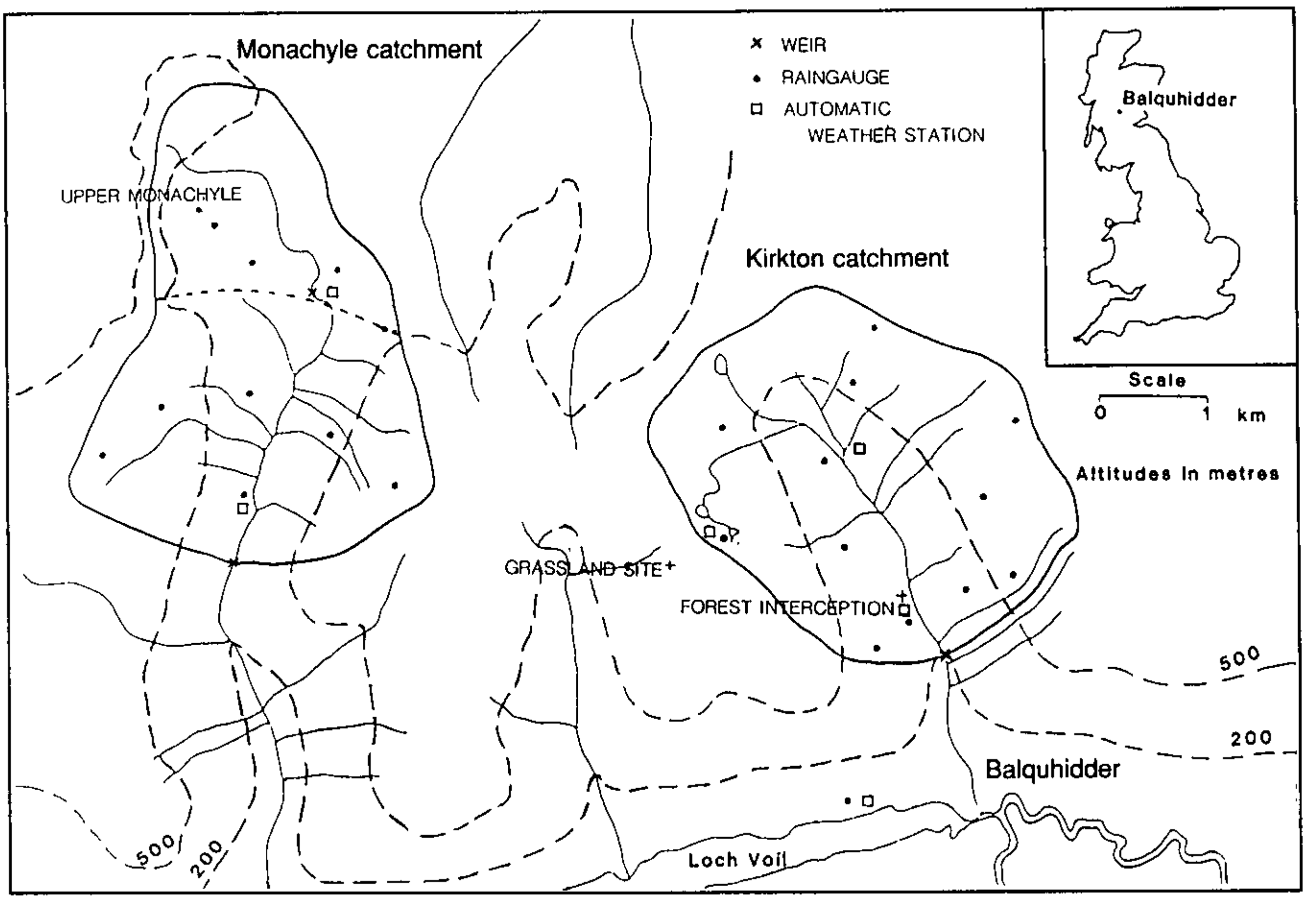


Figure 1 *The Monachyle and Kirkton catchments showing the main instrument networks*

total area of new drainage was 45 ha, or 6% of the total catchment area. Drainage lines, 20 to 30 cm deep, were perpendicular to the contours; shallow-gradient cut-off drains, 60 cm deep, were dug where necessary.

The subsequent planting covered an area of 111 ha, or 14% of the total catchment area.

2.2 Catchment instrumentation and networks

The main instrument sites are shown on the catchment map, Figure 1.

The measurement of precipitation has been discussed in detail in previously published reports and papers (Johnson, 1989; Johnson *et al.*, 1990) so only a brief description is given here. The main type of raingauge used is the ground-level gauge, installed with its rim parallel to the slope. For snowfall, standard gauges, with corrections for gauge exposure, tall snow gauges and snow surveys are used depending on the amount of snow accumulation.

The gauge networks were designed using a domain principle, where domains are determined by homogeneity of altitude, aspect and slope. Twelve gauge sites in each catchment are used. Time distribution of the monthly-read totals is achieved using the gauges at the automatic weather station sites and from a daily read standard gauge at Tulloch Farm. Catchment mean values have been calculated by the arithmetic mean of the 12 gauges, weighting the gauge catches by the area of the domain and by constructing isohyets and weighting the mean rainfall between isohyets by the area between the isohyets. Little difference was found between these three methods as illustrated in Johnson *et al.* (1990) where rainfall, calculated for the Kirkton catchment in 1986, showed a difference of less than 2% for monthly values and 1% for the annual values.

Streamflow is measured at three places in the catchments: at the outfalls from the Kirkton and Monachyle catchments and from the Upper Monachyle sub-catchment. Crump weirs are used at the main catchment sites with a flat V-weir at the Upper Monachyle (Johnson & Hudson, 1987). The use of Crump weirs in these mountain streams is taking these structures beyond their design limits for stream steepness, uniformity of flow and minimum measurable stage (British Standards Institution, 1969) and it was necessary to determine empirical rating curves using current meters (Hudson *et al.*, 1990). The siting of the Upper Monachyle weir in more suitable conditions, i.e. a straight, low gradient reach, precluded the need for independent calibration.

To cope with the harsh working environments, the stage measurements, obtained using float sensing systems, are backed up by pressure transducers for icing conditions, while secondary loggers safeguard the loss of data through battery failure. Water levels are sensed at ten-second intervals, converted to flow rates and integrated to give the flow volume in each quarter of an hour.

Six Didcot automatic weather stations (AWS) (Strangeways, 1976) have been used in the catchments, two at high altitudes, three at low altitudes and one outside both catchments at a very low altitude (Johnson & Simpson, 1991). Their locations were determined by altitude, vegetation and exposure. Seven parameters are monitored: radiation (solar and net), temperature (dry and wet bulb), wind (speed and direction) and rainfall. From these measurements, estimates of the potential evaporation (E_t) are derived (Penman, 1948).

The storage of water and snow in the catchments is very difficult to determine. Soil moisture is measured at four key locations in the catchments using a neutron probe (Bell & McCulloch, 1969). The sites are on the main soil and vegetation types and comprise a total of 24 access tubes down to depths of 2 m. Snow storage is estimated manually by daily observations of the snow line supplemented by depth and density readings when and where possible. Groundwater storage is not measured but can be estimated using within year water balances.

2.3 Catchment database

The data collected from the instrument networks has been organised into databases so that quality control procedures and accessing can easily be carried out. Data collection from the various networks started at different times but 1983 is the first year with complete flow and rainfall data. Table 3 lists the long-term and short-term networks from which data are available. Many discussions of data collection and quality control procedures have been published: where applicable the references are listed.

The main components of the Balquhidder database are the precipitation and streamflow records. These are presented in Table 4 as monthly totals for the two main catchments and also for the Upper Monachyle sub-catchment.

Table 3 *Components of the Balquhidder catchment database*

Component	Number of sites	Relevant reference
Long-term data base:		
Precipitation	25	Johnson *et al*, 1989 Johnson, 1989 Johnson *et al*, 1990
Streamflow	3	Roberts, 1989 Johnson & Hudson, 1987 Hudson *et al*, 1990
Automatic weather stations	6	Roberts, 1989 Johnson & Simpson, 1991
Manual weather station	1	
Snow	Regional	
Soil moisture	4	
Suspended sediment	2	Johnson, 1988
Bedload	2	
Streamwater solutes	8	Harriman & Miller, 1994
Precipitation quality	1	Devenish, 1986
Freshwater biology	5	Harriman & Miller, 1994
Short-term data from site studies:		
Forest interception	1	Johnson, 1990
Grassland water use	1	Wright, 1990
Nutrient cycling	3	Harriman & Miller, 1994
Sediment sources	Many	Stott, 1987
Bedload movement	Many	Drew, 1991

Table 4 *Monthly totals of precipitation (P) and streamflow (Q) for the Monachyle, Upper Monachyle and Kirkton catchments*

		Monachyle		Upper Monachyle		Kirkton	
		P	*Q*	*P*	*Q*	*P*	*Q*
1983	J	522.6	437.4	556.0	*****	433.2	333.7
	F	89.2	38.9	132.7	*****	87.3	63.5
	M	247.1	259.8	294.5	*****	209.0	191.3
	A	76.4	59.7	74.0	*****	96.9	71.8
	M	172.2	113.8	168.5	*****	137.5	96.5
	J	94.7	56.4	91.9	*****	83.8	60.1
	J	32.8	6.5	29.8	*****	40.6	19.5
	A	46.9	4.1	43.2	*****	45.1	12.0
	S	332.1	172.1	322.2	*****	291.3	143.7
	O	524.8	430.9	525.9	*****	416.7	354.2
	N	108.5	85.9	104.7	*****	95.8	83.7
	D	412.2	362.8	491.4	*****	343.4	291.5
Total		2659.5	2028.3	2834.8	*****	2280.6	1721.5

Table 4 *Continued*

		Monachyle		Upper Monachyle		Kirkton	
		P	*Q*	*P*	*Q*	*P*	*Q*
1984	J	416.3	204.7	412.3	*****	357.7	191.2
	F	193.3	215.9	191.6	*****	166.0	161.5
	M	169.7	126.5	168.1	*****	161.1	149.4
	A	109.1	156.9	105.5	*****	78.5	171.6
	M	26.5	16.2	26.1	10.3	25.0	34.6
	J	90.8	17.2	91.3	18.4	77.0	24.6
	J	65.6	12.7	66.4	16.4	58.0	18.5
	A	76.0	7.3	77.8	6.6	63.6	15.4
	S	258.6	149.0	253.4	145.6	220.9	100.2
	O	384.0	327.9	370.3	325.2	325.5	271.2
	N	506.1	403.9	514.7	*****	416.3	378.5
	D	352.2	290.7	354.4	*****	265.5	264.2
Total		2648.2	1928.9	2631.9	*****	2215.1	1780.9
1985	J	94.8	74.1	93.8	*****	81.5	69.8
	F	91.2	110.4	90.4	*****	78.4	118.3
	M	125.5	82.5	124.2	*****	107.2	83.8
	A	187.7	135.5	187.1	153.1	166.9	154.4
	M	122.1	82.5	130.2	89.1	112.4	84.9
	J	87.2	27.0	79.2	25.6	86.6	48.8
	J	271.2	181.1	268.1	198.1	261.7	175.8
	A	447.8	343.8	432.6	351.0	374.0	300.0
	S	303.0	231.7	303.4	229.4	272.2	211.2
	O	222.9	230.9	224.8	235.4	182.5	249.9
	N	237.2	135.7	234.9	139.7	202.0	105.5
	D	421.1	420.3	416.9	441.3	359.9	357.3
Total		2611.7	2055.5	2585.6	*****	2285.3	1959.7
1986	J	383.7	278.9	380.0	*****	326.7	216.9
	F	21.7	18.6	21.7	*****	18.9	37.0
	M	397.8	374.3	393.8	*****	338.2	300.2
	A	117.2	86.1	113.6	78.4	109.2	100.1
	M	441.1	389.1	427.3	365.2	378.2	331.2
	J	87.9	49.6	89.2	45.1	88.9	76.1
	J	116.5	37.8	111.0	30.9	109.9	50.5
	A	184.4	137.6	186.3	139.2	182.2	139.1
	S	69.3	25.7	72.6	25.7	51.4	26.4
	O	350.1	243.1	347.3	230.5	281.8	163.9
	N	535.8	450.7	556.7	454.6	414.5	389.0
	D	574.9	430.4	569.6	445.1	489.5	411.2
Total		3280.4	2521.9	3269.1	*****	2789.4	2241.6

..continued..

Table 4 Continued

		Monachyle		Upper Monachyle		Kirkton	
		P	*Q*	*P*	*Q*	*P*	*Q*
1987	J	104.3	138.4	103.3	144.1	88.6	142.9
	F	140.6	124.8	139.2	104.3	120.1	116.5
	M	212.4	178.2	210.5	185.1	181.5	160.7
	A	82.8	87.0	87.8	73.5	78.3	105.7
	M	86.1	27.2	83.8	25.5	83.9	42.3
	J	139.0	87.3	131.9	88.2	148.9	98.8
	J	113.5	62.4	111.7	59.0	98.9	61.1
	A	163.6	90.3	164.0	83.3	164.2	95.2
	S	341.8	263.5	348.7	270.4	250.0	215.4
	O	318.8	256.3	326.2	269.4	250.9	220.1
	N	196.7	172.5	199.6	183.5	149.9	143.6
	D	355.9	236.4	353.6	271.2	283.9	188.3
Total		2255.5	1724.3	2260.3	1757.5	1899.1	1591.6
1988	J	394.5	289.9	389.3	322.4	310.0	249.5
	F	248.9	273.8	246.5	304.1	223.1	223.5
	M	312.5	252.4	309.5	264.9	242.5	208.6
	A	104.5	113.2	101.5	82.0	100.9	128.3
	M	105.1	58.5	98.0	54.4	96.2	54.7
	J	30.5	19.7	28.2	12.3	35.8	37.2
	J	404.6	246.8	403.9	250.6	337.1	210.6
	A	302.1	216.9	301.4	212.0	256.4	183.4
	S	250.6	229.6	251.4	212.4	224.9	210.3
	O	390.6	328.5	389.2	321.2	309.5	308.0
	N	152.2	117.0	152.9	111.0	133.8	110.3
	D	256.2	242.2	257.7	228.5	222.6	201.4
Total		2952.3	2388.6	2929.5	2375.8	2492.8	2125.8
1989	J	506.9	450.2	502.3	470.3	432.6	359.7
	F	475.9	360.1	471.5	369.3	406.2	318.0
	M	419.2	432.0	414.8	483.6	368.8	356.6
	A	89.4	75.1	88.5	71.1	76.1	102.2
	M	66.2	46.2	67.4	33.9	62.5	47.9
	J	117.2	48.1	115.3	45.7	107.0	55.5
	J	77.9	23.9	77.9	20.8	77.4	36.4
	A	369.3	235.7	376.2	234.8	297.4	190.6
	S	228.5	198.2	261.6	214.7	160.9	144.3
	O	349.6	252.9	352.8	250.3	284.5	219.3
	N	120.4	134.8	122.6	137.2	92.9	135.0
	D	164.2	139.8	177.6	152.8	152.4	132.5
Total		2984.7	2397.0	3028.5	2484.5	2518.7	2098.0

2.4 Precipitation variations in the Balquhidder catchments

The precipitation time series for the Kirkton catchment is shown in Figure 3. The most prominent features of Figure 3 are the relatively dry summer of 1984 and the wet winter of 1988-89 with the six-month moving average suggesting an increase in rainfall over the period. From the daily data in the 1983-89 period, precipitation greater than 0.5 mm was recorded on 62% of the days, with 20% of the days having more than 10 mm.

To study the rainfall distributions over the catchments, regression analyses have been carried out relating rainfall to site details: longitude, latitude, altitude, slope and aspect. Data from periods when only rain fell have been used to avoid the uncertainties in snow periods. Linear regressions have been obtained for both catchments separately and combined, taking the annual mean rainfall at each site from eight years of data.

When the catchments are analysed separately the most important individual site parameter, from the coefficient of determination, is the altitude in the Kirkton and aspect in the Monachyle. With the two catchments combined, longitude becomes the most important, i.e. a more regional variation in rainfall. The Balquhidder catchments are situated in a very steep, but non-linear, west-east gradient of precipitation, so regional position would be expected to dominate rainfall totals.
When multiple regressions are carried out, more of the rainfall distribution is explained. The three topographic factors, altitude, slope and aspect, combine well for the separate catchments but not when they are considered together. Combinations of the three best individual parameters, longitude, latitude and altitude give good results for both the individual and combined catchments (Equation 1).

$$\text{Rain (M+K)} = 477 - 0.062\ \text{Lo} - 0.005\ \text{La} + 0.066\ \text{Al} \qquad (1)$$

Where Rain is the mean monthly rainfall; M+K the combined data from both catchments; Lo is the longitude of the site; La is the latitude and Al the altitude.

2.5 Streamflow in the Balquhidder catchments

The time series of monthly flow totals for the Kirkton catchment (Figure 4) again suggest an upward trend over the period of study. The

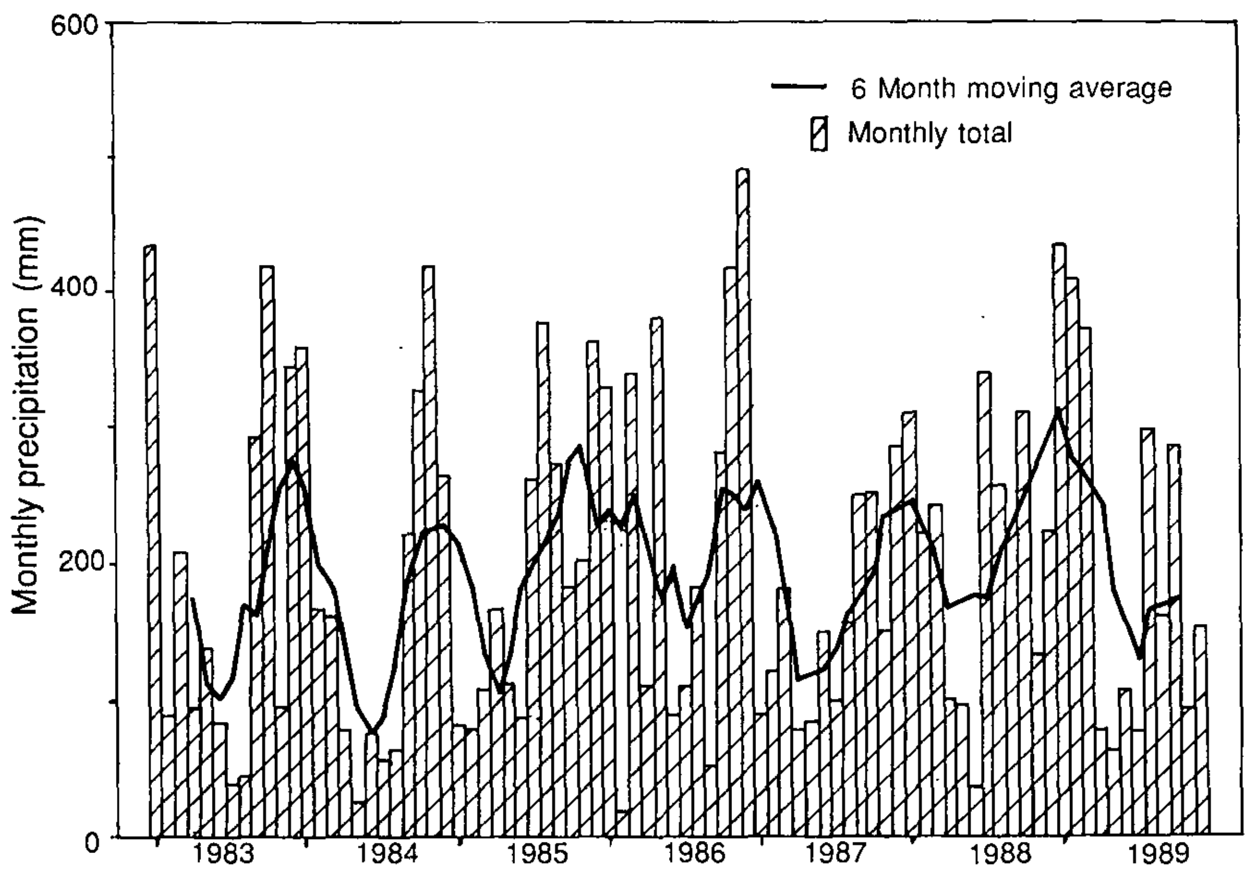


Figure 3 *Kirkton catchment monthly precipitation totals, 1983-89*

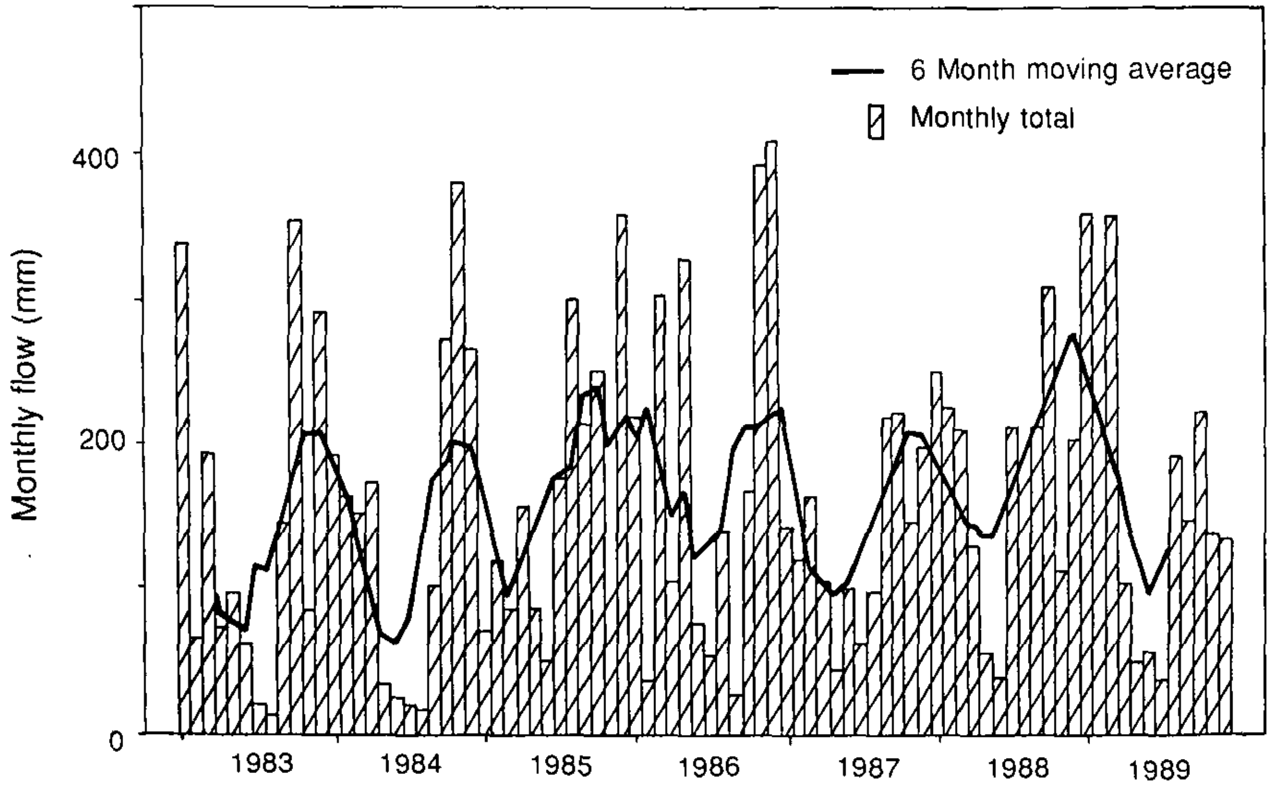


Figure 4 *Kirkton catchment monthly flow totals, 1983-89*

comparison of the daily flows in both catchments is shown in Figure 5. A least-squares regression analysis shows the relationship between the catchments to be:

$$\log(K\text{ flow}) = 0.253 + 0.681 \log(M\text{ flow}) \quad (2)$$

Coefficient of determination = 0.912
(K=Kirkton catchment; M=Monachyle catchment)

The prominent feature of the comparison is the difference between the regression line and the 1:1 line. Low flows are greater in the Kirkton than in the Monachyle; high flows are greater in the Monachyle. The crossover value, when both catchments are equal in flow, is 6.21 mm day^{-1}, which is slightly greater than the mean flow values of 5.18 mm day^{-1} (Kirkton) and 5.75 mm day^{-1} (Monachyle).

Comparing the flood peaks in the Kirkton with the two Monachyle weirs (Figure 6) shows that the Monachyle catchment is more flashy than the Kirkton catchment. The relationship is, however, not linear, with the higher peaks tending to become more equal. The pronounced flashiness of the Upper Monachyle, probably a result of the extensive peat cover in this part of the catchment and the small size of the catchment appear to control the magnitude of the peaks recorded at the Monachyle outfall.

2.6 Errors in precipitation and streamflow measurements

Errors in precipitation and streamflow measurements in upland research catchments are inevitable. Systematic errors can be reduced to a minimum by good experimental design but significant random errors can be expected in these rugged catchments. Point rainfall measurement has been widely studied in many different environments around the world and the ground-level gauge is now the WMO-recommended gauge for use in exposed conditions (Sevruk & Hamon, 1984). The correct siting of these gauges within homogeneous domains can provide good estimates of the rainfall input to upland catchments (Johnson *et al.*, 1989). However, as the absolute rainfall totals are unknown, it makes the estimation of measurement errors very difficult. Considering the type of gauge used, the extensive network assessments which have been carried out and previous reports on rainfall measurement (Sevruk, 1989), a systematic error of 1-2% is considered reasonable for the rainfall estimation.

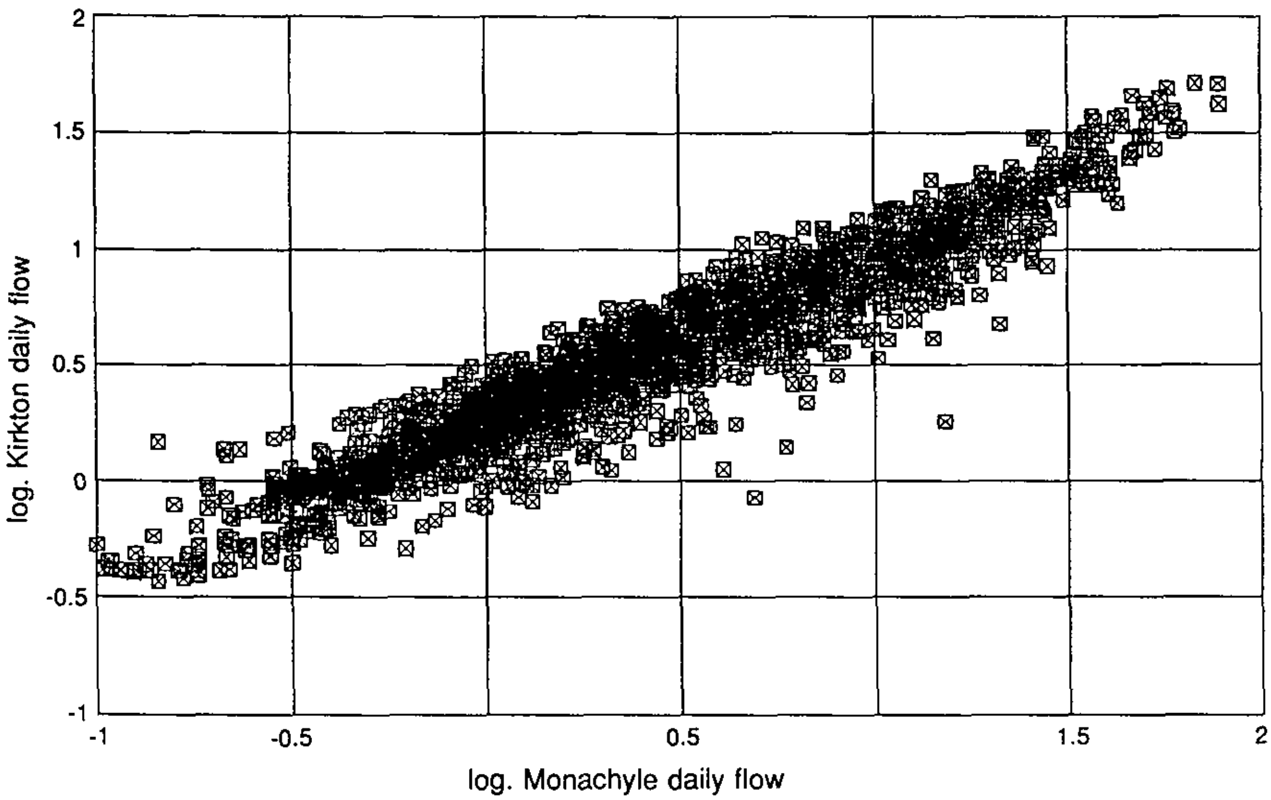


Figure 5 *Comparison of the daily flows between the Kirkton and Monachyle catchments, 1983-89*

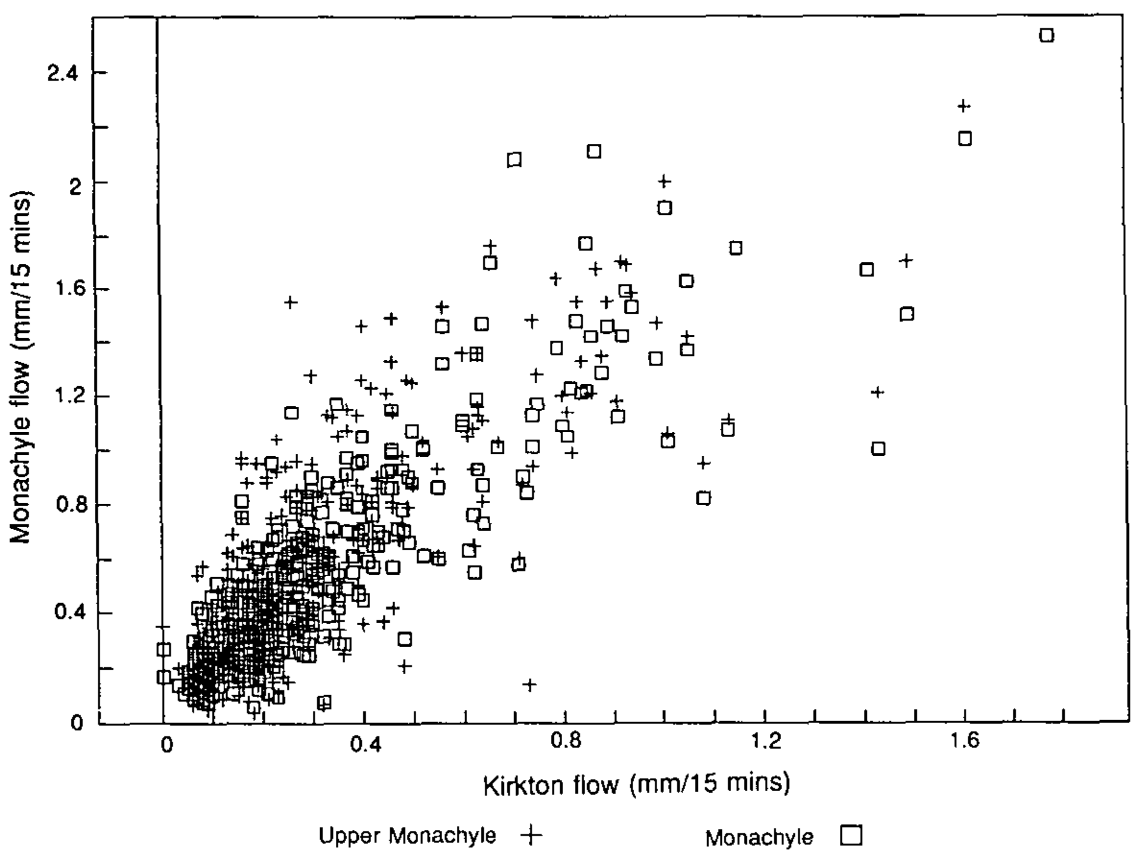


Figure 6 *Comparison of the 15-minute flow maxima between the Monachyle, Upper Monachyle and Kirkton, 1983-89*

Table 5 *Estimated errors in the catchment water balance*

		Estimate 1	Estimate 2
Monachyle	Precipitation (P)	59 mm	142 mm
	Streamflow (Q)	43 mm	86 mm
	(P-Q)	73 mm	166 mm
Kirkton	Precipitation (P)	49 mm	120 mm
	Streamflow (Q)	39 mm	78 mm
	(P-Q)	63 mm	143 mm

Random errors in rainfall measurement, mainly caused by observer error, are more difficult to quantify but through rigorous quality control on the data any gross errors can be eliminated. Smaller errors can not be distinguished from natural variability but are considered to be less than 5% of the true value for a single gauge. Once bulked into a catchment mean this random error is reduced to less than 1% of the mean of 12 gauges. Therefore the combined error (systematic plus random) for rainfall is estimated to be 2%.

Errors in the measurement of snowfall are more difficult to quantify. Snowfall generally only affects precipitation totals between January and March with the higher altitude gauges affected much more frequently than those in the valley bottoms. For 'partial' snow events the high altitude gauges are corrected using relationships with low altitude gauges established in rainfall conditions. Whether this applies to snowfall is debatable however this is currently the best technique available. Using this technique the error in the measurement of snowfall input to the Balquhidder catchments is estimated to be at best the same as that in rainfall (2%) and at worst no more than 20% from the true value. Considering the consistency of the winter water balance results with results from other seasons the estimation of the snow inputs appears to have been accomplished with a

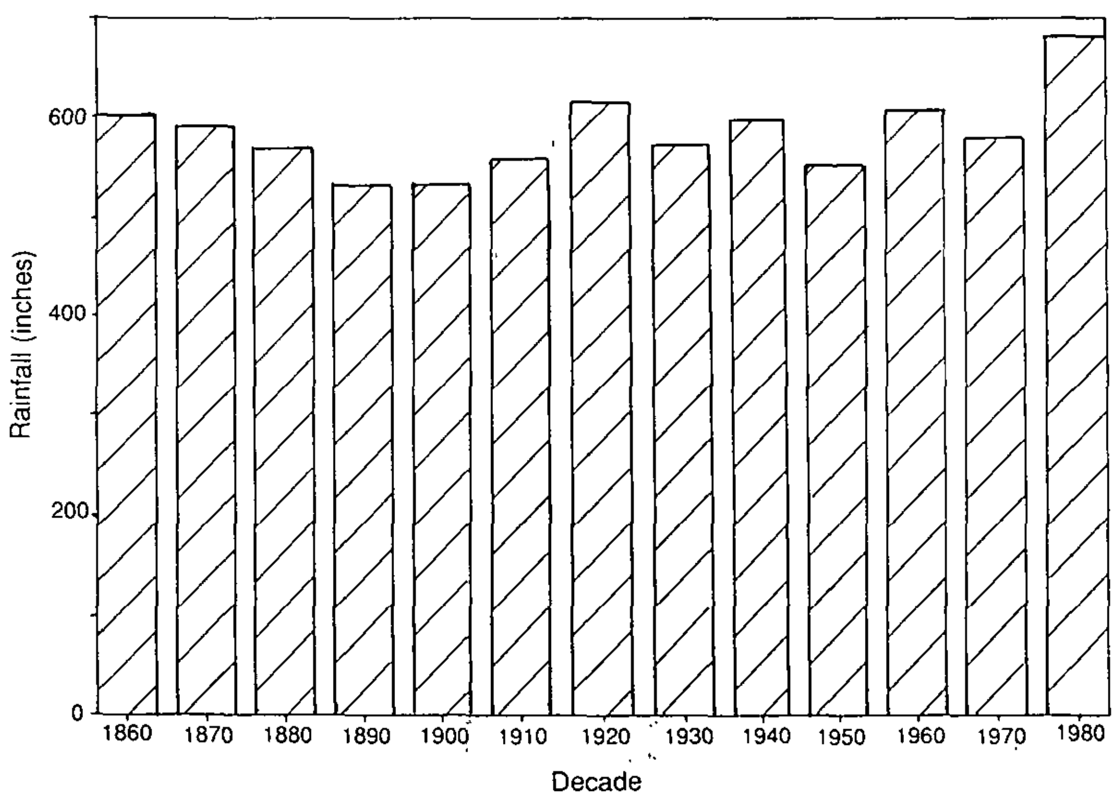


Figure 7 *Total decade precipitation from Loch Venachar, Central Scotland*

similar error factor as in rainfall. Therefore a 20% error in snow is a very pessimistic error.

By considering the proportions of annual precipitation which fall as rain and as snow, an estimate of the error in the annual totals can be made. Combining these errors gives an estimate of the annual precipitation error for each catchment, Table 5. It should be noted however that the methods of checking and correcting catchment mean precipitation inputs adopted in these catchment (Johnson *et al.*, 1990) make it extremely unlikely that the errors in the annual totals have ever approached the extreme of this range.

Errors in streamflow are potentially more systematic than random. Serious systematic errors in the rating equations were identified and corrected early in the experiment (Hudson *et al.*, 1990). Other systematic errors due to instrument sensitivity can be quantified as, say, 1 mm in stage values. Random errors in the form of bed level fluctuations remain unknown quantities, but other problems such as winter icing can be eliminated in the data quality control process. Percentage errors in annual discharge totals are difficult to quantify. Considering all the possibilities, an estimate of 2% is probably reasonable.

By combining the errors for the annual catchment precipitation and streamflow, two estimates, have been derived for the (P-Q) values (see Table 5).

2.7 1983-1989 Precipitation in an historical perspective

Annual precipitation data have been extracted from the Meteorological Office British Rainfall records for the Loch Venachar station some 16 km south of Balquhidder. The data set is shown in Figure 7 as total precipitation in each decade. The 1980s stand out as a decade of very high precipitation.

Of the 129 years of records from 1861 to 1989, the wettest year was 1928, with 2076 mm. Three of the years during the Balquhidder study rank in the top ten wettest years: 1989 (5th), 1986 (7th) and 1988 (8th). Taking groups of consecutive three-year periods, the wettest was 1881-83 with 5529 mm. Four of the Balquhidder study periods were ranked in the top ten: 1987-89 (2nd), 1986-88 (3rd), 1984-86 (4th) and 1985-87 (6th).

This shows that the Balquhidder study period, 1983-89, has been an exceptionally wet period.

3 Site studies of interception and transpiration rates

The understanding of a complex hydrological system such as an upland catchment can only be achieved by detailed studies of the processes taking place within the system. Potential evaporation, which can be computed from meteorological data using the Penman (1948) expression, is controlled both by the available energy and by the advection of dry and warm air over the evaporating surface.

Potential evaporation has a large spatial variability in complex topographical catchments such as the Monachyle and Kirkton. Analysis of the data from the AWS sites (Blackie & Simpson, 1993) has shown that potential evaporation is significantly greater at the high altitude, exposed sites than at the lower valley bottom sites. As surface water bodies in the Balquhidder catchments are very small, most of the catchment evaporation is from the vegetation. Actual evaporation from the vegetation occurs as transpiration when soil moisture is freely available to the root system or as direct evaporation of water intercepted on the leaf canopy. The processes taking place for each vegetation type must therefore be fully understood so that the catchment scale water balance results can be interpreted and models developed to predict land-use effects on water resources elsewhere.

The three main vegetation types in the catchments are heather, forest and grass. These are coarse vegetation types, common to most Scottish Highland catchments. Heather evaporation experiments were carried out by the Institute of Hydrology near Killin, 8 km northeast of Balquhidder, and the results have been reported elsewhere (Calder *et al.*, 1984; Hall, 1985). Both interception and transpiration rates were studied: since the results were considered to be applicable to the Balquhidder catchments, no further heather studies were carried out in the catchments. Several forest evaporation studies have been carried out in other UK upland forests: Calder (1976), Gash *et al.* (1980), Anderson & Pyatt (1986), Hudson, (1988), Anderson *et al.* (1990) and Calder (1990). Because of the perceived importance of forest evaporation to the overall Balquhidder study a further study was undertaken in the Kirkton forest, where the interception losses were measured over a three-year period. The remaining vegetation type is upland grass for which no other comprehensive data exist. A detailed study of grass was carried out as, in terms of areal cover, it is one of the dominant vegetation types.

3.1 The seasonal water use of upland grass

Upland grass has been identified in the past as having a significantly different water use from lowland grass (Calder & Newson, 1979). In the uplands, the grasses have a winter dormant period because of the low air temperatures when transpiration effectively ceases. Grasses in the lowlands usually suffer from water stress in the summer due to the high evaporation demand relative to rainfall. Therefore during the winter lowland grass water use could be expected to be proportionally higher than that of upland grass and with reversal during the summer. This pattern is complicated by frequent winter snow cover in upland catchments which further reduces transpiration and by summer water stress in those upland areas where very thin soils limit moisture storage.

To study the seasonal water use of upland grass at Balquhidder a pair of lysimeters were installed at a site in Glen Crotha, between the Monachyle and Kirkton catchments (Figure 1), and operated between 1987 and 1989 (Wright & Harding, 1993). The site was on a small level terrace at an altitude of 595 m. The soil was mainly peat, having a depth of 200-1300 mm, and the predominant vegetation was perennial grasses (*Festuca ovina* and *Nardus stricta*) and marsh plants (*Carex* and *Juncus*) with patches of heather (*Calluna vulgaris*) and bilberry (*Vaccinium myrtillus*).

The main instrumentation comprised two monolith weighing lysimeters and an automatic weather station (Wright, 1990). The lysimeters were 800 mm in diameter and 650 mm deep with an automatic pump system to maintain the water status within the soil samples to that of the surrounding soils. The weight of the soil samples was monitored continuously using a load cell to give storage changes; the other water balance variables were monitored using a raingauge for the input and tipping buckets to monitor the pumped output.

Table 6 *Evaporation totals (mm) for the two lysimeters during the snow-free periods 1988 and 1989*

Period	*23 March - 21 September 1988*	*18 April - 18 October 1989*
No. of days	188	183
Lysimeter A	330	354
Lysimeter B	308	352
E_t	397	375

Daily and seasonal evaporation rates from the lysimeters were calculated from rainfall, drainage and weight changes of the soil blocks. Measurements were taken only from April to November as the system was unable to cope with snowfall or prolonged sub-zero temperatures. Potential evaporation, E_t (Penman, 1948), was calculated from an AWS on site and the biomass composition was sampled throughout the two seasons.

The totals of evaporation for the two seasons of operation are shown in Table 6 as well as the E_t values for the same periods. The results show that measured evaporation totals were lower than the E_t values for both periods, being 80% and 94% of E_t in 1988 and 1989 respectively.

A biomass index, expressed as the ratio of the live vegetation weight to the total biomass weight, was estimated at approximately monthly intervals each time taking 30 random samples of 0.25 m^2. A sinusoidal curve was fitted through the points (Figure 8). Figure 9 shows the mean measured evaporation, E_m, expressed as a ratio of E_t. The ratio is around unity in summer but falls to around 0.5 in the winter; the mean annual ratio is estimated to be 0.75. The biomass index and the evaporation ratios show a clear link for the April to September period.

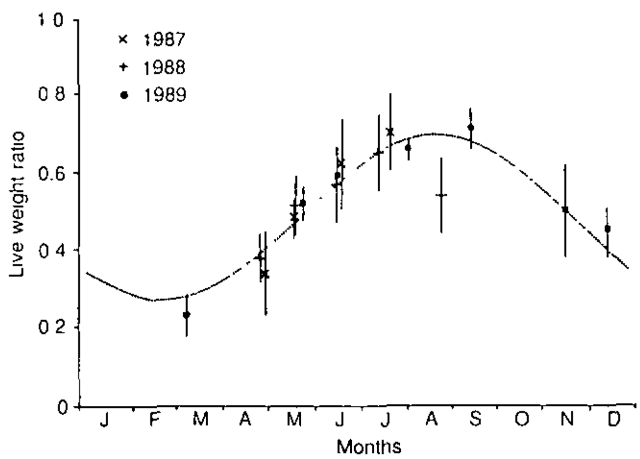


Figure 8 *Biomass index for upland grass in the Balquhidder catchments*

The main use of these results is in the development of a grass component of a seasonal water-use model which can be applied to other sites to estimate the likely effect of land-use change on

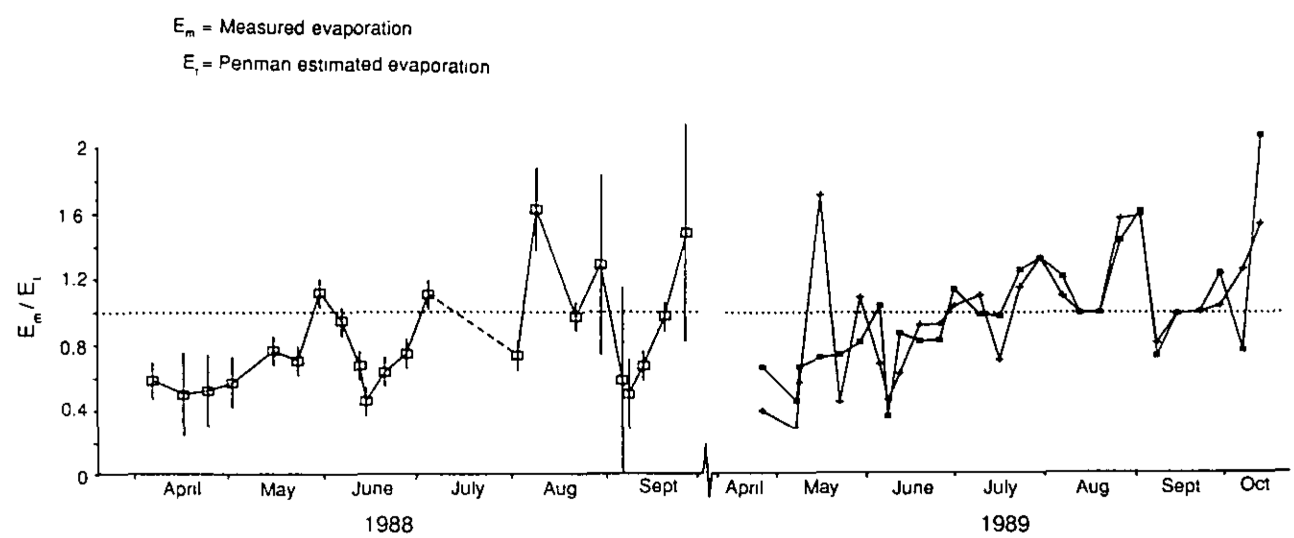


Figure 9 *Evaporation results from the grass lysimeters for 1988 and 1989*

catchment water use. The model is based on physical principles of evaporation and plant physiology and uses inputs of daily rainfall, temperature and E_t. Three versions of the grass model were tested (Wright & Harding, 1993). In the first — the Penman model — water use is equated to E_t where E_t is calculated using the Penman (1948) equation with the addition of the net radiation term. In the second, evaporation is related to the biomass index. The third adjusts the evaporation using temperature as the control.

The simple Penman model overestimates the evaporation particularly in the early part of the year but the use of a sinusoidal crop factor with a single optimised parameter increased the explained variance but still overestimated the losses by 5.8%. The temperature model was developed in several forms from the unoptimised use of air temperature to the two-parameter optimisation of near surface temperature. The unoptimised temperature function, when used with air temperature, produces a poor fit, overestimating the total losses but the fit improves when optimisation is carried out using near-surface temperature.

Optimisation was carried out on the 1989 data and, using the same parameter values, the 1988 evaporation was predicted. The modelled values were within 0.03% of the observed (Figure 10) which indicates the success of the model and the potential for applying it to other years.

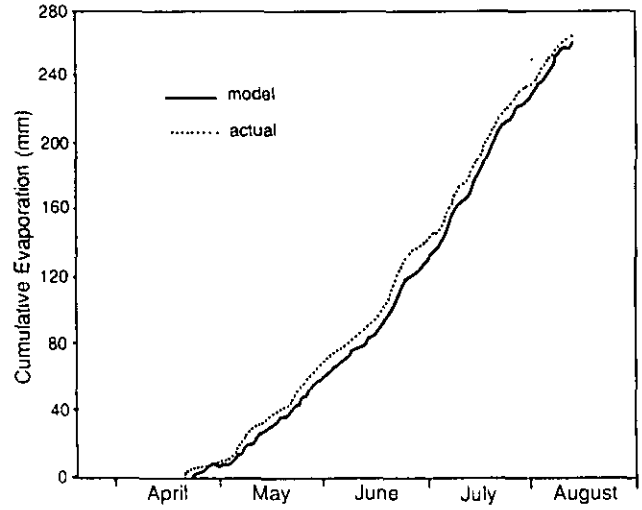


Figure 10 *Comparison of the actual and modelled evaporation from the grass lysimeters during 1988*

3.2 Forest interception

A forest interception site was operated in the Kirkton catchment from October 1983 to June 1986 (Johnson, 1990). The location of this site (Figure 1) was in the lower part of the forest area, close to an established raingauge site. Precipitation, throughfall and stemflow measurements were taken at approximately two-week

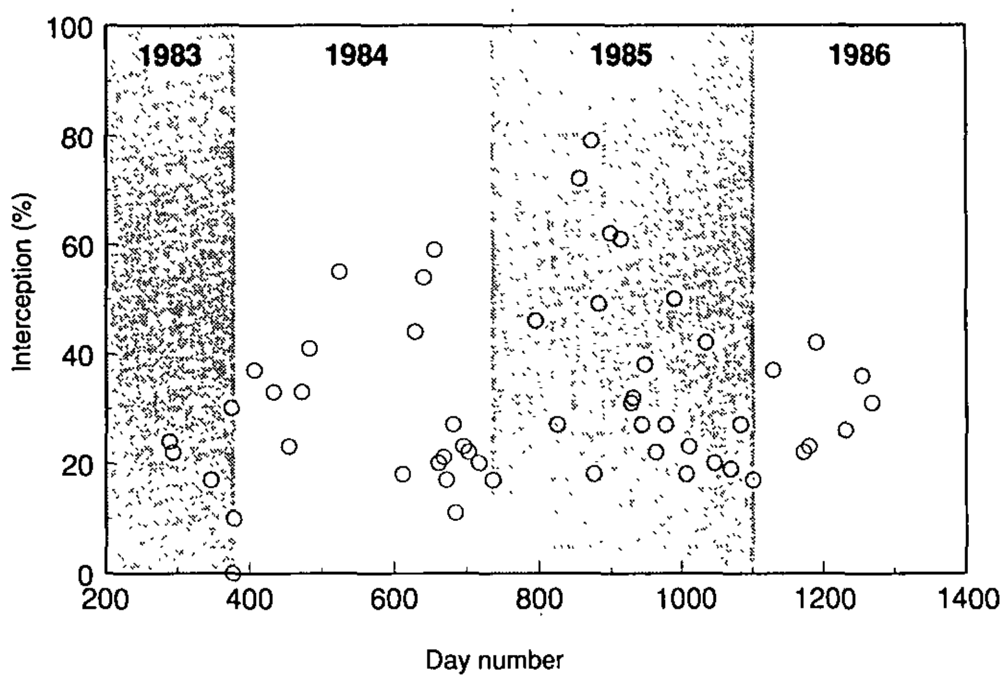


Figure 11 *Interception loss from the Kirkton forest, 1983-86*

intervals for the 33-month period. Throughfall was measured in a 30×30 m square using 60 randomly-placed collectors and stemflow was measured on nine tree stems systematically selected by girth.

The difference between the precipitation and the sum of the throughfall and stemflow is assumed to be a measure of the interception loss from the forest canopy. The nominal two-weekly totals of interception loss are shown in a time series in Figure 11. The large variability has no obvious seasonal trend although the summer mean values are greater (34%) than the winter values (26%). Table 7, summarising the results, shows that over the whole period throughfall constituted 69% of the precipitation, stemflow 3% and therefore interception loss 28%.

A comparison with other UK published results (Table 8) shows that the Balquhidder mean interception of 28% is the second lowest after the Plynlimon result. This is consistent with the results published in Calder & Newson (1979) from British forests which show that the interception fraction decreases with increasing rainfall. Two of the higher interception values,

Table 7 *Summary of results from the Kirkton forest interception site*

	P	T	S	I
Total (mm)	5791	3984	175	1632
Per cent of gross P: Annual		69	3	28
Summer		64	2	34
Winter		71	4	26
Per cent of net P (T+S)		96	4	—
Max 2-week mean (% of P)		93	7	79
Min 2-week mean (% of P)		21	0	0
Standard error of mean		2.03	0.23	2.19

P = Precipitation T = Throughfall S = Stemflow I = Interception — = not included

Table 8 *Interception results from upland catchments in the UK*

Site and reference	A	T	S	I
Greskine (Ford & Deans, 1978)	14	61	39	30
Stocks reservoir (Law, 1956)	25	89	11	38
Kielder (1) (Anderson & Pyatt, 1986)	25	82	18	29
Plynlimon (Hudson, 1988)	29	82	18	25
Kershope (Anderson *et al.*, 1990)	35	86	14	38
Balquhidder (Johnson, 1990)	50	96	4	28
Kielder (2) (Anderson & Pyatt, 1986)	63	98	2	49

A = Age of trees (years)
S = Stemflow (% of net precipitation)
T = Throughfall (% of net precipitation)
I = Interception (% of gross precipitation)

Kielder (2) and Stocks could also be explained by the structure of the forests. Anderson & Pyatt, 1986, give the possible explanation to the high Kielder result as being the greater height of the monitored stand of trees above the general canopy level while the Stocks result is possibly explained by the site being a relatively small open structure of trees.

Comparing the relative proportions of throughfall and stemflow in forests of different ages (Table 8 and Figure 12) has shown a result which potentially has significance for water quality in juvenile forests. These proportions show a general trend from around 15 years when throughfall increases and stemflow decreases with age. Stemflow and throughfall in the age range younger than 14 years have also been interpolated in Figure 12. This has used the fact that throughfall must be 100% at an age of 0, as it is defined to include direct precipitation. Figure 12 suggests that the tree age of around 10 years is an important time in the forest development, when stemflow reaches a maximum and throughfall a minimum. Canopy closure is generally considered to occur at 10-15 years and the two processes do appear to be closely related.

The explanation of this change with tree age is probably in the tree structure with young branches being shorter, straighter and angled upwards. The older tree branches are longer and tend to be more horizontal or even bent downwards towards the ends. Therefore, the routing of water along the branches could be towards the stem in young trees and away from the stem in old trees.

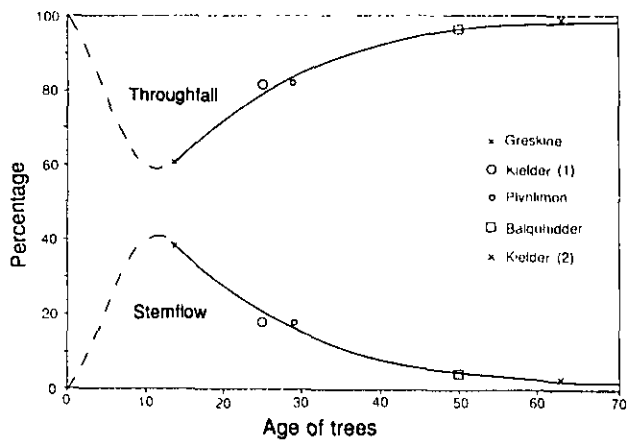


Figure 12 *Variation with age of the proportion of throughfall and stemflow*

4 Modelling the impacts of land-use change

Development of models from the Balquhidder results is an essential part of the study. These models should bring together the results from individual site studies and from the catchment scale so as to gain a better understanding of the relative components in the catchment systems. Different combinations of these models and different complexities can be used depending on the range and quality of data available.

The results from the grassland and forest site studies, described in the previous section, have been combined with results from other studies in Scotland and elsewhere in the UK on heather and snow to develop a catchment water use model (THISTLE). Streamflow models, such as the IH land-use model, TOPMODEL and IHACRES developed elsewhere, have been applied to the Balquhidder catchments to identify hydrological contrasts between the two catchments and any hydrological changes which have taken place in the period of the experiment, and to provide reasoned arguments for the causes of these differences and changes.

Applying the models presented in this section as forecasting tools is also seen as an important part of forestry development in the uplands. Any planned changes, such as afforestation, should be assessed for their likely impact on the natural environment. The availability of models at different levels of sophistication will enable developers to carry out initial impact assessments on all potential sites and to use more specialist knowledge to apply the complex models to the most likely sites.

4.1 Process model of catchment evaporation (THISTLE)

Results from the site studies, such as those described in Section 3 of this Report, form the basis for the development of a process model of evaporation in upland catchments (THISTLE). The aim of the model is to predict the effects of afforestation on the water use of upland catchments throughout the UK. The model is physically based and takes into consideration the major vegetation types: upland grass, heather (*Calluna vulgaris*), coniferous forests, as well as evaporation of snow from a forest canopy or open moorland. The general lack of data from upland catchments, probably including those catchments planned for forestry or water resources development, means that there must be a compromise between more accurate but complex models and simpler models requiring more easily acquired data. The approach taken at Balquhidder has been to develop the THISTLE model from the detailed process studies of evaporation from the main vegetation types and then to use these to derive a simpler model.

The catchment water use models have their origins in the annual model of Calder & Newson (1979) but have been developed to predict the evaporation from a catchment on shorter time-scales and with a wider range of vegetation types. Evaporation process studies have been carried out at Balquhidder and other research sites in the UK, on some of the major vegetation types in upland catchments (Calder, 1986; Hall, 1987). The aim is to develop a model which uses vegetation, daily precipitation and daily potential evapotranspiration and the spatial distribution of these variables to predict catchment water uses.

Three types of model have been derived: an annual whole catchment model, a seasonal whole catchment model and a seasonal model distributed into altitude zones: these are described in detail in Hall & Harding (1993).

The annual model is based on the Calder-Newson model which is a physically based model developed from insights gained from process studies carried out in Mid-Wales. It has here been extended to include estimates of evaporation from catchments containing a heathland component. The main assumptions are that the entire catchments are covered by a combination of grass, heather and trees; the two other vegetation types, bilberry and moss, have been classified as heather and grass respectively. It is also assumed that the annual evaporation from grass on the Balquhidder catchments is 0.75 E_t (Section 3.1) and no allowance is made for snow.

Seasonal models

The seasonal models estimate the daily evaporation from each main vegetation type.

They make the same assumptions for vegetation cover as the annual model. It is assumed that evaporation from snow is zero except when stored on the forest canopy.

Evaporation from the grassland is calculated using a seasonally dependent function developed by Wright & Harding (1993) while evaporation from the heather and forest is calculated as the sum of transpiration and interception loss terms. Transpiration from the heather and forest is estimated using E_t multiplied by an appropriate transpiration factor (Hall & Harding, 1993). The daily interception losses are calculated using an exponential model (Calder, 1986) with parameters from heather and forest derived from the relevant process studies (Hall, 1987; Johnson, 1990)

The altitude zone model allows for the effects of altitude on evaporation and rainfall. In the model each catchment is divided into three altitude zones, each represented by an AWS with classification into vegetation cover within each zone (Table 9). Evaporation from each zone is the sum of the evaporation from each class of vegetation in that zone and the catchment evaporation is then the sum of the evaporation from the three zones.

Output from the seasonal models is in the form of cumulative daily estimates of the transpiration and interception loss from each of the vegetation types. Figures 13 and 14 show the transpiration and interception losses per unit area for the Kirkton vegetation in 1988. The models assume that the transpiration and interception loss rates from grass are the same.

Both forest transpiration and interception exceed that of heather; the interception loss from forest being more than twice that from the heather. Forest brash is assumed to have an interception loss similar to deep heather. The large difference between grass, heather and forest in the early part of 1988 is due to snow cover at high altitudes, resulting in the grass and heather having zero losses.

The resulting total catchment evaporation for each vegetation type (Figure 15) is computed from the daily transpiration and interception

Table 9 *Percentages of main vegetation types in selected altitude ranges*

	Altitude (m)	Grass	Heather	Forest	Other
Monachyle	<400	57.2	42.8	0	0
	400–600	34.2	65.8	0	0
	>600	64.3	35.7	0	0
Kirkton	<400	6.0	0.5	81.7	11.8
	400–600	41.5	11.0	41.4	6.1
	>600	77.0	23.0	0	0

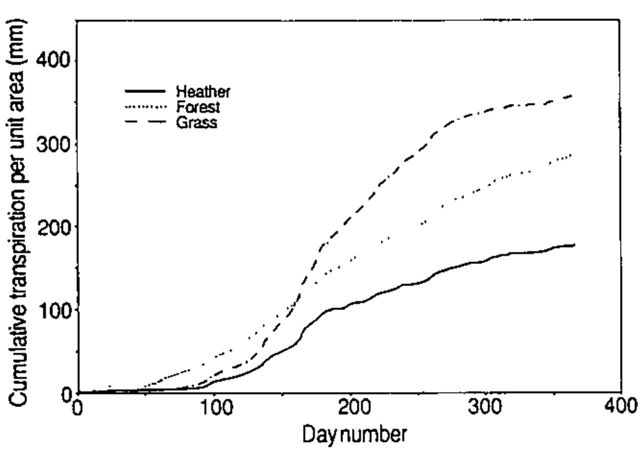


Figure 13 *Cumulative daily estimate of transpiration from three vegetation types in the Kirkton catchment, 1988*

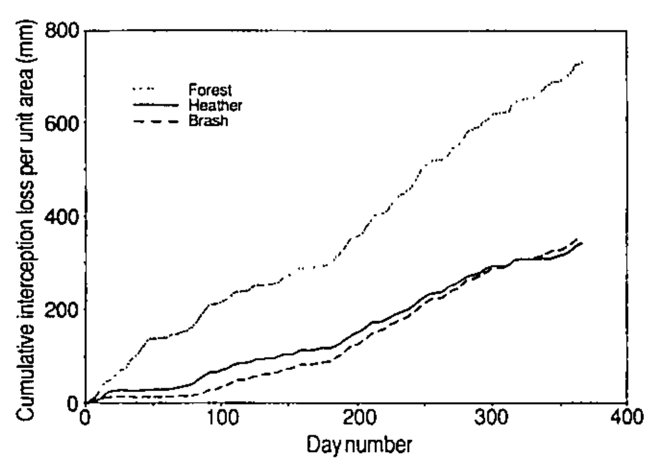


Figure 14 *Cumulative daily estimates of interception loss from three vegetation types in the Kirkton catchment, 1988*

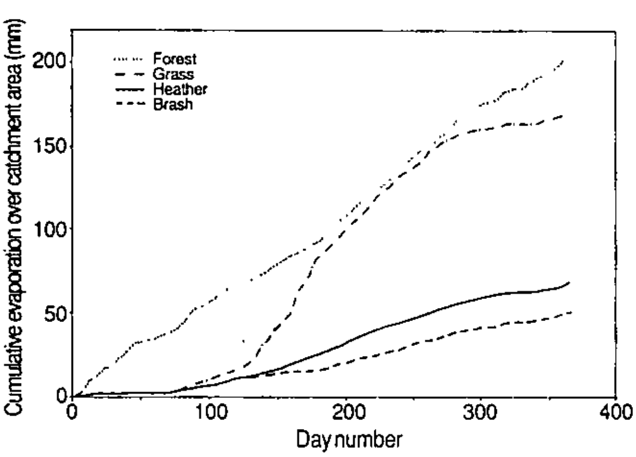


Figure 15 *Cumulative daily total evaporation from the vegetation components in the Kirkton catchment, 1988*

losses and the areal cover of each vegetation type in different altitude zones. The simplified vegetation distributions in Table 9 have been produced by including bilberry with heather, moss with grass, bracken with grass (bracken seasonal) and brash with heather.

It is interesting that in 1988, when almost half of the Kirkton forest had been felled, the forest area still had the largest water use. Moreover, although the evaporation from grass per unit area is much less than that from forest or heather, its large areal coverage, especially in the altitude ranges of greatest potential evaporation in the Kirkton catchment (Section 5.3), results in the total annual grass evaporation being almost as much as the forest and much more than heather. The distribution of the main vegetation types with altitude is therefore important in determining the total evaporation from a catchment.

Figure 16 compares the Kirkton and Monachyle seasonal model estimates of water use with the water balance (P-Q) results (Section 5.1). The discrepancy in the comparison, with the model underestimating in Monachyle and overestimating in Kirkton, appears to be systematic. Application of the annual model produced similar departures from the observed (P-Q) values. This is discussed in more detail in Section 5.4.

One area of uncertainty in the process models is the transpiration of upland grass. The work carried out at Balquhidder (Section 3.1) required a deep soil: this is not typical in the catchments and a vegetation stress factor should probably be incorporated into the grass model. However, the fact that most summers during the measurement period have been wet suggests that such a factor could be small. Other important sources of uncertainty are total evaporation losses from bilberry and mesomires and evaporation from snow cover on rough moorland vegetation.

On the basis of these considerations, the uncertainty in the water use model estimates is considered to be some 15%. Potential errors in precipitation and flow measurements result in water balance, (P-Q), errors that have been estimated at 10-15% (Section 2.6). With these possible errors considered, the error bars of the

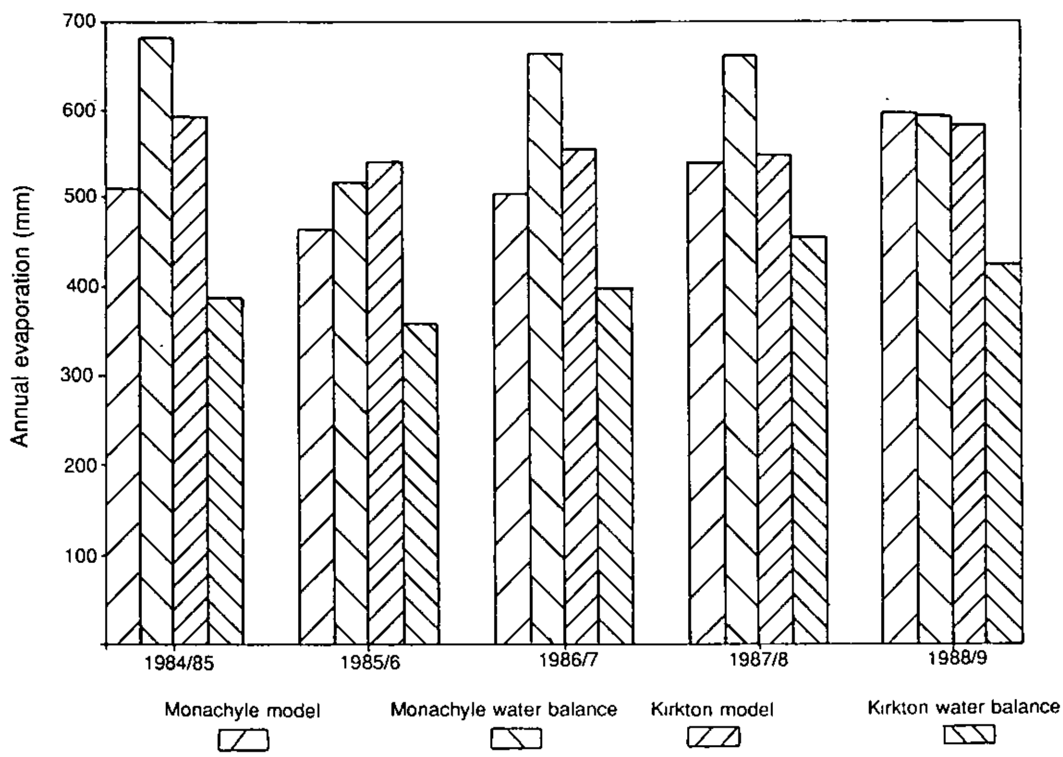


Figure 16 *Comparison of the catchment water use results from the model and water balance methods*

model estimates and the water balance results overlap, but the systematic nature of the differences suggests that further investigation is required. It should be noted also that the quoted 15% uncertainty in the model estimates does not include the uncertainties in the Penman E_t and catchment precipitation data on which the model operates.

From the seasonal models, developed from the components of the vegetation cover, a simplified annual water-use model has been derived. This version is for use in catchments where limited data can be expected. It provides estimates of the average annual water use of forest, grassland and heather, and requires as input the long-term annual rainfall total and the average potential evaporation. The catchment average water use is calculated from the sum of the water uses of individual vegetation types, weighted by their proportional areal cover.

An example of this simple model of water use as a function of rainfall are shown in Figure 17. The example uses an annual potential evaporation of 470 mm, approximately that measured for the Balquhidder catchments. The calculations are only shown for an annual precipitation of above 1000 mm: the model makes no allowance for summer water stress and so should not be used in the drier parts of the country or where soils are especially thin. The model assumes 100% cover for the vegetation types shown.

Figure 17 can be used to give an indication of water use (interception plus transpiration) in other catchments, and of the possible effects of land-use changes such as afforestation. The calculation would be more accurate if variations of E_T were taken into account, but to a first approximation Figure 17 can be used.

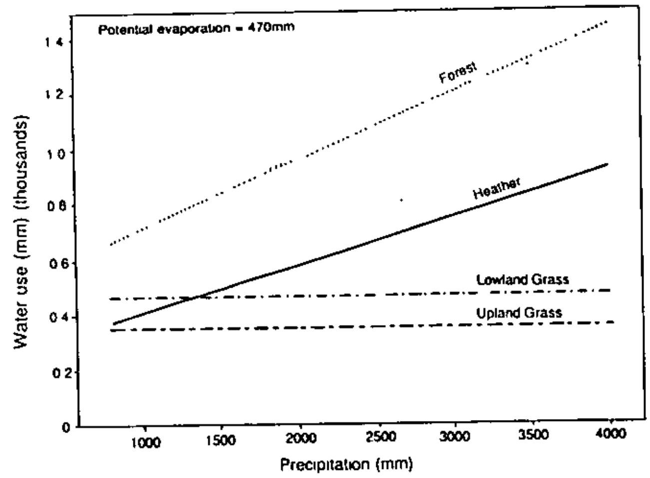


Figure 17 *Generalised models of annual water use of individual vegetation types*

Application of the THISTLE model to the Monachyle catchment shows how the model could be used as a predictive tool. Taking the planted area to be 14% of the total catchment area and assuming that it replaced both grass and heather, the water use of the vegetation components can be calculated. Evaporation from the forest increases with time and decreases from the grass and heather, as shown in Table 10. The most dramatic time is around canopy closure (11 to 15 years) when forest evaporation increases to 241 mm, i.e. 38% of the total catchment evaporation.

4.2 A land-use model to estimate streamflow

The THISTLE model (Section 4.1) incorporates the evaporation processes identified with the major vegetation types on the Balquhidder catchments into a model for the prediction of

Table 10 *Catchment water use model applied to the Monachyle catchment with a developing forest*

Age of trees (years)	E_c	E_g	E_h	E_f
0-5	521	189	300	32
6-10	559	174	279	106
11-15	630	147	242	241
16-20	663	134	224	305
>20	671	131	219	321

E_c = Annual catchment evaporation, mm
E_g = Annual grass evaporation, mm
E_h = Annual heather evaporation, mm
E_f = Annual forest evaporation, mm

catchment water use. This provides a means of estimating, on a seasonal or annual basis, the probable effects of land-use change on the water balance. For many water resources assessment purposes there is a need to translate these effects into an estimate of the changes in the volume and seasonal pattern of streamflow emerging from the catchment. Rainfall/runoff models, as exemplified by the family of Institute of Hydrology Lumped Conceptual Models (Blackie & Eeles, 1985), of which HYRROM is the best known example, can be used to forecast streamflow patterns from rainfall and potential evaporation data once the models have been calibrated and validated on a few years of good streamflow data from the catchment.

One of these models, the IH land-use model has been applied to the Balquhidder catchments to estimate the effects of the land-use changes on streamflows. The land-use model was developed to extend the usefulness of the lumped conceptual model by incorporating the physical process models of evaporation from each major vegetation type (forest, grassland and heather) into the general model structure. An early version of this approach was applied with some success to assess the effects of afforestation on water yield from the catchments of the Elan Valley reservoirs and was also applied to a number of FRIEND catchments (Gross *et al.*, 1989). In this version (Figure 18) the loss functions used for transpiration and

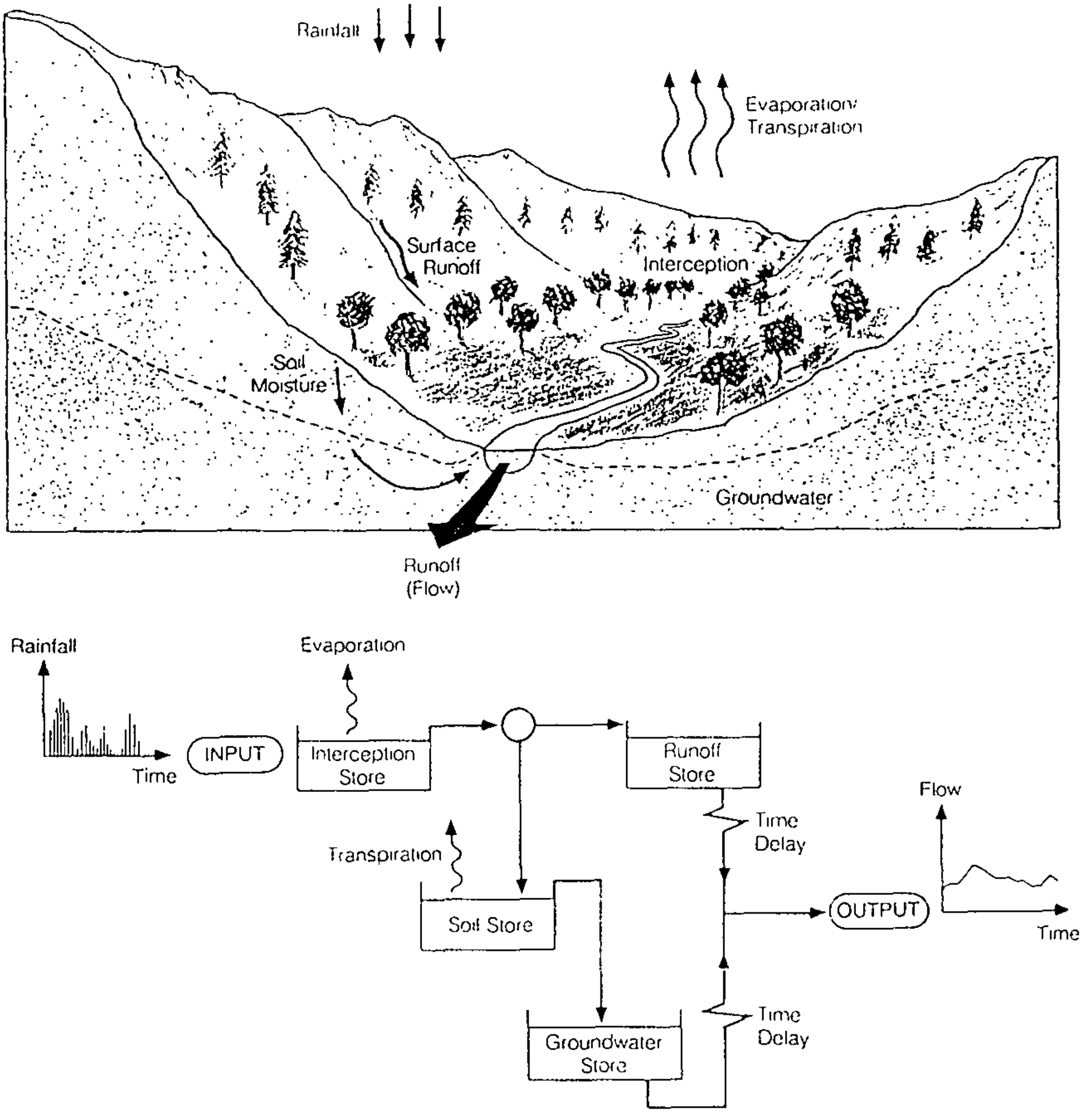


Figure 18 *The HYRROM model*

interception are taken from the THISTLE model and are applied to the areas in each catchment under forest, grass and heather, as determined by vegetation surveys (Roberts *et al.*, 1993) prior to the land-use changes. After partitioning effective rainfall between surface runoff and infiltration, transpiration loss, soil moisture changes and recharge to ground water under each vegetation area are computed on a daily basis. The surface runoff and the recharge components are then lumped and reservoir and delay functions similar to those incorporated in the HYRROM version are used to compute the rapid response and baseflow contributions to streamflow. These are then combined to give predicted daily streamflow values. The structure of the model is described in greater detail in Eeles & Blackie (1993).

The models for each catchment were calibrated on data for the period May to December 1985, a period for which continuous good records were available and within which no major snow accumulations occurred. Over this period the parameters not evaluated from the THISTLE functions were optimised, initially using the Rosenbrock routine with subsequent fine tuning by the Simplex method (Nelder & Mead, 1965).

The Monachyle streamflow hydrograph was accurately simulated during this calibration period with a daily correlation of 0.90 and a volume error of only +0.7% but the Kirkton simulation was not as good, giving a correlation of 0.86 and a volume error of -3.9%. A possible reason for this underestimate in the Kirkton streamflow is the use of E_t data from the Kirkton High AWS to represent catchment mean E_t. Subsequent data from the Lower Kirkton AWS suggests that the Kirkton High data overestimate the catchment mean E_t by some 10%.

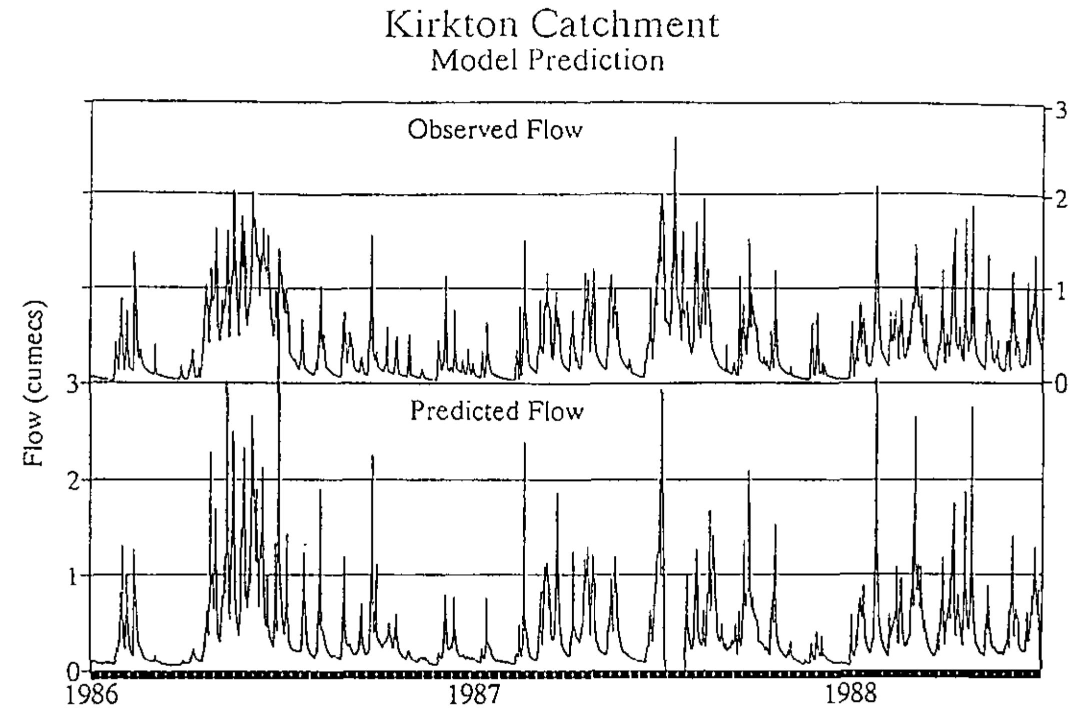
Since land-use changes occurred in both catchments from 1986 onwards it was not possible to follow the model calibration by a model validation, in the strictest sense, on a comparable run of data. Instead the models were used to simulate the streamflow that would have occurred in the period January 1986 to December 1988 in the absence of land-use change. The Kirkton model was then re-run with the areas of vegetation changed to represent the felling that occurred in this period. As can be seen from the summary data in Table 11 that the simulated flow in the Monachyle for this period, when 14% of the catchment was being planted, was within 0.2% of the observed flow, suggesting that the planting had no significant effect on the streamflow at this early stage. By contrast the Kirkton 'no change' simulation was 6.5% lower than the observed whilst the 'felling' simulation was 3.4% lower, comparable to the error in the calibration period. This suggests that a small change in streamflow response had been brought about by the felling.

The model was then used to produce estimates of the long term effects of a range of different levels of mature forest cover on the two catchments. Twenty five years of rainfall data for each catchment were synthesised using the 1983-88 regression relationships between observed catchment rainfall and the long term records from a gauge at the nearby Lochay Power Station (OS grid reference NN 545 350). No comparable station was available for extending the Penman E_t record but, as a substitute, the mean annual E_t distributions from the 1983-88 period were used to provide E_t inputs for the remainder of the 25 year period.

The 'Monachyle' and 'Kirkton' models were then applied to these synthetic data sets to produce a 25 year time series of simulated daily flows with the areas of mature forest in each catchment set at 0%, 20%, 40%, 60%, 80% and 100%. For each setting the remaining areas in the catchments were apportioned between grass and heather in

Table 11 *Mean monthly flows: observed and simulated*

Period	Comment	Observed (mm)	Simulated (mm)	Volume error (%)
Monachyle				
5/84-12/85	Calibration	164.1	165.2	+0.7
1/86-12/88	Prediction	184.3	184.7	+0.2
Kirkton				
5/84-12/85	Calibration	155.3	147.3	-3.9
1/86-12/88	Prediction – no felling	167.3	156.5	-6.5
1/86-12/88	Prediction – progressive felling	167.3	161.6	-3.4



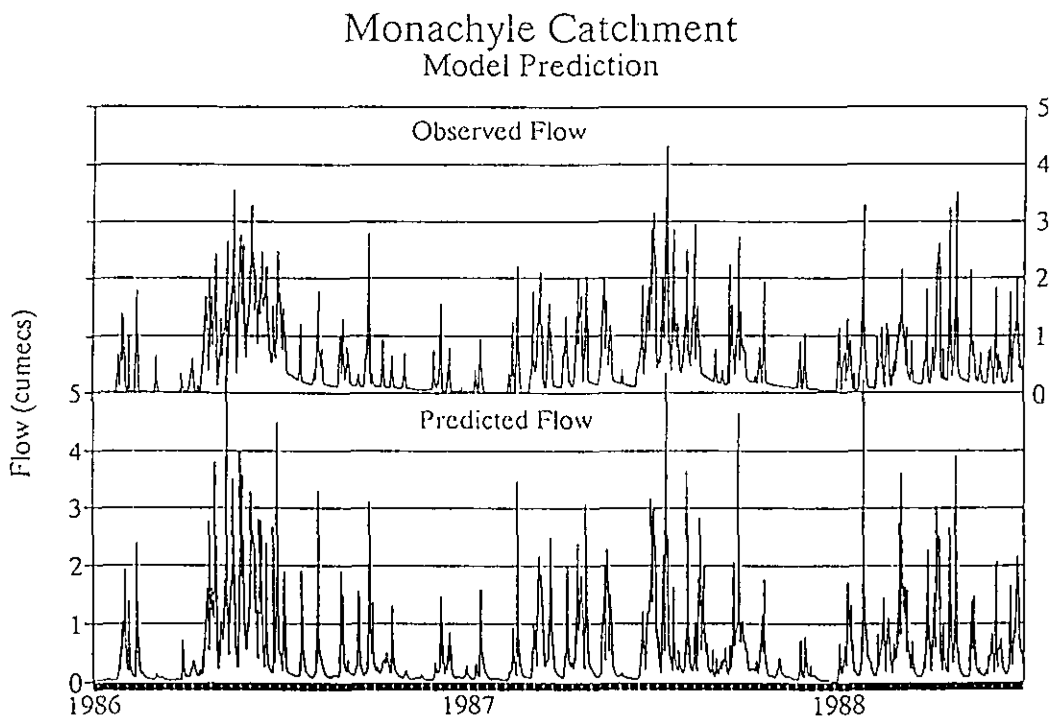


Figure 19 *Comparison of observed and predicted flows for the HYRROM evaluation period, 1986-88*

the ratios existing in the 1984-85 calibration period. The results are summarised in Figure 19 in terms of the mean percentage changes in streamflow, relative to the 0% forest runs, resulting from each level of forest cover. The greater reductions predicted in the 'Kirkton' scenario are due to the residual area of the catchment being predominantly under grass as compared to the 50:50 heather:grass cover in the Monachyle. The actual values of the reductions relate to the rainfall and climatic conditions in these catchments, factors which must be taken into account in any attempt to extrapolate to other sites.

The data sets produced were subsequently analysed to produce an assessment of the water resource implications of varying levels of afforestation in regions with similar climate and catchment response characteristics to the Balquhidder area (Gustard & Wesselink, 1993). Their findings are summarised in Section 5.5 of this Report.

4.3 Topographic model for streamflow analysis (TOPMODEL)

TOPMODEL is a physically based, semi-distributed model developed for use in predicting and understanding rainfall-runoff mechanisms. It provides a compromise between the complexity of a fully distributed model such as IHDM (Calver, 1988) and the relative crudity of lumped models such as Birkenes (Christophersen *et al.*, 1982). Heterogeneity in catchment topography is incorporated into TOPMODEL by means of a topographic index; the movement of water through the catchment is founded on a simple representation of physical processes.

TOPMODEL was applied to the Balquhidder catchments with these three aims: (a) to compare the hydrological response of the two catchments, (b) to relate these responses to the flow generation mechanisms operating in the catchments, and (c) to identify any effects the land-use changes may have brought about. A fuller description of the application is given in Robson *et al.* (1993).

Catchment topography is represented by means of a topographic index, $\ln(a/\tan\beta)$, where a is the area draining through a grid square per unit length of contour and $\tan\beta$ is the average outflow gradient from the square. The index is calculated from a digital terrain map across a grid covering the catchment. A high index value usually indicates a wet part of the catchment: this can arise either from a large contributing drainage area or from very gentle slopes. Areas with low index values are usually drier resulting either from steep slopes or from a small contributing drainage area. Grid squares with the same index value are assumed to behave in a hydrologically similar manner. As a result of this assumption, the catchment's topography may be summarised by the distribution of the index values.

TOPMODEL identifies two sources of stream water. The first of these sources is water draining from subsurface saturated zones. The second source is rainwater falling onto completely saturated parts of the catchment. This water is assumed to move or displace water quickly to the stream through, for example, macropore flow, old water displacement or overland flow. The saturated contributing area will both grow and decline during the course of a storm event.

Maps of $\ln(a/\tan\beta)$ provide information which can be used to help characterise a catchment's hydrological and hydrochemical behaviour. The maps can be used to help identify source areas within the catchment, which are potentially important in the control of the chemical characteristics of the stream and in sediment transport. The maps provide a simple tool which allows hydrologically important differences resulting from the topography to be identified.

Maps of the index values show that the two catchments are quite different in terms of the spatial distribution of $\ln(a/\tan\beta)$ (Figures 20 and 21). The index varies smoothly across the Kirkton catchment, increasing almost monotonically with height. High index values are concentrated along a continuous band near the stream, widening towards the catchment outlet. Two additional source areas are also visible on the higher parts of the catchment: one to the northeast and the other to the west near two small lochans.

The Monachyle map appearance is much more irregular — a direct result of its more rugged topography. A large proportion of high $\ln(a/\tan\beta)$ index values occur in the flat Upper Monachyle sub-catchment. Further high index values are also seen along the lower stream banks, although this band is neither so wide nor so smooth as for the Kirkton catchment.

The cumulative distributions of the indices are compared in Figure 22. The distributions are fairly similar, although the Monachyle catchment has a slightly larger proportion of the higher index values. This means that there is likely to be more flow generated in the Monachyle from the saturated contributing (source) areas.

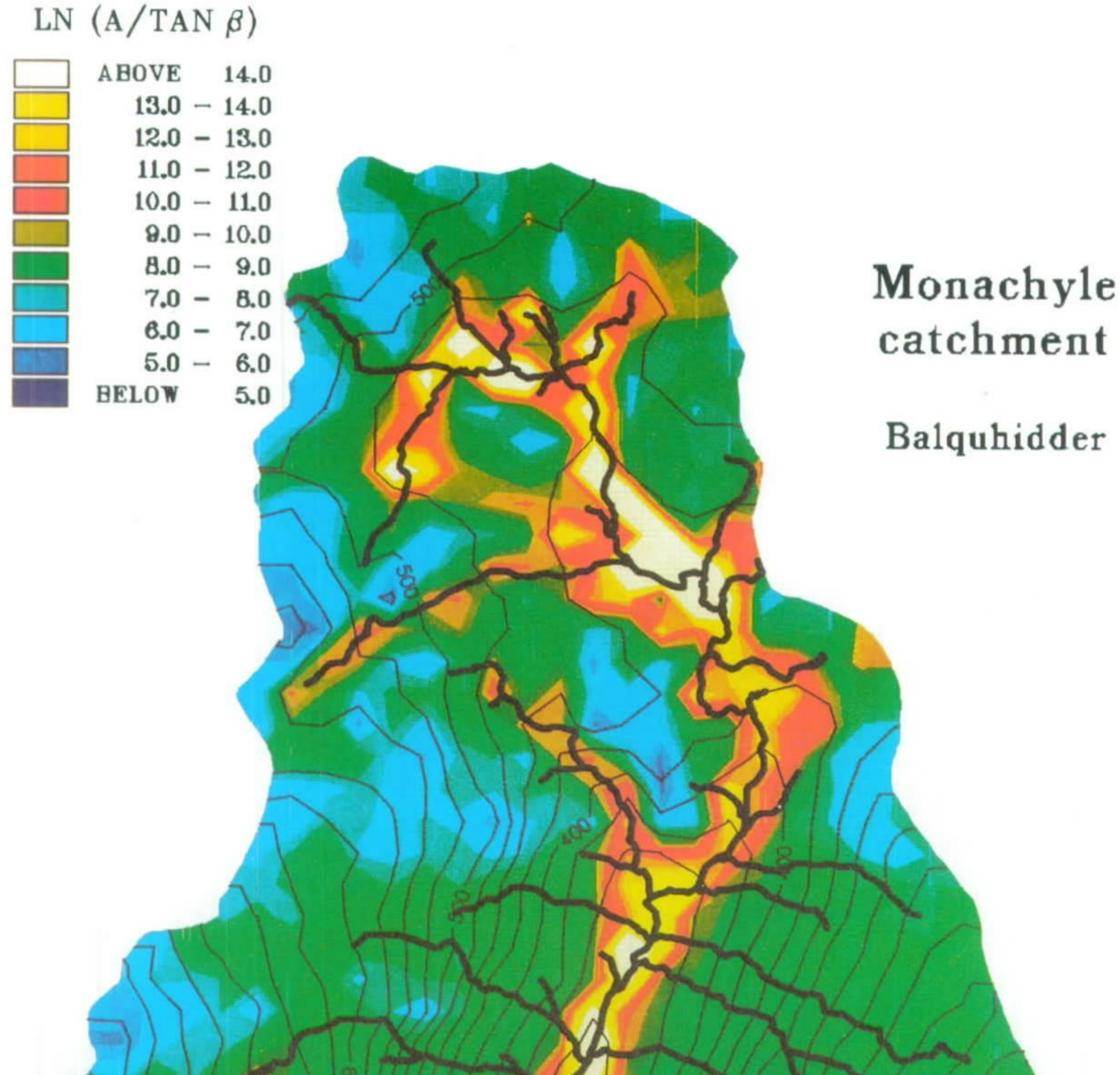


Figure 20 *Variations in the TOPMODEL index values for the Monachyle catchment*

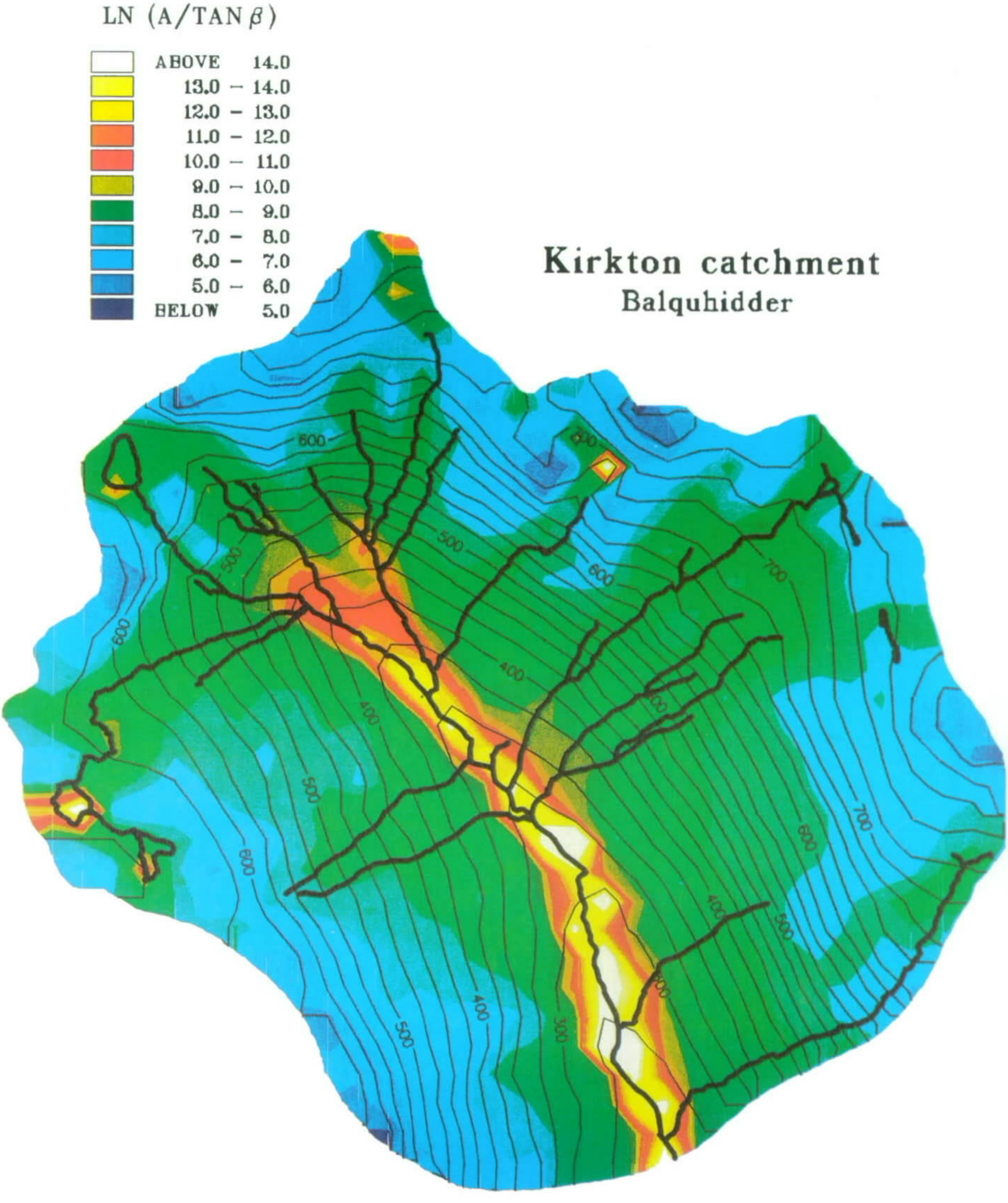


Figure 21 *Variations in the TOPMODEL index values for the Kirkton catchment*

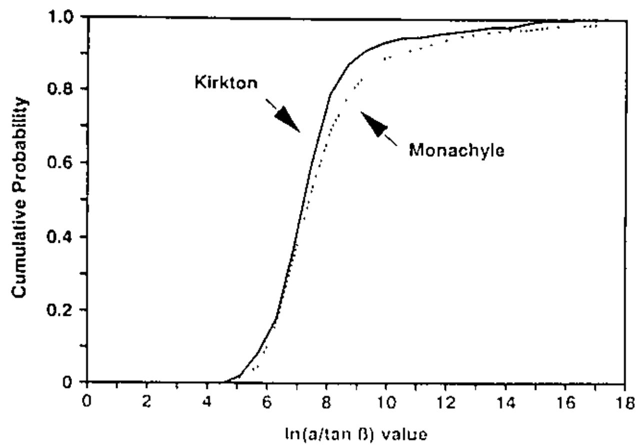


Figure 22 *Cumulative distributions of TOPMODEL index values*

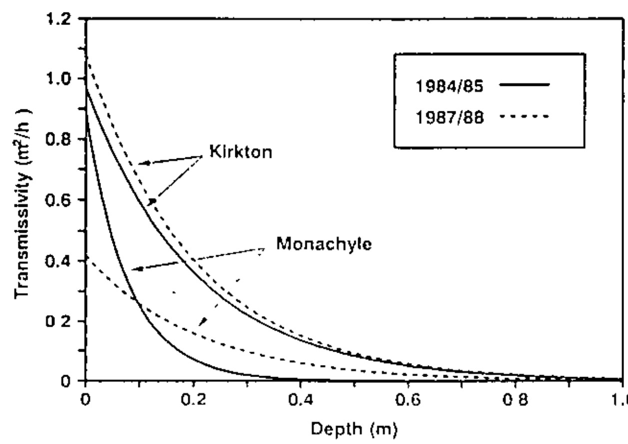


Figure 23 *TOPMODEL transmissivity profiles for the Monachyle and Kirkton catchments before and after the land-use changes*

TOPMODEL was calibrated for both catchments using daily rainfall and flow records for the year June 1984 to June 1985. The modelled flow is subdivided into subsurface flow and saturated overland flow. Both catchments are very flashy and a relatively high proportion of the total response is made up of water from saturated contributing areas. The Kirkton catchment gives the higher proportion of subsurface flow; it also gives the better fit. The higher saturated overland flow for the Monachyle has a physical correspondence with the extensive peat areas in the Upper Monachyle sub-catchment which would be capable of generating such flows (see also Section 2.5).

A validation run, using the estimated parameters from 1984-85, was undertaken for both catchments between June 1987 and June 1988 (Figure 24). During the winter of 1987/88 both catchments show a period of poor model fit when snow storage and melt affected the results. The calibration and validation runs can also be used to assess whether any change in response has occurred in either catchment. Little improvement in fit is seen for the Kirkton catchment and there is no evidence to suggest that any change in flow generation mechanisms or flow routing has occurred.

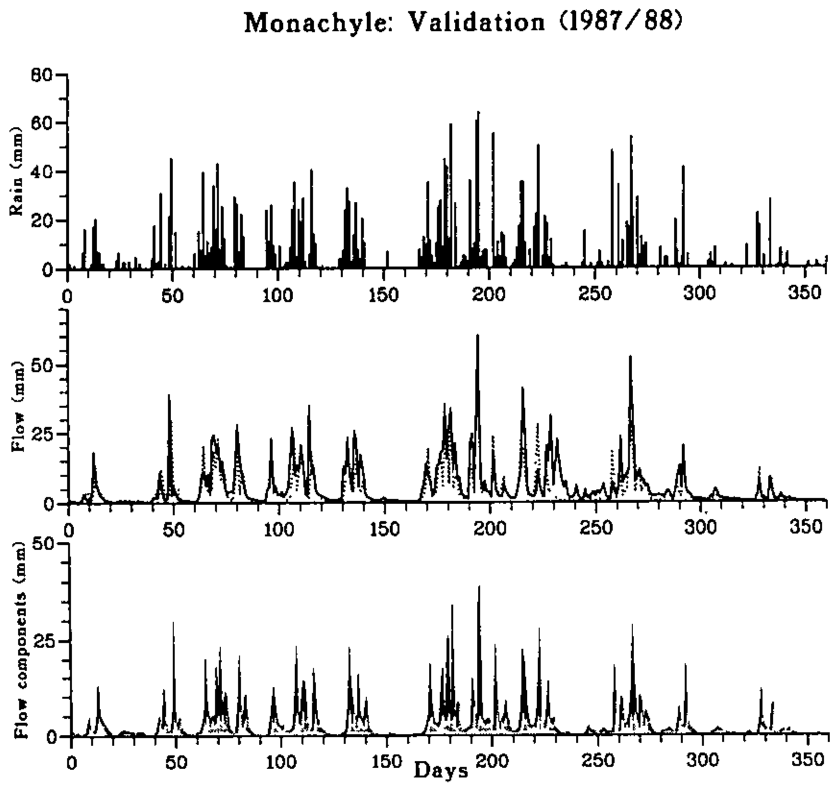
For the Monachyle catchment an improved fit is achieved with substantial differences in the optimised parameter values. To illustrate these differences, the transmissivity profiles for both catchments are plotted in Figure 23. The profile indicates how quickly water moves laterally at different depths. For 1984/85 there is fast movement near the surface in both catchments but with water moving relatively slowly at depth in the Monachyle. There is little difference between the Kirkton profiles for the two years, but for the Monachyle in 1987/88 there is a substantial reduction in the shallow subsurface flow and a corresponding increase in the subsurface flow at depth.

Despite the altered transmissivity profile between the two periods, the total subsurface flow from the Monachyle has not changed as a proportion of the total flow. Instead, the pattern of subsurface flow emergence has changed, with the 1987/88 subsurface response being more damped than in 1984/85. These changes may be a result of the land-use changes in the Monachyle in which 6% of the catchment was ploughed. Although the ploughing covered a very small proportion of the catchment, the results from this model indicate that the areas ploughed (i.e. the lower slopes) are hydrologically very sensitive.

4.4 Streamflow separation model (IHACRES)

A recently developed catchment rainfall-streamflow model, IHACRES (Jakeman *et al.*, 1990), has been applied to the Balquhidder catchments. The objective was to quantify the basic differences in quick and slow flow dynamic response characteristics of the two catchments to rainfall and to detect if any changes may have occurred as a result of the land use changes (Jakeman *et al.*, 1993).

IHACRES is based on unit hydrograph theory and system identification techniques are adopted whereby rainfall excess is the input to a system of linear storages. Full details of the model including parameter estimation are given in Jakeman *et al.* (1990). The model enables the separation of hydrographs into identifiable flow components on the basis of the information in rainfall and streamflow data. It then allows the computation of the magnitudes and character-



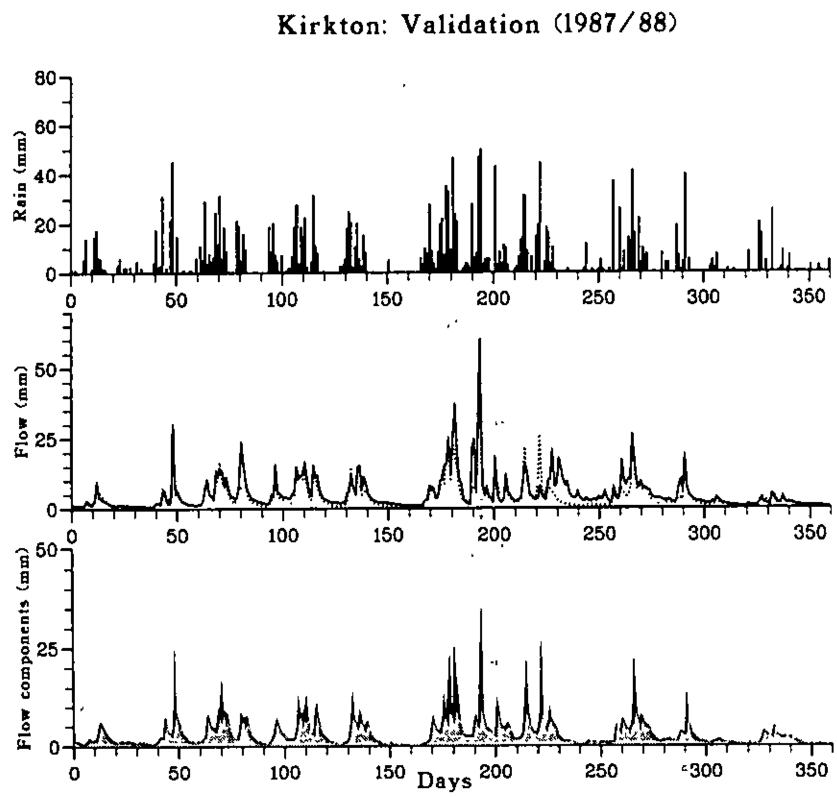


Figure 24 *TOPMODEL validation run, 1987-88*

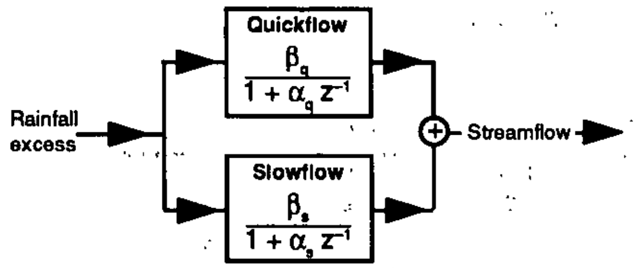


Figure 25 *Schematic diagram representing the rainfall-streamflow model, IHACRES. Parameter α is directly related to the time constant of a flow component reservoir. β/(1+α) is the contribution of a flow to the total flow volume.*

istic response times of the separate unit hydrographs for these flow components.

Generally there are two identifiable components corresponding to two linear storages acting in parallel, they have different response times to rainfall and consequently are referred to as quick and slow components of streamflow.

IHACRES also calculates separate characteristic response times, relative contributions to the flow peaks and volumetric throughputs for the quick and slow flow components. These analyses were used on daily data for the Monachyle and Kirkton catchments for the five consecutive 12-month periods starting in July 1984, which included the periods before and after the start of the land-use changes.

As discussed in Section 2.5, the Monachyle catchment has a flashier response and lower baseflows than the Kirkton, even though it is the larger catchment. Differences between the two catchments' physical characteristics, such as slope, soils, glacial deposits, vegetation and drainage density, undoubtedly cause this difference in the flow regimes.

The effect of antecedent rainfall on catchment streamflow response was investigated by use of a rainfall-rainfall excess model Jakeman *et al.* (1990). No improvement was obtained in the predicted streamflow using a range of values for this parameter. This was thought to be due to the regular occurrence of rainfall and relatively low rates of evaporation minimising the effect when considering daily data. For the model, rainfall excess was therefore considered to be proportional to rainfall.

The relationship between rainfall excess and streamflow was described using a series of

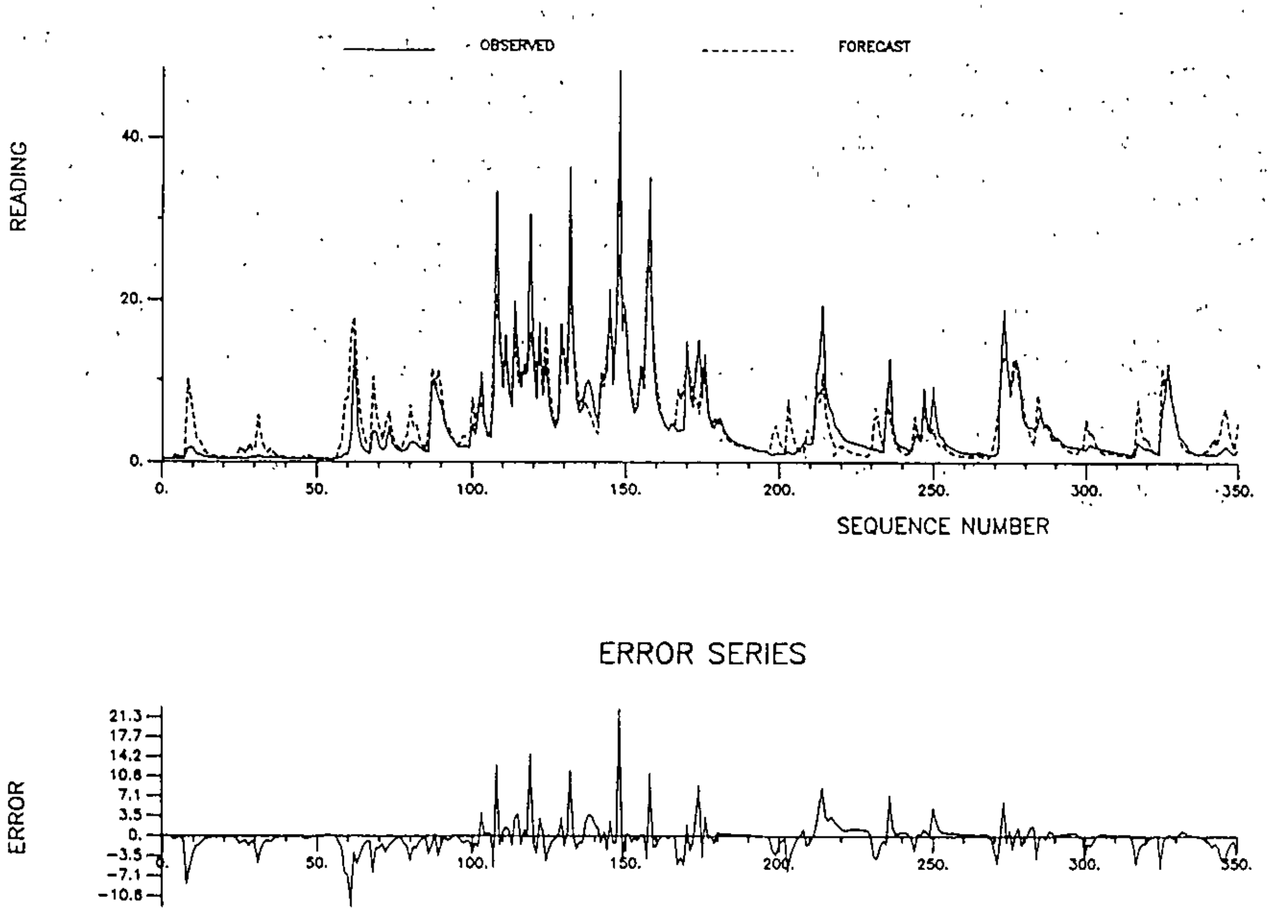


Figure 26 *IHACRES model fitted to the Kirkton 1984-85*

Table 12 *Dynamic response characteristics of Kirkton (first row) and Monachyle (second row) catchments estimated by IHACRES using annual sets of daily rainfall-streamflow data*

	Period of estimation				
	1984-85	*1985-86*	*1986-87*	*1987-88*	*1988-89*
Response time, quick (days)	1.39 1.00	1.35 0.85	1.49 0.84	1.26 1.03	1.47 0.84
Response time, slow (days)	20 –	46 39	35 43	16 29	25 13
Volume throughput, quick	0.72 1.00	0.85 0.93	0.72 0.85	0.62 0.76	0.74 0.83
Volume throughout, slow	0.28 0.00	0.15 0.07	0.28 0.15	0.38 0.24	0.26 0.17
Peak flow, quick	0.964 1.00	0.993 0.997	0.978 0.994	0.937 0.98	0.974 0.979
Peak flow, slow	0.036 0.000	0.007 0.03	0.002 0.006	0.063 0.017	0.026 0.021

linear storages. In all but one year (Monachyle 1984-85) the appropriate configuration was a quick flow storage and a slow flow storage acting in parallel. Figure 26 shows an example of the IHACRES model fitted to the Kirkton daily streamflows for 1984/85. Although there are discrepancies over some parts of the record it is considered that the dynamics of the quick and slow flow components are adequately represented by the model.

Similar model fits were obtained for other years for both catchments. It should be noted that no adjustments were made to rainfall inputs to account for the effects of variable catchment wetness or seasonal variations in evapotranspiration.

The basic hydrological differences between the catchments have been quantified by the IHACRES analysis. The model yields values of characteristic response times, volumetric throughput and the relative contributions to the peak of the unit hydrograph for each 12-month period, Table 12.

The characteristic response times for the Kirkton average 1.37 days (quick flow) and 31 days (slow flow). For the Monachyle the equivalent figures are 0.91 and 31 days respectively. Relative volumetric throughputs for the quick and slow flow components average 0.73 and 0.27 respectively for the Kirkton and 0.87 and 0.13 respectively for the Monachyle. The relative contributions of quick and slow instantaneous unit hydrograph (IUH) peaks to the IUH peak for total streamflow average 0.969 and 0.031 respectively for the Kirkton and 0.991 and 0.009 respectively for the Monachyle.

These results show clear differences between the catchments confirming that the Monachyle is the flashier catchment but the Kirkton has the higher baseflows. There is, however, little indication that, on a daily time scale, the hydrology of either catchment has been significantly altered by the land-use changes.

5 Catchment evaporation

5.1 Annual catchment water balance

Water balance results from Plynlimon in Mid-Wales show that in the two neighbouring catchments with similar rainfall totals, the 70% forested Severn catchment has a greater water use than the grassland Wye catchment (Kirby *et al*, 1991). Over the 11 year period 1975-1985 the water use of the Severn was 549 mm while in the Wye it was 351 mm, the difference being equivalent to 8% of the mean precipitation. A similar experimental methodology was used in the Balquhidder catchments but direct comparison of these two catchments was found to be difficult due to the different rainfall totals, the Monachyle being the wetter catchment by some 400 mm per annum.

The basic method of evaluating an annual catchment water balance involves the accurate measurement of the precipitation input, P and the streamflow, Q. In the Scottish upland environment both of these measured variables are considerably larger than in lowland environments but the measurement is complicated by large spatial variability, significant snowfall input and by the flashy nature of the streamflow. The estimation of the long-term water balance (P-Q) is therefore critically dependent on the accuracy of measurement of the input variables.

The instrument networks in the Balquhidder catchments for measuring P and Q were described in Section 2.2 and the spatial and temporal variations in precipitation and flow in Sections 2.4 and 2.5.

The precipitation data were for most years derived from the catchment networks by the arithmetic mean approach, after the application of the corrections described in Johnson *et al* (1990). A different method was applied for the 1983 data. Examinations of 1983 data published previously revealed that data for certain winter months were in error. Corrected values for these months were derived using relationships with other raingauge sites as described in Blackie (1993).

The streamflow data, expressed as a depth in millimetres over the plan areas of the catchments were obtained from the volume flows given by the updated rating curves modified after intensive current metering checks on the structures (Hudson *et al*, 1990). A catchment water balance equation can be expressed as:

$$AE = P - Q \pm S \qquad (3)$$

where: AE = actual evaporation
P = precipitation input
Q = streamflow output
S = change in storage

The storage terms in the equation comprise snow, soil moisture and groundwater storages. Over a period of years the cumulative (P-Q)

Table 13 *Summary of the water balance results 1983-1989 for the Monachyle (M) and Kirkton (K) catchments*

	P (mm)		Q (mm)		P–Q (mm)	
Year	*M*	*K*	*M*	*K*	*M*	*K*
1983	2659	2281	2028	1721	631	560
1984	2648	2215	1929	1781	719	434
1985	2612	2285	2056	1960	556	325
1986	3280	2789	2522	2242	758	547
1987	2255	1899	1724	1592	531	307
1988	2952	2493	2389	2126	563	367
1989	2985	2519	2397	2098	588	421
Mean 83-89	2770	2354	2149	1931	621	423
% P					22.4	18.0

term becomes a more accurate estimate of AE as the storage terms simply fluctuate within a range prescribed by the physical characteristics of the catchment.

Table 13 show the annual totals of precipitation and streamflow for both catchments from 1983 to 1989 inclusive and Figure 27 the annual (P-Q) values. The mean annual catchment evaporation totals, Monachyle 621 mm (22% of precipitation) and Kirkton 423 mm (18%), show that the evaporation is greater from the moorland catchment than from the forest and grass one. Superficially this appears to contradict the Plynlimon results but it is only valid to make direct comparisons of two catchments if they are subjected to closely similar precipitation and Penman E_t values. The process studies (Sections 3.1 and 3.2) and the development of the process model, THISTLE (Section 4.2) have shown that the distribution of vegetation types with respect to catchment climatic zones can broadly explain the overall water use in each catchment and that the evaporative behaviour of the forest and grass vegetation is similar to that found at Plynlimon.

Figure 28 shows the annual differences in the evaporation amounts (Monachyle - Kirkton) between the catchments. There appears to be a downward trend, with the two catchments' evaporation totals becoming closer together. There is no obvious step or change in slope in Figure 28 around 1986 to coincide with the changes in land use.

A comparison of the (P-Q) values with the annual precipitation is shown in Figure 29. Considering data from both catchments together, there is a general increase in catchment water use with precipitation, described by the regression equations:

$$\textit{Evaporation} = 0.275\ \textit{Precipitation} - 184 \qquad (4)$$

or

$$\textit{Evaporation} = 0.205\ \textit{Precipitation} \qquad (5)$$

There is no obvious grouping of the years before and after the land uses changed, again indicating no apparent effect of the planting or clearfelling. It is interesting to note (Figure 29) that the three years with the lowest evaporation, 1985, 1987 and 1988, were also the three years with the highest proportions of precipitation falling in the summer months.

5.2 Penman potential transpiration estimates

A catchment study aimed at determining water use is of limited value unless there is a basis for comparison with results obtained elsewhere and for the extrapolation of results to other areas. A widely used basis for comparing meteorological conditions is the Penman (1948) estimate of potential evaporation, E_t.

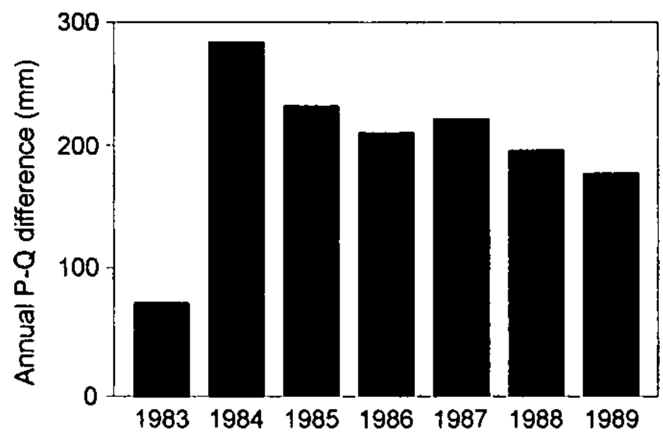


Figure 28 *Annual evaporation totals for the Balquhidder catchments, 1983-89*

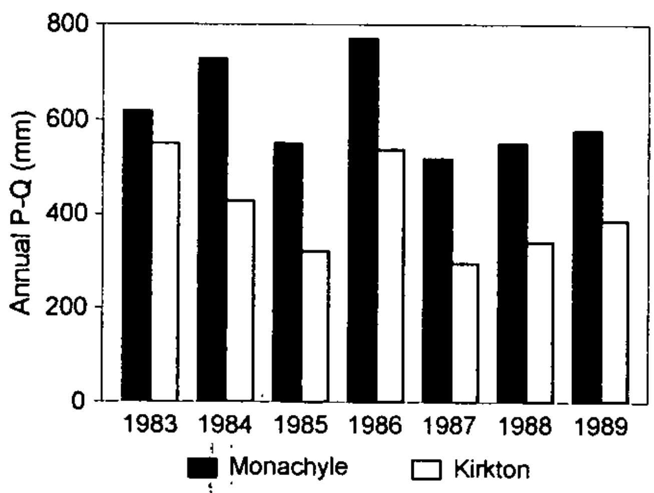


Figure 27 *Annual difference (Monachyle - Kirkton) between the catchment evaporation totals*

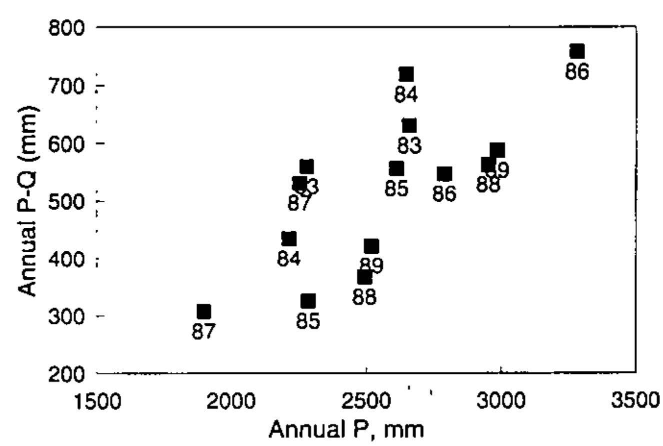


Figure 29 *Annual catchment water use (P-Q) as a function of annual precipitation (P)*

__Table 14__ Estimates of annual E_t (mm) from each AWS at Balquhidder for the period 1983-88

	TF	MG	UM	KH	LK
Altitude (m)	*135*	*310*	*430*	*668*	*275*
1983	438	496	517	521	416
1984	504	557	634	635	518
1985	370	392	464	446	347
1986	415	458	584	558	449
1987	415	443	492	491	389
1988	447	463	527	516	411
Mean	431	468	536	528	422

At Balquhidder an initial network of three automatic weather stations (AWS), Tulloch Farm (TF), Monachyle Glen (MG) and Kirkton High (KH), was installed over the altitude range and this was later supplemented by two further stations, Upper Monachyle (UM) and Lower Kirkton (LK), (Johnson & Simpson, 1991). The estimates of annual E_t totals for the period 1983-1988 are summarised in Table 14. Early problems with sensors and magnetic tape loggers required some infilling using well defined inter-site relationships (Blackie, 1987). The values obtained suggest that E_t is greater at the high altitude sites than in the valley bottoms. This is contrary to the traditional assumption, for example in MAFF Technical Bulletin 16 (Ministry of Agriculture , Fisheries and Food, 1967) that E_t decreases with altitude. However the results shown in Table 14 show that there is not a simple relationship between E_t and altitude or exposure, as the mean value for the Upper Monachyle site (430 m) is marginally higher than that from the higher altitude Kirkton High site (668 m).

The period July 1989 to June 1990 was selected for a more detailed study because it includes data from the lower Kirkton (LK) site within the clearfelled area. By then also, all stations were equipped with the more reliable solid state (Campbell CR10) loggers and most sensor problems had been rectified. The mean values of the meteorological variables over this 12 month period are presented in Table 15.

The Penman expression can be presented as the sum of an energy balance term and an aerodynamic term:

$$E_t = \frac{\Delta}{\Delta+\gamma} \cdot R_n + \frac{\gamma}{\Delta+\gamma} \cdot EA \qquad (6)$$

where R_n = Net radiation;
EA = Constant × Specific humidity deficit × *f* (wind speed);
Δ = Slope of the saturated humidity/ temperature curve at dry bulb temperature;
$\gamma = C_p/\lambda$;
C_p = Specific heat of air at constant pressure;
λ = Latent heat of water.

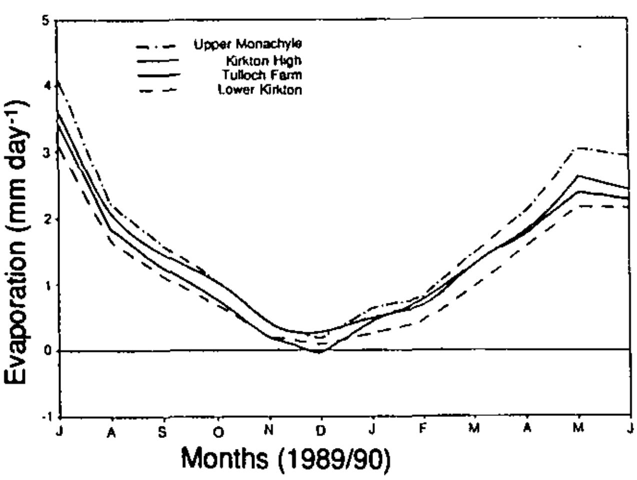


***Figure 30** Monthly mean values of E_T for four Balquhidder automatic weather stations, July 1989 to June 1990*

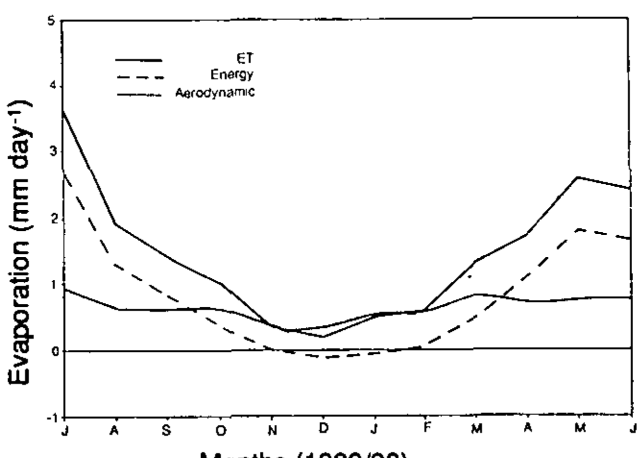


***Figure 31** Monthly contribution of the energy balance and aerodynamic terms to the Penman E_t estimate*

Table 15 *Mean values of meteorological data and totals of Penman Et and its two components from July 1989 to June 1990*

	TF	MG	UM	KH	LK
AWS data					
Solar radiation (Wm^{-2})	91.0	85.6	94.6	94.6	87.7
Net radiation (Wm^{-2})	41.5	34.5	51.0	43.7	36.0
Air temperature (°C)	8.2	7.6	6.5	5.1	7.4
Wind speed (ms^{-1})	2.24	3.44	4.36	5.89	1.84
Penman terms					
E_t (mm)	496	-	623	544	437
Energy balance term (mm)	309	257	372	311	266
Aerodynamic term (mm)	187	-	251	233	171

The first term in Equation 6 is normally referred to as the energy balance term and the second as the aerodynamic term. In Figure 30 the monthly means of the daily values of E_t are shown for four of the stations, indicating a similar ranking of stations to Table 14. The UM site consistently gives the highest value through the year and the LK the lowest value. The percentage contributions of the energy balance and aerodynamic terms to E_t for the 12-month period, given in Table 16, show that the energy balance term is greater than the aerodynamic term for all stations. Their distributions through the year differ, however and Figure 31 shows that the energy balance term is the greater in the summer and the aerodynamic term is greater in winter.

The variables contributing to the aerodynamic term are wind speed, specific humidity deficit and, less directly, temperature. Values for all sites lie in the range 0.15-0.95 mm day^{-1} with the ranking the same as for E_t (i.e. the highest value for Upper Monachyle and the lowest for Lower Kirkton). Blackie & Simpson (1993) show detailed analyses of the seasonal patterns of wind speed, specific humidity deficit and temperature and conclude that although the effect of the higher wind speeds at the upper sites is dominant there is still a considerable influence from the specific humidity deficit term.

Table 16 *Percentage contributions of the energy balance term (EB) and the aerodynamic term (AD) in the Penman E_t estimate at four sites in the Balquhidder catchments*

Station	EB	AD
TF	62%	38%
UM	60%	40%
KH	57%	43%
LK	61%	39%

TF = Tulloch Farm; UM = Upper Monachyle
KH = Kirkton High; LK = Lower Kirkton

The energy balance term has the variables net radiation and a function of temperature. Detailed analysis of the individual variables is again given in Blackie & Simpson (1993), and they conclude that net radiation is the dominant variable in determining the energy balance term and hence the summer E_t values.

5.3 Development of the Calder-Newson water use model

To predict catchment water use the Calder-Newson approach estimates the water use from the main vegetation types and sums the individual totals determined by the proportional area of the catchment covered by each (Calder & Newson, 1979). The version used here, the whole catchment annual model of Section 4.2, incorporates a function for heather water use as well as the forest and grass components in the original Calder-Newson expression. This approach therefore uses climatological information from the automatic weather stations (Section 5.2) and results from the process studies (Sections 3.1 and 3.2)

The equations for predicting annual water use in the catchments are:

Kirkton (7)

$$AE=A_F[0.28P_F+(1-RD/365).FAC_F.E_{tF}] \\ +0.61.FAC_G.E_{tG}+(A_G-0.61).FAC_G.E_{tF}$$

Monachyle (8)

$$AE=A_H(I.P+(1-RD/365).FAC_H.E_t)+A_G.FAC_G.E_t$$

Table 17 *Results of applying the annual model to the Kirkton data*

	P-Q	AE[1]	AE[2]	AE[3]
1983	560	472	436	436
1984	434	532	489	489
1985	325	444	413	413
1986	547	518	477	501
1987	307	403	365	405
1988	367	425	383	459
1989	421	447	394	495
Mean	423	463	423	457

[1] Using $FAC_G = 0.65$
[2] Using $FAC_G = 0.53$
[3] Using $FAC_G = 0.53$ and A_F and A_G held constant at 0.39 and 0.61 respectively (i.e. no felling)

Table 18 *Results of applying the annual model to the Monachyle data*

	P-Q	AE[1]	AE[2]
1983	631	585	590
1984	719	645	643
1985	556	565	572
1986	758	698	707
1987	531	538	539
1988	563	634	642
1989	588	684	686
Mean	621	621	626

[1] Using $I_H = 0.21$
[2] Using $I_H = 0.23$ and $FAC_G = 0.82$

where AE is the catchment water use; A_F, A_H and A_G are the proportional areas of forest, heather and grass respectively, P_F and P_H are the annual mean precipitation totals over the forest and heather covered areas respectively, RD is the number of rain days, E_{tF}, E_{tH} and E_{tG} are the Penman estimates over the forest, heather and grass areas respectively, FAC_F, FAC_H and FAC_G are the factors to be applied to E_t to give forest, heather and grass transpiration respectively and I is the proportion of the annual precipitation lost as interception. The mean values of P, E_t and RD for each vegetation type are given in Blackie (1993).

When this model is applied with the appropriate values obtained from process studies the agreement with the catchment water balance estimates is not particularly good, as discussed in Section 4.2. In an attempt to identify possible reasons for the differences, Blackie (1993) progressively adjusted the parameters in the Kirkton and Monachyle versions until good agreement with the water balance results was achieved. Tables 17 and 18 show the results from the two most successful runs from the Kirkton and Monachyle respectively. For the Kirkton the progressive clear-felling from 1986 is taken into account with the proportional area of forest reducing from 0.39 in 1985 to 0.20 in 1989. The value of FAC_F was taken to be 1.0 while FAC_G was varied between 0.53 and 1.0; Hall and Harding (1993) showed that for one upland grass site at Balquhidder FAC_G for a complete year should be around 0.75. The output from the model run which was closest to the water balance (P-Q) data was when FAC_G was reduced to 0.53. This is significantly less than the value suggested by Hall and Harding (1993) and is thought to be due to widespread moisture stress reducing the transpiration rates from the grass growing on shallow soils.

Initially the Monachyle model runs used values of INT_H and FAC_H of 0.2 and 0.5 respectively taken from Calder (1986) and FAC_G equal to 1.0. The FAC_G value for the Monachyle would be expected to be significantly different from that in the Kirkton and that obtained from the grass lysimeters as the majority of the grass area in the Monachyle is at low altitude and is generally ungrazed and on wet soils. The model is very sensitive to variations in the INT_H parameter and the best agreement with the water balance (P-Q) results was obtained when INT_H equalled 0.21. If the FAC_G parameter is reduced to a value of 0.82 then the INT_H parameter has to be adjusted to 0.23 to maintain agreement with the (P-Q) results.

The optimised models were also used to explain the effects of land-use changes on the catchment water uses. For the Kirkton the results show reductions in annual water uses of 24 mm, 40 mm, 76 mm and 101 mm, as the area of forest is reduced from 39% to 20%. Applying the model to the 1983-89 period, but with zero forest cover, gives an estimated mean annual water use of 256 mm (i.e. 167 mm lower than the estimate with 39% forest).

The prediction of the effects of afforestation in the Monachyle indicates that the 1986 level of planting (14%) will increase the water use by 43 mm when the forest matures whereas increasing the area under forest to 31% and 56% would produce annual water use increases of 96 mm and 172 mm respectively.

5.4 Impact of land-use change on water resources

In the previous sections of this report the water use of catchments with various types of land use has been investigated using a number of process and catchment studies. These studies have focused on understanding and modelling evaporation and transpiration processes and on estimating the impact of land-use change on flows. Although the implications for water resources have been generalised to other regions of the UK (Newson & Calder, 1989) there have been only a limited number of detailed studies of the water resource implications of land use change (Calder & Newson, 1979).

In this section the flow predictions from the land use conceptual model (Eeles & Blackie, 1993), described in Section 4.2, are analysed using flow duration curves, annual minimum series and storage-yield relationships. By simulating flows for various land-use scenarios the impact of land-use change on water resources can be estimated. This analysis is described in more detail in Gustard and Wesselink (1993). The measured and simulated daily flow series were analysed using procedures described in the Low Flow Studies report (Institute of Hydrology, 1980) for deriving flow duration curves and annual minimum series and by Brown (1991) for deriving storage-yield relationships. Table 19 summarises the low flow statistics derived from the observed and simulated data.

Direct comparisons of the flow statistics between the two catchments do not allow the impact of land-use change to be assessed. This is because comparisons of the water use between two catchments is of limited significance as a result of the large differences in precipitation and Penman potential evaporation between the two catchments. To determine the sensitivity of low flows to land-use change it is therefore necessary to model the influence of land use change on each catchment and then derive low flow statistics from the simulated time series.

Mean flow

Comparison of the observed and simulated mean flows (Table 19) shows that the mean of the modelled flows is within 5% of the observed mean. The mean flow of the simulated records for the longer period 1964-88 is, in both catchments, lower than for the observed record 1984-88.

The mean flow was determined from the simulated flow records 1964-88 (Table 20) for various proportions of forest. For example, in the extreme land-use change scenario the Monachyle mean flow decreased from 0.404 to 0.315 $m^3 s^{-1}$ (i.e. by 22%) as the proportion of forest in the catchment increased from 0 to 100%. In the Kirkton catchment the mean flow decreased from 0.325 to 0.248 $m^3 s^{-1}$ (i.e. by 24%) when the same change in land use was simulated.

Table 19 *Summary of flow statistics for observed (Obs) and simulated (Sim) data*

	Monachyle			Kirkton		
	Obs 1984-88	*Sim 1984-88*	*Sim 1964-88*	*Obs 1984-88*	*Sim 1984-88*	*Sim 1964-88*
Mean flow (m^3s^{-1})	0.517	0.525	0.404	0.418	0.402	0.298
Flow duration curve						
Q95 (m^3s^{-1})	0.027	0.028	0.020	0.057	0.028	0.023
Q50 (m^3s^{-1})	0.192	0.251	0.188	0.243	0.209	0.150
Flow frequency curve						
MAM10 (m^3s^{-1})	0.019	0.028	0.019	0.051	0.027	0.020
Storage for given yield [1] and return period of 20 years						
Yield 20%	n.a.	n.a.	2.2	n.a.	n.a.	3.3
Yield 50%	n.a.	n.a.	10.9	n.a.	n.a.	6.9
Yield 80%	n.a.	n.a.	25.6	n.a.	n.a.	36.4

[1] Yield as percentage of mean flow for 0% forest. Storage as percentage of annual average runoff for 0% forest.
n.a. = not applicable

Table 20 *Summary of flow statistics for land-use change simulation over the period 1964-1988*

	Monachyle		Kirkton	
Forest cover (%)	0	100	0	100
Mean flow (m^3s^{-1})	0.404	0.315	0.325	0.248
Flow duration curve				
Q95 (m^3s^{-1})	0.020	0.017	0.024	0.020
Q50(m^3s^{-1})	0.188	0.130	0.165	0.121
Flow frequency curve				
MAM10 (m^3s^{-1})	0.019	0.016	0.020	0.019
Storage for given yield [1] and return period of 20 years				
Yield 20%	2.8	4.9	2.7	4.6
Yield 50%	13.7	24.8	14.1	23.7
Yield 80%	32.0	56.3	32.0	51.1

[1] Yield as percentage of mean flow for 0% forest. Storage as percentage of annual average runoff for 0% forest.

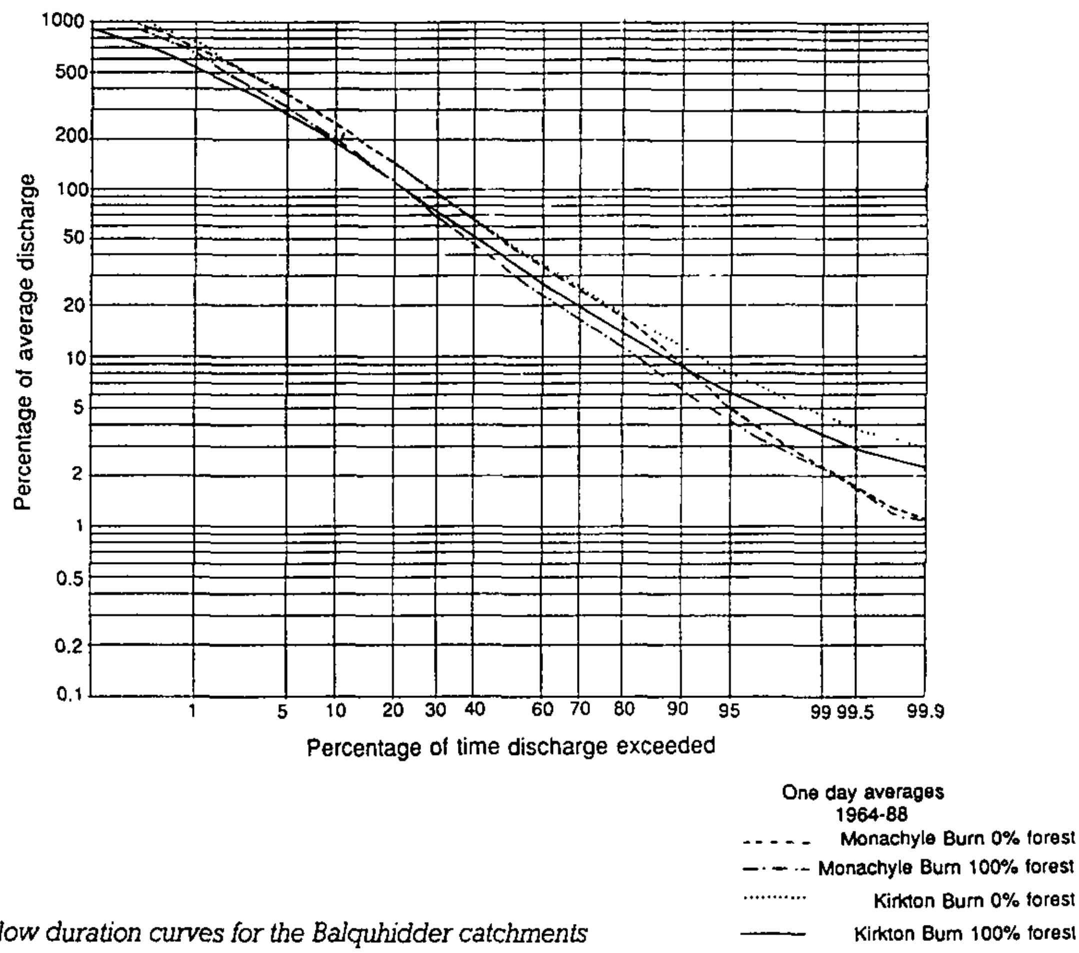


Figure 32 *Flow duration curves for the Balquhidder catchments*

Flow duration curves

Flow duration curves were derived for each catchment from the simulated data for the period 1964-88 for 0 and 100% forest (Figure 32). To facilitate comparison of curves between the catchments and with different land uses the discharge was standardised by the mean of the simulated flow series for 0% forest. In both catchments the flow duration curve shifts down with increasing proportion of forest, except at flows below the 99 percentile. Thus over most frequencies discharges are predicted to diminish as a result of increasing the proportion of forest on the catchment. For example, the estimated changes are a reduction of Q95 from 0.020 to 0.017 $m^3 s^{-1}$ and of Q50 from 0.188 to 0.130 $m^3 s^{-1}$ in the Monachyle, and a reduction of Q95 from 0.024 to 0.020 $m^3 s^{-1}$ and Q50 from 0.165 to 0.121 $m^3 s^{-1}$ in the Kirkton.

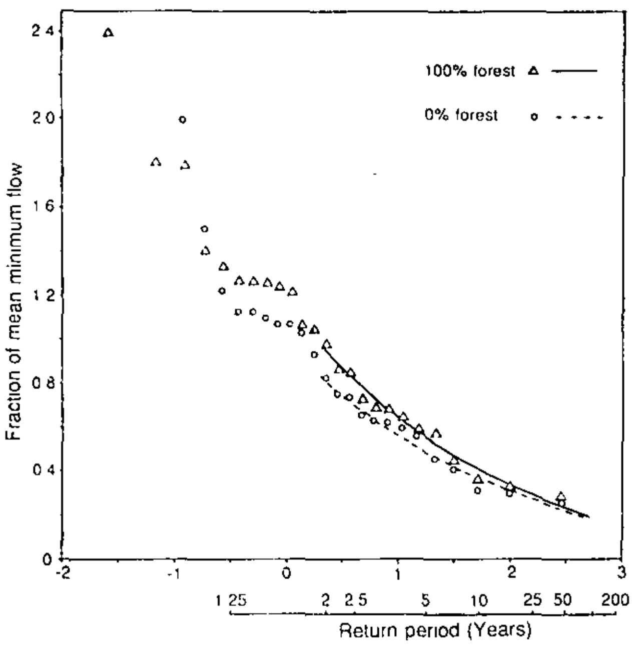


***Figure 33** 10-day minimum flow analysis for the Monachyle catchment, 1964-88*

Ten-day annual minimum series

The 10-day annual minimum series were plotted for the simulated data with 0 and 100% forest (Figure 33). In the Monachyle and the Kirkton individual minima are lower with 100% forested land use although the reduction is generally greater for the higher annual minima and is less pronounced on the Kirkton.

Storage-yield relationship

Figure 34 shows the storage-yield curves for simulated daily flows for the period 1964-88 for a return period of failure of 20 years. For each catchment the relationships are shown for 0, 50 and 100% forest cover. The curves have been standardised using the simulated mean flow for 0% forest so that direct comparisons can be made. The yield for a given storage decreases when afforestation increases. For example the reservoir needed to maintain a yield of 50% of the average flow in the Monachyle catchment with 0% forest has a volume of 14% of the mean annual runoff whereas with 100% forest the volume required is 25% of the mean annual runoff. Figure 34 shows a similar sensitivity of the storage-yield relationship to changing land use on the Kirkton catchment.

In summary the simulation runs of the calibrated model indicate that for both catchments, with increasing afforestation: (1) the mean flow decreases; (2) the flow duration curve shifts down; (3) the annual minimum series are lower; (4) the storage needed to maintain a given yield increases.

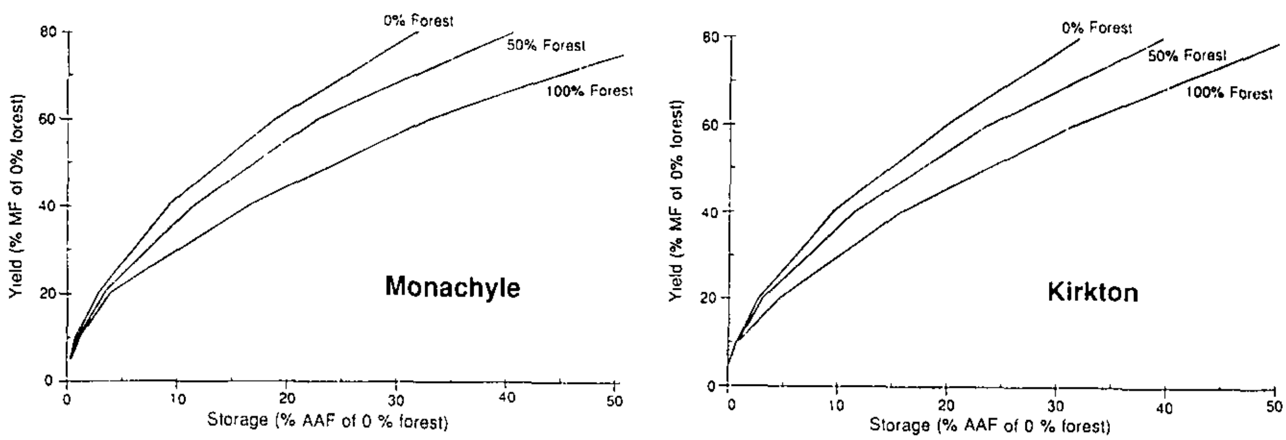


***Figure 34** Storage-yield diagram for the Balquhidder catchments including modelled land-use change*

6 Fluvial sediment studies

Fluvial sediment loads have some of the most wide-ranging implications for stream and river water quality. Frequent problems associated with sediments are reported, including the quality of public water supplies (Greene, 1987), reservoir siltation (McManus & Duck, 1985), fish habitats (Mills, 1985) and the transport of contaminants (Walling & Kane, 1982).

Suspended and bed loads are controlled by many factors, from the soils and geology of the catchment to the release and transport mechanisms such as rainfall intensity and river discharge. The release of sediment can at times be predictable, for example erosion by raindrop impact, or almost unpredictable, as in river bank collapse. This mixture of predictable and unpredictable processes is notorious in sediment analyses, quantification of river loads and catchment modelling.

In the Balquhidder catchments the sediment problem appears to be typical of most Highland catchments. Natural causes of erosion include raindrop impact, streamwater, frost, and surface drying and cracking. These processes occur to varying degrees in both catchments every year: in a study by Stott (1987) on the catchment sediment sources, the erosion of stream banks by water action was identified as the dominant

Table 21 *Summary of the sediment discharge results from the Balquhidder catchments, 1983-89*

Monachyle Year	P	SSC	n	SSL	BL	TSL	Y
1983	2659	12.6	245	293	2	295	38.3
1984	2648	20.2	91	280	2	282	36.6
1985	2612	8.8	71	326	2	328	42.6
1986	3280	40.9	179	934	3	937	121.7
1987	2255	58.9	438	909	1	910	118.2
1988	2952	25.0	741	493	2	495	64.3
1989	2985	40.0	739	1419	3	1422	184.7
1983-85 (before ploughing)	2639	14.0	407	300	2	302	39.2
1986-89 (after ploughing)	2868	38.9	2097	939	3	942	122.3
Kirkton Year	P	SSC	n	SSL	BL	TSL	Y
1983	2281	65.7	123	321	20	332	48.5
1984	2215	49.1	94	275	13	288	42.0
1985	2285	23.9	116	526	17	543	79.3
1986	2789	154.2	319	4353	27	4380	639.4
1987	1899	51.7	432	599	6	605	88.3
1988	2493	123.3	1096	4044	14	4058	592.4
1989	2519	121.1	876	3610	31	3641	531.5
1983-85 (before clearfelling)	2260	48.0	333	371	17	388	56.6
1986-89 (during clearfelling)	2425	114.9	2722	3151	19	3170	462.8

P *Total annual precipitation, mm*
SSC *Mean suspended sediment concentration, mg* l^{-1}
n *Number of samples in period*
Y *Sediment yield, t* km^{-2}.
SSL *Suspended sediment load, tonnes*
BL *Bed load, tonnes*
TSL *Total sediment load, tonnes*

natural process. In forested catchments there is also the complication of man-induced erosional processes such as increased drainage, ploughing, soil exposure, roads and vehicles. The results from the sediment studies from both catchments are discussed below.

6.1 Sediment sources within the Balquhidder catchments

Sediment sources within both catchments were extensively monitored between 1984 and 1986 (Stott, 1987). The main sources were found to be the tributary streams, with suspended loads dominating the bedloads by a ratio of 30:1. Comparing the two catchments, the monitored tributaries in the Kirkton catchment had twice the sediment yield of the monitored tributary in the Monachyle catchment. Size analyses on samples taken from the tributary banks showed that between 70% and 90% of the material was less than 2.8 mm in diameter, i.e. in the size range likely to be transported in suspension. Pebble tracing showed that movement of the material in the bed was very slow, especially in the forested catchment where organic debris jams hold back significant amounts of material. Therefore, as the relatively small amounts of bedload move very slowly, it is unlikely that significant changes will be detected at the catchment outfalls.

Since the work of Stott was published, the sediment sources have been monitored by taking spot samples in storm events around eroding sites. This work concentrated on the clearfelling in the Kirkton, as resources were limited, and whereas several other studies have been done on land cultivation (Robinson & Blyth, 1982; Francis & Taylor, 1989) little work has been done on clearfelling.

By several series of spot samples taken from forest road drains, the heavy use of roads in the timber extraction phase has been identified as a major new source of suspended sediment. Road surfaces can become very loose, especially in confined turning areas, and the route taken by surface water into the drains and tributaries is critical in determining how much sediment reaches natural water courses.

6.2 Bedload

Bedload measurements in both catchments have shown that bedload contributes a very small percentage of the annual catchment load. Without the use of traps and mechanical diggers or sophisticated measurement techniques such as developed by Reid (1984) the sampling is very difficult. Spot sampling and the development of rating curves were initially used to estimate the loads. Because of sampling problems at high flows, another method was tried later: tethering a sampler to the stream bed throughout flood events. Unfortunately the sampler had too small a capacity and was frequently washed away and damaged. The original rating curve method, with extrapolation into high flow ranges, has been used to estimate the load since 1987. Table 21 gives the best estimates of the annual bedloads.

6.3 Suspended sediment

The quantification of the suspended sediment discharged from a catchment usually relies on measurements of the sediment concentration in the stream. Table 21 shows that there have been significant changes in the mean annual suspended sediment concentrations (SSC) for both catchments between 1983-85 and 1986-89.

Although these coincide with the land-use changes in both catchments, the sampling schemes have also changed from event sampling in 1983-86 to continuous automatic sampling since 1987. This has resulted in the number of samples taken at low flows increasing considerably, although the number of samples at high flows is similar. The sample distribution in the 1987-89 period will therefore be more closely related to the flow durations than the 1983-86 samples, which are biased to the higher flows. Therefore the mean SSC is likely to be overestimated in the 1983-86 period as SSC generally increases with flow.

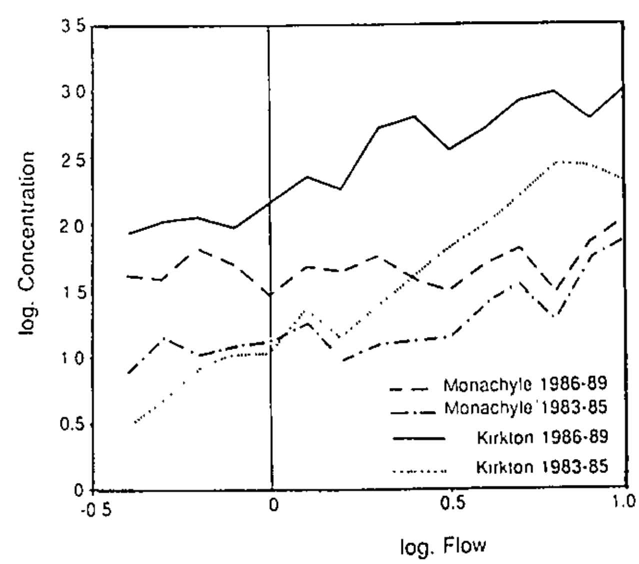


Figure 35 *Group average suspended sediment concentration for the Monachyle and Kirkton catchments*

Table 22 *Annual rating equations of suspended sediment concentrations (SSC) and streamflow (Q)*

	Kirkton			Monachyle	
1983	log (SSC) = 0.960 + 1.292 log (Q)	(r^2 = 0.560)	1983	log (SSC) = 0.691 + 0.818 log (Q)	(r^2 = 0.321)
1984	log (SSC) = 1.056 + 1.186 log (Q)	(r^2 = 0.616)	1984	log (SSC) = 0.910 + 0.443 log (Q)	(r^2 = 0.113)
1985	log (SSC) = 0.784 + 1.732 log (Q)	(r^2 = 0.567)	1985	log (SSC) = 0.768 + 0.275 log (Q)	(r^2 = 0.134)
1986	log (SSC) = 1.767 + 0.885 log (Q)	(r^2 = 0.252)	1986	log (SSC) = 1.331 + 0.239 log (Q)	(r^2 = 0.087)
1987	log (SSC) = 1.245 + 0.034 log (Q)	(r^2 = 0.000)	1987	log (SSC) = 1.076 + 0.011 log (Q)	(r^2 = 0.000)
1988	log (SSC) = 1.636 + 0.416 log (Q)	(r^2 = 0.061)	1988	log (SSC) = 0.996 + 0.289 log (Q)	(r^2 = 0.040)
1989	log (SSC) = 1.901 + 0.594 log (Q)	(r^2 = 0.177)	1989	log (SSC) = 1.491 + 0.350 log (Q)	(r^2 = 0.132)

r^2 = Coefficient of determination

The annual rating equations for SSC from both catchments (Table 22) show that there have been changes in the gradient of the equations and also in the scatter of data points. The Monachyle equations show a steady decrease in the gradient from 1983-87 with a possible upturn in the last two years. The scatter of data, given by the coefficient of determination, is large throughout, but particularly so in the period 1986 to 1988.

The Kirkton equations show a much clearer difference between the 1983-85 and 1986-89 data. The gradient becomes much gentler, because of increases in the low flow concentrations, and there is a large increase in the scatter. These findings compare favourably with results from the Loch Ard catchments, some 20 km south of Balquhidder (Ferguson *et al.*, 1992), where clearfelling was also being studied.

Figure 35 shows the mean SSC in specific flow ranges, group averages, for the two periods before and after the land uses changed. Although the SSC are shown in logarithmic units the mean values were calculated from the normalised data. Both catchments show increases in SSC in all flow ranges, but the increase is greater in low flows than in higher flows. The increase in SSC in the Monachyle low flows is around 3 times, whereas in high flows it is around 1.2 times. For the Kirkton the increase in SSC at low flows has been around 15 times, whereas at high flows it is around 4 times.

6.4 Sediment loads

The calculation of a catchment annual sediment load from data comprising spot samples is fraught with problems. The unreliability of the rating curve method has been discussed many times before, notably in Walling & Webb (1981) and Ferguson (1986). For a highly variable data set, such as the Balquhidder data, the group averages of SSC are considered to be the best method for the suspended load calculation. The mean SSC for each individual flow group remain independent of neighbouring group values, unlike a global rating curve.

Averages are calculated from each group of SSC data and applied to the flow data to derive annual loads (Table 21). By using this method the large smoothing effect, using logarithmic data in rating equations, is provided. Bedload calculation has proved more difficult because of the problems with sampling. The bedload rating equations derived from the 1983-85 period have been applied to subsequent years of flow data to provide an estimate of the loads in later years.

There is clear evidence from Table 23 and the double mass curve of monthly streamflow and sediment load (Figure 36) that sediment loads in both catchments have increased since 1986. The increase is much greater for the forested Kirkton catchment (2782 t) than for the moorland Monachyle (640 t). However, not all of the increase should be attributed to forestry: annual precipitation has also increased since 1986.

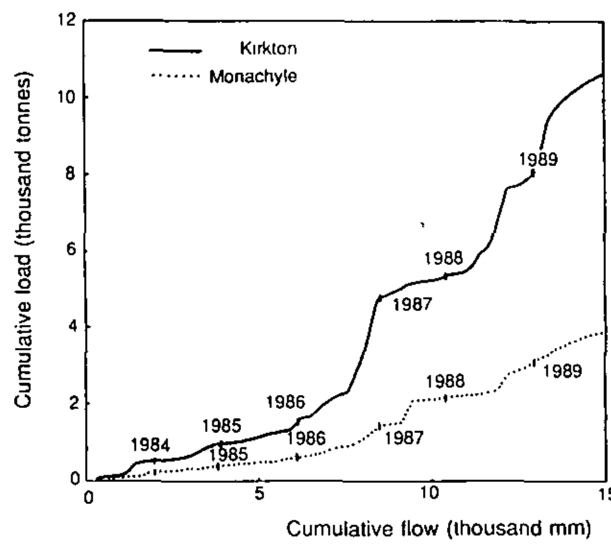


Figure 36 *Double mass curve for the Monachyle and Kirkton monthly flows and suspended sediment loads*

***Table 23** Division of the annual suspended sediment loads (tonnes) into the 'natural load' and the 'forestry load'*

	Monachyle		**Kirkton**		
	Natural	*Forestry*	*Natural*	*Forestry*	*Area felled (ha)*
1986	443	491♦	711	3642	41
1987	247	662	235	364	31
1988	344	149	358	3686	23
1989	*404*	*1015*	*672*	*2938**	
1989	1269	150	2110	1500+	7
Mean	576	363	853	2298	

** 1989 data derived from 1983-85 relationships*
+ Estimated division of 1989 data - see text
♦ Ploughing and planting

The 1986-88 pattern in the forestry loads in the Monachyle indicates a similar trend to the one derived from the Coalburn catchment data (Robinson & Blyth, 1982), although the peak sediment load was delayed by about a year in the Monachyle. The Monachyle load division also shows a large increase in forestry load in 1989.

As there was little visual evidence of reactivation of plough lines in this period, the load increase is assumed to be due to the exceptionally heavy rainfall at the start of 1989. In the first three months of 1989 a total of 1402 mm was recorded in the Monachyle catchment, i.e. 47% of the annual total. This appears to have activated many new natural sediment sources which continued to supply material throughout the year. Therefore the Monachyle 1989 forestry load has been estimated to be similar to the 1988 load: the remaining load is considered to be natural load (Table 23). As similar rainfall was experienced in the Kirkton, the natural load has also been increased by the same ratio as the Monachyle increase and the forestry load adjusted.

The Kirkton catchment results show that forestry loads are high for wet years when felling was greatest (1986 and 1988). The very dry year 1987 shows a very low sediment load, showing that even during the most active felling, high rainfall is still needed to transport the sediments. The adjusted 1989 load also fits in with a year of reduced forestry activity within the catchment, even though the rainfall was high.

7 Conclusions

The ten years of research at Balquhidder have produced a wealth of results concerning upland afforestation and water resources in Highland Scotland. The original objectives of the study, listed at the start of this report, have mostly been fulfilled.

The Balquhidder study has replicated the Plynlimon study in mid-Wales looking at the effects of upland afforestation on water resources. In each case two catchments have been studied, one partially covered by a mature coniferous forest and the other by grassland (Plynlimon) or moorland (Balquhidder).

Instrument networks have measured precipitation input, storage changes within the catchments and the streamflow from the catchments. From these data the annual water use has been shown to average 423 mm for the Kirkton and 621 mm for the Monachyle.

Five automatic weather stations distributed throughout the catchments have shown that in general potential evaporation increases with altitude and exposure although the relationship is not simple in these catchments with rugged topography. Wind speed, specific humidity deficit and net radiation control the potential evaporation distribution with the latter term being the dominant. Site studies of evaporation rates from grass, heather and forest have shown that grass has a very low annual evaporation rate compared to heather and forest and is estimated to be 0.75 of the annual potential evaporation. Distribution of the main vegetation types in an upland catchment is critical in determining the catchment evaporation rate.

A catchment evaporation model (THISTLE) has been developed from the process studies carried out at sites within the Balquhidder catchments and other UK studies. The major vegetation types and areal cover have been identified from ground and aerial surveys and related to catchment topography. Intensive site studies on the evaporation rates from grass and the interception of forest have been carried out through different seasons to develop the individual components of the composite catchment evaporation model.

The effects on streamflow of the land-use changes in the catchments have been assessed using existing models. These have shown how sensitive upland catchments can be to changes, although these changes are often difficult to detect and require long-term monitoring. It has also been proposed that the models can be used to design forest developments and to reduce their impacts to a minimum. Catchment water yield models have been used with the Balquhidder data to indicate the potential effects of forestry on catchment reservoir management.

The Balquhidder research has therefore fulfilled most of the original objectives of the project and in doing this has produced a range of research results which will be of value to water resources management. The application of the results to other regions of Scotland should be the next step and also the implications of changes in forestry practice to the results. The need to continue the monitoring at Balquhidder is frequently demonstrated in the demands for long-term precision data sets which well-established research catchments can supply.

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The Balquhidder Catchment and Process Studies

A special issue of *Journal of Hydrology* (Volume 145 Nos. 3-4), published 1993

CONTENTS