Effects on Water Resources of Upland Management Practices

A Report submitted to the

Department of the Environment

on completion of

Contract PECD 7/7/133

Compiled by:

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of

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The INSTITUTE OF HYDROLOGY is a component body of the
NATURAL ENVIRONMENT RESEARCH COUNCIL

Executive Summary

The water resources of upland Britain provide the greater part of the nation's water supply. In addition they are used to produce a significant contribution to the electricity supply, particularly in Scotland, and are exploited by the freshwater fisheries industry to the considerable benefit of the rural economy. These industries exist because of the large volumes of high quality streamflow emanating from the upland areas. The high precipitation received in the uplands is the origin of this streamflow but the volume, its time distribution and its quality are influenced significantly by the vegetation cover present and the way it is manipulated. Changes in the land-use which modify either the quantity or quality of streamflow are a source of economic concern to these industries as well as environmental concern to all organisations with interests in the uplands.

The effects of upland management on streamflow quality have been studied intensively in a concurrent project, also funded in part by DOE, and a report has been submitted[(1)].

This project is designed to obtain detailed information on the effects on streamflow volume and on stream sediment loads of upland afforestation. It is targeted at the more extreme climatic conditions exemplified by the Highlands of Scotland where the main thrust of upland afforestation is now concentrated. This area provides a contrast to earlier intensive studies in mid-Wales in that forestry is replacing a vegetation complex dominated by heather rather than upland pasture and a large proportion of the preciptation falls as snow. It was anticipated, correctly as this report demonstrates, that models developed from previous studies in less extreme conditions would prove inadequate in predicting water use and streamflow changes in these areas.

The project consists of studies of two typical Highland catchments at Balquhidder in Central Region as they are subjected to various phases of afforestation and of studies of the key hydrological processes controlling water use, streamflow response and sediment yield. Details of the evolution of the project and of the other funding agencies involved are given in Appendix 1.

In 1984 DOE agreed a contract with the Institute of Hydrology covering 25% of the cost of the project, initially for a period of two years. In the light of the early findings this contract was enlarged and extended for a further two years. This report covers the information gained during the entire contract period.

In the period covered by the extended DOE contract much new information has been gained on the interactions of land use and hydrology in the more extreme upland conditions characterised by the Balquhidder catchments and the sites used for the process studies. This has made it possible to extend the range of existing predictive models and improve the basic structure of them, to the extent that they now produce more accurate predictions not only in Highland Scotland but also for sites elsewhere in Britain.

The catchment studies produced unexpected results from the three year period prior to land use changes being implemented. Water use by the heather/grass covered Monachyle catchment was found to be significantly higher than that by the part mature forested, part grassland Kirkton catchment. Not only that, but the best current estimates of Penman potential water use, ET, for the catchments suggest that water use in the Monachyle is greater than ET, whilst that for the Kirkton is significantly less than ET. Neither of these results was anticipated when the programme was initiated. Existing models would have predicted water use for the Kirkton to be significantly greater than Penman ET. The Kirkton findings, indeed, made it necessary to expand the programme to incorporate an additional study to clarify the water use processes of the high altitude grassland within this catchment.

A combination of the initial findings from this additional study with the results from the other process studies and with existing knowledge has resulted in a provisional model which can reproduce the Monachyle results with reasonable accuracy. The general applicability of this model is demonstrated by the fact that it also predicts water use by the Plynlimon catchments in Wales more accurately than previous models. This model requires further confirmation before it can be used with confidence in the Kirkton combination of forest and high altitude grassland, but this should be forthcoming within the next two years with the completion of the grassland study.

Results for upland Wales and elsewhere have shown that a major loss mechanism from forests is the interception of rainfall by the forest canopy and its subsequent evaporation. Studies of the interception of snow by forest canopies at Aviemore and Balquhidder have shown such losses are at least as large when precipitation is in this form, and in some circumstances the losses can be larger. An hourly model to describe this process has been developed and tested. A simpler model which can be incorporated in the simple catchment models described above is under development.

The catchment studies have also brought to light the fact that Penman ET is much higher at altitude than had been assumed previously. Summer values in particular are significantly higher on the upper reaches of the catchments than at the valley bottom sites, contrary to the previous assumption of a reduction with altitude. This finding calls into question the basis for the present methods of estimating regional ET values for upland areas by extrapolation from low altitude sites.

During the three year Phase I period of the catchment studies, before the clear-felling of the forest in the Kirkton and the forest planting in the Monachyle, it was found that sediment losses from the Kirkton were approximately 50% higher than those from the Monachyle. These losses were mainly in the form of fine, suspended material with less than 2% occurring as bedload movement. The reasons for the greater loss from the Kirkton were not positively identified but the sources appeared to be in the lower (forested) reaches of the tributary streams. The Kirkton catchment also contained a system of forest roads, not present in the Monachyle. In the first year of Phase II of the studies, when the felling in the Kirkton and the planting in the Monachyle began, large increases in sediment loads were apparent by the end of the year in both catchments and losses at these higher rates have continued through the second year. Whilst the magnitudes of these increases, quoted provisionally in the range 3-5 times in both catchments, are still the

subject of investigation, the reasons for them have been identified as the ploughing and drainage of 6% of the Monachyle and the intensified use of the road system in the Kirkton.

A number of proposals for future work are made in the final section. Of highest priority are the completion of studies already started, such as the high-altitude grassland study, the continued development of the simple seasonal model and the continuation of the catchment studies through the present phase of land use changes so that the effects of these on water use and sediment loss rates can be quantified.

A number of other strategic studies which would be of great relevance to prediction of the effects of land-use on upland water resources are also submitted for consideration. These include a re-examination of the basis for estimating the evaporative climate in Highland Scotland in the light of the findings of the present studies. By implication this would also be relevant to the other upland areas of Britain. Also included are a proposal to extend the work on the relationships between land use and low flows and one to mount a study of the interception and transpiration of larch, a proposal which was deferred because of other priorities during the present project.

(1) "Upland Management and Water Resources". A report submitted to Department of the Environment and Welsh Office by NERC on completion of Contract PECD 7/7/159, April, 1988.

Contents

1. Introduction

By the late 1970s it was becoming apparent that the main thrust of upland afforestation for the rest of the 20th Century and beyond would be concentrated on Highland Scotland. Against this background, the research results from studies of the hydrological effects of upland afforestation, carried out mainly in mid-Wales and Cumbria, and the prediction models developed from these results were being scrutinised to determine their validity in the very different climatic, topographic and vegetation conditions in Highland Scotland. Sufficient doubts were expressed to warrant the planning of new studies in this environment. From discussions with a wide range of interested parties, a research programme proposal was evolved by the Institute of Hydrology. After further evaluation and discussion a 'consortium' of agencies lead by DOE and the Scottish Development Department agreed in 1981 to fund the initial stages of this programme. Also included in the consortium were WRC, representing Scottish water supply interests, Forestry Commission, the North of Scotland Hydro-Electric Board, British Waterways Board and, initially, the Department of Energy. In addition, a major contribution to the costs of the programme has come from NERC Science Budget.

In 1984, DOE agreed to a further contract to cover the period 1984-86. This was subsequently extended, with modified objectives, to cover the period to March 1988. Details of the contract and its objectives are given in Appendix 1. This report is submitted in accordance with the requirements of this contract.

This contract, in common with those prepared by the other 'consortium' members supporting the programme, had as its objective the improvement of the information base so that the hydrological effects of afforestation could be predicted more accurately over a wider range of environments than was possible with the existing models. The programme designed to meet this objective was particularly concerned with those aspects of the Scottish Highland environment which had not been covered by previous research. As indicated above, this direction was in response to the fact that this region will be the focus for new afforestation for the foreseeable future. The economic importance of clarifying the effects of afforestation in this region was reflected by the organisations forming the 'consortium'. Water supply, hydro-electric power generation, canal operations and freshwater fisheries could all be directly affected by any significant changes in streamflow whilst forestry had an obvious interest in determining whether their case for expansion in this region could be justified.

Whilst the emphasis of the programme is on conditions pertaining to forestry in Highland Scotland, it must be emphasised that the knowledge obtained in these extreme conditions has relevance throughout Britain. As an example, it has been found that improved predictions of water use in upland Welsh catchments are obtained by the use of models modified to incorporate preliminary findings for this programme.

The research programme comprised two main components which were to be pursued in parallel. These were a 'process studies' component and a *'catchment studies' component. The process studies were directed initially to* aspects such as the water use characteristics of heather and the interception of snow by forest canopies which were perceived as being important features of the hydrological cycle in this environment. The first phase of the catchment studies was aimed at providing water use and sediment transport information from two similar catchments typifying the Highland environment, of which one was under a heather/grass/bracken vegetation complex and the other contained a typical area of mature forest. These studies identified further processes which required to be quantified before existing models could be expected to reproduce the results obtained from the catchments and led to the modification and extension of the contract as mentioned above. This extension also included a second phase of the catchment studies in which the established instrument networks would be used to determine the changes in water use, streamflow response and sediment yield brought about by initial forest planting in one catchment and progressive clear felling of the mature forest in the other.

In the following sections the work carried out under both components of the programme and the results emerging are summarised. Much of the detail has already been presented to DOE and the other funding agencies in routine reports, in reports presented at the annual meetings of the Steering Committee of the funding consortium and at the two-day Workshop held in Edinburgh in December 1987. With the blessing of the funding agencies a number of papers have been published on the results. Copies of these are included in Appendices 2-5.

Whilst it has no direct bearing on this DOE contract, it should be noted that a number of organisations have mounted self-funded climatic and biological studies within the instrumented catchments at Balquhidder used in the catchment component of this programme. Hydrological data have been made freely available to these organisations and IH staff have assisted in their field activities. As a result the harvest of information reaped from the investment in these catchments has been much greater than originally envisaged, with detailed information on the effects of forestry and forestry operations on streamwater chemistry, nutrient cycling and aquatic biota being added to the water quantity information reported on here. The results emerging from these self-funded activities within the general framework of this programme are relevant in that they will provide interesting comparisons with the results from the DOE project on upland management and water quality [1] on which a final report has now been submitted.

(1) "Upland Management and Water Resources" A report submitted to Department of the Environment and Welsh Office by NERC on completion of Contract PECD 7/7/159, April, 1988.

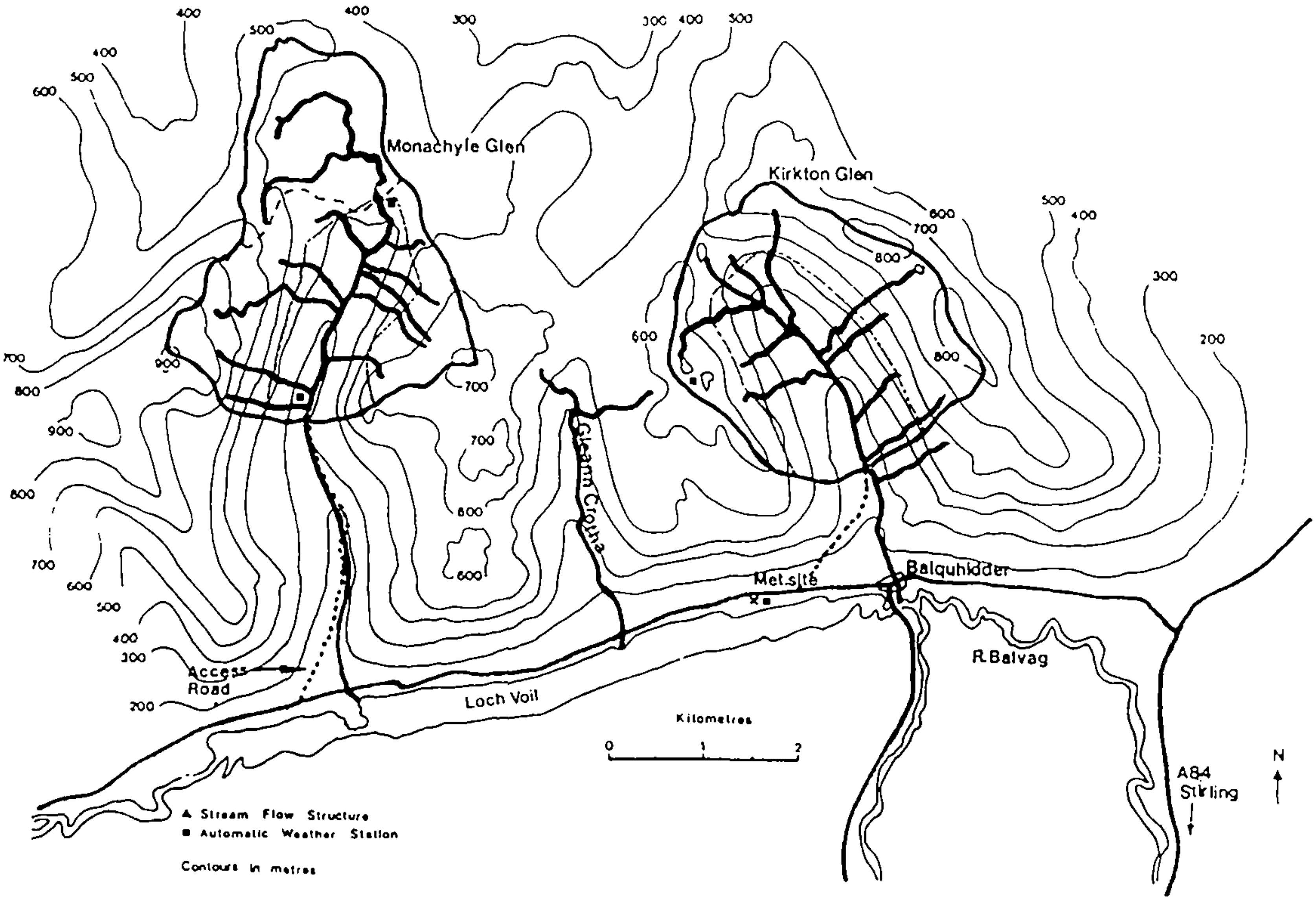


Figure 1. *The Balquhidder catchments*

2. The Balquhidder Catchment Studies

Results from the two catchments at Balquhidder which were instrumented in 1981/82 form the basis of the work covered in this part of the report. These catchments, chosen originally to typify Scottish Highland conditions of climate, topography and soils, are the Monachyle Glen of 7.7 km^2 and the Kirkton Glen of 6.85 km^2 located as shown in Fig. 1. Both are aligned approximately N-S and range in altitude from just under 300 m to over 800 m. Whilst they are generally similar in topography, geology and soils, they are not identical in these respects. The underlying geology is mainly Ben Lui schists but a survey of the Kirkton commissioned by SDD (Robins & Mendum 1987) has revealed outcropping of the Loch Tay Series of metamorphosed limestones which are not present in the Monachyle. Whilst the survey suggests no significant cross-boundary flow in the limestone, its presence means that the Kirkton stream is much less acid than that from the Monachyle. The main valley slopes are generally similar, though there is more exposed rock in Monachyle, particularly on the west side, than in the Kirkton. Soils are generally shallow and are a complex of peats, peaty gleys and brown earths in both though there is an area of gentler gradient containing deeper peat at the head of the Monachyle catchment. This area has been gauged separately as a nested sub-catchment.

Perhaps the greatest difference between the catchments that has become apparent during the study period is the difference in precipitation. Whilst its time distribution is very similar in both, the more westerly Monachyle receives on average 17% more than the Kirkton.

The vegetation cover on the catchments at the start of the study consisted of a mixed heather, grass, bracken and scrub forest cover on the Monachyle, with heather dominant overall, though grasses and rushes dominate in the valley bottom. In the Kirkton a mature forest cover in which spruce was the main species dominated the lower 40% of the catchment with a high altitude grassland complex on the slopes above the forest planting limit of 500 m, with heather becoming dominant on the ridge tops.

Since the start of Phase II of the study early in 1986, land preparation and planting has progressed in the Monachyle to the point where 10% of the catchment (14% of the lower catchment) has been planted so far.

Clear-felling started on the lower, western side of the Kirkton in 1986 and by the end of 1987 40% of the forest had been felled.

Installation of the instrument networks began in 1981 with part of the raingauge network and the Automatic Weather Stations (AWS) at the Lower Monachyle and Kirkton High sites. The basic raingauge networks of 11 sites in each catchment were completed in 1982 with further additions of snow gauges and standard gauges in the Kirkton clearing sites in 1983 and 1984. Additional gauges were installed in 1986 and 1987 to check on the performance of the basic networks. The design philosophy of these networks, illustrated in Figures 2.1.1 and 2.1.2 is described in detail in Section 2.1.1.

Two more AWS were installed, at Tulloch Farm in 1982 and at the Upper

Monachyle site in 1984. As a check on meteorological conditions within the Kirkton, a further AWS was installed above the forest canopy, as shown in Fig. 2.1.2 in 1986.

The main Crump weirs at the catchment outfalls were installed in 1982 and became fully operational by July and October in the Kirkton and Monachyle respectively. The accompanying low flow flumes became operational in July 1982 and August 1983. The all aluminium trapezoidal flume in the upper Monachyle was fabricated at IH. It was then knocked down into appropriate size packages and transported from the Monachyle road head to the site by helicopter in April 1983. It became fully operational in July 1983. Details of these structures and their ratings are given in Sections 2.3.1 and 2.3.2. In addition to the instrumentation for precipitation, streamflow and meteorological measurements, equipment was also installed at each main streamflow structure to monitor both suspended and bedload sediment movement out of the catchments. This was supplemented by studies of sediment sources within the catchments carried out by a CASE student from Stirling University. As part of the Process Studies programme, three sites within the catchments were chosen for intensive soil moisture monitoring using the neutron probe technique. One was under heather close to the upper Monachyle site, one under grass close to the lower Monachyle site and the third was under mature spruce in the Kirkton. Adjacent to this latter site a mature, even stand of spruce on flat ground was instrumented to measure throughfall and stemflow. These measurements, in conjunction with direct precipitation measurements in the adjacent clearing, yielded estimates of interception losses in the forested area of the catchment until this forest block was felled in 1986.

2.1 PRECIPITATION

It was recognised from the outset that the accurate assessment of precipitation to these catchments would present considerable difficulties. The altitude ranges from under 300 m to over 800 m meant that a considerable range of precipitation could be expected. For much of the winter this would consist of mixed precipitation with many periods of snow accumulation at the higher altitudes. The steep slopes, rugged microtopography and high wind speeds would require specialist gauges to obtain point measurements. Measurement of snow inputs, difficult even on level terrain when accompanied by high windspeeds, would be particularly difficult here especially as the topography and the limited manpower precluded systematic depth/density surveys.

It was concluded on the basis of long experience in the Plynlimon catchment that the best method of point measurement of rainfall would be the ground level gauge with anti-splash grid (Rodda 1967). Both gauge and grid would have to be level with and parallel to the surrounding surface, necessitating cosine corrections to the observed catch on steep slopes. Because of the difficulties inherent in operating tipping bucket systems on sloping sites and the errors arising where these are used in frost prone conditions, the basic networks would have to use manually read storage gauges. Time distribution would be derived from a sparse network of recording gauges at 'easier' sites.

Whilst the ground level gauge is the best answer for rainfall measurement at windy sites it is of little use when snow accumulates and drifts. Estimation of snow inputs would have to be by other means. The methods tried and those finally adopted are discussed in Section 2.1.2.

2.1.1 Network Design

Clearly it was necessary to install dense networks of gauges in each catchment if the anticipated large variations in precipitation were to be sampled adequately. On the assumption that the major controls would be altitude, aspect and slope, the networks were designed on the basis of domain theory. This is a stratified random sampling technique which distributes gauges at random within each 'domain' of altitude, aspect and slope in proportion to their frequencies of occurrence. Details of the application of the theory to these catchments have been presented in earlier reports. The resulting networks of 11 gauges in each catchment are shown in Figs. 2.1.1 and 2.1.2. As a check on the validity of the measurements obtained, a number of additional gauges were installed in 1986/87 in domains where the long-term figures showed consistent large departures from the catchment means. These additional gauges indicated by, e.g., (2) after the site codes are also shown in Figs. 2.1.1 and 2.1.2.

2.1.2 Snow Estimation

The above networks of ground-level gauges were designed to estimate liquid precipitation inputs. A number of methods of estimating snow inputs have been considered and tried over the period of the study. These included networks of snow poles and networks of melt-gauges, neither of which proved particularly useful. The method used to estimate inputs when the complete catchments experience snow-fall is based on a network of 5 of the main network sites in the Kirkton catchment. These sites are in sheltered clearings where it is possible to obtain accurate estimates of the input in each snow event using either standard Meteorological Office gauges or 1 m tall snow gauges installed adjacent to the ground level gauges. These are supplemented by depth/density sampling when necessary. At an early stage in the study it was observed that the between-site relationships in the main networks for 'rainfall-only' periods remain remarkably constant with time (see Section 2.1.4). This stable distribution pattern for liquid preciptation is assumed to apply also to snow inputs. Measurements at the five 'snow' sites are then used with these inter-site relationships to estimate inputs at the remaining 17 sites, the measurements being obtained from the standard Meteorological Office gauges when minor falls occur and from the tall gauges when the former are over-topped.

Whilst complete snow cover on the catchments is generally restricted to the December-February period, the high altitude raingauge sites can experience snow inputs at any time between October and May. To correct the readings of the ground level gauges at these sites for reading periods when snow was observed to occur, a similar approach to the above is used, i.e. the inputs of the affected gauges are estimated using the established between-site relationships.
To obviate the use of 3 different types of gauges, a 1 m tall shielded snow/rain gauge has been designed. A prototype is now on test within the catchments with encouraging results.

2.1.3 Time Distribution

The networks of ground level gauges are read at approximately monthly intervals by the resident observer. To reduce these readings to a common time base for analytical purposes the design intention was to use a smaller network of recording gauges. This comprised of gauges attached to each of the four AWS plus one additional event recorder in each catchment. To assist in detailed analysis of the streamflow from the catchments a time-distribution to hourly intervals was considered to be desirable. For other purposes daily or monthly intervals were considered to be adequate.

At an early stage in the studies it became apparent that it would not be possible to achieve a continuous data base of hourly time distributed rainfall. Intermittent logger problems and frequent erroneous readings in winter due to freezing, snowmelt and drift accumulation meant that large parts of the recording gauge records were suspect. This, incidentally, served to justify the choice of storage gauges rather than recording gauges from the main networks. For summer periods, a reasonably consistent body of hourly distributed data has now been established but an alternative method had to be adopted to obtain the continuous time distributed record necessary for water balance and other analyses. This method was based on the daily gauge readings taken at the Tulloch Farm manual meteorological site (Fig. 1.).

Period gauge totals for each site were compared with the Tulloch Farm total for the same period and time distributed proportionally into daily intervals. Timing errors due to differences in reading time between Tulloch Farm and each site make the accuracy of the daily values so obtained dubious. The errors are effectively random however and become progressively less significant when these values are bulked into longer period totals.

2.1.4 Inter-Site Relationships

Precipitation network design is not an exact science. The relative effects of such features as altitude, slope, aspect and location differ from catchment to catchment. Consequently the effectiveness of a particular design has to be assessed after a significant body of data has been acquired. In this case a number of interesting points have emerged from the analysis.

The most significant of these is the remarkable stability of the between-site relationships. This is demonstrated in Tables 2.1.1 and 2.1.2 where the ratio of each gauge to the catchment arithmetic mean for snow-free periods in each of three successive years are presented. The ratios of each site relative to the mean of the five snow measuring sites in the Kirkton are also included in these tables and show similar stability. As indicated in 2.1.2, these intersite relationships have been used to infill gaps in the individual site records, particularly during snow periods. The complete annual records for each site, including months infilled by this method, are listed in Table 2.1.3 where it can be seen that the ratios remain essentially similar.

Whilst this stability in the pattern of rainfall distribution within catchments and between catchments is interesting and encouraging, it does not offer an immediate indication of the physical factors which control it. Consideration of the catchment isohyetal maps in Figs. 2.1.3 and 2.1.4, derived from the 1982-86 annual means, indicates that altitude and aspect play some part. As shown in Fig. 2.1.5, longitude is also an important factor but none of these offer a complete explanation. In particular the consistently low values in domain C3Y (see Fig. 2.1.4) in the Kirkton and domains B2Z and B1Y (Fig. 2.1.3) in the NE of the Monachyle are puzzling. To check on the readings from gauge C3Y in the Kirkton two additional gauges were installed in the domain in 1986 and 1987. Comparison of the catches in all three gauges during snow free periods in Fig. 2.1.6 shows some scatter but gives no indication that the original gauge was in error. Equally, no evidence of gauge error has been found for the Monachyle gauges.

The longitudinal trend of rainfall over the area and its rapid decrease with decreasing altitude on the 'sheltered' east facing slopes are consistent with the predominantly westerly rain bearing winds and the N-S configuration of the catchments with the highest land to the west of the Monachyle (Fig.2. 1). The anomalous patterns on the west-facing slopes (Figs. 2.1.3 and 2.1.4) are less easy to explain but are possibly a product of the sheltering effects of, and the macro-turbulence created by, the westerly ridges.

2.1.5 Catchment Means

In the absence of well defined relationships between precipitation and topography the best method of computation of catchment areal means becomes a matter of debate. The domain theory requires that each gauge be weighted by the area of the domain sampled. Alternatively, these dense networks can be regarded as a random sampling system and the arithmetic mean computed. Further possibilities are the Theissen polygon approach or integration of the isohyets. The latter is always open to objection on the basis of the subjective element involved in drawing the isohyets and the Theissen method is not normally considered suitable for areas containing steep local rainfall gradients.

Computations of annual totals for both catchments by the domain weighted and arithmetic mean approaches give very similar results, as shown in Table 2.1.4. This is essentially because the networks are self-weighted, i.e. the number of gauges per unit area in each domain is relatively uniform. The 1% difference in the Kirkton arises mainly from the higher than average weighting of the low reading C3Y domain. The standard errors computed for the annual arithmetic means are, of course, to be treated with caution in this context since it has been shown that persistent systematic differences exist between gauges and it is not valid to regard them as an unbiased series of estimates of the mean.

Considering the uncertainties surrounding both estimates, the arithmetic means have been used for the catchment water balance computations in Section 2.5.

TABLE 2.1.1 Precipitation distribution within the Monachyle during rainfall only periods

	GROUND LEVEL GAUGES											CATCHMENT MEAN	KIRKTON CLEARING MEAN
	A1X	A3X	B1W	B1X	B1Y	B2W	B2X	B2Z	B3Z	C2W	C2Z	(MM)	(CM)
TOTALS, 7.83-11.83	994	1069	1075	1035	953	1049	1019	821	1021	1183	1067	1026	843
RATIOS, GAUGE/MM	0.97	1.04	1.05	1.01	0.93	1.02	0.99	0.80	0.99	1.15	1.04		0.822
RATIOS. GAUGE/CM	1.18	1.27	1.27	1.23	1.13	1.24	1.21	0.97	1.19	1.40	1.27	1.216	
TOTALS, 6.84-12.84	1650	1744	1825	1741	1580	1757	1741	1445	1665	1902	1741	1708	1391
RATIOS, GAUGE/MM	0.97	1.02	1.07	1.02	0.93	1.03	1.02	0.85	0.97	1.11	1.02		0.814
RATIOS, GAUGE/CM	1.19	1.25	1.31	1.25	1.14	1.26	1.25	1.04	1.20	1.37	1.25	1.228	
TOTALS, 4.85-10.85	1554	1622	1666	1622	1495	1686	1658	1429	1564	1800	1695	1617	1382
RATIOS, GAUGE/MM	0.96	1.00	1.03	1.00	0.92	1.04	1.02	0.88	0.97	1.11	1.05		0.854
RATIOS, GAUGE/CM	1.13	1.17	1.21	1.17	1.08	1.22	1.20	1.03	1.13	1.30	1.23	1.171	
TOTALS, ABOVE PERIODS	4198	4435	4565	4398	4028	4492	4417	3695	4229	4885	4503	4351	3616
RATIOS, GAUGE/MM	0.97	1.02	1.05	1.01	0.93	1.03	1.01	0.85	0.97	1.12	1.04		0.831
RATIONS, GAUGE/CM	1.16	1.23	1.26	1.22	1.11	1.24	1.22	1.02	1.17	1.35	1.25	1.203	

TABLE 2.1.2 Precipitation distribution within the Kirkton during rainfall only periods

	GROUND LEVEL GAUGES											CATCHMENT MEAN	KIRKTON CLEARING MEAN
	A1W	A2W	A3W	A3Y	B3W	B3Y	C1W	C3W	C3Y	D2Y	D3Y	(KM)	(CM)
TOTALS, 7.83-11.83	822	849	826	809	910	872	977	936	726	933	949	874	843
RATIOS, GAUGE/KM	0.94	0.97	0.95	0.93	1.04	1.00	1.12	1.07	0.83	1.07	1.09		0.965
RATIOS. GAUGE/CM	0.97	1.01	0.98	0.96	1.08	1.03	1.16	1.11	0.86	1.11	1.13	1.036	
TOTALS, 6.84-12.84	1363	1455	1373	1324	1439	1421	1553	1504	1082	1483	1497	1409	1391
RATIOS, GAUGE/KM	0.97	1.03	0.97	0.94	1.02	1.01	1.10	1.07	0.77	1.05	1.06		0.987
RATIOS, GAUGE/CM	0.98	1.05	0.99	0.95	1.03	1.02	1.12	1.08	0.78	1.07	1.08	1.013	
TOTALS, 4.85-10.85	1322	1477	1334	1319	1447	1477	1504	1531	1180	1567	1586	1431	1382
RATIOS, GAUGE/KM	0.92	1.03	0.93	0.92	1.01	1.03	1.05	1.07	0.82	1.09	1.11		0.965
RATIOS, GAUGE/CM	0.96	1.07	0.97	0.95	1.05	1.07	1.09	1.11	0.85	1.13	1.15	1.036	
TOTALS, ABOVE PERIODS	3507	3781	3533	3452	3797	3770	4034	3972	2988	3983	4032	3718	3616
RATIOS, GAUGE/KM	0.94	1.02	0.95	0.93	1.02	1.02	1.09	1.07	0.81	1.07	1.09		0.974
RATIOS, GAUGE/CM	0.97	1.05	0.98	0.95	1.05	1.04	1.12	1.10	0.83	1.10	1.12	1.027	

TABLE 2.1.3 *Ratios of Gauge Catch to Catchment Mean Precipitation*

Monachyle

	A 1X	A 3X	B 1W	B 1X	B 1Y	B 2W	B 2X	B 2Z	B 3Z	C 2W	C 2Z	Mean
1982	0.9587	1.0198	1.0885	1.0097	0.9089	1.0340	1.0693	0.8252	0.9575	1.1208	1.0075	3100.3
1983	0.9757	1.0396	1.0457	1.0068	0.9401	1.0260	1.0258	0.8004	0.9674	1.1329	1.0397	2810.6
1984	0.9553	1.0194	1.0615	1.0172	0.9206	1.0279	1.0177	0.8434	0.9950	1.1166	1.0256	2582.4
1985	0.9622	1.0099	1.0363	1.0071	0.9240	1.0383	1.0211	0.8708	0.9692	1.1162	1.0449	2519.5
1986	0.9646	1.0155	1.0447	1.0170	0.9116	1.0637	1.0293	0.8241	0.9483	1.1322	1.0492	3147.5
Mean Factor	0.9634	1.0209	1.0561	1.0117	0.9205	1.0387	1.0338	0.8315	0.9663	1.1241	1.0331	
Mean	2728.3	2891.4	2990.8	2865.1	2607.0	2941.6	2927.8	2354.8	2736.7	3183.6	2925.9	2832.1

Kirkton

	A1W	A2W	A3W	A3Y	B3W	B3Y	C1W	C3W	C3Y	D2Y	D3Y	Mean
1982	0.9433	1.0130	0.9931	0.9207	0.9975	1.0074	1.0963	1.1884	0.8507	1.0175	0.9722	2761.2
1983	0.9202	1.0010	0.9462	0.8946	0.9919	0.9974	1.1240	1.1335	0.8175	1.0761	1.0976	2368.1
1984	0.9880	1.0404	0.9701	0.9128	0.9962	1.0110	1.0895	1.0708	0.7825	1.0633	1.0753	2162.4
1985	0.9391	1.0258	0.9338	0.9223	1.0055	1.0249	1.0538	1.0696	0.8378	1.0861	1.1013	2208.0
1986	0.9485	1.0286	0.9346	0.9498	0.9963	1.0168	1.1383	1.0681	0.7906	1.0576	1.0709	2684.0
Mean Factor	0.9471	1.0213	0.9563	0.9209	0.9973	1.0113	1.1020	1.1088	0.8165	1.0582	1.0560	
Mean	2307.9	2488.6	2330.2	2244.1	2430.3	2464.4	2685.4	2701.9	1989.8	2578.7	2582.9	2436.8

TABLE 2.1.4 *Comparison of Areal Precipitation Estimates*

	MONACHYLE			UPPER MONACHYLE			KIRKTON		
	Domain	Arithmetic	SEE	Domain	Arithmetic	SEE	Domain	Arithmetic	SEE
1982	3088	3100	79	3153	3169	97	2729	2761	73
1983	2801	2811	71	2829	2835	51	2344	2368	72
1984	2575	2582	56	2600	2606	61	2123	2162	58
1985	2515	2519	50	2521	2533	53	2195	2208	54
1986	3142	3147	79	3165	3189	84	2643	2684	75
Mean	2824	2832	66	2854	2866	68	2407	2437	
% Diff.		+ 0.3			+ 0.4			+ 1.2	

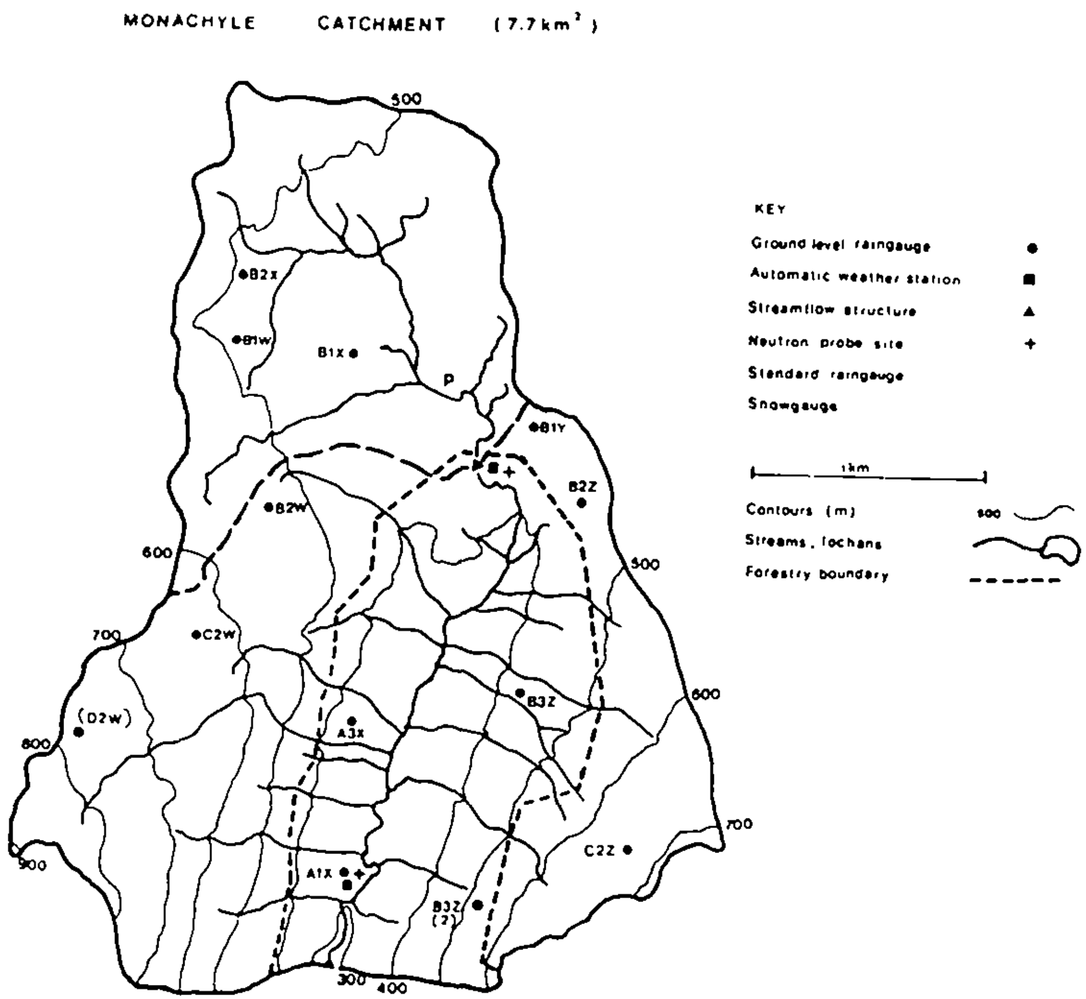


Figure 2.1.1 Instrument network in Monachyle catchment

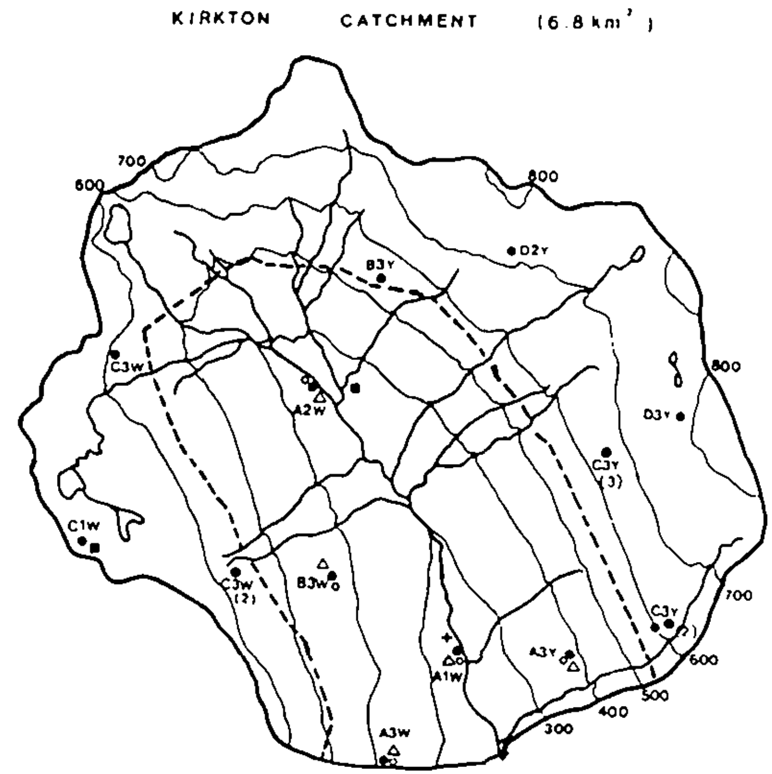


Figure 2.1.2 Instrument networks in Kirkton catchment

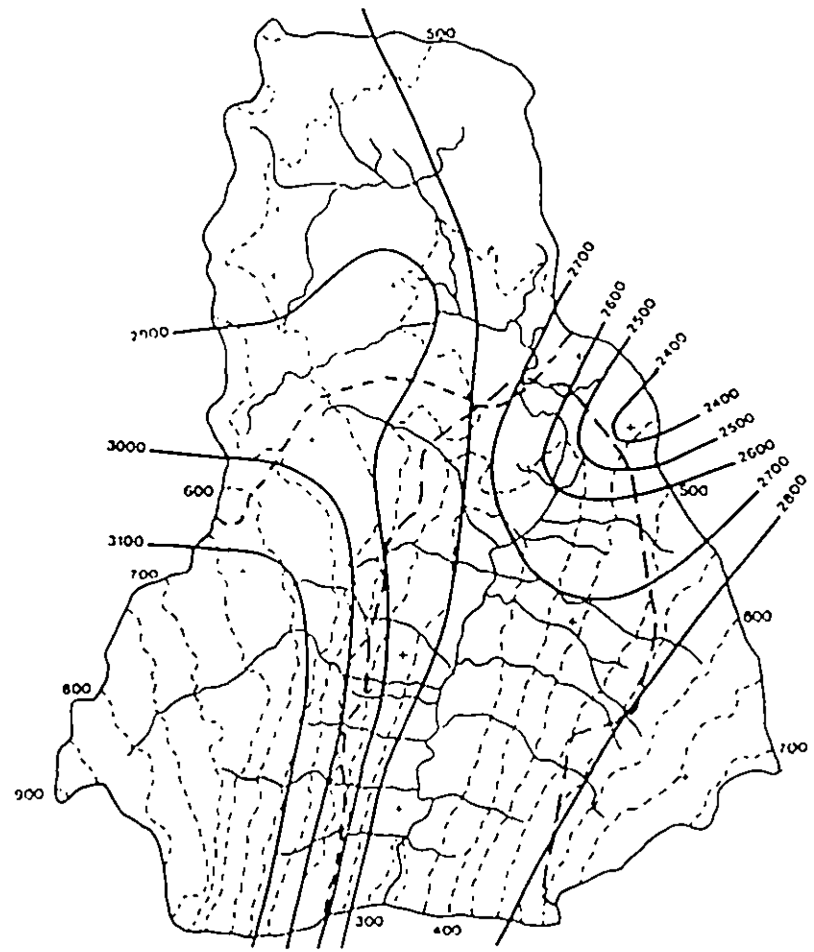


Figure 2.1.3 *Monachyle mean annual precipitation 1982-86*

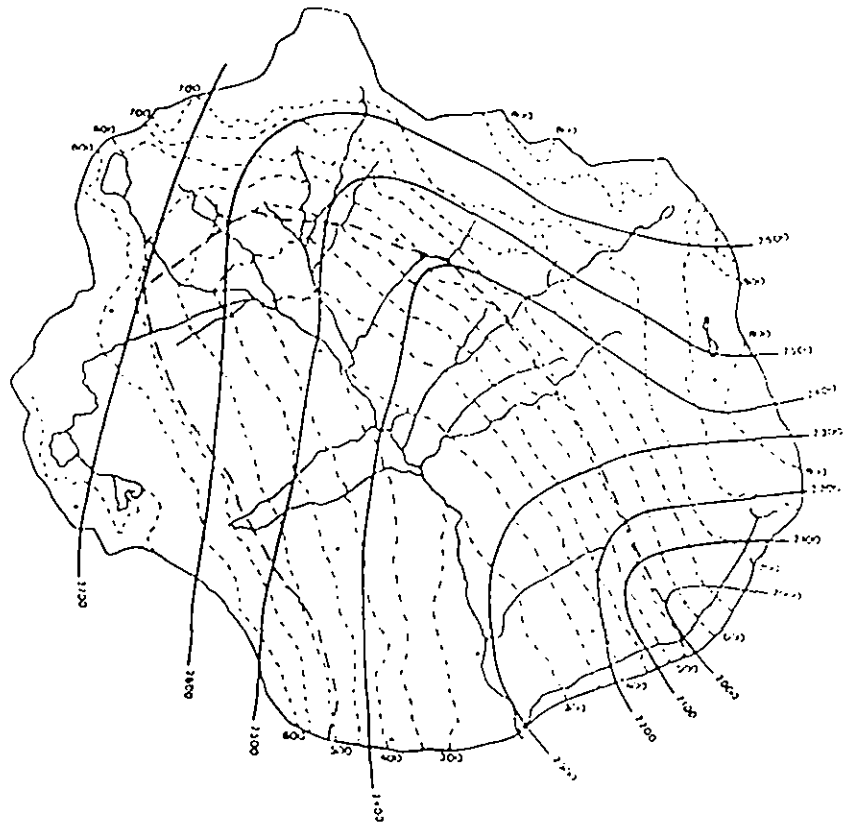


Figure 2.1.4 *Kirkton mean annual precipitation 1982-86*

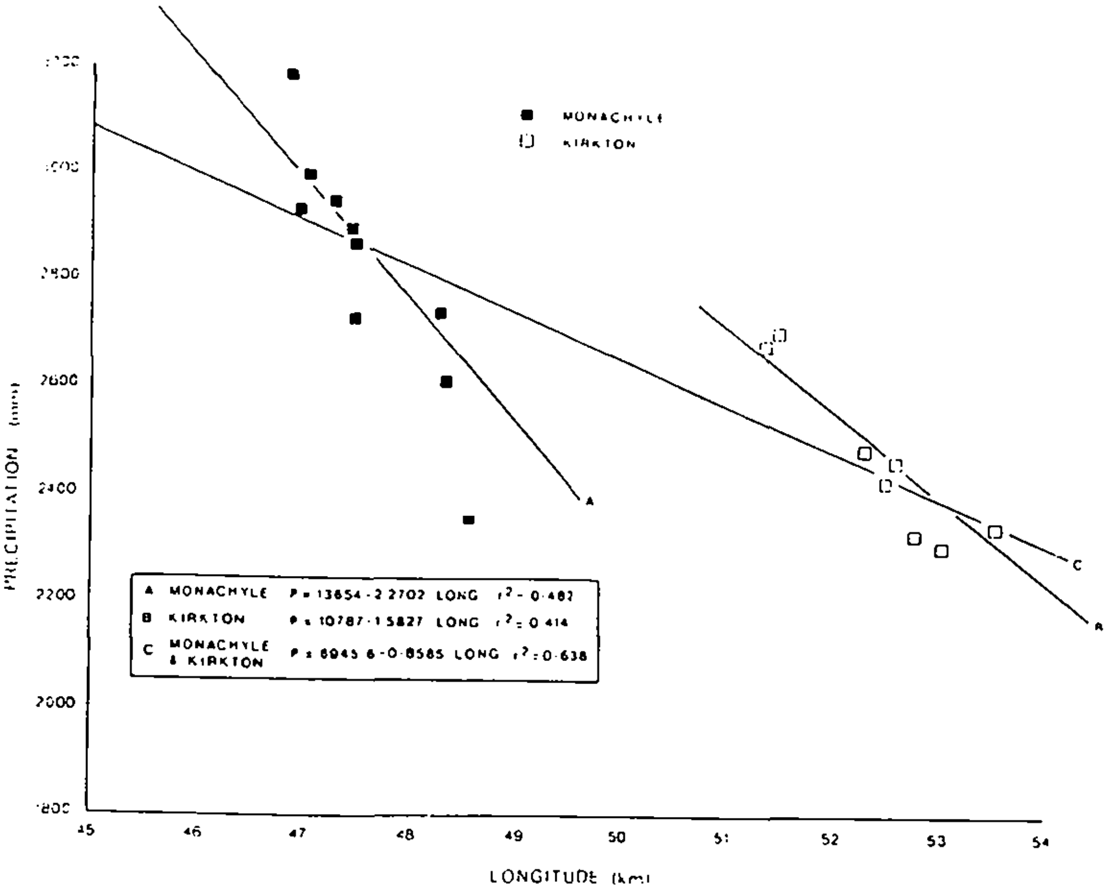


Figure 2.1.5 *Relationships between mean annual precipitation and longitude*

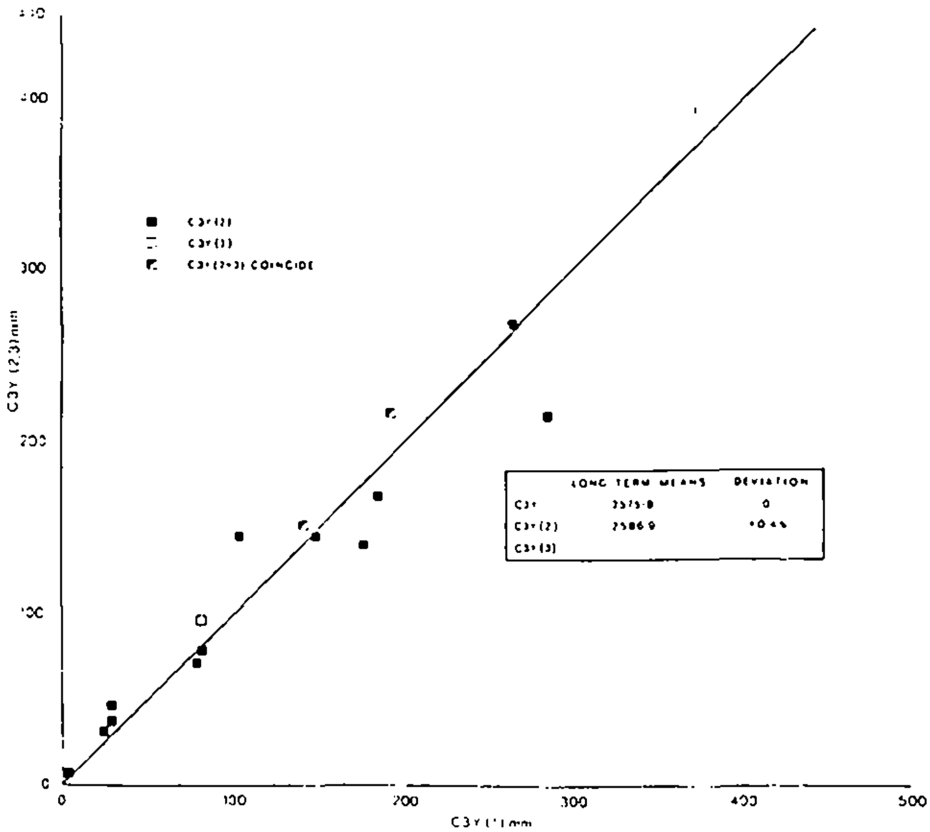


Figure 2.1.6 *Comparison of original gauge, C3Y(1) and check gauges in Kirkton domain C3Y*

2.2 KIRKTON FOREST INTERCEPTION

The interception of a proportion of the rainfall by the forest canopy and its subsequent rapid loss by evaporation is the main process resulting in higher total water use by forest than by shorter, aerodynamically smoother vegetation in wet upland Britain. Interception loss has been studied in a number of areas and found to be dependent on rainfall total, frequency and duration. Within the range of environments sampled in Wales, England and southern Scotland this loss has ranged from 27% to 38% (Anderson & Pyatt, 1986).

Whilst detailed interception studies, particularly of snow interception by forest, formed an integral part of this overall programme, no site suitable for the sophisticated techniques being employed could be found within the Kirkton forest and this part of the study was carried out elsewhere (see Section 3.1). Nevertheless it was considered important that some indication of interception loss rates within the catchment be obtained and a relatively simple study was initiated.

2.2.1 Experimental Details

A 30 m square plot containing a relatively even stand of Sitka spruce situated adjacent to one of the precipitation network sites (A1W, Fig. 2.1.2) was chosen for the study. The plot contained 87 trees of heights ranging from 18-20 m and with an average spacing of 3.2 m.

Throughfall of both rain and snow was sampled using 60 plastic containers each 36 cm deep with a rim diameter of 29 cm. These were positioned at random within the 900 one-metre squares of the plot with the distances from the nearest trunk and the canopy density directly above carefully noted. The contents of the buckets were measured volumetrically at approximately fortnightly intervals shorter during hot spells in summer to minimise errors from evaporation loss. During snow periods the buckets were weighed and the contents of a sample number of them melted to give volume measurements.

Stemflow was sampled on 9 trees in the plot, selected to cover the range of girths. Neoprene collars were used to channel the flow into closed 200 litre capacity containers. Precipitation inputs were obtained from the adjacent site A1W, from the ground level gauge during rainfall periods and from either the standard gauge or the tall snow gauge during snow periods.

2.2.2 Results and Discussion

Readings were taken for a total of 54 periods within the duration of the study from October 1983 to June 1986, when the site had to be cleared prior to felling. Of these 54 periods, measurements from all 60 buckets were obtained on 37. In the remaining 17 one or two of the buckets had been disturbed by sheep or deer. The effect of this loss was minimal in that the mean throughfall for the 37 periods was 67% of the precipitation whilst the mean for all 54 periods was 66%.

The variability of mean throughfall as a percentage of precipitation is illustrated in the time series plot in Fig. 2.2.1. Within-site variability was even greater, ranging from 0% to 191%. Nevertheless the mean throughfaii was found to be well correlated with period precipitation as shown in Fig. 2.2.2, whereas the relationship between stemflow and precipitation was much weaker. Consequently the correlation between interception and precipitation is poorer than that for throughfall (Fig. 2.2.3).

The overall mean interception figure from the 54 periods is 32% of precipitation. This is within the predicted range for UK upland areas receiving precipitation in the range 2000-2500 mm/annum. Considering the frequency of snowfall at this site and the very high interception losses from snow observed elsewhere (see Section 3.1.2) it is surprising that the mean interception figure is not higher.

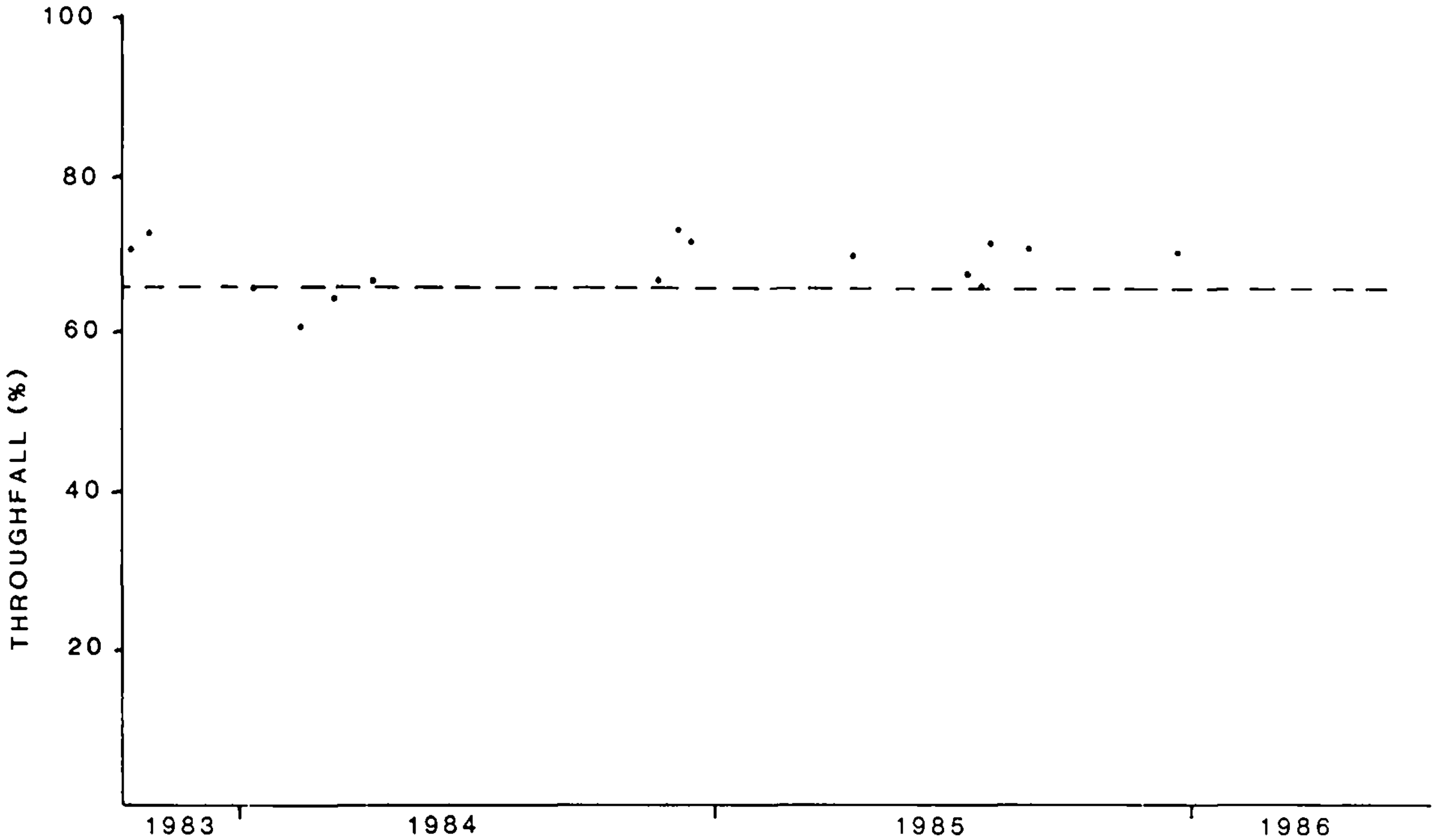


Figure 2.2.1 *Throughfall (as % precipitation) at Kirkton interception site for each observation period*

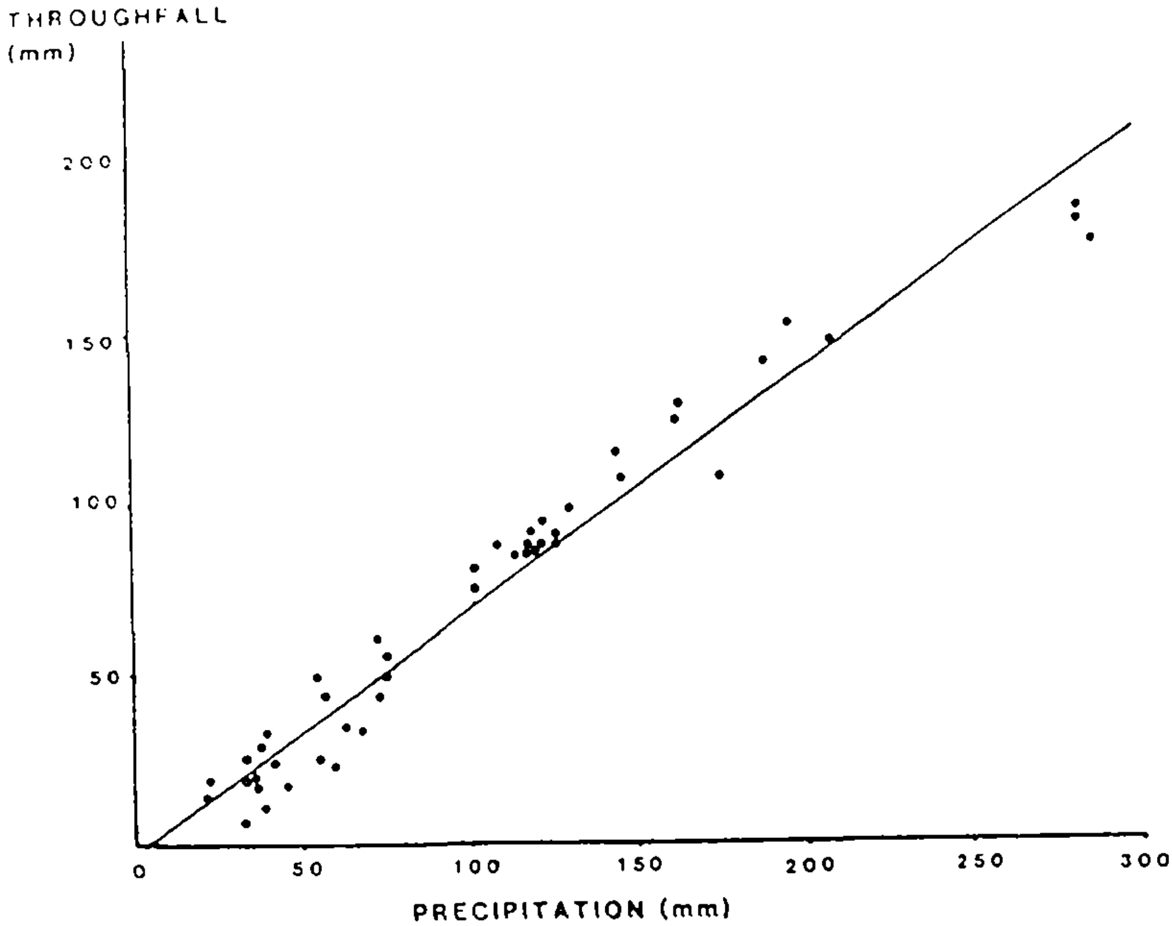
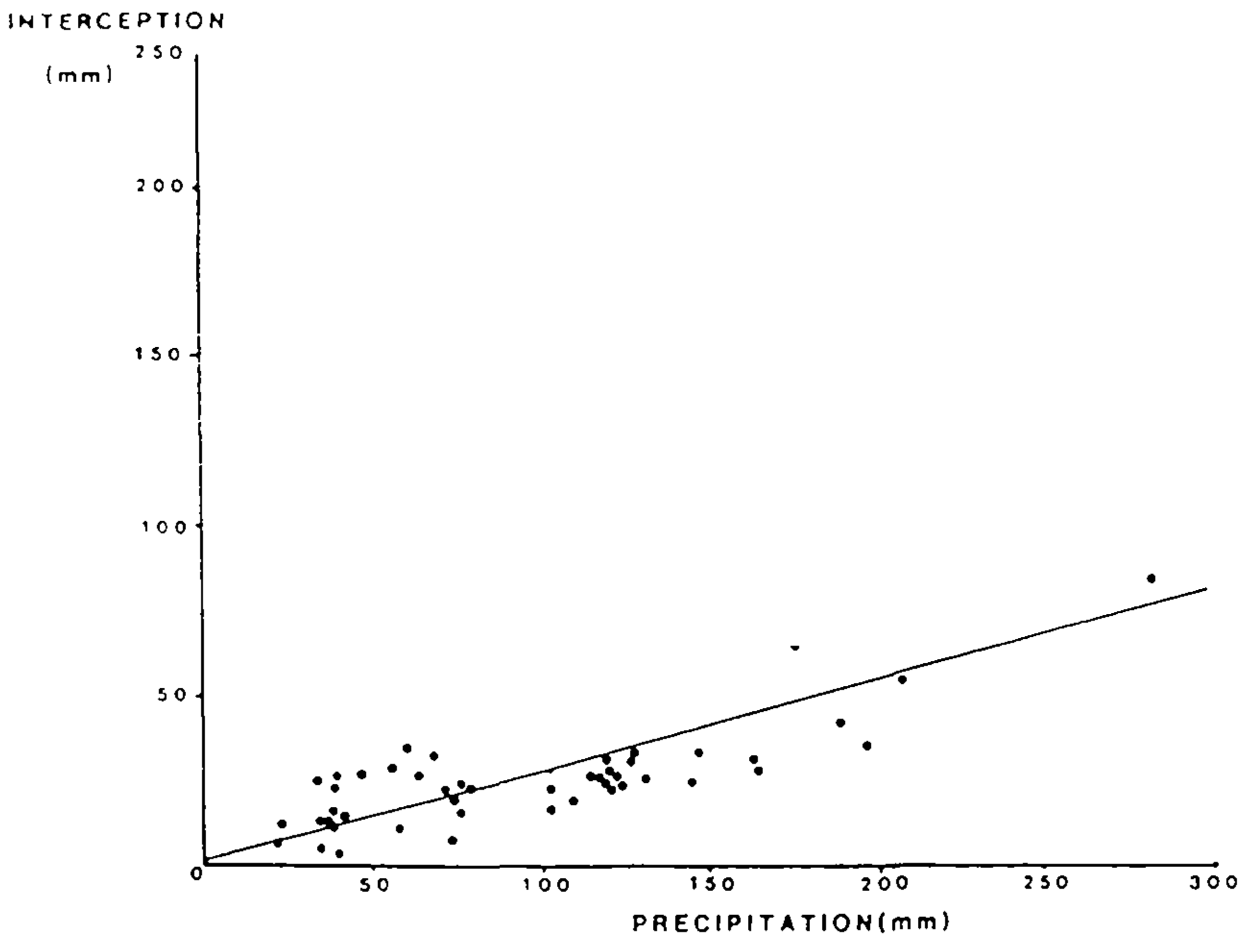


Figure 2.2.2 Throughfall versus precipitation



Figures 2.2.3 Interception versus precipitation

2.3 STREAMFLOW

In order to estimate catchment water use by the water balance approach it is essential to obtain continuous, accurate records of streamflow as well as precipitation. With the probable annual magnitudes of these terms it was considered that it would be necessary to measure streamflow to an accuracy of better than 5% if it was hoped to identify significant differences in water use between the catchments. This requirement was an important factor influencing the choice of catchments for the study. Whilst the steep rocky streambeds of the Balquhidder catchments and the probable wide range of flows presented difficulties, watertight rock reaches were identified at the outfalls of these catchments where it was considered technically possible to meet the flow measurement requirements.

2.3.1 The Structures

Of the various structure designs that would meet the requirements of these sites the choice made for the main catchment outfalls of both catchments was a simple Crump weir supplemented by an additional short trapezoidal structure to give the required accuracy at the very low flows. To contain the 50 year return period flows, estimated at 26 m^3s^{-1} and 30^3m s^{-1} for the Monachyle and Kirkton respectively, crest widths of 5 m and 7 m were selected. This choice of structure design was acknowledged to be a compromise between the accuracy required and the ease of construction on these difficult sites. The approach conditions in the streams, particularly in the Kirkton, were close to the upper acceptable limits and it would be necessary therefore to check in situ the validity of their theoretical ratings. Particular attention was paid to the construction of the crests. To minimise damage from large boulders moving through in high flows these were machined from stainless steel and levelled in using a technique which gave an accuracy of better than 1 mm over the crest lengths. The low flow structures, pre-formed in fibreglass and laboratory calibrated, were installed in series with the Crumps in such a way that they would drown out at medium to high flows without affecting the main structures. Both types of structure were equipped with float operated potentiometric water level recorders capable of an accuracy of ± 1 mm. The outputs from these were logged at 5 minute intervals. Back-up on the main structures was provided by chart recorders and, at a later date, punched paper recorders. The main structures were both fully operational by October 1982.

The decision to install an additional structure at the outfall of the upper sub-catchment of the Monachyle (Fig. 2.1.1) presented considerable logistical difficulties. A suitable structure for this site was agreed as a flat V weir of 1:10 cross-slope with vertical side-walls 3.2 m apart. To minimise transport and installation costs this was fabricated from aluminium alloy with sections being brought in by helicopter from the road-head 2 km distant. This structure, equipped with water level recording equipment identical to that on the main structures, became operational in August 1983.

energy flux correction factor (β) can be quantified, which has a value > 1.0 at low flows and high flows and < 1.0 in the mid-range of flows. This fluctuation appears to be related to the deviation of the centroid of velocity either side of the mid-point of the weir. β may prove to be a useful factor for future use, if it can be further quantified as a true measure of flow asymmetry.

Whilst spot checks on low and medium flows had given no immediate cause for concern over the Monachyle rating, it was decided that a full current metering check would be advisable. Techniques similar to those used on the Kirkton were employed during 1986 and 1987.

The resulting revised rating derived from this exercise is compared with the original theoretical rating in Fig. 2.3.6. Surprisingly the revised rating gives flow values some 5% lower than the original. Possible reasons for this are still being investigated.

The accumulated water level observations from both main structures have been reprocessed using these revised ratings to give updated figures for flow. The revised figures for the Kirkton were incorporated in the Report on the Preliminary Analysis of the Phase I catchment results presented to the consortium in 1986 and also in the paper by Blackie (1987). The revised Monachyle figures were summarised in the December 1987 Workshop presentation.

2.3.3 Low Flow Accuracy

It can be seen from Figs. 2.3.5 and 2.3.6 that no current meter readings were taken in either of the Crump structures below approximately 100 mm stage. This was because approach velocities fall below the operational range of the current meters at these low flows. Checks on the validity of the extrapolations of the ratings to low flows are provided by comparing simultaneous observations in the Crumps and the trapezoidal low flow 'Lothian' flumes. Examples of such comparisons for extended low flow periods are given for the Monachyle and Kirkton in Figs. 2.3.7 and 2.3.8 respectively. Whilst the Crump stage readings become progressively less sensitive, in the Monachyle particularly, as the British Standards recommended low stage limit of 30 mm is approached, the agreements are seen to be reasonable.

In Table 2.3.1 the cumulative flows computed from both structures over significant periods of low flow in the Monachyle are compared. The differences are seen to be insignificant, suggesting that the Crump structure and its revised rating could be used throughout to compute cumulative flow for water balance purposes. Consideration of Fig. 2.3.8 suggests that a similar conclusion is applicable to the Kirkton.

A further comment on the validity of using the Crump ratings in the low ranges comes from an examination of flow frequencies for the period 1983-86. As can be seen from the daily time series plots (Figs. 2.3.12 and 2.3.13), flows are in these ranges for a considerable proportion of the time, 35% and 60% in Monachyle and Kirkton respectively as illustrated in Figs. 2.3.9 and 2.3.10. However, as also indicated in these figures, the proportions of the volume flows occurring in the overlap ranges are only 3% and 20% respectively. Of even more relevance, only 0.8% of the Monachyle flow and 1.8% of the Kirkton flow occurs at stages below the British Standard Crump limit of 30 mm.

It can be concluded therefore that no significant error is introduced into the cumulative volume flows used in the water balance by using downward extrapolations of the current-meter ratings of the Monachyle and Kirkton Crump weirs. However, where accurate short term totals or spot readings in low flow periods are required, the values obtained from the 'Lothian' flumes should be used.

2.3.4 Catchment Flow Computation

Using the revised Crump structure ratings described in 2.3.2 and the original theoretical rating for the upper Monachyle structure, the 5 minute water level observations were converted to volume flows and are stored as mean 15 minute flows on the data-base. The water level recording systems have performed well and relatively few gaps have occurred in the main structure records. A variety of methods have been employed to infill these gaps. The records from the back-up chart and punched tape recorders or from the low-flow structures have covered most of the gaps associated with recorder malfunctions. Those apart, the main problem periods have arisen in winter when the float wells have frozen up.

This problem has been particularly acute at the upper Monachyle site and it has not been possible to produce complete winter streamflow data for the sub-catchment until winter 1986-87. To counteract the problem there, pressure transducers were installed in the float well and in the approach section of the structure in 1986. After a period of cross-checking between them, and with the float recorder in ice-free periods, a comparison of their records was used to identify periods when the well was frozen. During such periods the record from the transducer in the approach section has been used to give water level and hence volume flows.

Whilst the icing problem is less severe in the main structures it has affected parts of the December-February record in each year. During such periods the observer has visited these sites at intervals of a few days, broken the ice in the wells and, when necessary, removed any ice adhering to the Crump crests. The subsequent spot readings of water level have then been used to compute flow. Since such periods of heavy frost coincide with low flows varying little with time, interpolation between the spot readings using the low flow recession curves has been used to infill the records. A very few short periods of doubtful record remain where snowmelt events have resulted in a rise in flow before the ice melted or was broken in the float well. These are not considered to have any significant effect on the monthly or annual flow totals.

A comparison of flows from the upper and main Monachyle structures revealed very close agreement in daily totals, expressed as mm depth over

TABLE 2.3.1 Comparison of cumulative flows (mm depth) over Significant Low Flow Periods in Monachyle

Period	Low Flow Flume		Crump Weir	
19/6/86-16/7/86	10.87		11.09	
18/7/86-26/7/86	2.89		3.12	
		13.76		14.21
4/5/85-14/5/85	5.79		7.46	
2/6/85-12/6/85	5.48		4.09	
15/6/85-17/6/85	1.51		1.35	
1/7/85- 4/7/85	2.69		2.18	
		15.47		15.08
5/5/84- 7/5/84	2.12		2.33	
10/5/84-24/5/84	6.20		5.91	
26/5/84-31/5/84	1.94		1.94	
6/6/84-11/6/84	2.65		2.37	
14/6/84-21.6.84	3.17		2.53	
24/6/84-26/6/84	1.46		1.17	
28/6/84-30/6/84	0.92		0.72	
1/7/84- 9/7/84	1.43		1.28	
14/7/84-31/7/84	4.30		4.05	
1/8/84-29/8/84	4.52		5.01	
		28.72		27.31

their catchments. This relationship was used to infill a few daily totals in each record when no other method was available. The close agreement between these sites in terms of monthly flow totals is demonstrated in Fig. 2.3.11.

The monthly totals of flow from the two main catchments are displayed as a time series in Fig. 2.5.2 in section 2.5 and annual totals are given in Table 2.5.1.

2.3.5 Hydrograph Analysis

As might be expected from steeply sloping catchments with variable but generally shallow soil depths in this rainfall regime, the streamflow responses of both are very flashy. Time to peak in both catchments is typically in the range 4-15 hours with a return to base flow in 10-30 hours. As can be seen from the time series plots of daily flows in Figs. 2.3.12 and 2.3.13 however, the Monachyle is flashier than the Kirkton with consistently higher peaks and lower base flows during prolonged dry periods such as the summer of 1984. This is further demonstrated in the flow duration curves in Fig. 2.3.14.. Monachyle flows are seen to exceed 7.0 cumecs for 0.02% of the time, as compared to 0.01% in the Kirkton, but are lower than 0.1 cumecs for 75% of the time as compared to only 42% in the Kirkton.

Base flow indices for various catchments in the UK are listed below. These indices are the proportion of flow categorised as base flow, so that the chalk catchments have a high base flow index and clay catchments a low index. The Balquhidder catchment indices are provisional figures but show again that there is a greater proportion of base flow in the Kirkton compared to the Monachyle.

Catchment	Base flow index
Foston Beck (chalk)	.95
Cam (chalk and clay)	.78
Kirkton	.46
East Dart	.42
Monachyle	.41
Wye	.41
Severn	.31
Mole (clay)	.25

During a dry spell in the 1986 summer period a survey of the distribution of the contributions to base flow in the Kirkton was carried out. Using a salt dilution gauging technique the discharges of the tributaries were estimated by proportional analysis with the base flow measured at the catchment outfall. At that time 15 feeder streams on the west side of the catchment and 17 on the east were flowing. These accounted for 89% of the total baseflow, the remainder coming from seepage directly into the main channel. Of the tributary flow, 37% came from the west side of the catchment and 63% from the eastern side. These results accord with the observations on shallow groundwater storage and flow in the report by Robins & Mendum (1987). Their hydrogeochemical sampling and mapping suggested that the bulk of the baseflow was of relatively high pH as a result of shallow groundwater flow through cracks, faults and fissures in the limestone areas of the east and north-east parts of the catchment. Flow from the west side is much lower, emanating mainly from the lochans close to the ridge and is much more acid, comparable in this respect with the Monachyle tributaries.

Despite the large expanse of relatively gently sloping deeper peats in the upper

Monachyle, base flow recesses much more rapidly in this catchment than in the Kirkton. This accords with observations elsewhere that saturated peat sheds surface water rapidly but releases stored water very slowly indeed. Rapid shedding of surface water from the peat and from the expanses of *steeply sloping exposed rock on the west side of the catchment* would also explain the higher peak flows observed.

These very different response characteristics mean that little can be learned about the effects of forestry practices on floods and low flows by comparison <u>between</u> the catchments. Such information must come from <u>before</u> and <u>after</u> comparisons <u>within</u> the catchments when the planting in the Monachyle and the felling in the Kirkton are completed.

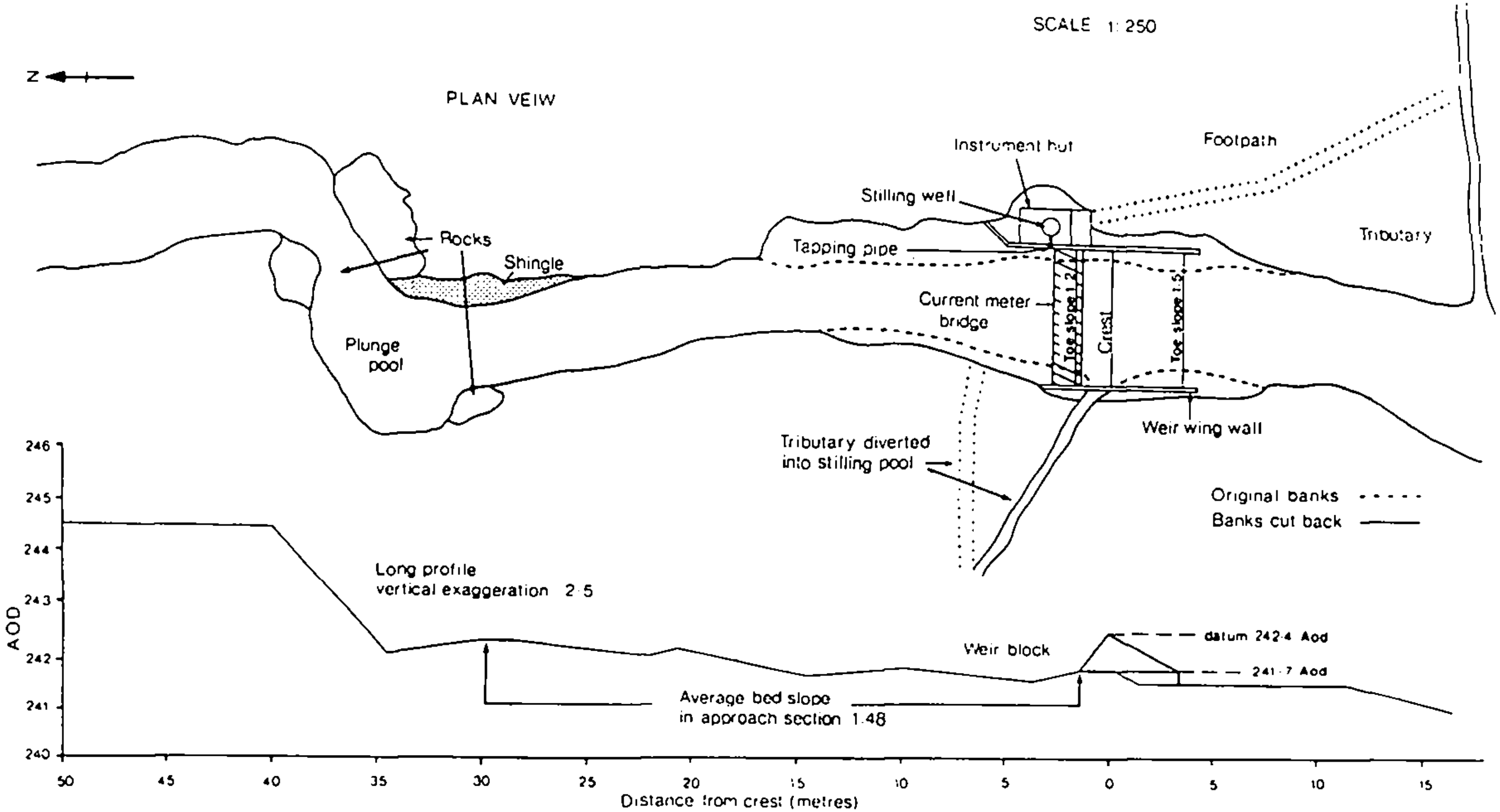


Figure 2.3.1 *Kirkton Crump weir approach geometry*

$$Q = C_D \sqrt{g} (h + \alpha Va^2/2g)^{3/2}$$

where	Q	discharge ($m^{-3}.sec^{-1}$)
	C_D =	coefficient of discharge
	b	weir width (m)
	g	9.81 m. sec^{-2}
	h	stage (m)
	α	approach velocity distribution correction coefficient (Coriolis)
	Va	mean aproach velocity (m. sec^{-1})

When calculated by an iteration procedure:

$$Q_n = C_D \; b \sqrt{g} \; (h + \alpha \; Q_{n-1}^{\;2} / (2g((h + p) \;\; b)^2)^{3/2}$$

where	n =	nth iteration
	p	height of weir crest above upstream bed level (m)

FIGURE 2.3.2 *Crump Weir Discharge Equation*

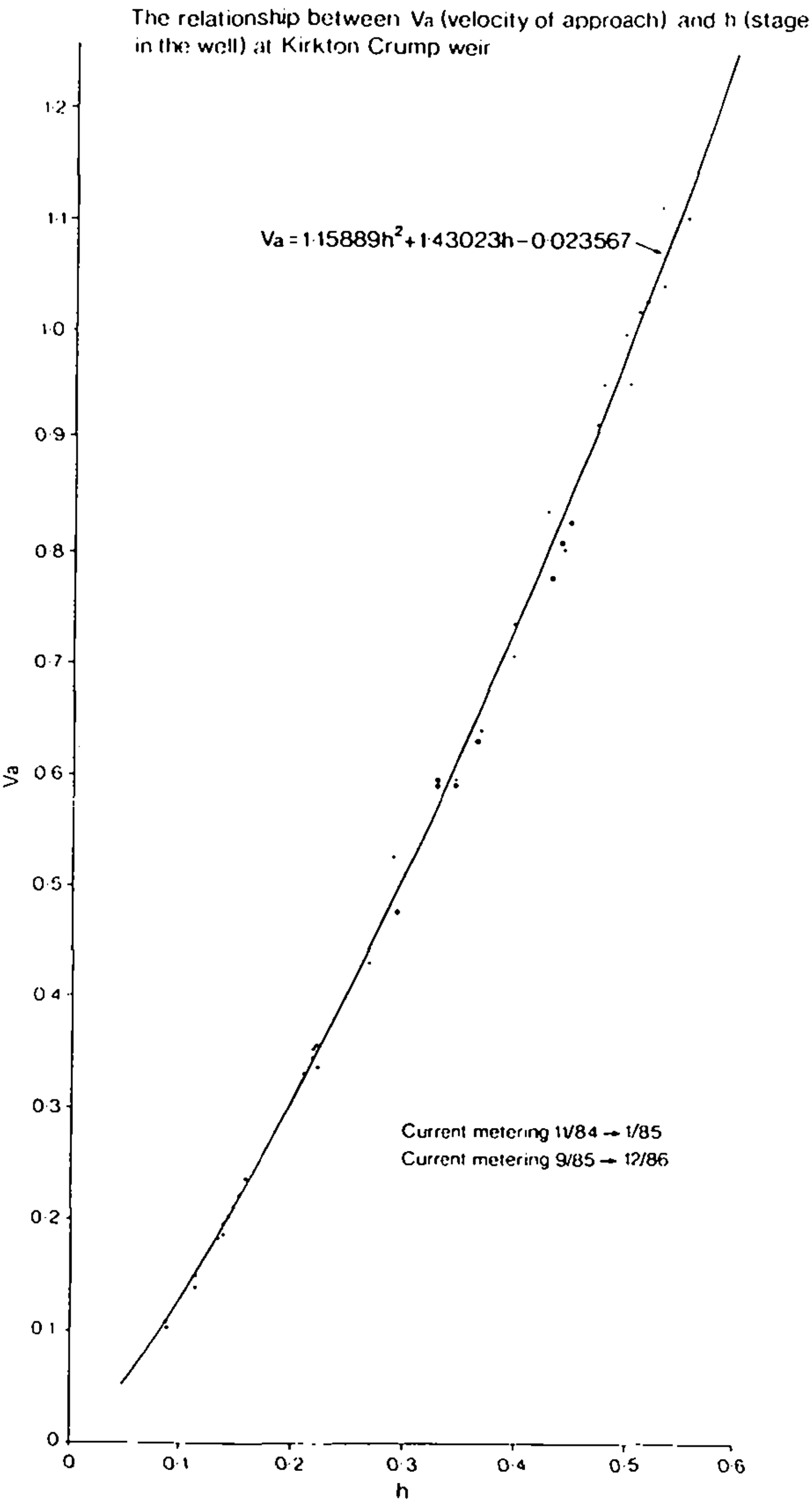


Figure 2.3.3 *Kirkton Crump weir, velocity of approach (va versus stage (h)*

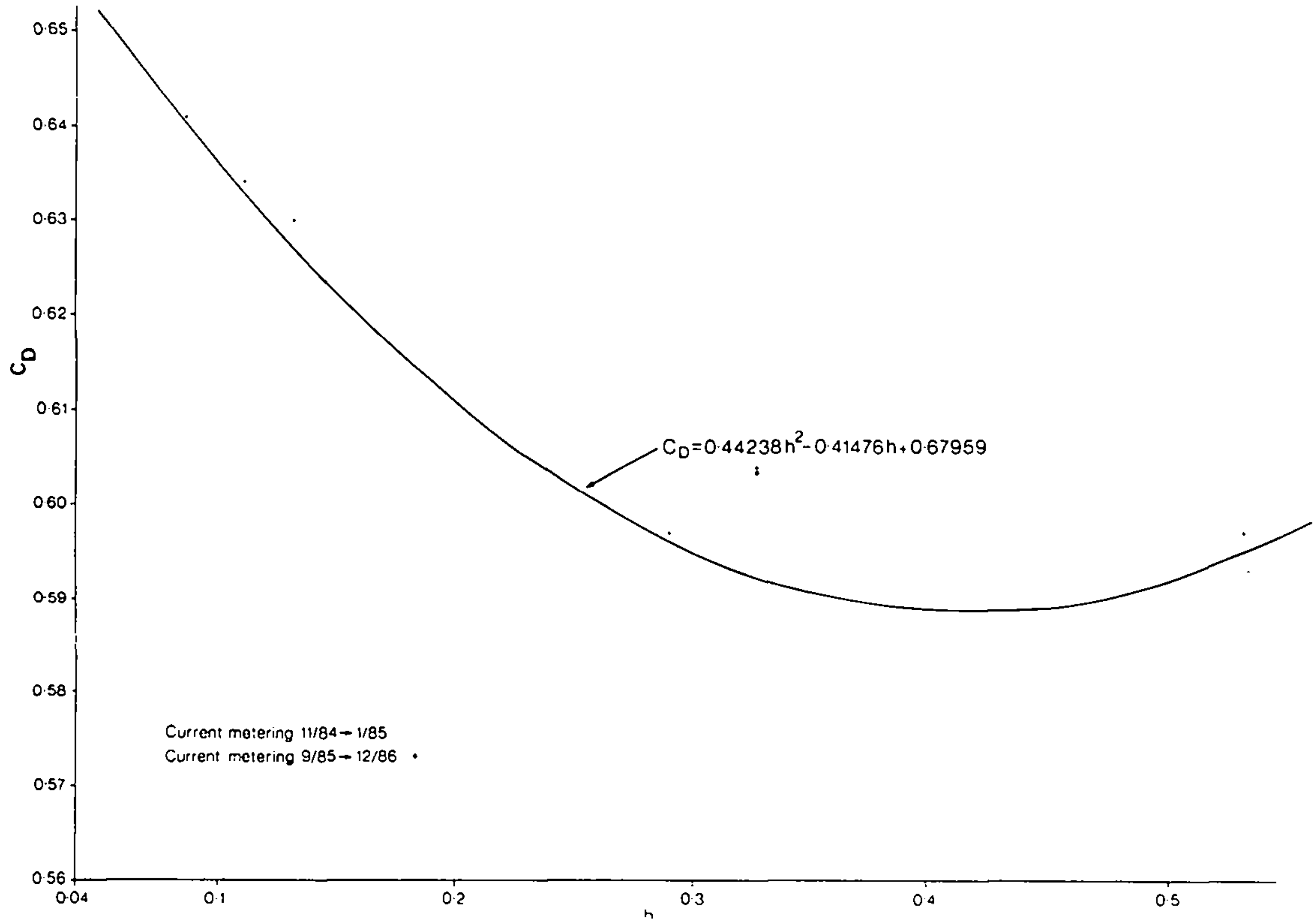


Figure 2.3.4 *Kirkton Crump weir, computed discharge coefficient (C_D) versus stage (h)*

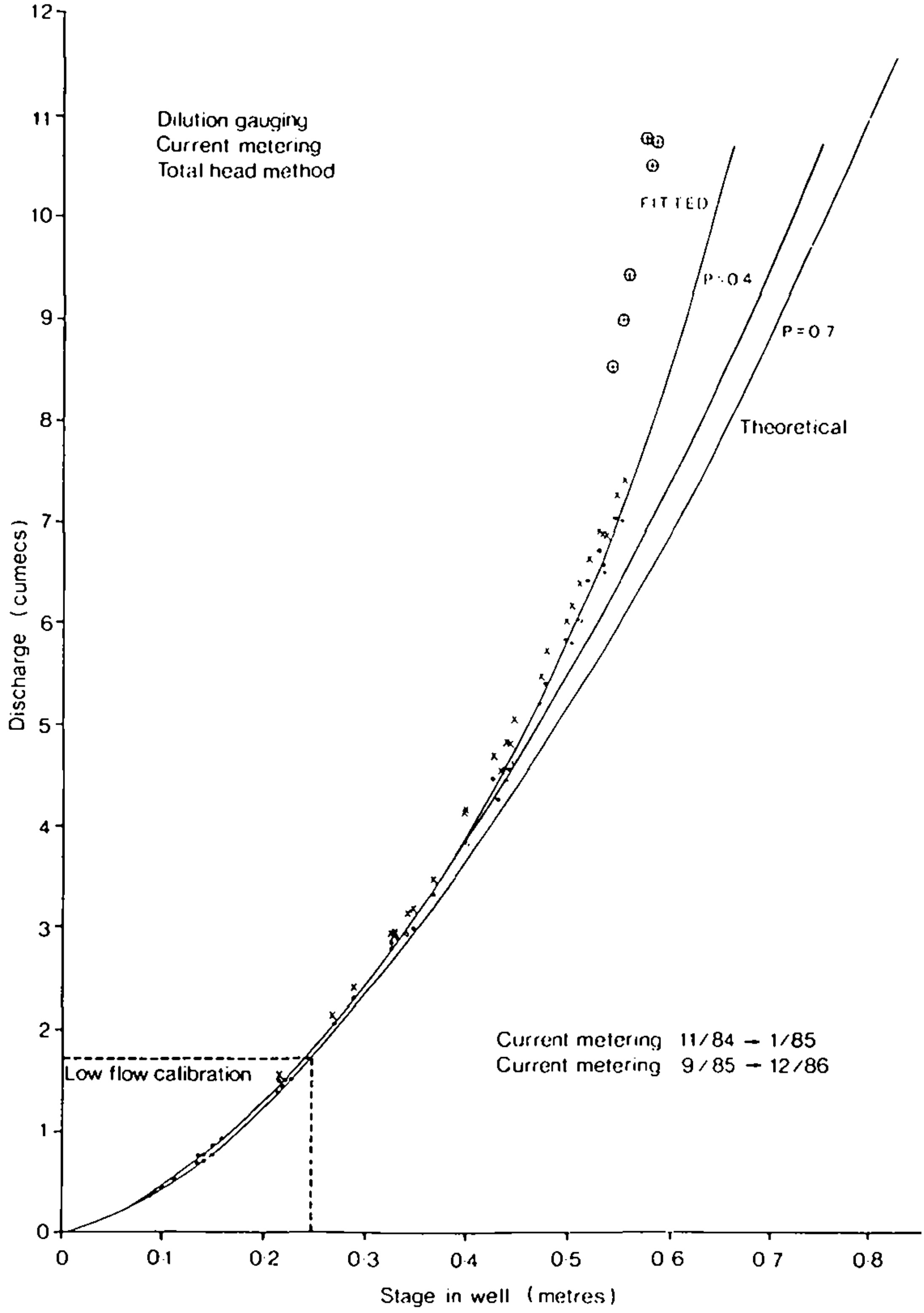


Figure 2.3.5 Kirkton Crump weir, stage/discharge relationships

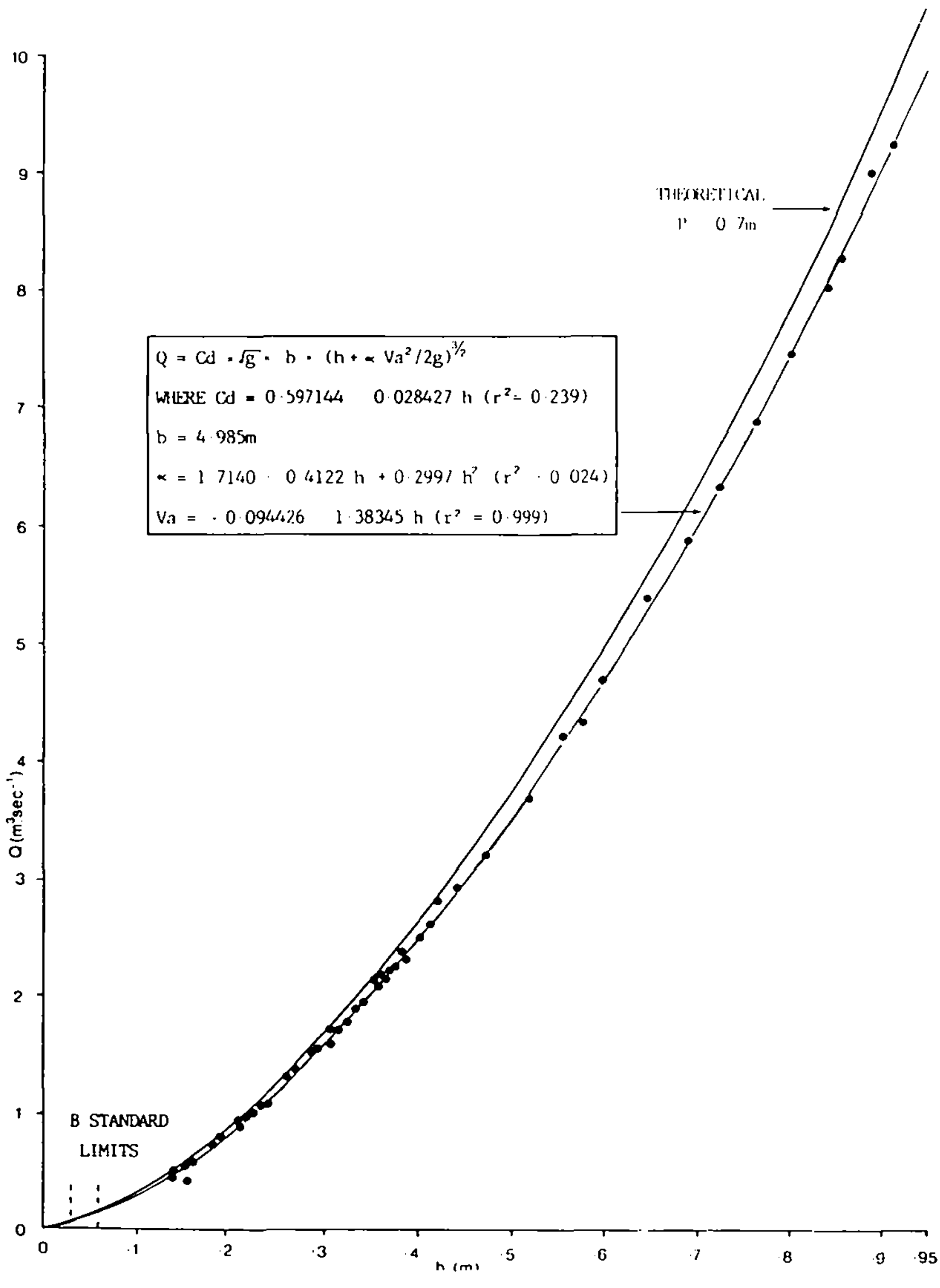


Figure 2.3.6 Monachyle Crump weir, stage/discharge relationships

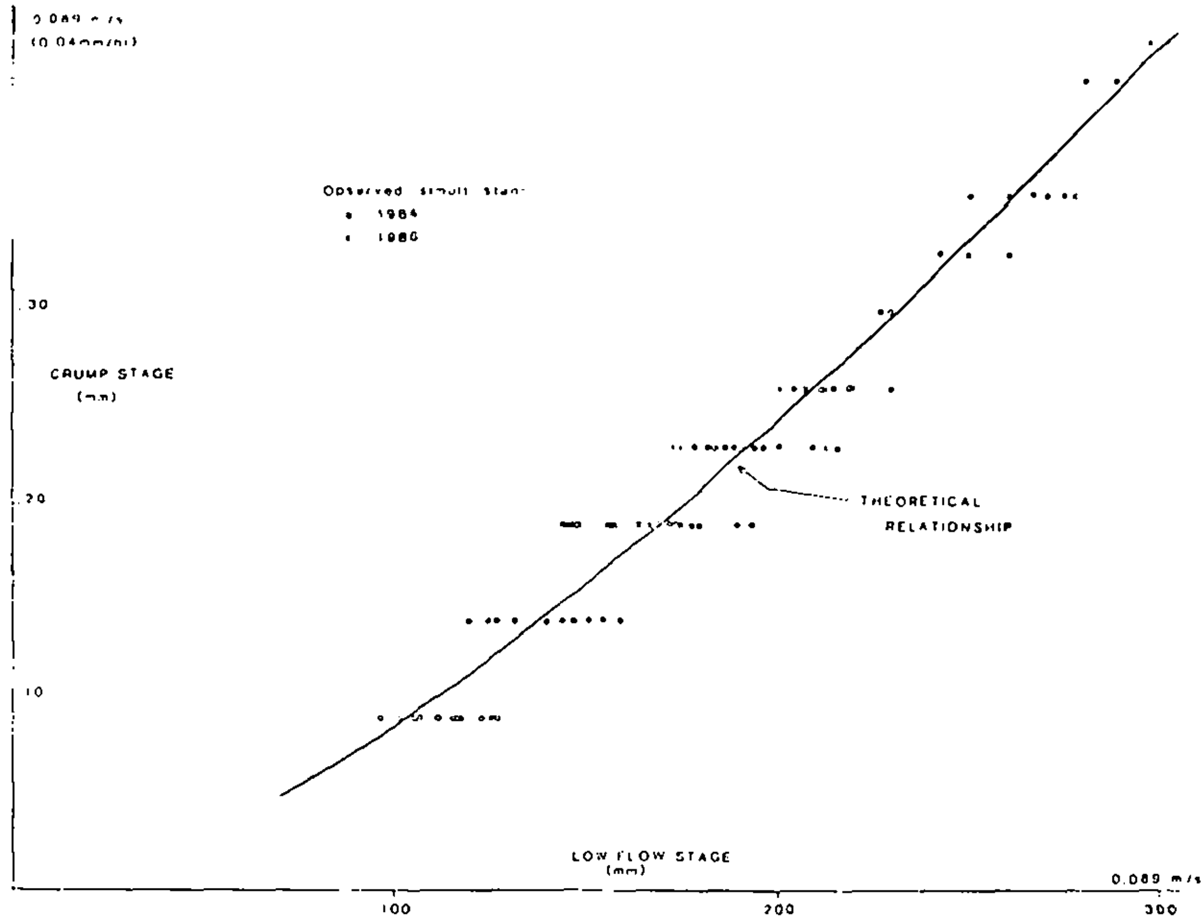


Figure 2.3.7 Comparison of simultaneous Crump and low flow flume readings, Monachyle

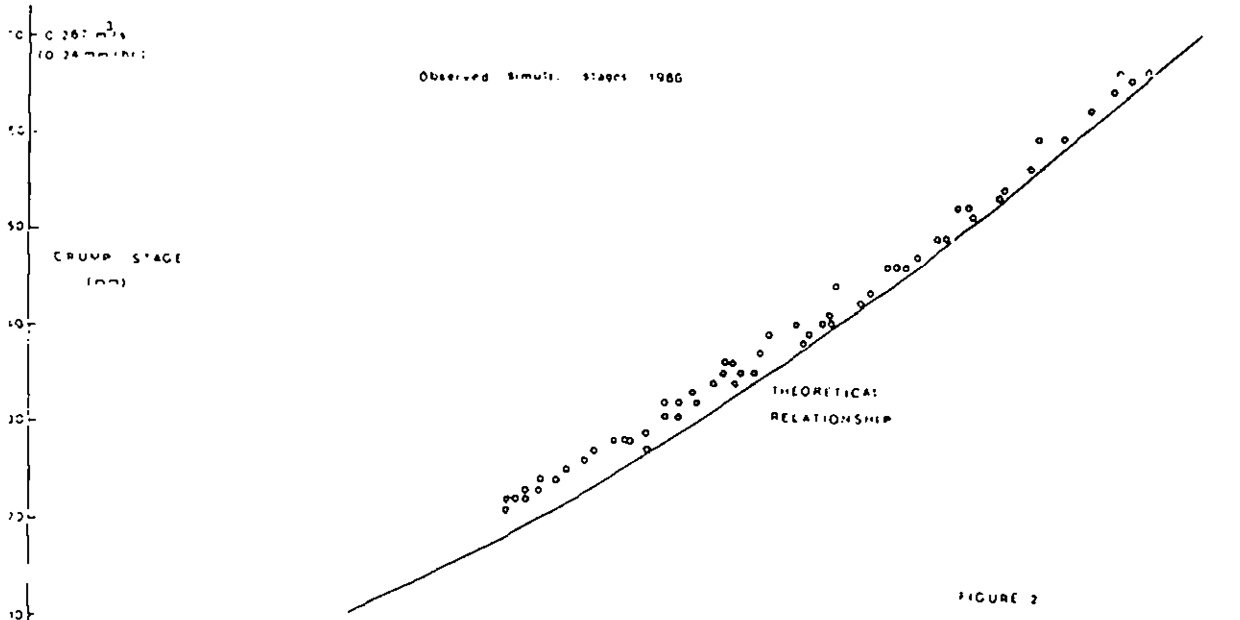


Figure 2.3.8 Comparison of simultaneous Crump and low flow flume readings, Kirkton

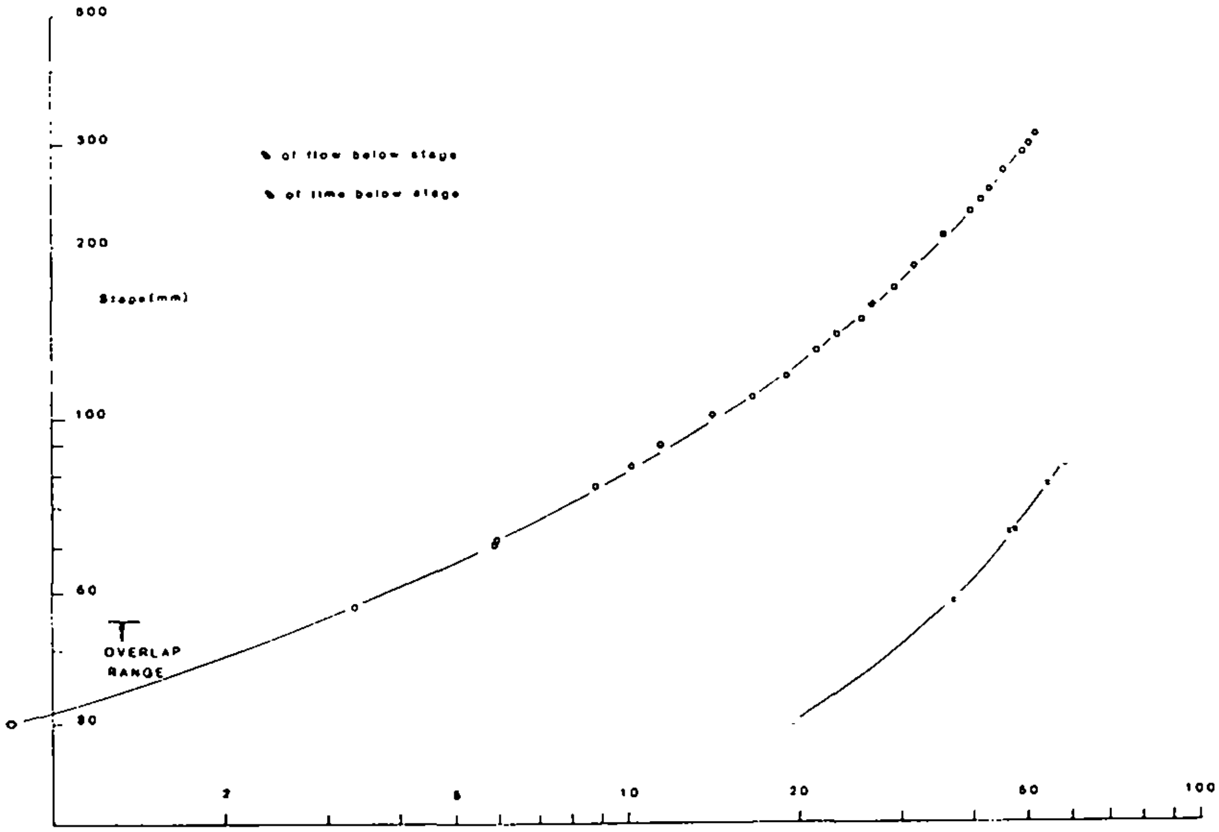


Figure 2.3.9 Monachyle low flow frequencies, 1983-85

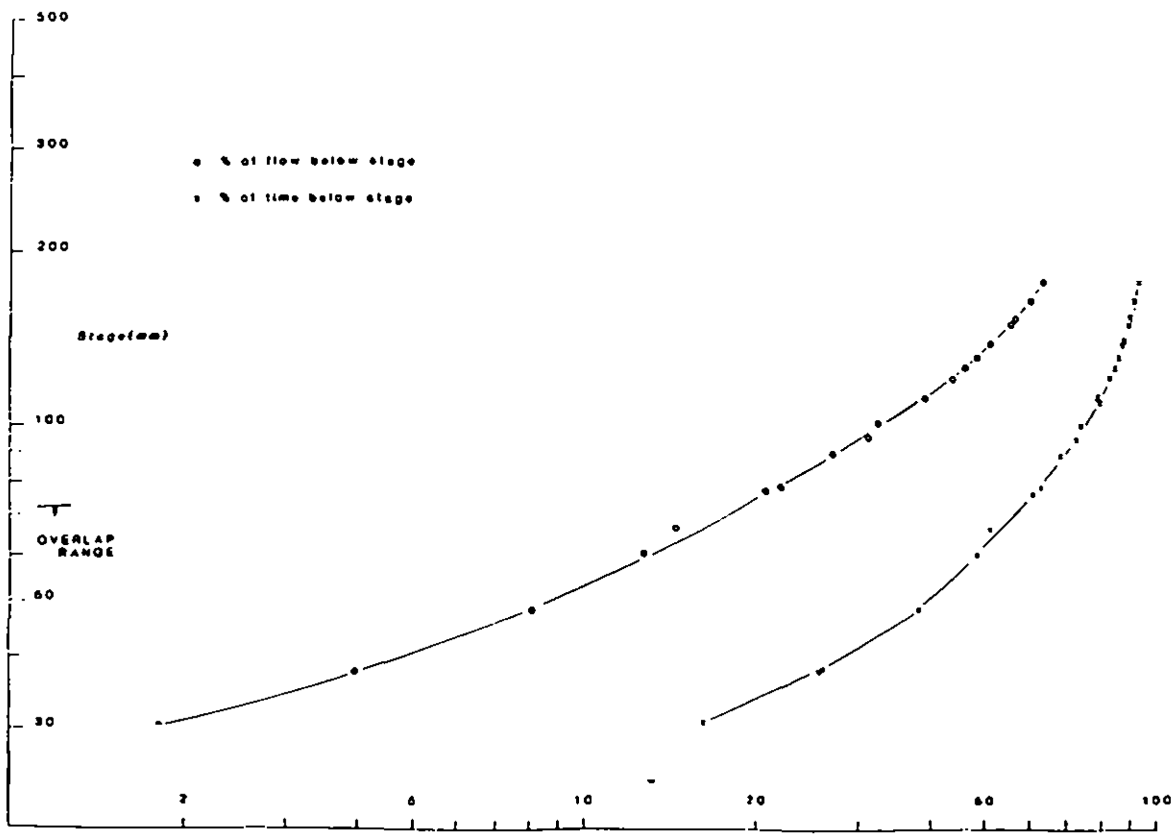


Figure 2.3.10 Kirkton low flow frequencies, 1983-85

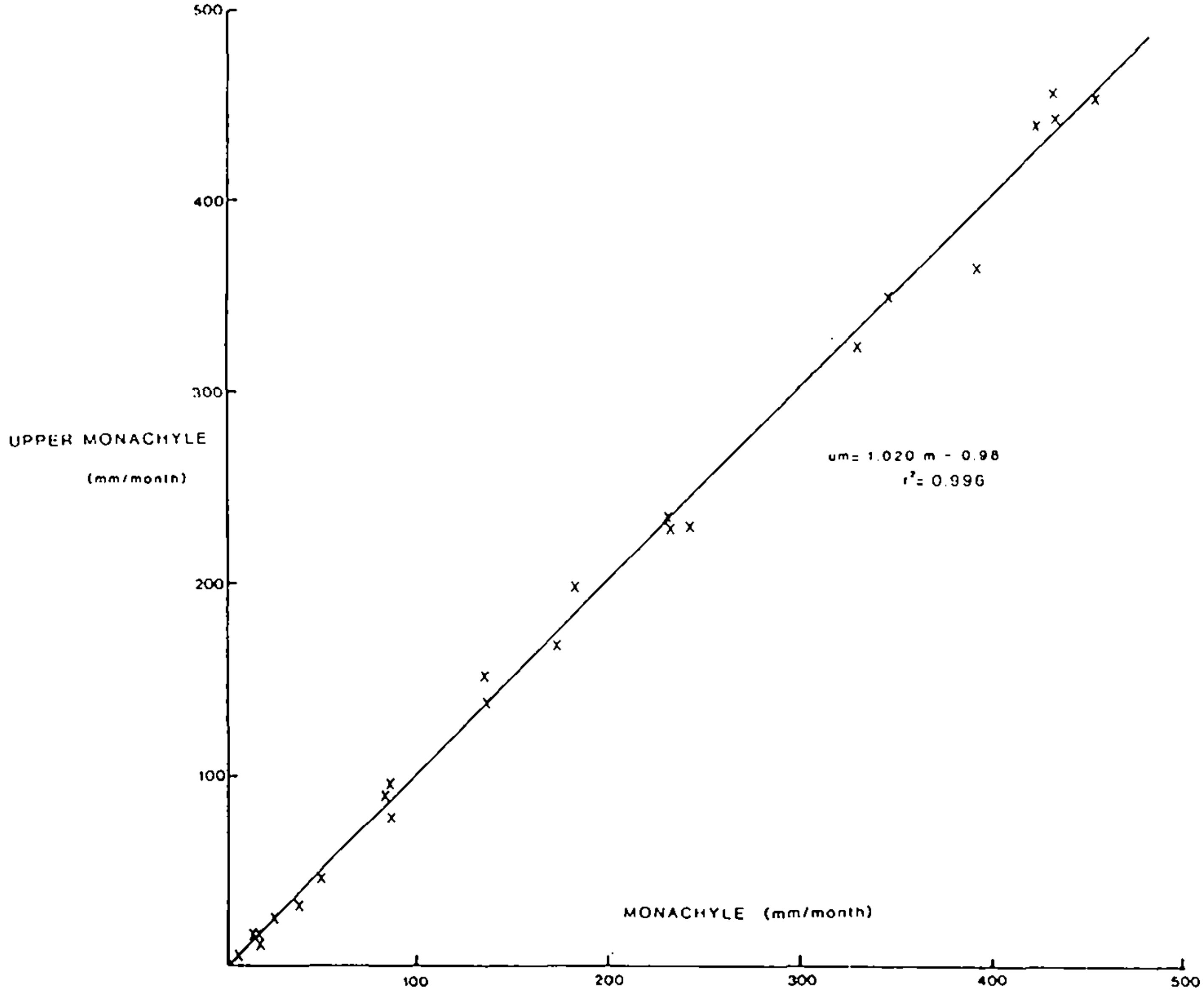


Figure 2.3.11 *Monachyle and Upper Monachyle monthly flows*

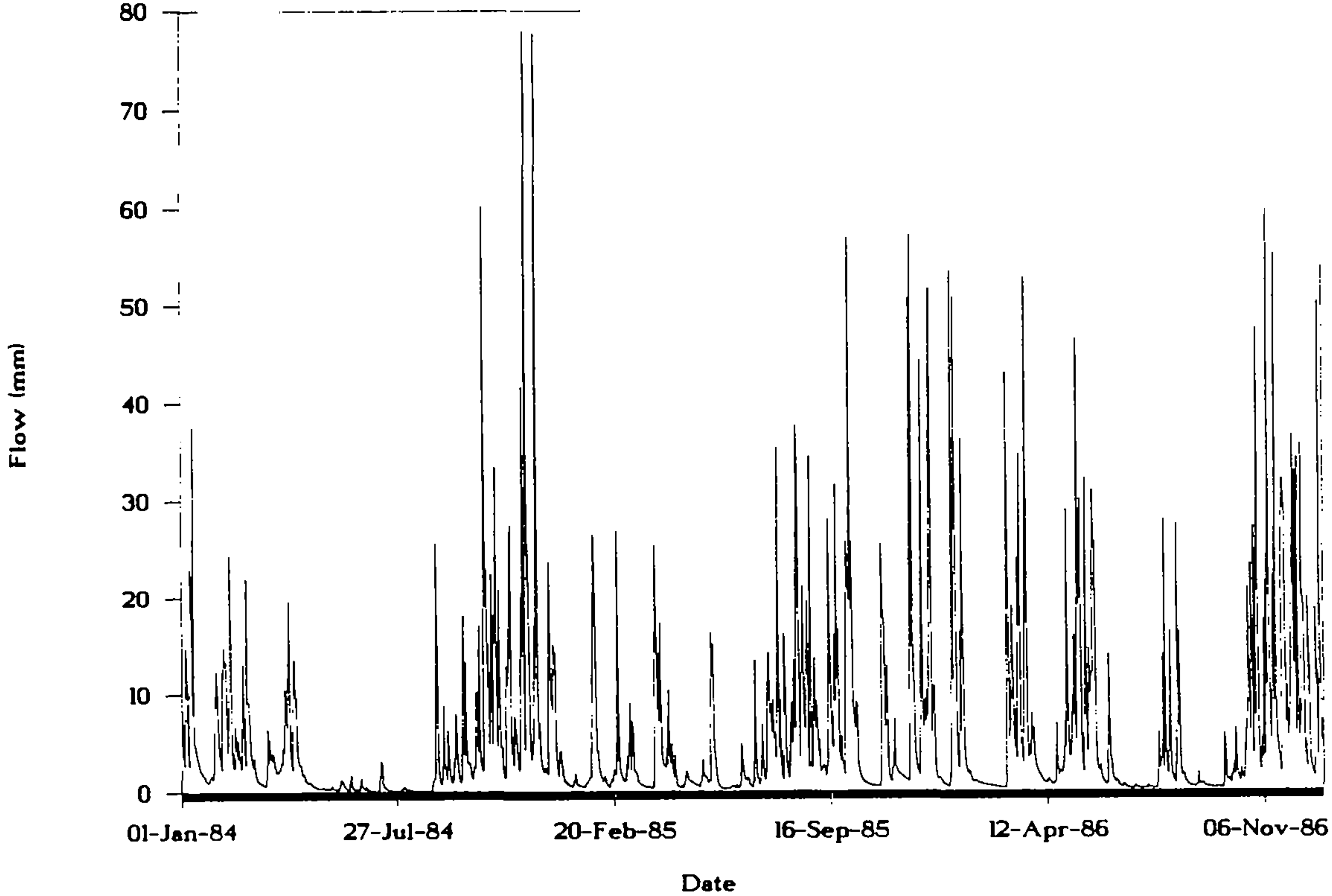


Figure 2.3.12 Monachyle daily flows

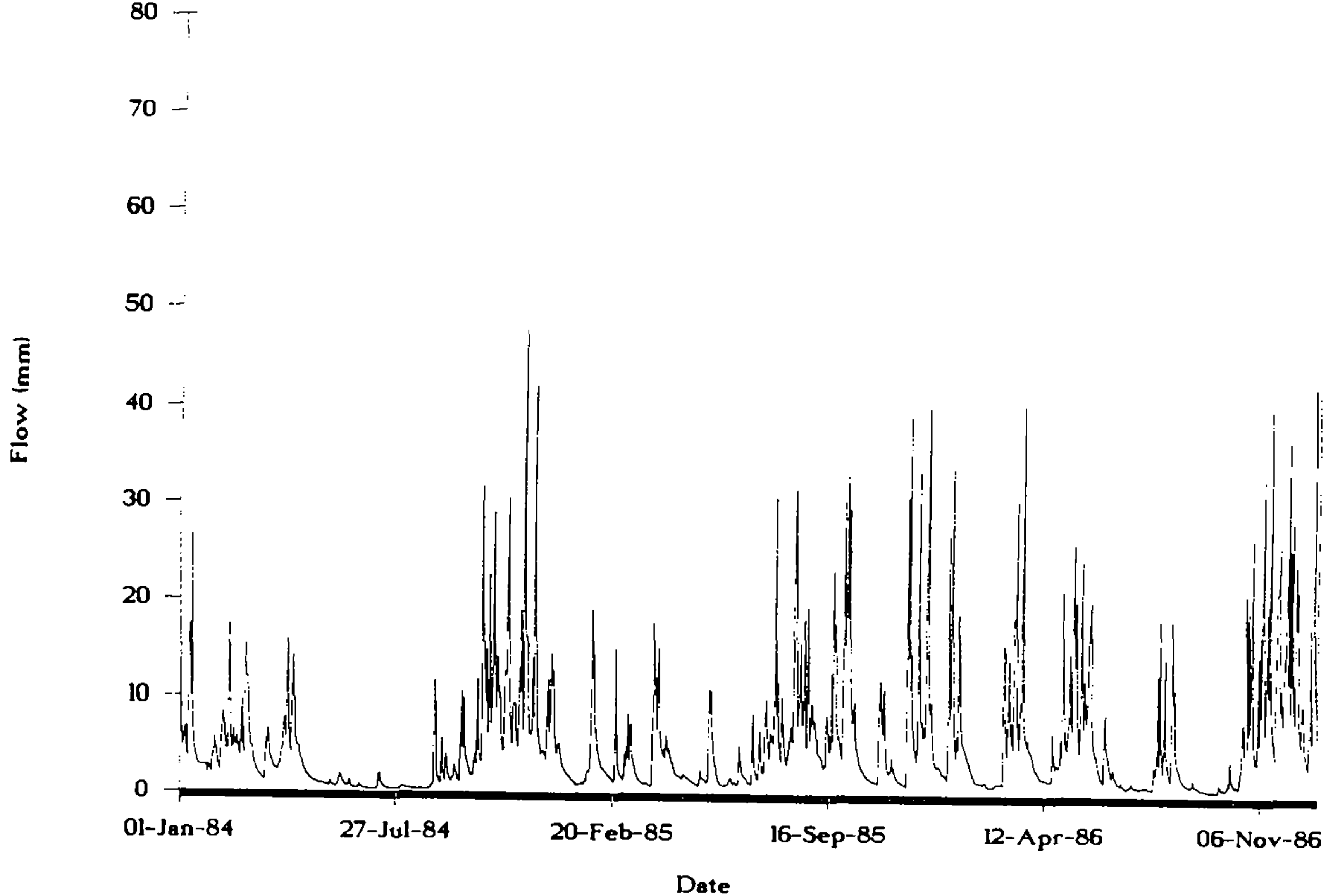


Figure 2.3.13 *Kirkton daily flows*

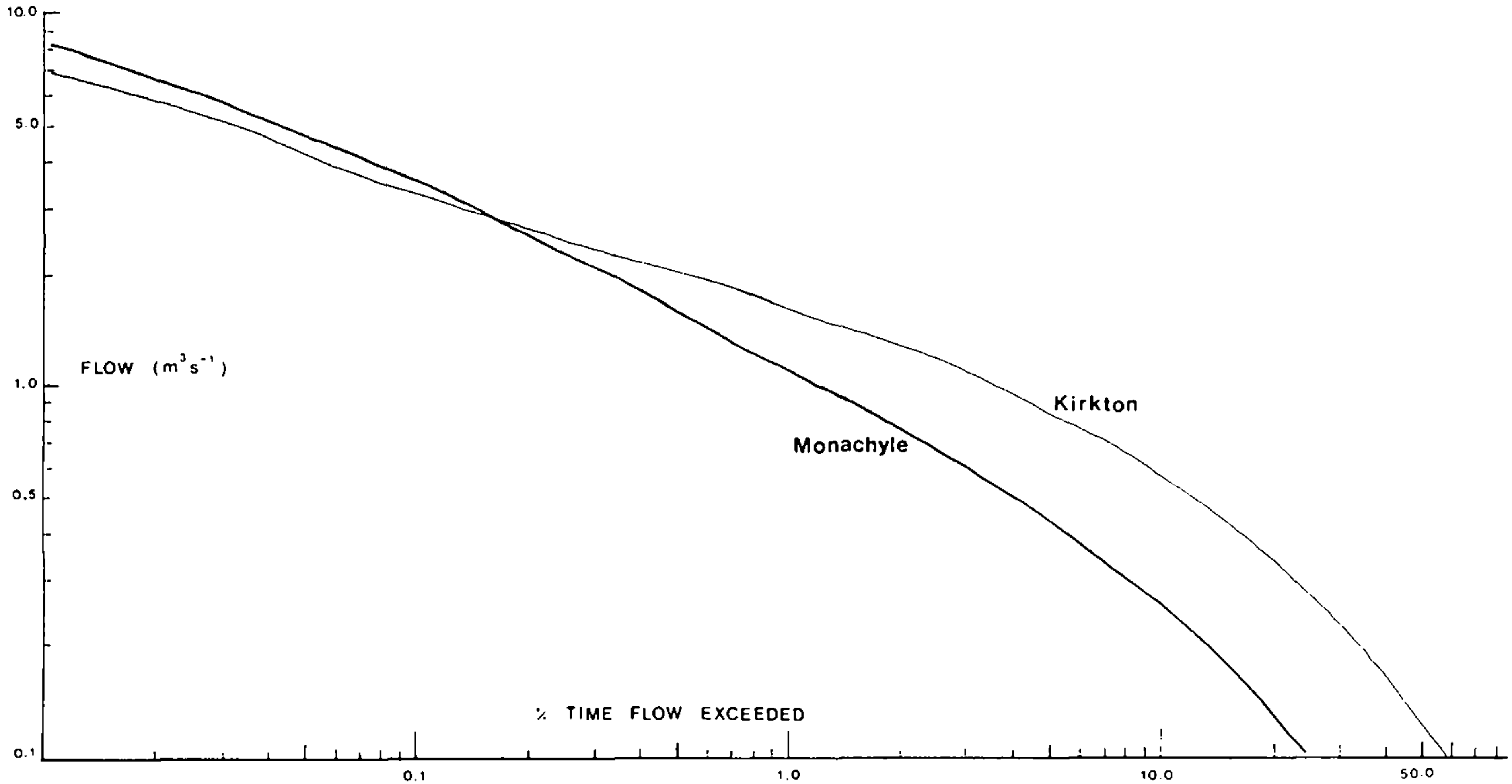


Figure 2.3.14 Monachyle and Kirkton flow duration curves

2.4 METEOROLOGICAL DATA

An essential part of the study of the land use effects on water resources is a definition of the specific climatic conditions in which the observed catchment responses occur. Precipitation has been discussed in detail in Section 2.1 but the other variables such as radiation, temperature, humidity and wind speed all influence vegetation growth, water use and soil stability and must be sampled in the area. A useful 'method of integrating those variables which control water-use or evapotranspiration by the vegetation is the method due to Penman (1948) which provides an estimate of the 'potential' rate of water use, ET, by a grass cover in conditions where moisture supply is not limiting. This estimate of water use, or variants of it, is widely used in hydrological studies as a reference level to which water use by different vegetation types can be related. These relationships can then be used, together with precipitation data, to estimate water use by these vegetation types in other areas where climatic conditions are different.

2.4.1 Penman Estimates

As indicated in Section 2. a network of 4 AWS was installed in the catchments to sample the range of climatic conditions and provide the data necessary for the computation of Penman ET values. These four stations, were located to sample variations primarily with altitude. They are the Kirkton High station at 670 m, the Upper Monachyle at 470 m, the Monachyle Glen at 300 m and Tulloch Farm at 140 m. In topographical terms the upper two stations are sampling 'ridge top' situations in the Monachyle and Kirkton catchments, while the Monachyle Glen and Tulloch Farm sites sample conditions in the bottom of N-S and E-W valleys. Following analysis of the preliminary results from these sites a fifth station, Kirkton Forest, was installed above the forest canopy in the Kirkton valley bottom at an altitude of 380 m to sample conditions there.

These stations sample solar and net radiation, temperature, humidity, windspeed, wind direction and precipitation at 5 minute intervals. The data are accumulated on Microdata magnetic tape loggers, the tapes being changed at fortnightly intervals. Tapes from a large number of such stations in use around the world are translated in a central facility at IH, Wallingford. This frequently leads to delays in obtaining and processing the data so that malfunctions of the loggers or the individual sensors may continue for long periods before they are identified and rectified. This unsatisfactory situation should be rectified in the near future when the loggers are due to be replaced with processor controlled solid state systems from which usable data can be extracted by the user.

The first year of operation of the Kirkton High and Monachyle Glen sites produced only intermittent periods of data. Thereafter a higher capture rate was achieved on all stations but intermittent problems with individual sensors meant that complete sets of data from which Penman ET could be computed were available for relatively few months.

A preliminary analysis of mean daily values of Penman ET from 'complete' months up to 1985 (Blackie 1987) indicated that the relationships between the stations were stable and well defined. Using these relationships to infill missing months indicated that annual ET values for the exposed high level stations were similar and significantly higher than those from the lower altitude valley bottom sites. This apparent increase in Penman with altitude was surprising since it was contrary to the assumptions on which regional estimates of ET are based (MAFF, 1967) (see Section 3.5).

Data from subsequent 'complete' months in 1986 and 1987, give no indication of any significant changes in the relationships. Insufficient good records have been obtained from the Kirkton Forest site for this yet to be used in a detailed comparison but the preliminary indications are that they will conform to the pattern established by the other sites.

Using the inter-site relationships (Blackie, 1987) to infill missing months, the annual totals in Table 2.4.1 have been estimated. As can be seen, the probability is that within-catchment variations in ET will exceed those between the catchments.

2.4.2 Climate, Altitude Relationships

Clearly a more rigorous approach to identifying the reasons for the altitudinal variations of Penman ET is required before it can be used effectively as a basis for predictive models of water use by the range of vegetation within these or any other catchments.

A start was made on analysing the altitudinal differences of the individual variables by Johnson (1985). He found pronounced differences between Tulloch Farm (140 m) and Kirkton High (670 m) in temperature, net radiation and windspeed. For the one year of data analysed, mean temperature was 4.8°C lower at Kirkton, whilst mean windspeed was 3.0 m s^{-1} or 110% higher. Net radiation was similar in the winter months but up to 50% higher at Kirkton in summer.

In Figs. 2.4.1 to 2.4.5 monthly mean daily values of solar, net, temperature, saturated humidity deficit and wind speed are plotted against the Tulloch Farm values for all complete months for all stations. These indicate surprisingly close values of solar radiation at all sites but marked differences in the other variables. The general trends are in the same sense as those identified by Johnson. The similarity in the between site relationships from year to year helps to explain the stable between-site Penman relationships. Comparison of the slopes of the regression lines in the above figures suggests that factors other than altitude are involved. The presence of snow at some stations and not others during the winter months undoubtedly plays a part but factors such as low cloud and differences in soil moisture in the summer months must have some influence.

Clearly, however, the reason for the higher Penman ET values at the high altitude stations is that they experience much higher net radiation and wind speed, which suggests that exposure rather than altitude is the significant factor.

More complete runs of data and further analysis is required before any generally applicable model of climatic variation can be formulated as a basis for estimating catchment mean Penman ET values.

For the present the similar values derived from the two exposed sites have been used as reference values in the water balance analysis in Section 2.5.2.

TABLE 24.1 Estimated Annual Penman ET Totals (mm)

	1983	1984	1985	1986	1987	1983-85 means	1983-87 means
Kirkton High (670 m)	522	635	446	558	492	534	531
Upper Monachyle (470 m)	(540)*	634	464	584	492	546	543
Monachyle Glen (300 m)	495	557	392	458	443	481	469
Tulloch Farm (140 m)	438	504	370	415	415	437	428

* Estimated from the other stations

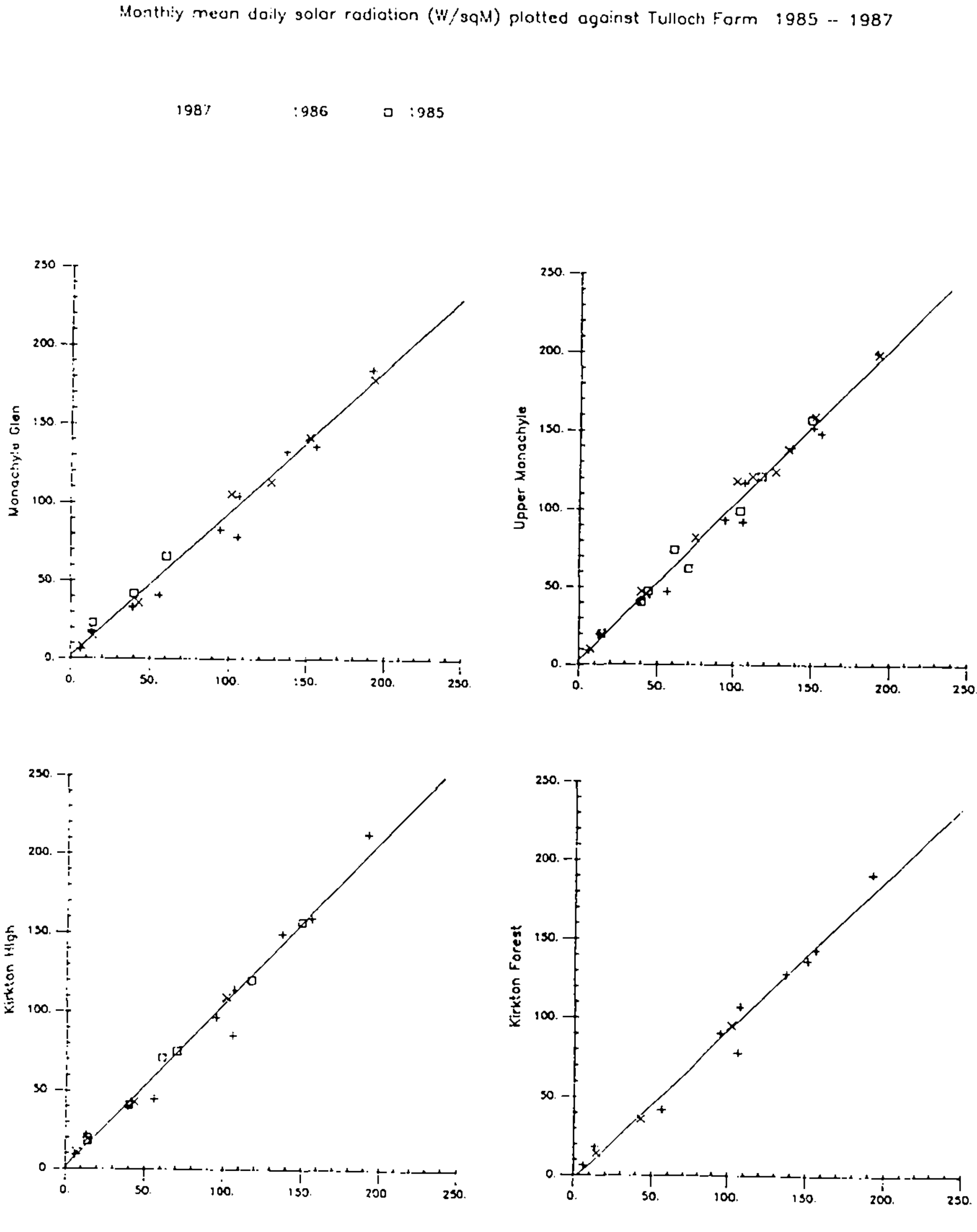


Figure 2.4.1 Between-site solar radiation relationships

Monthly mean daily net radiation (W/sqM) plotted against Tulloch Farm 1985 – 1987

+ 1987 × 1986 □ 1985

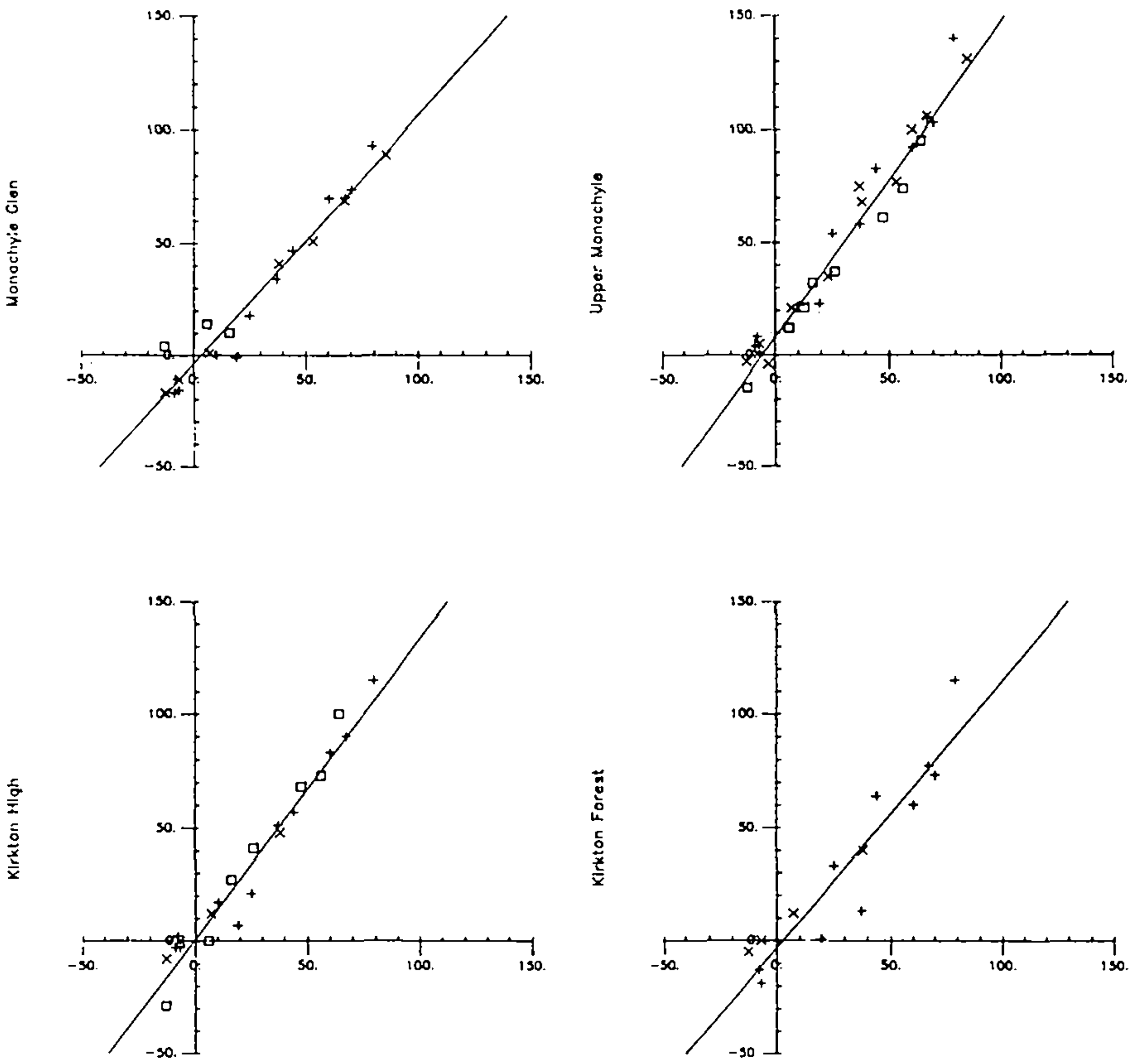


Figure 2.4.2 Between-site net radiation relationships

Monthly mean daily Temperature (Deg C) plotted against Tulloch Farm 1985 - 1987

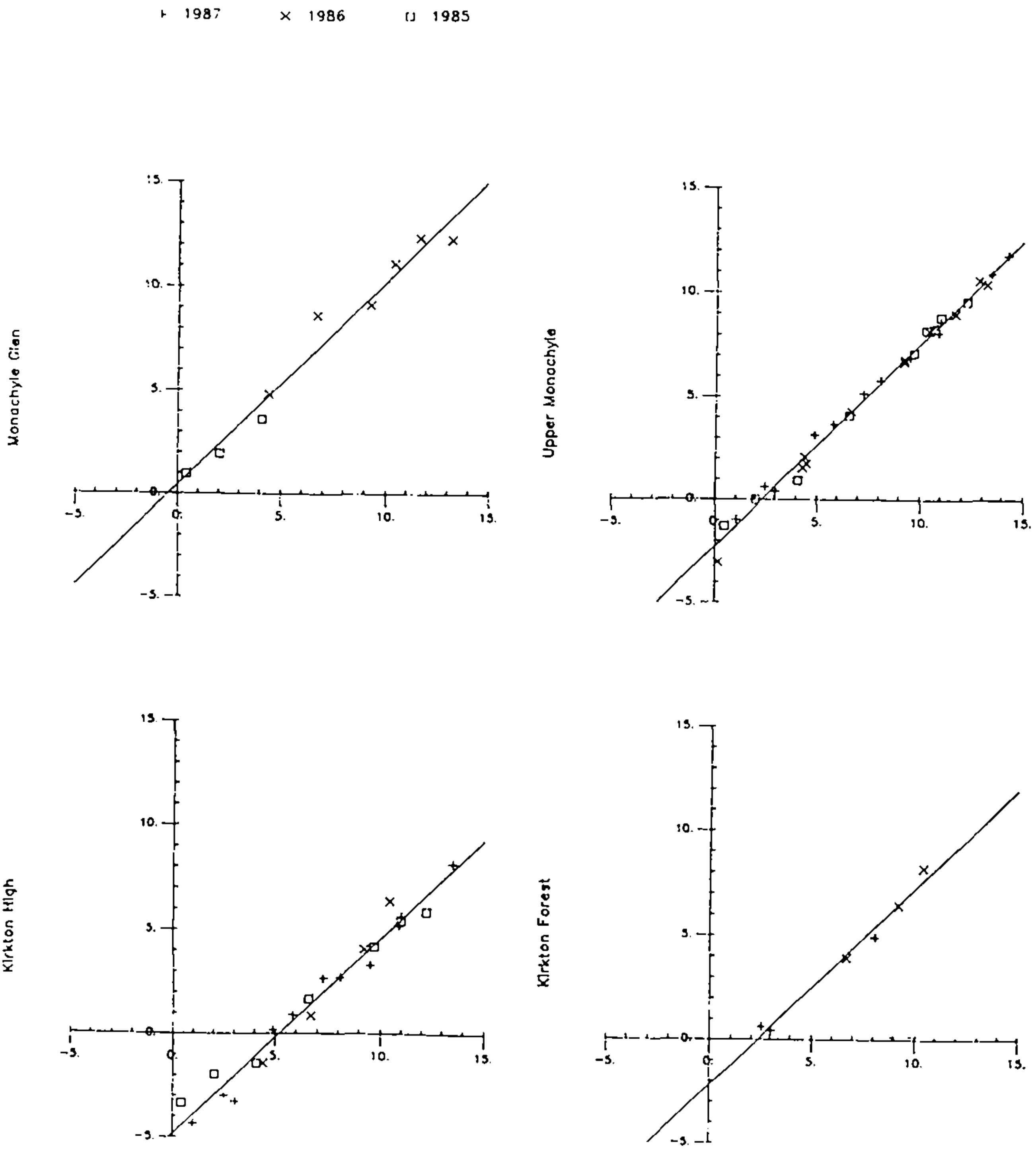


Figure 2.4.3 Between-site temperature relationships

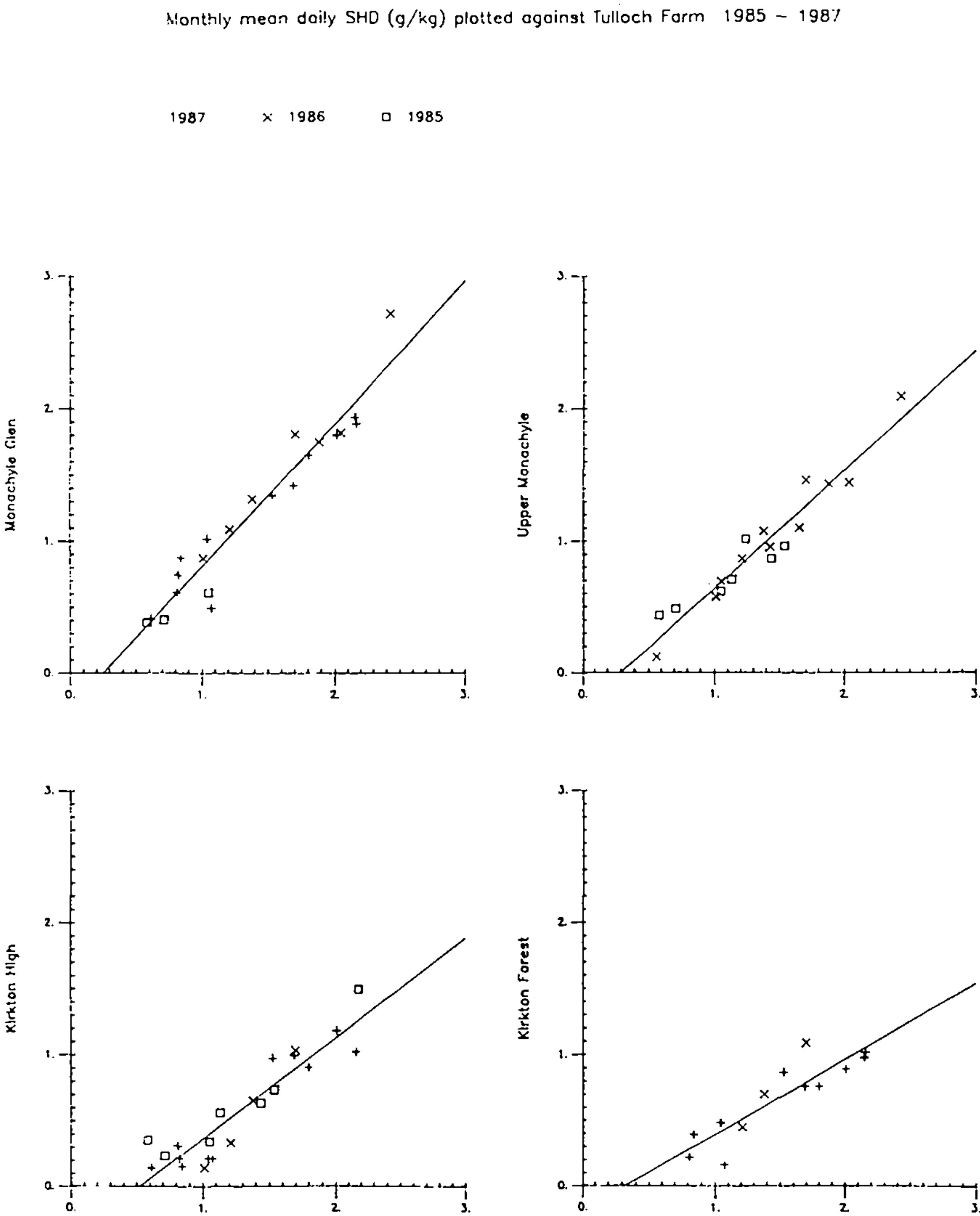


Figure 2.4.4 Between-site saturated humidity deficit relationships

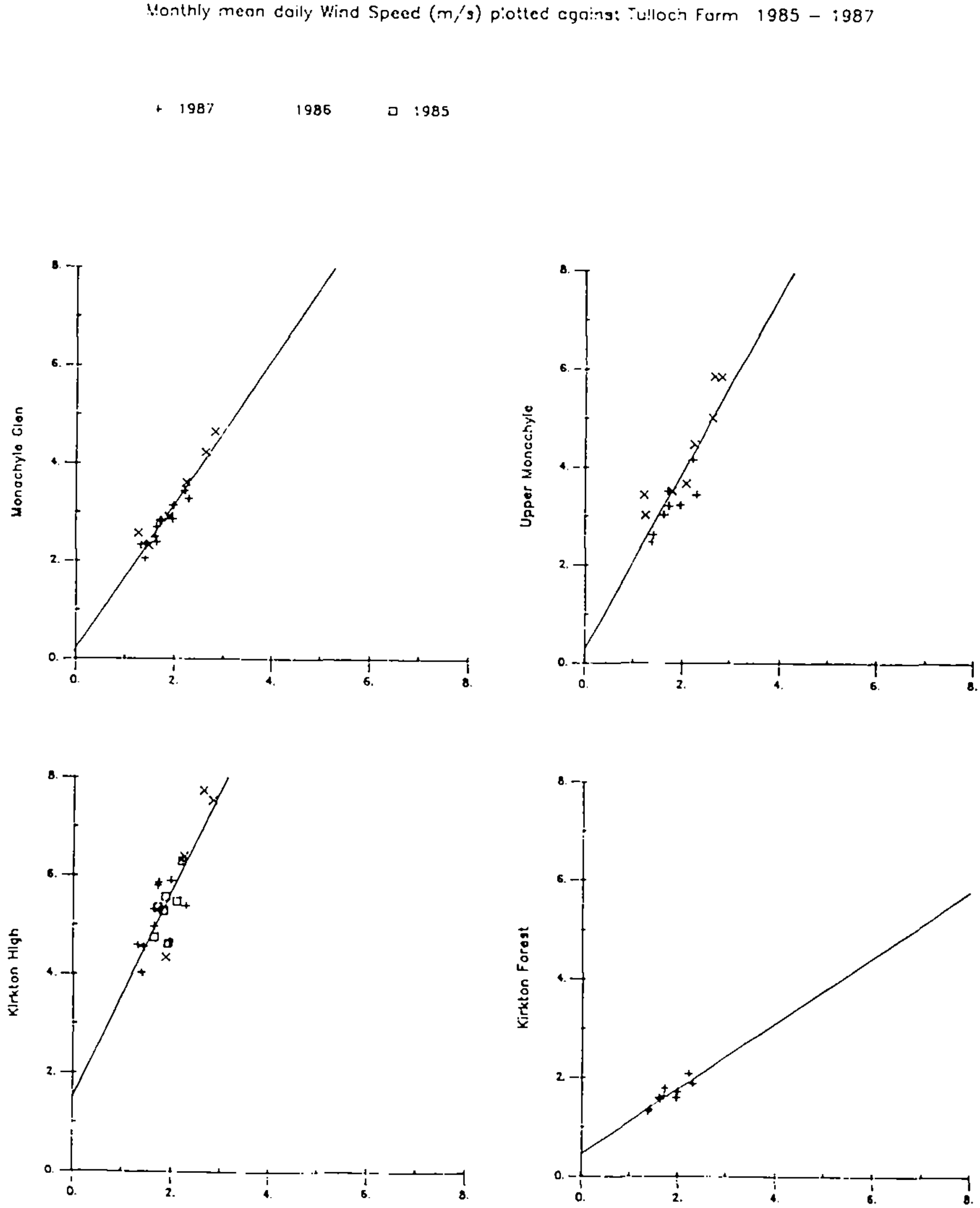


Figure 2.4.5 Between-site windspeed relationships

2.5 CATCHMENT WATER BALANCES

The fundamental expression governing catchment hydrology is the continuity or water balance expression. Over any given period for a 'watertight' catchment

$$\text{INPUT} = \text{OUTPUT} + \text{STORAGE CHANGE}$$

i.e. Precipitation = streamflow + water use + storage change
P Q AE ΔS

Rearranging gives the water use of the catchment as:

$$AE = P \quad Q \quad \Delta S.$$

Whilst P and Q can be measured accurately, the storage term presents problems in most catchments. The absolute total storage in the catchments is irrelevant in this context, the values of interest being the magnitudes of the fluctuations $\pm \Delta S$ about the long term mean storage levels. In catchments where the soils and the ground water aquifers are reasonably uniform, it is possible to estimate these components of ΔS over a period from network observations of soil moisture and either groundwater level observations or storage discharge relationships derived from the streamflow recession in long dry periods. Whilst normally these are the major components of ΔS, other components can be of importance. These include short term surface storage of storm water in transit and longer term storage in snowpack.

Where it is not possible to measure any or all of these components of ΔS, a first approximation to AE is given by:

$$AE \approx P - Q.$$

Obviously the approximation becomes more accurate over longer periods as P-Q increases progressively relative to ΔS.

In these circumstances it is important to assess the potential range of storage change so that the probable error associated with the P - Q approximation can be assessed and hence the minimum period over which this can be expected to give acceptable estimates of water use.

2.5.1 Storage Changes

In the Balquhidder catchments the soils are generally shallow but very variable in depth and type, making systematic sampling of soil moisture unrealistic.

The topographical and geological evidence suggest that ground water storage is likely to be limited to a series of small, irregular, unconnected shallow aquifers so that groundwater observations are not feasible and the frequency of inputs of precipitation make the delineation of recession curves difficult. Consequently the estimates of water use from the water balances are limited to the approximation.

$$AE \approx P - Q.$$

The probable uncertainty in these estimates of water use resulting from the absence of the ΔS term can be assessed by consideration of the data now available from the catchments.

An indication of the probable range of the soil moisture component of ΔS is available from neutron probe data obtained as part of the process studies (Section 3.6). Three sites with deeper than average soils under heather, grass and mature spruce were instrumented to give approximately weekly soil moisture readings during summer periods. At the end of the most extreme dry spell experienced, in summer 1984, these sites showed deficits of 50 mm, 60 mm and 100 mm respectively. Consideration of the soil depths and vegetation cover on the catchments suggests that mean catchment deficits at this time would not be greater than 50 mm. For the rest of the observation period at the three sites, deficits rarely approached 50 mm, suggesting that the component of ΔS is unlikely to exceed 20-30 mm over most periods.

An indication of the magnitude of groundwater storage is available from the streamflows during the exceptional dry spell from late April through August 1984, illustrated in Fig. 2.5.1, which started with high baseflows after the completion of snowmelt. Over the period, baseflows dropped from 1.8 mm/day to 0.1 mm/day in the Monachyle and from 3.5 mm/day to 0.4 mm/day in the Kirkton. The baseflow components are estimated as 85 mm and 32 mm respectively. Under more normal conditions therefore the groundwater component of ΔS is unlikely to exceed ± 50 mm in Kirkton and ± 20 mm in Monachyle.

Short term surface storage of storm water in the catchments can be considerable, as witnessed by daily streamflows in excess of 60 mm in both catchments (Figs. 2.3.12 and 2.3.13). As indicated in Section 2.3.5, however, transit time of this water is generally of the order of 1-2 days. Provided the periods under consideration neither start nor end on days experiencing major storm events this component of ΔS is unlikely to exceed 20 mm.

The remaining component of ΔS is surface storage of snow. Whilst snow can be present in parts of these catchments at any time between October and May each year, it is only during periods of major accumulation that it becomes a significant component of storage. The rugged terrain makes it impossible to carry out systematic depth/density surveys of the complete catchments in such periods but partial surveys carried out in two accumulation periods give some indication of the possible range of storage. One of these was in a period of medium accumulation in early 1985 when the estimate of the water equivalent of the snow pack was in the range 20-30 mm. The period of greatest accumulation observed in the catchments was January-March 1984. A partial survey in January, before accumulation reached its peak, suggested water equivalent storage as high as 180 mm. In these catchments, therefore, snow storage is potentially the largest component of ΔS.

The probable value of ΔS between dates on which no major storm events have occurred or on which no significant snow accumulation is present, is therefore seen to be in the range ± 40-80 mm. A major storm on either date could increase this by a further 20 mm. However, if one of the dates is within a period of snow accumulation this range could extend to values greater than ± 200 mm.

This range of possible values of ΔS clearly precludes estimation of monthly water use using the P-Q approximation. Seasonal and even annual estimates must be treated with caution unless the start and end conditions are known. Over periods of two years or longer, however, provided they do not start or end in times of deep snow cover, the error introduced by ignoring ΔS is unlikely to be significant. Thus long term estimates of water use can be obtained from these catchments but, to obtain monthly or seasonal estimates, the data must be used in conjunction with other approaches. Process based models which have had their storage simulation components calibrated against the long term catchment data would be one such approach.

2.5.2 Results

The land uses in the two catchments remained unchanged until the end of 1985. Usable measurements of P and Q for both main catchments became available from December 1982. In the preliminary analysis of these data presented in 1986 and in the paper by Blackie (1987) the Kirkton streamflow figures were those computed from the revised rating, but the Monachyle figures were from the original theoretical rating. The latter have been recomputed using the revised rating (Section 2.3.2) and the revised figures are presented here. A number of minor corrections have been incorporated also in the precipitation estimates.

A time series plot of monthly values of P and Q is presented in Fig. 2.5.2. This plot is extended to include the first two years of Phase II of the study covering the initial stages of land preparation and planting in the Monachyle and of clear felling in the Kirkton. This plot demonstrates the close similarity in time distribution of both precipitation and streamflow between the two catchments and the consistent difference in precipitation. The lower values of flow in the Kirkton in wet months and higher values in dry months discussed in Section 2.35. are also evident.

Cumulative plots of monthly P, Q, P-Q and ET are shown in Fig. 2.5.3 and annual totals of P, Q and P-Q are compared with Penman ET totals in Table 2.5.1. Both of these indicate that water use, estimated by the P-Q approximation, was higher in the heather dominated Monachyle than in the part-forested Kirkton during Phase I. Furthermore, the P-Q estimates of water use are higher than the exposed site ET estimate in Monachyle but lower than the equivalent estimate in the Kirkton. These differences are also seen to extend into the early stages of Phase II.

Consideration of the discussions of the precipitation and streamflow data in Sections 2.1 and 2.3 implies that both of these quantities are probably estimated to within 1-3% on an annual basis, though there are suggestions from the precipitation/altitude relationships that Monachyle precipitation may be underestimated because of the absence of a sampling point in the high altitude domain in the SW area of the catchment. Similarly the checks on the C3Y rainfall anomaly in the Kirkton suggest that the domain weighted estimate, some 1% lower than the arithmetic mean presented here, may be the better. In other words, if there are systematic errors in the estimates of catchment water use arising from the methods of computing the catchment mean precipitation, they are likely to have produced an underestimate in the

TABLE 25.1 Annual totals (mm) of Precipitation (P), Streamflow (Q), Estimated Water Use (P-Q) and Penman Potential Evaporation (ET))

Period	MONACHYLE (Heather/grass)				KIRKTON (Forest + Grass)			
	P	Q	P-Q	ET	P	Q	P-Q	ET
PHASE I, CONTROL PERIOD								
1983	2811	2028	783	540*	2368	1721	647	522
1984	2582	1929	653	634	2162	1781	381	635
1985	2520	2056	464	464	2208	1960	248	446
Means	2638	2004	634	546	2246	1821	425	534
PHASE II, LAND USE CHANGES								
1986	3147	2522	625	584	2684	2242	442	558
1987	2198	1724	474	492	1841	1592	249	492
Means	2673	2123	550	538	2263	1917	346	525

TABLE 2.5.2 Comparison of P, Q and P-Q for Periods when Upper Monachyle Flow Data were Available (mm)

	MONACHYLE			UPPER MONACHYLE			'LOWER' MONACHYLE		
Period	P	Q	P-Q	P	Q	P-Q	P	Q	P-Q
8/83-11/83	995	693	302	996	726	270	994	679	315
5/84-10/84	887	530	357	885	523	362	888	534	354
4/85-12/85	2225	1788	437	2237	1863	375	2221	1758	463
Means			365			335			377
4/86-12/86	2405	1850	555	2443	1815	628	2390	1865	525
1987	2198	1724	474	2236	1757	479	2183	1711	472
Means			515			553			499

Monachyle and an overestimate in the Kirkton.

For the three year period 1983-85 to the end of Phase I of the study, the errors in the cumulative water use estimates resulting from the omission of ΔS are likely to have been small. Consideration of the evidence available on the soil moisture, groundwater, surface water and snow storage components on the lines discussed in Section 2.5.1 suggests ΔS values in the range -20 to -50 mm in both catchments. These are clearly insignificant in relation to the P-Q totals of 1900 mm and 1276 mm for the Monachyle and Kirkton respectively.

An indication of the probable variations in ΔS over successive 12 month periods is given in Fig. 2.5.4 where moving 12 month totals of P-Q for both catchments are compared with ET totals for the same periods. Assuming that true annual AE has some reasonably consistent relationship with ET, the departures from the parallel between the P-Q and ET lines in Fig. 2.5.4 can be interpreted as indications of ΔS. Thus, for example, when the January-March 1984 period of snow accumulation enters and leaves the 12 month totals departures of up to 300 mm are seen to occur. These are not inconsistent with the depth density estimates described in Section 2.5.1. Apart from these major departures smaller departures are present in other 12 month periods. The 180 mm departure between 9/84 and 8/85 in the Monachyle is consistent with the exceptionally dry conditions at the end of August 1984 and the very wet July/August of 1985 illustrated in Figure 2.5.2.

Because of the freezing-up of the float well, it was not possible to obtain complete winter estimates of Q from the Upper Monachyle sub-catchment until 1986/87. Comparison of 'summer' P, Q and P-Q data with that from the main catchment in Table 2.5.2, however, suggests that water use of this upper part for the catchment did not differ significantly from the lower part during Phase I. Comparison of the partial totals from 1986 and the complete year's totals for 1987, also listed in Table 2.5.2 suggests that water use by the lower part of the catchment may have been reduced during the ploughing and drainage operations in 1986 but any such reduction had disappeared by 1987.

2.5.3 Discussion

From the preceding section the best estimates of mean annual water use by the two catchments during the Phase I, 'undisturbed' period are seen to be:

	P-Q	'Exposed' ET
Monachyle	634	546
Kirkton	425	534

The discussion of probable errors suggests that neither systematic errors in P and Q nor the absence of the storage change term ΔS are likely to account for the water use difference between the catchments. The uncertainties in the computation of Penman ET at each site are difficult to assess but from the annual estimates based on the fragmentary data currently available (Table 2.4.1), the catchment means appear likely to be in the range 450-550 mm in both catchments.

The surprise finding was the very low value of water use for the Kirkton despite the presence of some 35% of mature forest. This percentage forest cover together with some 55% rough grass at the higher levels and some 10% mixed heather/grass cover on the ridges, would have resulted in a predicted water use of 710 mm applying the Calder & Newson (1979) model to the rainfall and meteorological data for Balquhidder. Clearly, either some major source of error was present in the data or the assumptions of the Calder & Newson model were not applicable in these conditions. The hydrogeological survey of Robins & Mendum (1987) ruled out any significant cross boundary transfer of water. The checks on the precipitation networks (Section 2.1.4) ruled out the possibility of errors large enough to account for the discrepancy. The on-site interception study (Section 2.2) gave no indication that the forested area was behaving differently from those studied intensively elsewhere. Logically, therefore, the source of the discrepancy had to be the water use of the high altitude grassland. In Calder & Newson and indeed in most water use models to date it is assumed implicitly that grass not subject to major moisture deficits uses water at the Penman potential rate. Some indication that this might not be entirely accurate has been obtained from the recently revised and as yet unpublished figures from the Plynlimon study in Wales, where the revised water use figures for the grassland catchment are some 80% only of Penman ET. This level of reduction in grass water use, when taken in conjunction with the expected losses from the forested area, would be inadequate to explain the above Kirkton value however. To determine a better basis for the estimation of water use by grass in these extreme conditions, a detailed study has now been mounted at Balquhidder. Details of this and preliminary results from it are given in Section 3.2.

The Monachyle water use figures for Phase I appear to exceed Penman ET. This was not unexpected in the light of results emerging from the parallel process study of the water use characteristics of heather. The application of a model derived from the results of this process study to the Monachyle data is discussed in detail in Section 3.3.1.

These comments serve to emphasise the value of the combined catchment and process scale approach to the determination of the effects of land use change. Without the catchment studies the need for further investigation of grass water use would not have been apparent. Without the process studies and the models developed therefrom, interpretation and subsequent extrapolation of the catchment results would be fraught with uncertainty.

Two years of data are now available since the start of Phase II of the catchment studies in which the lower part of the Monachyle is being progressively afforested and the mature forest is being felled in the Kirkton. Applying the most recent guidelines rigorously has resulted in only 6% of the Monachyle being ploughed in the total of 30% due for planting. Some 10% had been planted by the end of 1987. This minimal change in vegetation cover to date was unlikely to result in any major change in water use and the 1986 and 1987 values in Tables 2.5.1 and 2.5.2 appear to confirm this. Changes can be expected, however, as the planting is completed and the seedlings grow above grass/heather level. Other changes resulting from the early stages of the Monachyle land use change, notably the effects of erosion, are described in Section 2.6.

The progressive felling of the forest in Kirkton in Phase II of the study has reached the stage where 40% of the forest, mainly on the western side of the catchment, has been felled. The water balance figures for this period in Table 2.5.1 Suggest a downward trend in water use but a longer run of data is required before this can be confirmed.

Clearly it is desirable for both studies to be extended through the period of land use changes to determine the full effects of these phases of the forestry cycle on water use and on streamflow response. Already, however, it has become apparent that afforestation in Highland Scotland is likely to result in more complex changes than would have been predicted from the knowledge available prior to these studies.

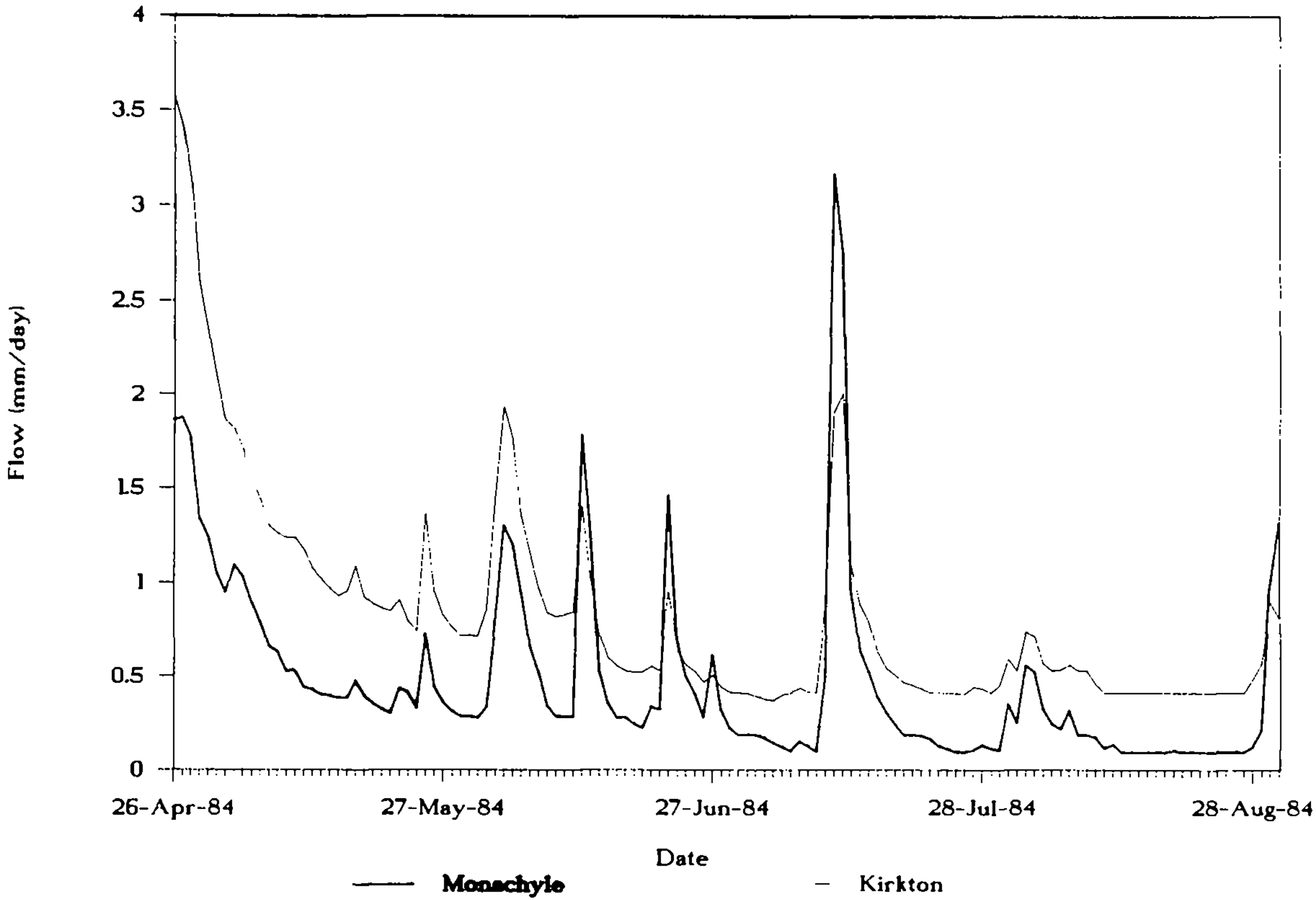
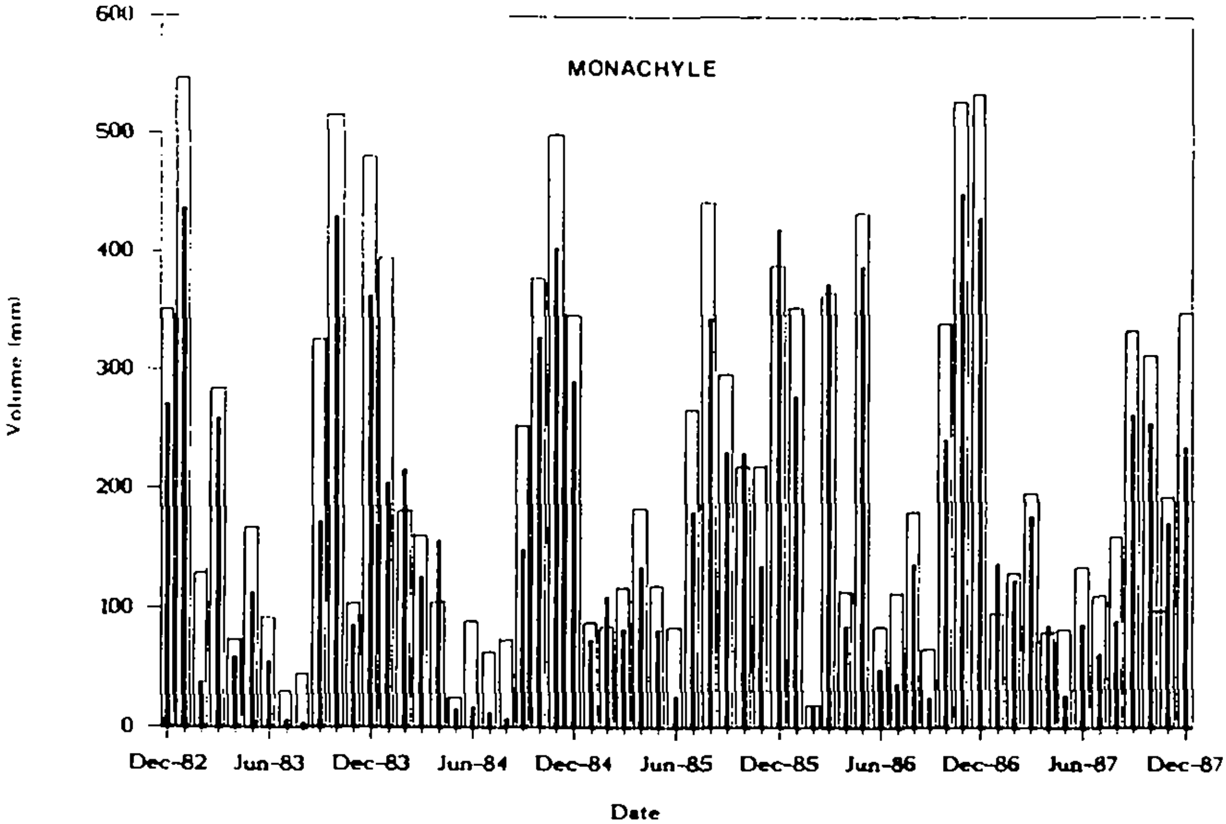


Figure 2.5.1 Dry period flows, 1984



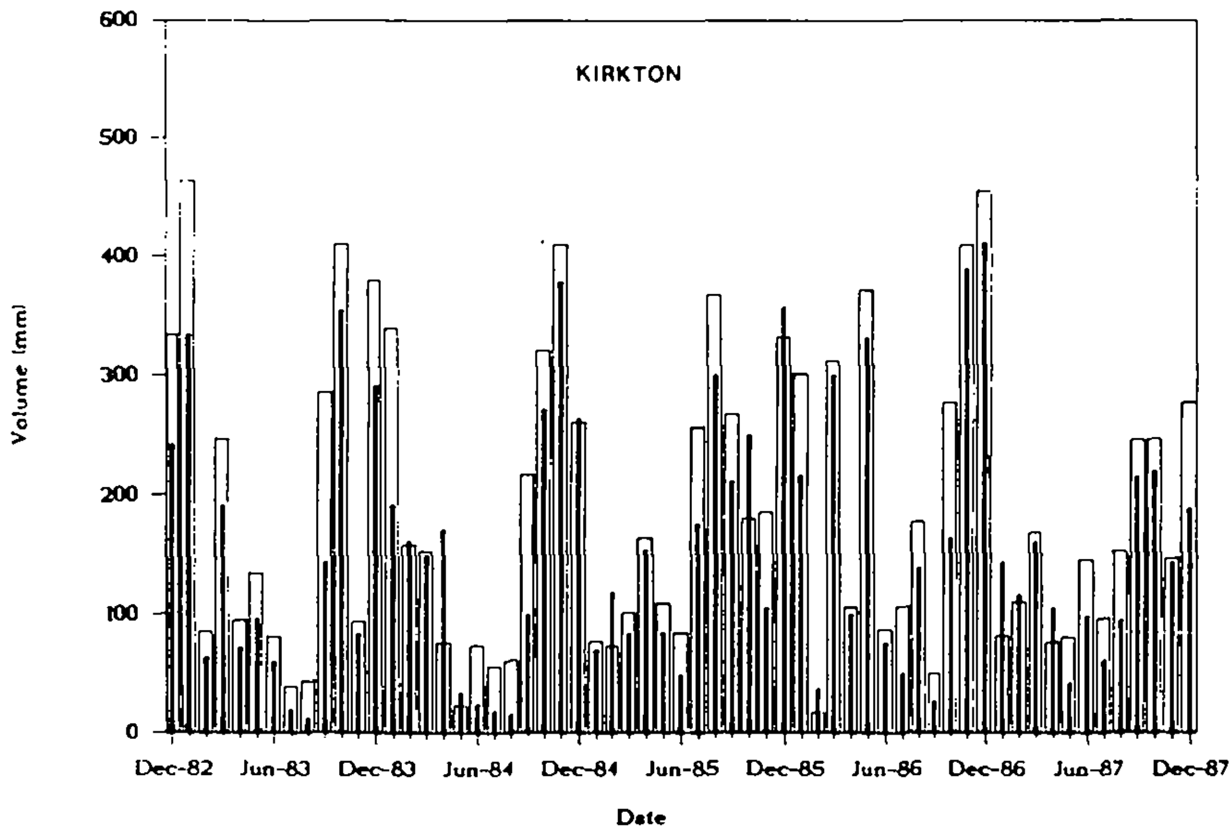


Figure 2.5.2 Monthly precipitation and streamflow

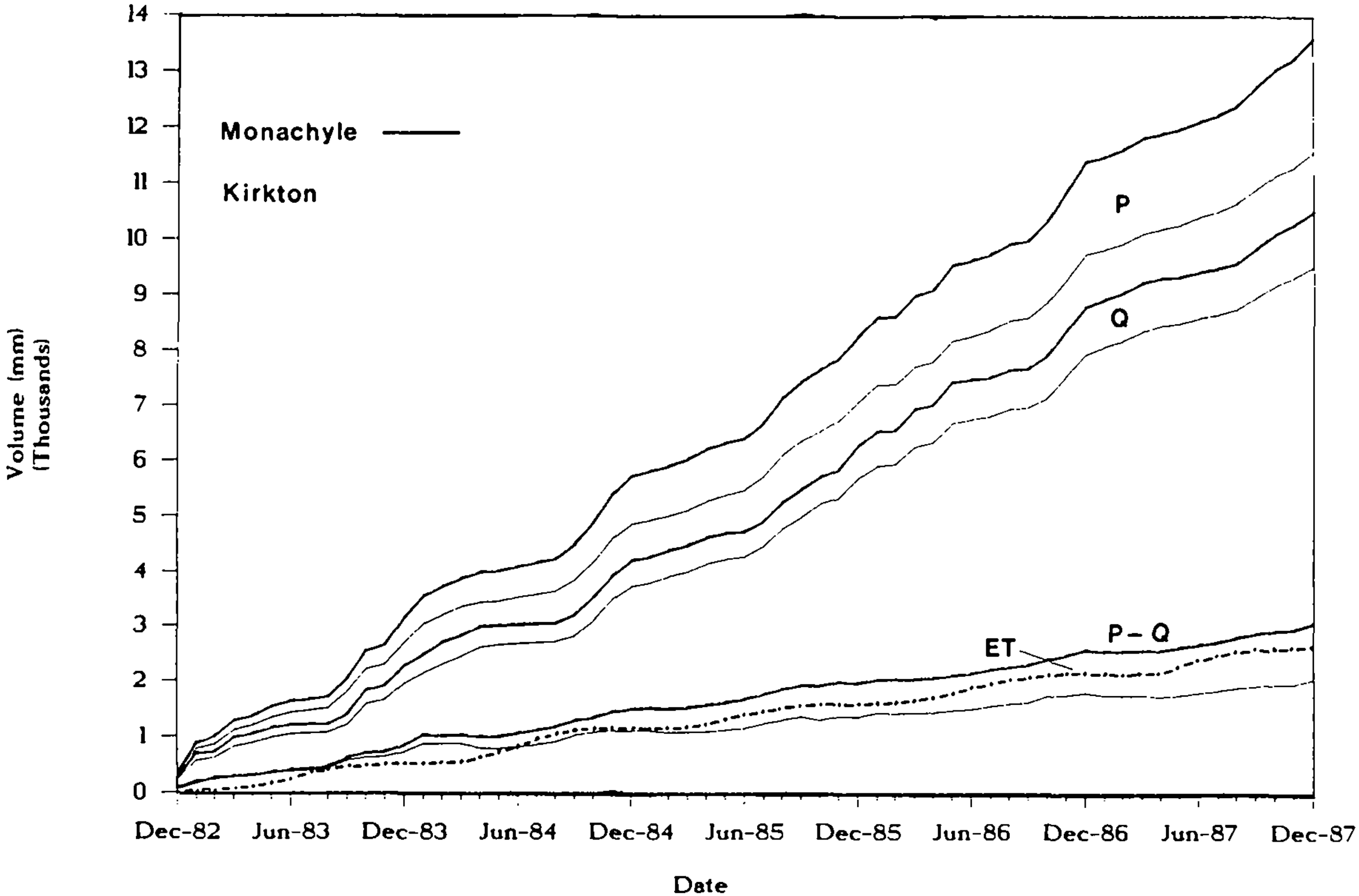


Figure 2.5.3 *Cumulative precipitation (P), streamflow (Q), estimated water use (P-Q) and Penman ET*

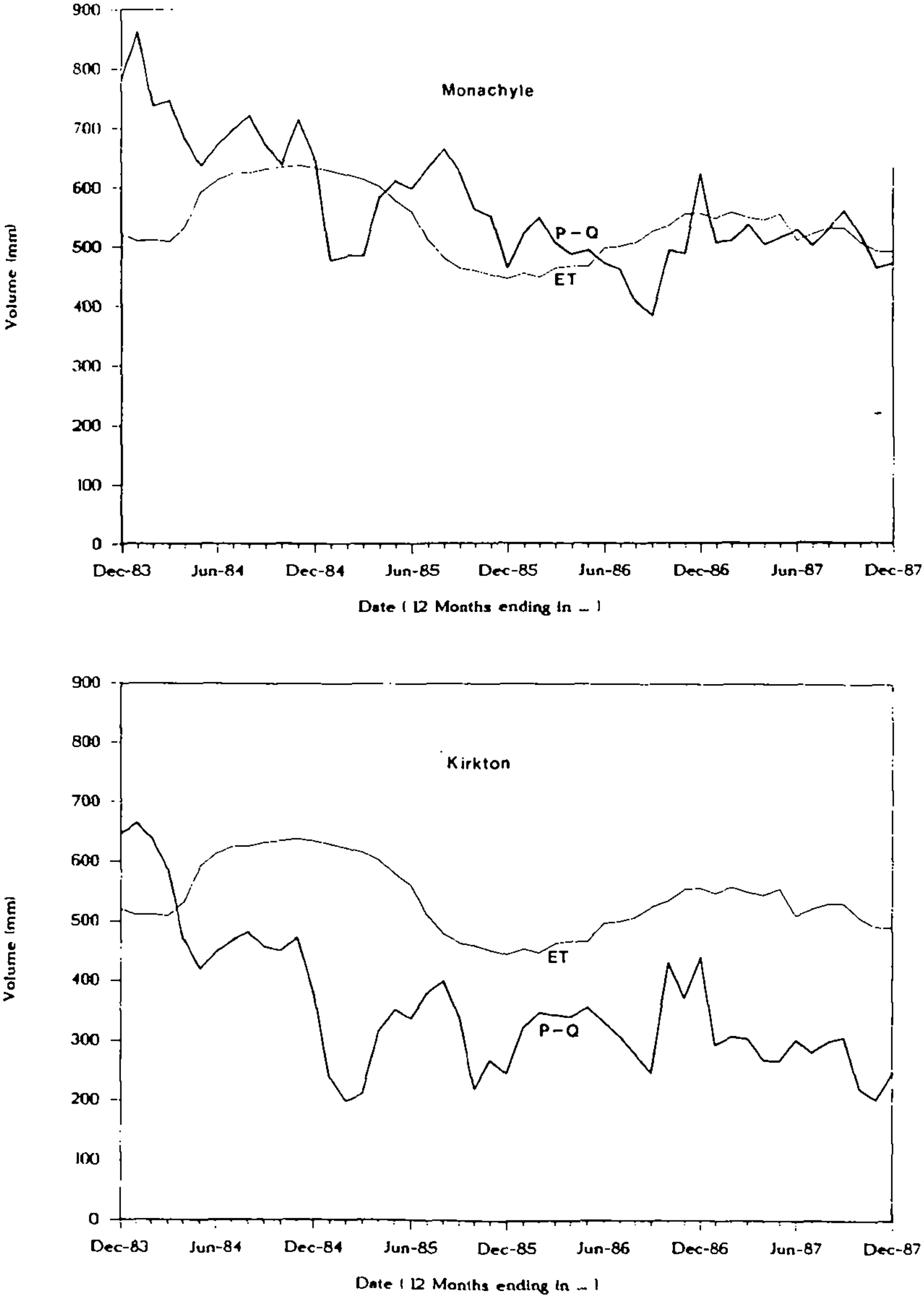


Figure 2.5.4 Twelve month running totals of estimated water use (P-Q) and Penman ET

2.6 SEDIMENT TRANSPORT

In studies at Plynlimon, Coalburn and elsewhere, it has been found that a significant effect of afforestation in upland Britain is to increase erosion. Newson (1980) reported sediment losses from a mature forested catchment at Plynlimon over five times greater than those from an adjacent grassland catchment. The reason for this increase in erosion has been shown to be the soil disturbance associated with the pre-planting ploughing and drainage required to establish the plantations. Robinson & Blyth (1982) in a study at Coalburn, Cumbria, established that losses from the plough lines there peaked within a few months of treatment but stabilised at levels higher than those recorded before treatment. The duration of these higher loss rates may vary from site to site with soil type, rainfall, slope and control measures adopted but the fact that losses were still five times greater at Plynlimon 30+ years after planting was sufficient reason to incorporate sediment studies in the Balquhidder programme from the outset.

During Phase I, two on-going studies were established. One was concerned with quantifying the sediment losses, both in suspended and bedload form from the two catchments and relating these to observed flows to construct sediment ratings. The second was concerned primarily with establishing the origins within the catchments of these sediment loads. These studies have now been extended into Phase II so that changes in the sediment responses during land preparation and initial planting in the Monachyle and clear-felling in the Kirkton can be quantified and compared with the pre-treatment ratings and so that the sources of any changes in supply can be identified.

2.6.1 Results

The main sources of sediment in both catchments prior to the land use changes were found to be the steep tributary streams, with only a small proportion coming from erosion of the main stream banks. Inputs to these side streams in the Kirkton appeared to occur primarily in the lower reaches within the forested area.

After initial experiments to determine the optimum sampling points and methods at both catchment outfalls, systems of sampling suspended sediment using both automatic vacuum samplers and USDH48 manual samplers and of bedload using Helley-Smith bedload samplers were evolved.

From samples taken over a range of flows on both the rising and falling limbs of the hydrograph, logarithmic ratings of sediment loads against flows were derived. The 1983 to 1985 Phase I envelopes enclosing 300 points and the curves fitted to them are shown in Figs.2.6.1 A and B. Seasonal variations in the ratings are still being investigated but it has been established that no significant differences existed between rising and falling stage sampling points. The mean bedload ratings over the period 1983-85 were:

Monachyle: $\log C = -2.27 + 2.48 \log Q \quad (r = 0.76)$
Kirkton: $\log C = -1.11 + 3.00 \log Q \quad (r = 0.74)$

Applying the appropriate ratings to the flow data in each year gave the annual losses shown in Table 2.6.1. Mean annual loss rates of suspended sediment for the undisturbed 1983-85 period were found to be 57 t km^{-2} from the Kirkton and 37 t km^{-2} from the Monachyle. Bedload was very much lower from both at 0.8 t km^{-2} and 0.1 t km^{-2} respectively.

During 1986 when work began on land preparation and planting in the Monachyle and on clear felling in the Kirkton the same sampling techniques were used but the frequency was increased so that some 300 samples were taken in each catchment. As can be seen from Figs. 2.6.1C and D maximum concentrations of suspended sediment did not increase significantly but there was a notable increase in the concentrations at low flows. Whilst the rating regressions were less well defined because of the increased scatter at low flows their application to the flow data indicated significant rises in annual sediment losses (Table 2.6.1). Sampling frequency was increased still further in 1987 to give almost continuous 8 hourly samples of suspended sediment in both catchments. The results obtained (Figures 2.6.1 E and F) show a continuation of the trend first observed in 1986 with an even wider range of scatter in concentrations at the very low flows. In this year also a significant increase in the maximum concentrations was observed, these occurring at low to medium flows rather than at the very high flows. Whilst there is still some indication of a sediment response to flood events, it is apparent from Fig. 2.6.1 that simple flow related rating curves are now inadequate to determine sediment losses from the catchments. The increased losses at low flows imply that sediment is available in large quantities in easily transportable form. Comparison with rainfall data, Fig. 2.62, suggests that rainfall intensity, implicitly an indicator of surface water movement, is a better basis for estimating sediment loss in the present state of the catchments than streamflow. The first estimates of the 1987 annual losses in Table 2.6.1 are provisional only, based on a combination of the poorly defined rating curve and a preliminary relationship with rainfall. This method is still under development. The apparent reduction, relative to 1986, in both catchments is a result of the much drier conditions and lower flows (see Fig. 2.5.2) rather than any stabilisation within the catchments.

2.6.2 Discussion

During 1986 land preparation for planting began in the Monachyle. The combination of the latest guidelines in planting practices with the topography, soils and geology of the catchment meant that only 6% of the catchment area was ploughed. Plough lines terminated some 20 m from the main water course and cut-off drains were dug across the ends of the furrows at slope angles of less than 3°, most of these also terminating well before drainage lines. Planting in non-cultivated areas has caused virtually no soil disturbance. Whilst sediment movement was observed in the plough lines immediately, this was not at first finding its way much beyond the ends of the cut-off ditches. However, as accumulations from the plough lines increased these concentrations of loose material began to be transported into the water courses, resulting in the 3-5 fold increases in the stream sediment loads indicated in Table 2.6.1. This concentrating effect of the cut-off ditches raises questions on whether this is the best approach to containing sediment movement. The plough lines are now being recolonised with a vegetation cover but large quantities of sediment in the ditches are still easily transportable. The duration of this higher rate of sediment loss and the level at which it stabilises relative to pre-planting rates will be of particular interest.

In the Kirkton the reasons for the higher sediment loads during Phase I were not positively identified. It is worth noting however that an established though lightly used road system was present in the forested area throughout, whereas no roads are present in the Monachyle. This road system was upgraded in late 1985 and extended to include two timber stacking areas when felling started. Timber extraction to the roads, by cable crane and by tracked vehicles driven on brash mats, has caused minimal soil disturbance. Use of the roads has increased dramatically however with some 4 lorry loads of timber moving out each day, necessitating on-going road repairs and maintenance. Thus the main source of the 1986 5-fold increase in readily transportable sediment appears to be the road system.

TABLE 2.6.1 Annual sediment loads (tonnes), adjusted for bias. Bedload given as > 1 mm and also total load in brackets.

	Suspended		Bedload	
	Kirkton	Monachyle	Kirkton	Monachyle
1983	483	337	6 (20)	< 1 (2)
1984	292	296	5 (13)	< 1 (2)
1985	386	228	6 (17)	< 1 (2)
1986*	1965	1027	Not available	
1987*	986	860	Not available	

* provisional figures

40% of the forest has now been felled and the remaining 60% is scheduled for removal by 1990. During this period second crop planting will begin on the earliest cleared areas. Removal of the mature forest means the removal of 32% interception loss (Section 2.2) so that the sparsely vegetated cleared areas will experience greater direct rainfall impact as the present brash covering decays and presumably greater surface water flow. Any effect of this on erosion rates has been swamped so far by the large increases in loss from the roads but should become more apparent as the area cleared increases.

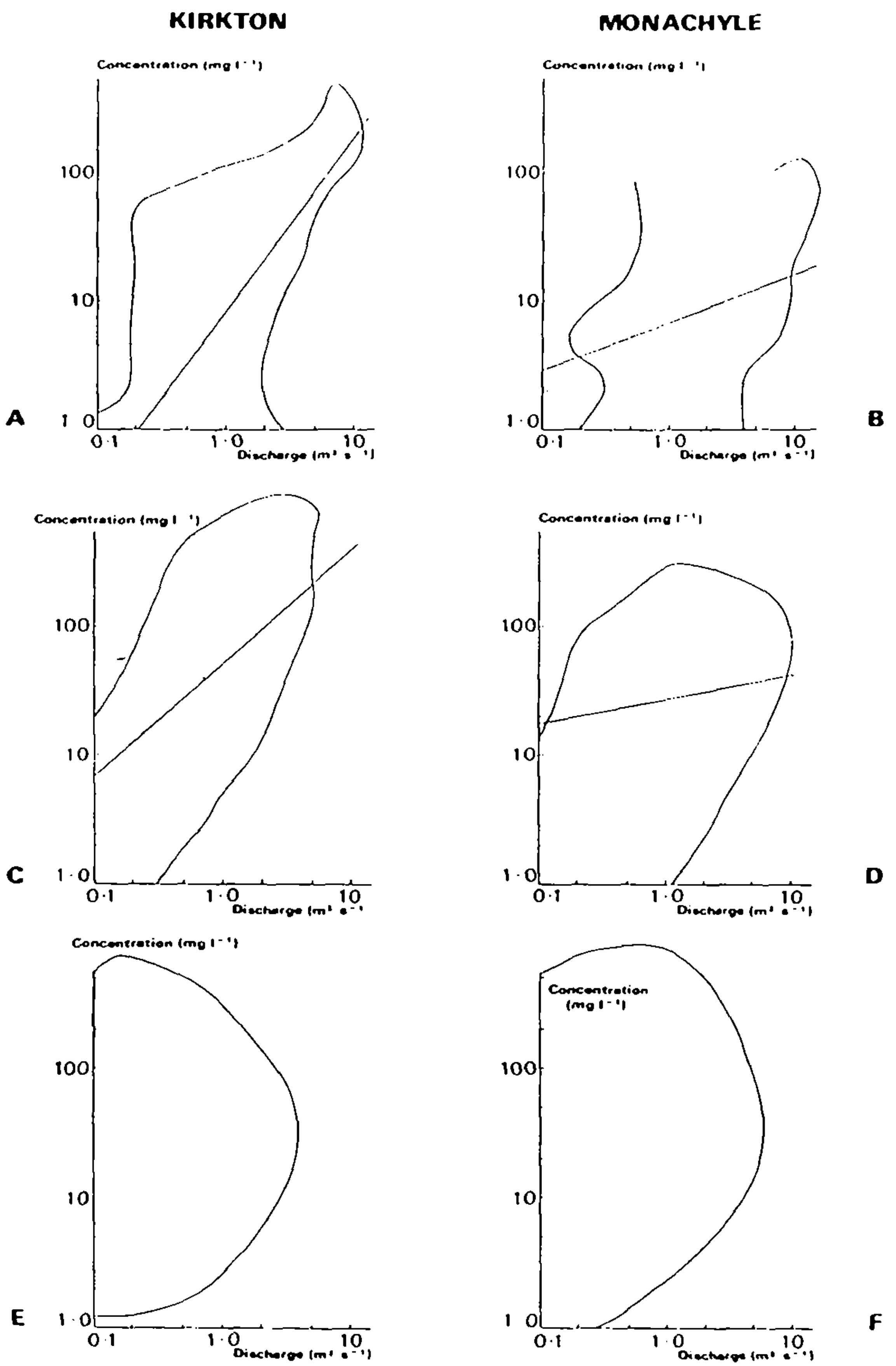


Figure 2.6.1 *Suspended sediment/discharge relationships*
A, B 1983-85; C, D 1986; E, F 1987

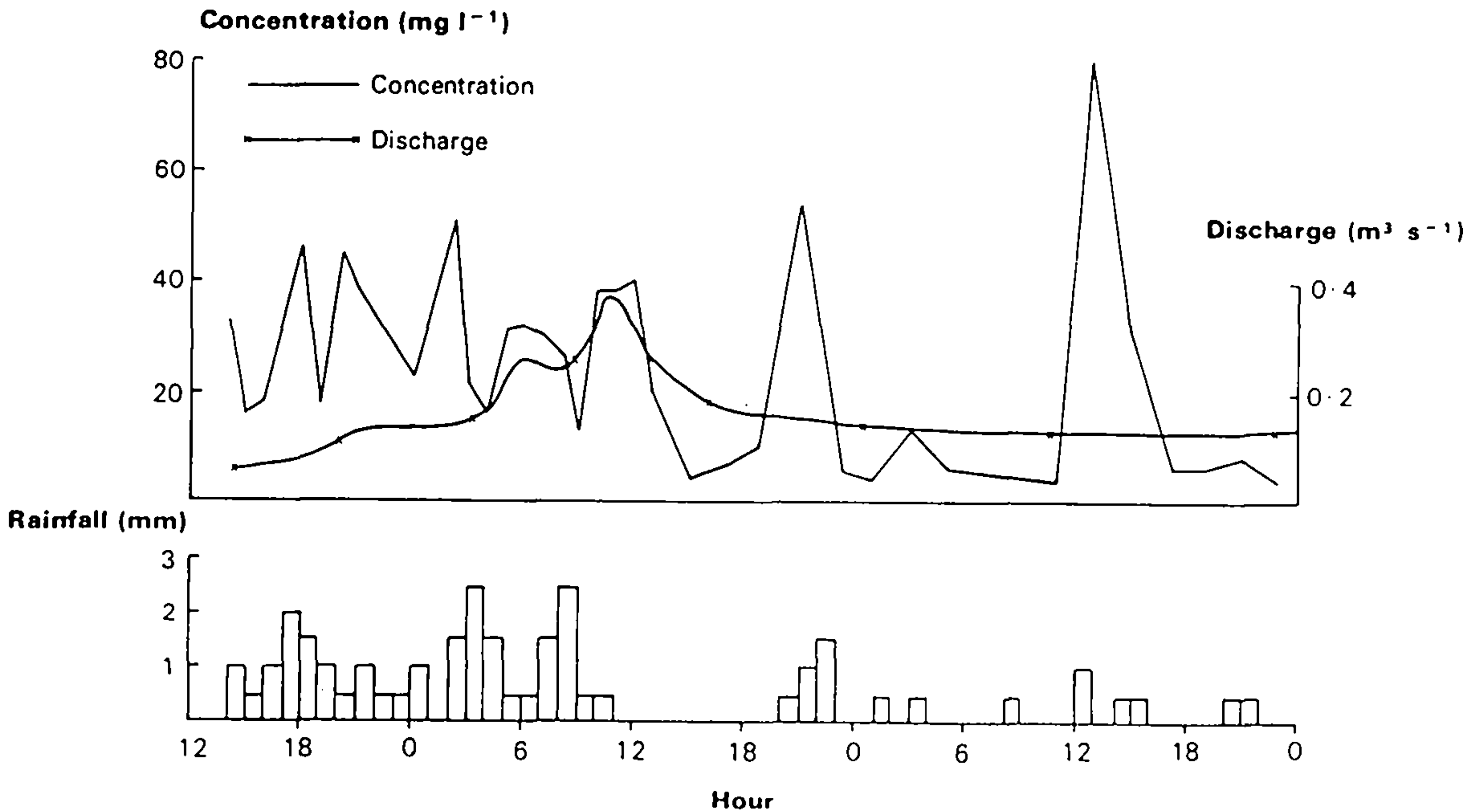


Figure 2.6.2 *Kirkton suspended sediment, flow and rainfall 29-31 May 1987*

3. The Process Studies

This part of the report describes the last three years work carried out as a continuation of studies to understand the evaporative processes operating in the upland environment in particular where the predominant ecosystems are coniferous forest, heather moorland and rough pasture.

During this time the following have been investigated:

> the characteristics of transpiration from heather and spruce forest from soil moisture studies;
>
> the storage and evaporation of intercepted snow from spruce forest canopies;
>
> the effect of line thinning on interception loss from forest canopies;
>
> the possibility of using chloride as an inert tracer to determine relative evaporation rates from spruce forest and heather moor;
>
> the relationship between low stream flows and soil moisture deficits (a preliminary study only).

The results of most of these studies have been incorporated into research models and an operational catchment model able to predict catchment evaporative losses on a seasonal basis. Also, these results and the results from the first phase of the catchment study have propagated further studies, in particular the high altitude grassland study, by highlighting areas of ignorance.

The original objectives and programme of research specified on the contract and its extension are given in Appendix 1.

The original objectives have in the main been covered with the major exceptions of the work on larch. A survey of potential sites for interception studies of larch was made in 1986/87 and a site tentatively chosen in the Hafren forest near the Plynlimon catchments. However it was decided that a major effort would be put into the upland grassland study and resources did not exist to take the larch study further.

In addition to the regular progress reports the studies described below have formed the basis of published papers, two of which are appended as Appendix 4 and Appendix 5.

3.1 SNOW INTERCEPTION BY CONIFEROUS FOREST

3.1.1 Introduction

The hydrological importance of snow interception loss from forests has been recognised for many years but has remained a difficult process to describe by predictive modelling. In the last 50 years many studies have attempted to quantity the effects of afforestation on river flow in regions where a large proportion of the precipitation is in the form of snow. The majority of these studies were either catchment experiments or snow surveys: e.g, the review papers of Jeffrey (1968) and Meiman (1968). The catchment studies, (e.g. Ayer (1959), Olitnik (1979), Swanson and Hillman (1977)), which represent areas having a wide range of climatic, vegetational and geological characteristics, often gave conflicting conclusions from which it is difficult to derive a general result. The snow surveys indicated that less snow accumulates below forest compared with clearings and open land, but there is much controversy over the interpretation of this result.

A small number of studies, including part of the work described below, have measured the interception capacity and subsequent evaporation rates by weighing snow-laden sapling trees (Escher & Leonard (1969) and Satterlund & Haupt (1970)). Although these experiments provide important evidence that evaporation rates can be appreciable, the results from isolated trees cannot be considered representative of a completely snow-covered forest canopy.

There has been no attempt in previous studies to describe the interception losses from snow-covered forest using physically based equations and no definitive study of the process has yet been reported.

3.1.2 Measurements

Equipment to investigate the evolution of a snow pack on a Sitka spruce canopy (*Picea sitchensis* (Bong) Carr), was installed in Queens forest near Aviemore, in the Highland region of Scotland, Fig. 3.1.1. Stored snow and water on the forest canopy was measured by the attenuation of gamma rays (Calder & Wright, 1986) and a weighed tree.

The gamma-ray attenuation system was based on an original design by the Applied Physics Department of Strathclyde University (Olszyczka, 1979). A collimated beam of gamma-rays, emitted by a 200 millicurie Caesium 137 radioactive source, was arranged to traverse 35 m through the forest canopy before striking a 0.3 m^2 detector. By scanning the canopy at height intervals of 1 m during dry and wet conditions, the vertical profile of canopy storage was evaluated. Total canopy storage was measured to an accuracy of 0.2-0.4 mm water equivalent depending upon the total mass in the beam and temperature effects on the instrumentation. The system was operated intermittently in the winters of 1983-84 and 1984-85 during which 16 storm periods were recorded. Typical density profiles measured in wet and snow conditions are shown in Fig. 3.1.2.

Figure 3.1.3 shows diagrammetrically the tree weighing experiment. The technique of tree cutting, described by Roberts (1977), was used. This involves supporting a selected tree within a scaffold frame and placing the severed trunk in a water container. A tree is able to remain in this condition for an entire winter without showing any signs of degradation of its physical structure. Statistics of trunk girth and stand density from the surrounding forest were used to aid tree selection and to estimate the average crown projected area.

The water container rested on three load cells connected to a solid state logger. Figure 3.1.4 shows the continuous record of snow stored on the weighed tree throughout a snow event together with storages estimated by the gamma-ray equipment.

In conjunction with the instrumentation for canopy storage measurement, two heated plastic-sheet net-precipitation gauges (Calder & Rosier, 1976) were installed in the forest close to the gamma-ray beam path. Two heated tipping-bucket raingauges were also installed in a forest ride near to the site in an attempt to measure the input of snow precipitation. Gross and net precipitation were recorded at 5 minute intervals together with other meteorological data from an automatic weather station mounted above the forest.

It is immediately apparent from Fig. 3.1.2 that the water equivalent of snow accumulated on the canopy can be at least an order of magnitude greater that that recorded in rain conditions. Observations from many storms indicated that evaporation rates (the difference between the loss rates from the canopy and the net-precipitation rate) can be large and not necessarily accompanied by large quantities of drainage. These observations of storage and evaporation, many of which were independent of gross snowfall measurement, demonstrate the potential importance of snow interception loss from forests.

The water balance and interception loss for six storms are shown in Table 3.1.1. As raingauge performance during snowfall is very variable, records from automatic raingauges cannot be used with any confidence. Therefore the storms in Table 3.1.1 are limited to those recorded while observers were present and the estimate of snow input has been derived from either a raingauge which was not aerodynamically affected by snow accumulations or from snow input estimates using the gamma-ray equipment in conjunction with ground sampling.

The 'greater than' sign, >, indicates an underestimate as only part of the event has been recorded and the storm total will be greater than, or equal to, the value shown.

3.1.3 Modelling

The detailed modelling of snow accumulation and depletion on a forest canopy is a formidable task; the varying windspeed and air temperature during snowfall may effect the quantity of snow retained on the canopy and water loss to the atmosphere may occur as sublimation from the snow or as evaporation from melt water retained on the leaves. In addition, the

TABLE 3.1.1 Snowfall events at Queens Forest, Aviemore

DATE	SNOWFALL	MAX STORAGE	DRIP	EVAPORATION	INTERCEPTION LOSS
	mm	mm	mm	mm	%
11-13.12.83	3.2	3.0	0.2	>2.5	75-94
25. 3.84	5.1	5.0	0.5	>3.0	58-90
17-13.12.84	13.5	7.5	4.2	9.3	69
24-26.12.85	17.7	7.5	10.6	7.1	40
15-23. 3.85	20.0	15.1	8.5	11.7	59
28. 3.85	9.0	8.5	>2,5	>2.5	50-72

distribution of snow and melt water may be very inhomogeneous through the canopy and successive periods of accumulation, sublimation, melt and freezing in different sequences will increase this inhomogeneity. Thus a snow-covered canopy presents a highly complex surface for the absorption of radiational energy and complex pathways for the transport of heat and water vapour.

No attempt has been made to investigate the phenomenon to this degree of detail. Instead, using the results from the gamma-ray experiment a more pragmatic perspective has been used to understand the principle processes and produce an effective and physically based model. The model structure is shown schematically in Fig. 3.1.5 and consists of a "build-up function" to partition the snow between the canopy and the forest floor, a parameterisation of the transfers of mass and energy between the phases of water and the atmosphere, and the mass balance of the liquid and water phases on the forest canopy.

Evaporation Rate

The evaporation rate of water from the canopy storage is calculated using the equations that define the fluxes of water vapour and heat from an aerodynamically rough surface, Monteith (1965). Hourly estimates of evaporation are derived from inputs to these equations of air temperature, humidity and radiational energy as measured by the automatic weather station. The roughness of the forest canopy is parameterised as the aerodynamic resistance, which is the resistance to the transport of water vapour from the wet surface to the atmosphere across a measured gradient of vapour pressure. It was found from the modelling that the presence of snow on a forest significantly alters the roughness of the surface. Therefore the relationship between storage and aerodynamic resistance is an important control within the model on the evaporation rate.

Phase Changes

In addition to the evaporation rate, the above equations yield an estimate of the temperature at the evaporating surface. During thawing or freezing the surface temperature must be constrained to 0°C and by monitoring the surface temperature within the model and its proximity to 0°C, the timing of the phase changes can be modelled.

Snow Build-up Function

For the snow events recorded at the Aviemore site a fairly well defined relationship existed between the water equivalent depths of snow (per unit ground area) lying on the canopy and the total snow precipitation (calculated from the sum of the measured canopy storage and snow lying on the forest floor) measured during and immediately after snow fall (Fig. 3.1.6). This relationship was used to calibrate a snow storage build-up equation relating the rate of snow build-up, dc_s/dt, (where the subscript, s, denotes snow or solid phase conditions) to the rate of precipitation, dP/dt:

$$dc_s/dP = (dc_s/dt)/(dP/dt) \qquad 1 - c_s/B$$

The snow build-up parameter B can be interpreted as the maximum water equivalent depth of snow (per unit ground area) capable of being held on the canopy and for the spruce forest in Scotland has a value of 31.5 mm, fitted by least squares to the observed data ($r = 0.994$).

Canopy Water Balance

The canopy water balance is described by a simple reservoir model, in which the snow pack is assumed to be able to hold 0.15 of its mass in the form of liquid water. When this threshold of water retention is exceeded, melt water is allowed to flow from the snow pack into a conventional drainage model for liquid water, Calder & Wright (1986).

3.1.4 Discussion and conclusions

Figure 3.1.7 shows the interception ratio data from Table 3.1.1 plotted against snowfall. Also shown is a typical rainfall interception function and the boundary conditions defined by the snow build-up function. The line describing a typical rainfall regime is based on the forest interception model by Gash et al (1980) using parameters appropriate to a hypothetical Sitka spruce forest in central Scotland (annual rainfall = 1000 mm): mean evaporation rate = 0.22 mm h^{-1}, mean rainfall rate 1.22 mm h^{-1} and canopy storage capacity = 1.2 mm. It can be seen that all of the snow events evaporated more water than the equivalent amounts of rainfall, emphasising the importance of snow interception loss from this particular forest stand. Of equal importance is the snow build-up function. A more open forest structure will constrain the upper limit of snow interception loss to a lower overall ratio, however, a more open forest structure may not affect the long term rainfall interception loss (see Section 3.5) implying that snow interception loss might be similar or even less than rainfall interception losses in certain forest types.

The performance of the model was generally good particularly in the periods of refreeze, sublimation and low melt rate. The timing of the onset of melting (and therefore drainage), was also fairly well predicted and always to within one or two hours of the observed data. When melt water became a significant part of the water balance, either the drainage was overestimated at the expense of predicted canopy storage, or the evaporation was overestimated.

It is interesting to note that during the melt phase, although lumps of accumulated snow were observed to dislodge from the canopy in addition to drips of meltwater and trunk drainage, concurrent measurements beneath the canopy indicated that the actual quantities involved were small in terms of millimetres of water equivalent. Consequently the phenomenon of solid water drainage has been excluded from the model.

The observations of snow interception by coniferous forest, which are independent of the need for accurate areal snowfall measurement, are probably the most detailed measurements of the evaporation from a snow-covered canopy described anywhere. They reveal that the processes of ageing, melt and evaporation are extremely complex but while the analysis presented here cannot be regarded as a complete description the important features can be clearly seen. They are:

(i) The storage of snow on the canopy can be very large, an order of magnitude larger than that of liquid water.

(ii) The evaporation rates from "wet snow" are of similar magnitude to those from a wet canopy (i.e. up to 0.5 mm h^{-1}) and can be described in a similar manner.

(iii) The aerodynamic resistance to heat and vapour transfer from a canopy storage dominated by snow, is much larger than that of a wet canopy. This is probably a result of the smoother surface of the snow covered forest.

(iv) Snow interception losses from a spruce forest with a closed canopy are likely to be higher than rainfall interception losses for the same amount of precipitation.

(v) Differing trunk densities which affect the closure of the canopy and structural differences between species are likely to significantly alter snow interception ratios.

The physically-based model described above, which required only meteorological observations (radiation, temperature, humidity and snowfall) as inputs, satisfactorily described the observations of evaporation and melt. Some work is needed to improve the performance of the model for certain types of snow event. However, the general performance is encouraging and the model can be expected to estimate accurately snow interception losses over an extended period. Further work is required before it is possible to simplify the model for inclusion in a simple catchment model such as that described in Section 3.3.

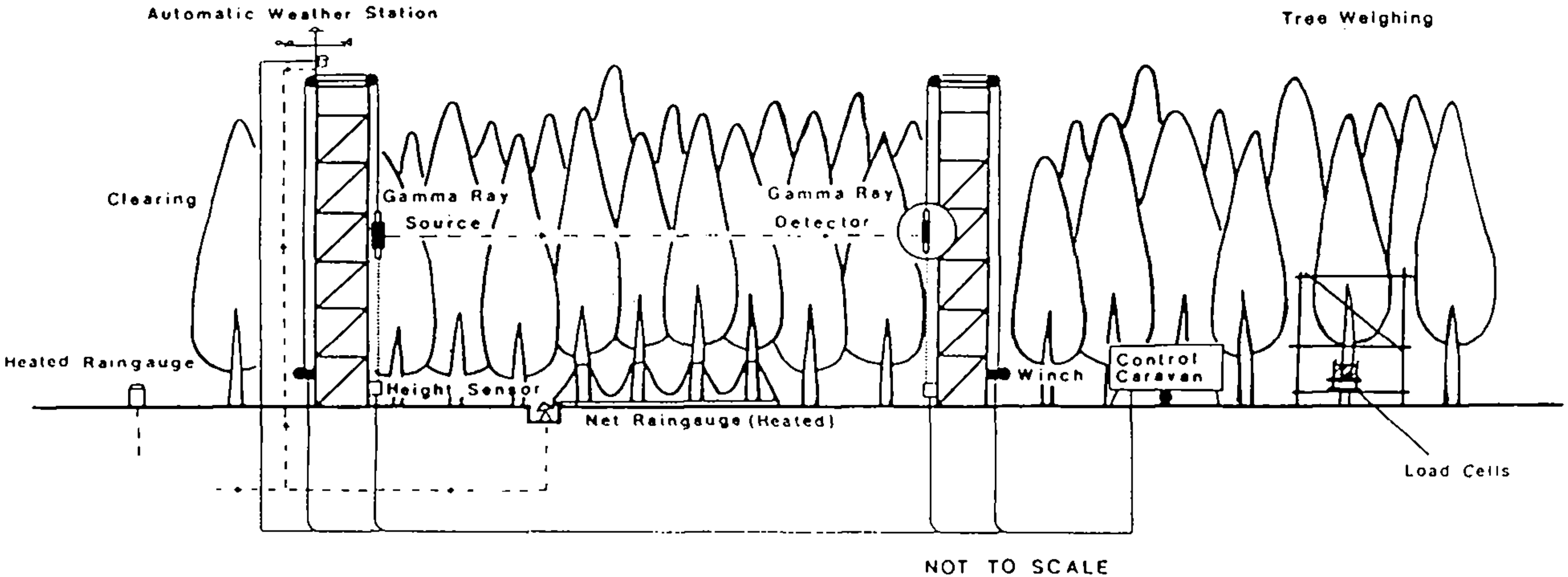


Fig. 3.1.1 Diagram of snow measurement equipment, Queens forest, Aviemore.

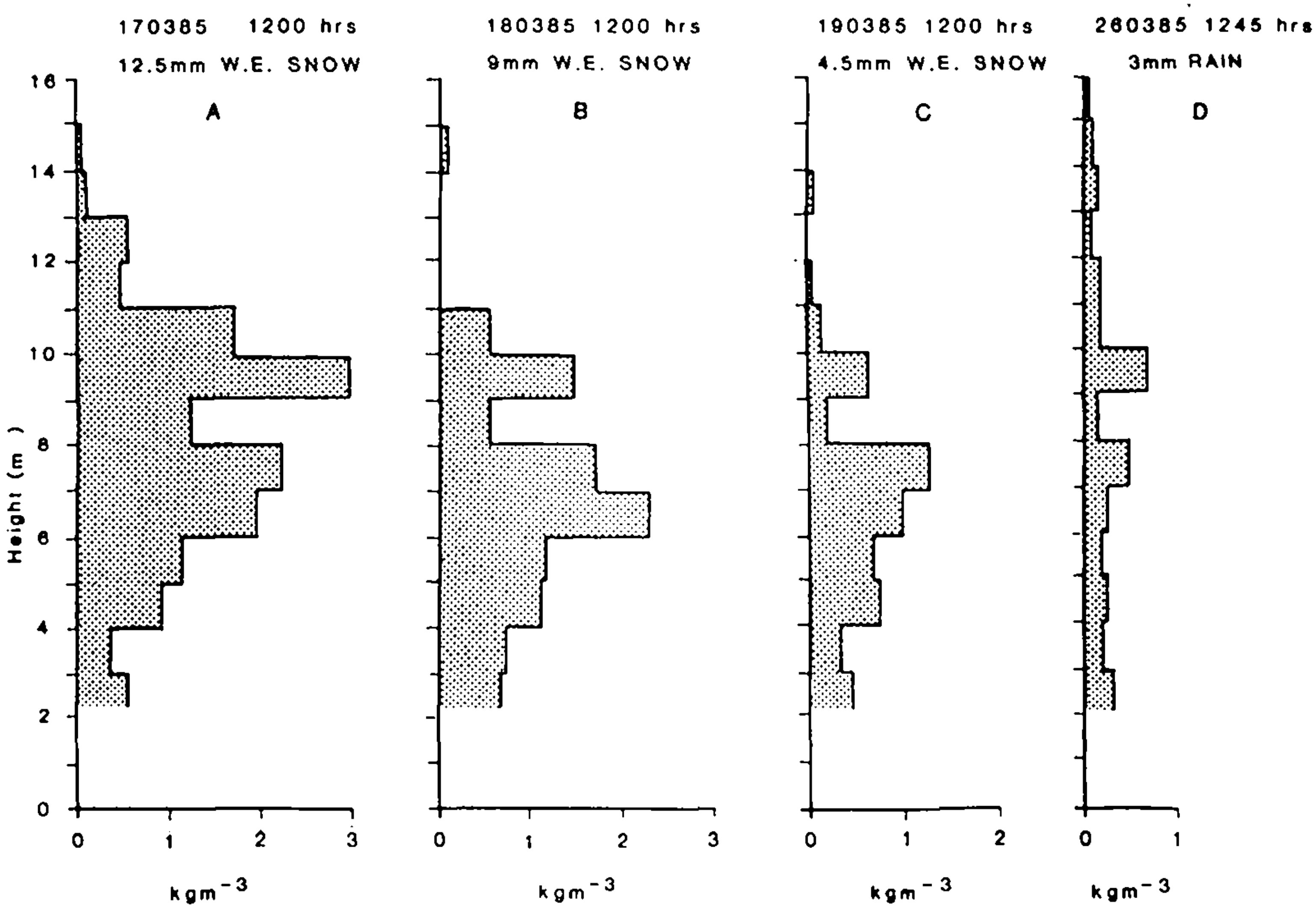


Fig. 3.1.2 Typical density profiles of snow and liquid water on the forest canopy at Aviemore.

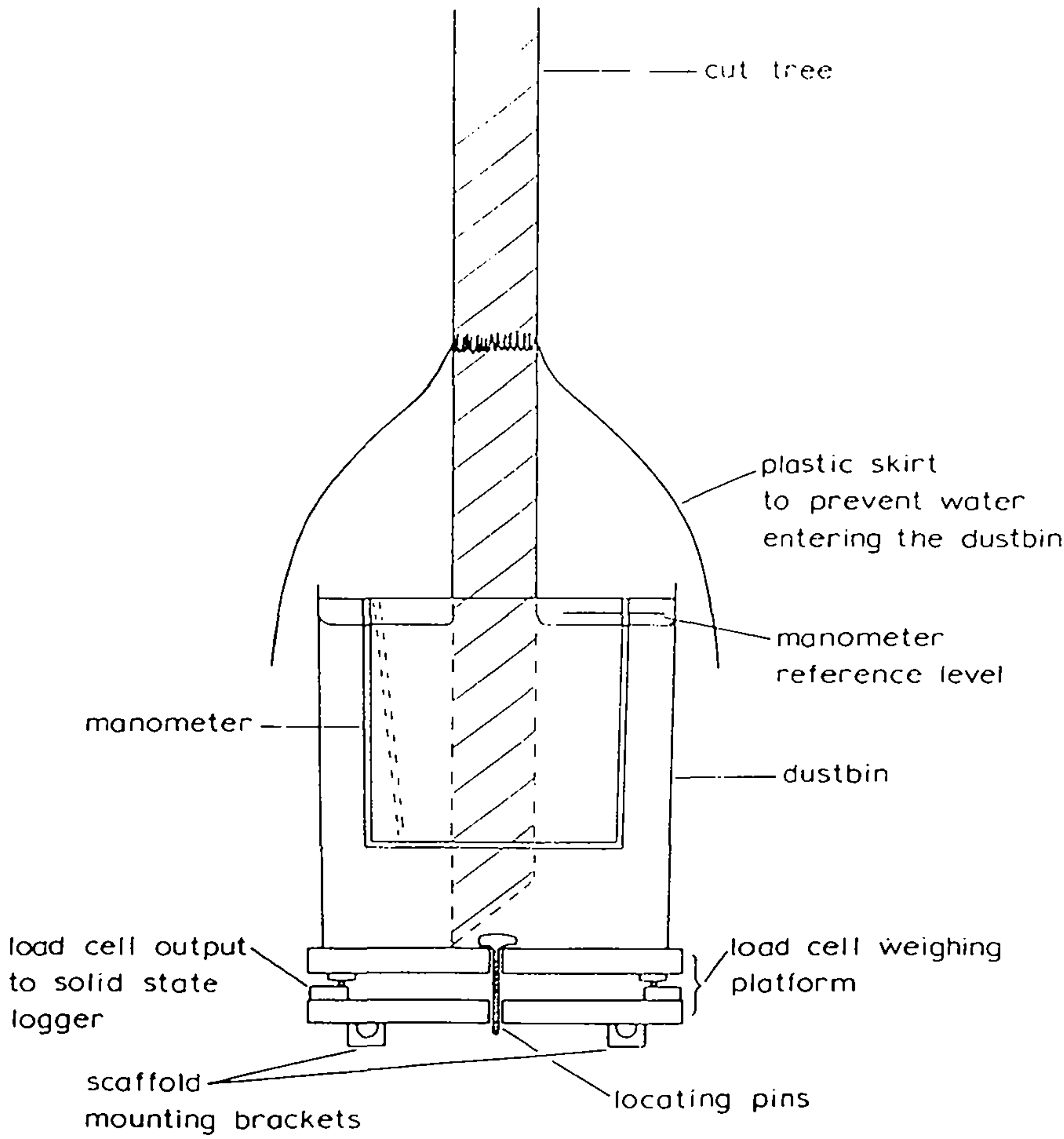


Fig. 3.1.3 Diagram of tree weighing equipment installed in Queens forest.

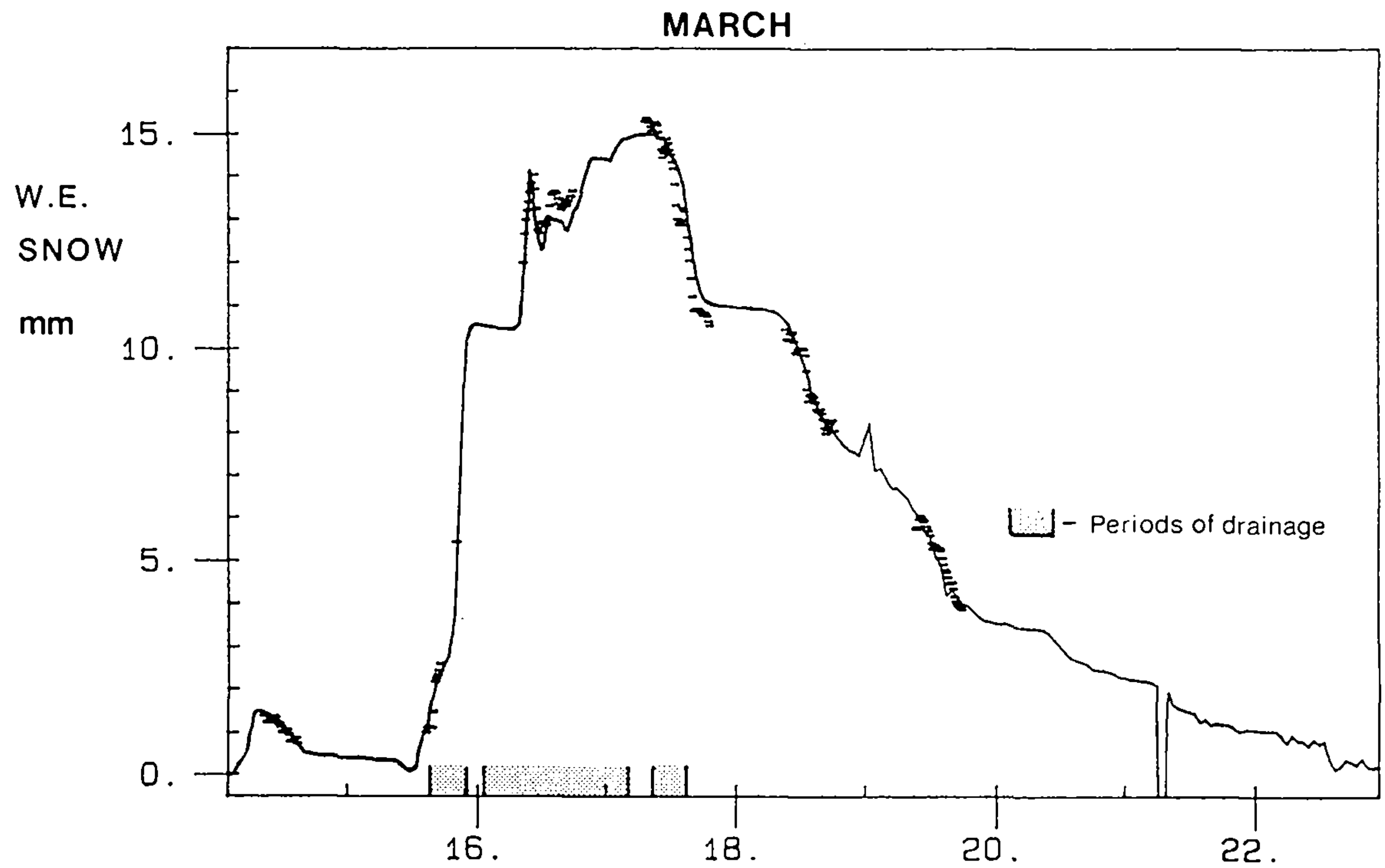


Fig. 3.1.4 Records of water equivalent of snow on forest canopy from the tree weighing (solid line) and gamma-ray attenuation method (-).

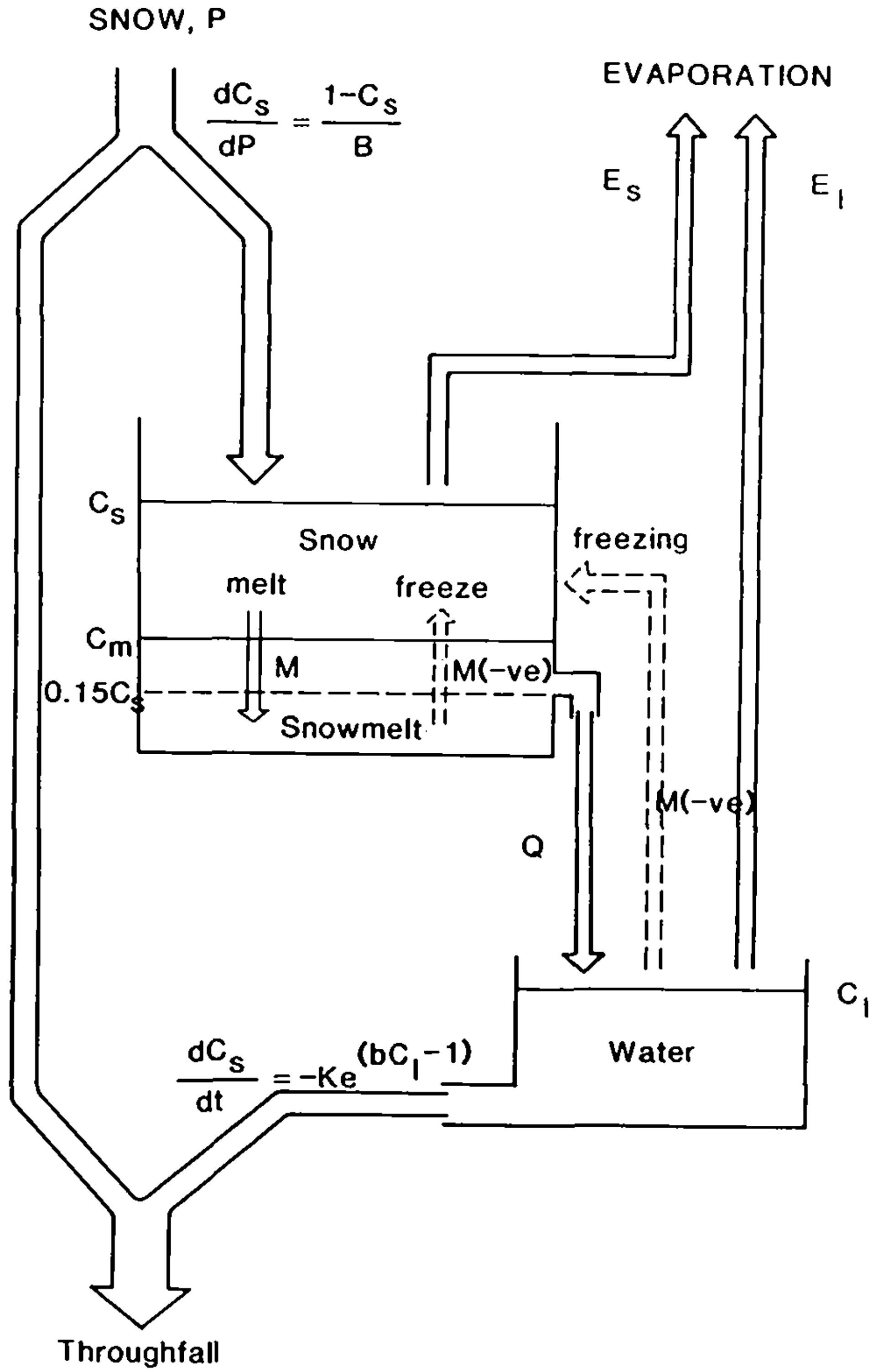


Fig 3.1.5 Diagrammatic representation of the snow interception model

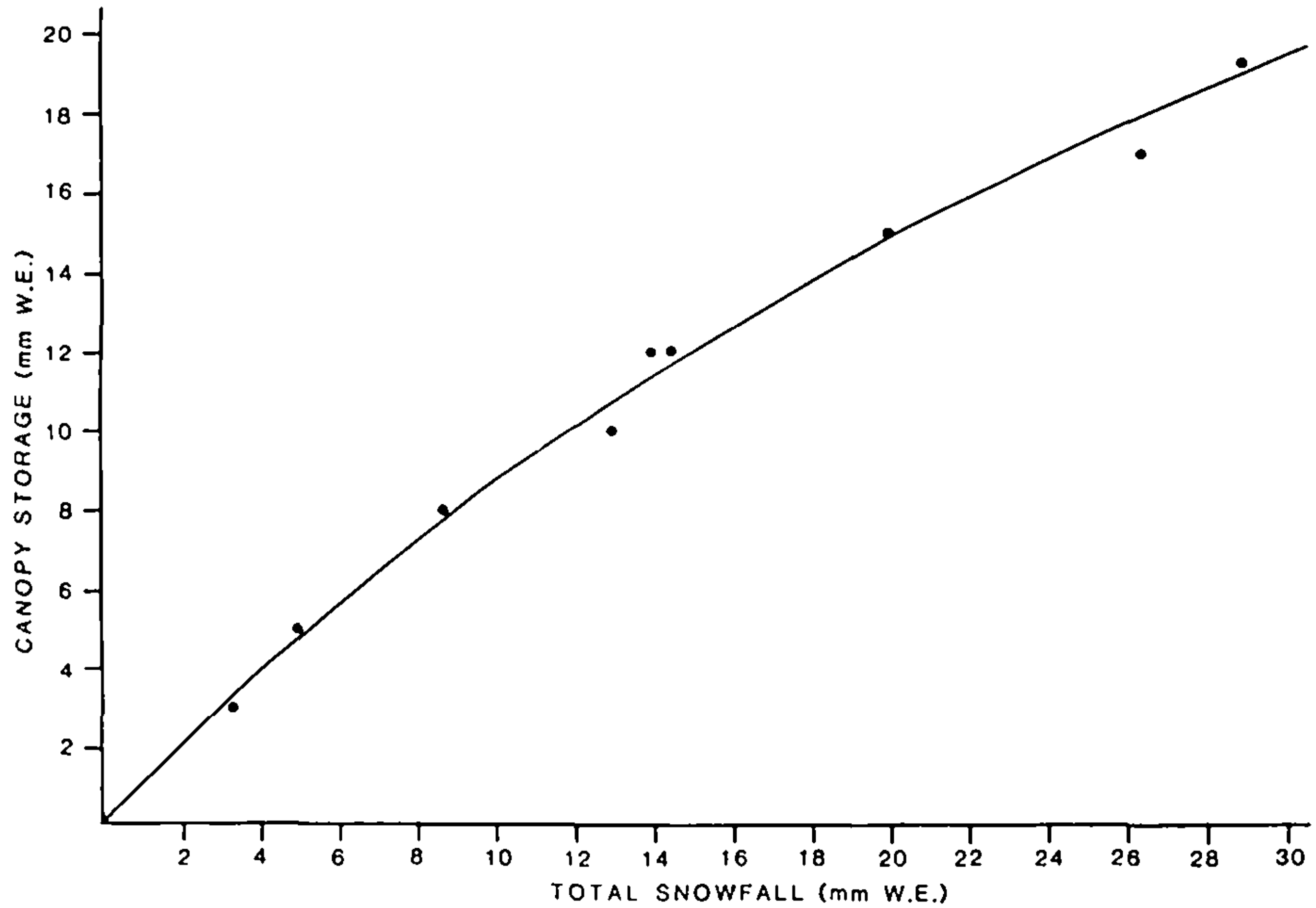


Fig. 3.1.6 Build-up function for snow on the forest canopy.

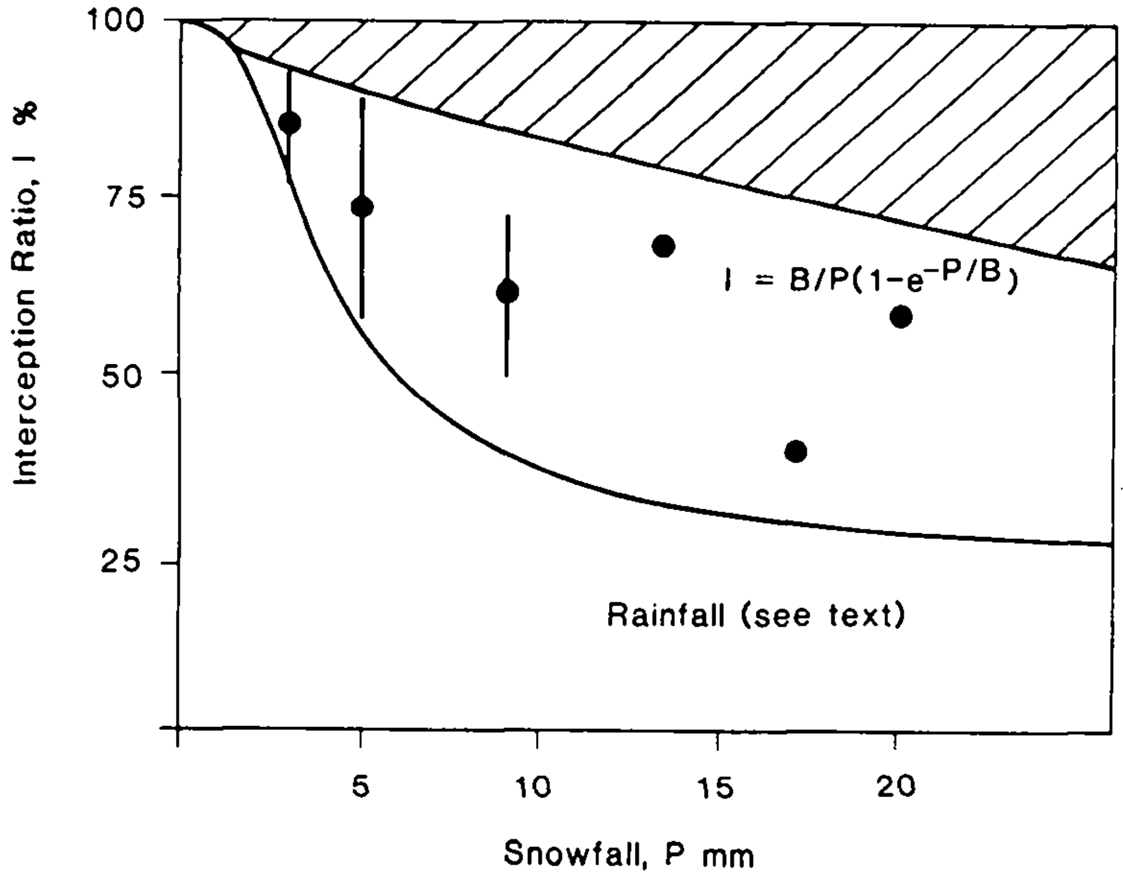


Fig. 3.1.7 Interception ratio for snowfall versus snowfall for individual storms.

3.2 HIGH ALTITUDE GRASSLAND STUDIES

3.2.1 Background

Over the years, in the absence of empirical data, it has become standard practice to assume that the evaporation rates from all grassland are correctly estimated by the Penman potential evaporation rate. However, the results of several catchment studies have cast doubts upon the validity of this assumption, and particularly upon the validity of applying the Penman equation to high altitude grassland.

Even for lowland grassland some seasonal discrepancy between the Penman estimate and evaporation calculated from water balance measurements has been observed. Thom & Oliver (1977) found it necessary to modify the Penman equation to account for the seasonal variation in evaporation observed by Edwards & Rodda (1970) from the water balance of a lowland catchment at Grendon Underwood. Discrepancies are also observed between the Penman estimates and the evaporation calculated from catchment results for the upland Wye catchment at Plynlimon (see Section 3.4).

In an early study using a wet-surface weighing lysimeter an experiment was carried out on lowland grass at Wallingford before the high altitude grassland experiment was begun. The wet-surface weighing lysimeter was set up to monitor the prevailing weather and evaporation rates from grass samples (height c. 10 cm) with varying degrees of wetness.

A comparison of the evaporation rates from dry and rain-wetted grass with the predicted E_t rates (using Penman's equation) showed no systematic difference between the two within the limits of experimental scatter. These results indicated that for estimating the evaporation from lowland grass after rainfall and during dry conditions the Penman equation is adequate.

To simulate evaporation from grass during rainfall when it becomes totally wet the samples were sprayed with weak (0.1%) solutions of a surfactant on days when the surrounding grass was thoroughly rain-wetted. This enhanced the drainage rate and produced a very thin film of water on the grass which evaporated very quickly. A direct comparison of measured evaporation rates with the Penman potential rate was not possible as these require data averaged over at least a day. Data from spray runs were therefore used to calculate the aerodynamic resistance (r_a). A comparison of these with r_a values measured over rain-wetted grass at Balquhidder suggested that the r_a values from the surfactant-sprayed grass may be lower, and therefore the evaporation rates higher than E_t. However, although this may give some enhancement of evaporative losses during winter it is considered unlikely to be a major effect. (The results of this work are given in more detail in Appendix 2.)

The results from the first phase of the Balquhidder catchments study raised further questions about the water use of high altitude grassland. These results gave an unexpectedly low mean annual water use of the partly forested (35%) Kirkton catchment of 425 mm compared with a Penman potential evaporation of 534 mm estimated from weather data collected by an automatic weather station at the top of the Kirkton catchment (Section 2.5.3). Process measurements made in the Kirkton forest indicated a water use comparable with forests elsewhere and higher than for grassland. Even after allowing for experimental errors these results implied that the grass on the Kirkton catchment uses considerably less water than predicted by the Penman potential evaporation.

From the above studies it was very apparent that our understanding of the evaporation processes from high altitude grassland was far from complete and for this reason the high altitude grassland study was set up.

3.2.2 Experimental Details

The high altitude grassland study is based upon three complementary experiments which will allow verification of the results. The separate objectives of the three experiments are:

(i) to determine the transpiration rates of undisturbed high altitude grass and other upland species;

(ii) to determine the rates of evaporation of intercepted rainfall, and

(iii) to monitor continuously over a prolonged period the total water balance of upland grass.

Two weighing lysimeter systems record changes in mass of the soil monoliths as a result of rainfall and evaporation. These are supplemented by soil moisture measurements to determine transpiration rates (during dry periods). A development of the wet-surface weighing lysimeter will be used during 1988/89 to study the rainfall interception of upland grass.

In addition to the three main experiment,s biomass measurements are made during the growing season.

A site representative of the high altitude areas of the Kirkton catchment was chosen on a terrace at an altitude of about 590 m on the eastern slope of Gleann Crotha (Grid ref: NN507225); this is located between the Kirkton and Monachyle catchments. Nine access tubes for making soil moisture measurements with neutron probe meters were installed in July 1986. They were set into the full depth of the peat which ranged from 0.45 m to 1.45 m. Six were installed in peat beneath grass and three beneath a mixture of bilberry and heather. Measurements were taken regularly from July until November 1986 and from April to November 1987.

An automatic weather station with additional sensors was also installed to monitor the meteorological variables required to calculate the potential evaporation at the site. This is used for comparison with the measured transpiration rates. The weather station was operated from July until November 1986 and April to November 1987; measurements are not required over the winter months.

Two identical monolith weighing lysimeter systems were installed and an instrument shed to house batteries and associated electronics was erected in April/May 1987.

The construction of the lysimeters is shown in Fig. 3.2.1. An undisturbed representative monolith of peat with its surface vegetation is contained in an aluminium tube of 80 cm diameter with a perforated bottom. (The peat sample was taken by pushing the tube into the ground by means of hydraulic rams and then digging away the surrounding peat until it was possible to use the rams to slide a steel cutting plate beneath the monolith. After lifting the sample the perforated aluminium base plate was bolted to the tube.) This sample cylinder rests on an aluminium spider with a central threaded hole into which is screwed a threaded rod with a lifting eye. This was used to lower the sample and cylinder into a slightly larger water-tight aluminium cylinder. The threaded road was then removed. The cylinder in turn rests upon a weighing platform, based upon a single large-capacity load cell, standing on a concrete base in the bottom of a hole. The height of the weighing platform was adjusted so that the surface vegetation of the sample was flush with the surrounding vegetation. Electric pumps beneath the load cell keep the hole free of standing water. The water level within the sample is maintained at the same level as that in the surrounding peat by means of an electric pump triggered by the signal from a dual pressure transducer comparator. The effectiveness of this method was tested by comparing readings given by tensiometers in the samples and in the surrounding peat. These showed that the water tension in the root zone within the lysimeters and in the surrounding peat remained the same within the natural variability expected.

The quantity of water pumped out of each lysimeter is measured by passing it through a recording raingauge. The output from these gauges, from the load cells and from a ground level raingauge is automatically logged at ten minute intervals. The data from the solid state stores of the loggers are transferred to disks for later analysis on microcomputers.

3.2.3 Results and Discussion

The grassland study is still in its early stages. Because of financial constraints the equipment was not installed at the optimum time in March or early April. However, some interesting results are already emerging.

Estimates of the Penman potential evaporation calculated from meteorological data collected by the automatic weather station at the grassland Gleann Crotha site over the summer months of 1986 and 1987 are in agreement with estimates derived from data collected at the two other high altitude Kirkton and Monachyle weather stations. These Penman values are high (450 to 600 mm a year) and show an increase with altitude. This differs from the traditionally accepted low altitude values (about 400 to 450 mm a year) and a decrease with altitude. Analysis of the data suggests that the high values are produced by occasional days of very high evaporative demand resulting from prolonged sunshine with high windspeeds and low relative humidities. The Penman values for the Gleann Crotha site were about 8% to 15% less than the values for the higher and more exposed Kirkton site.

It is unlikely that the vegetation could sustain such high evaporation rates in this environment for three reasons:

(i) the temperatures at high altitudes are low and the grass is dormant for much of the year; observation shows that the grass is only just beginning to emerge from dormancy in mid-May when the Penman rate is typically 3 to 4 mm a day;

(ii) there is evidence that at high evaporative demands the stomata of plants close, preventing excessive water loss;

(iii) soils at high levels in the Kirkton catchment are thin and soil water may be limiting.

There is now some evidence from the weighing lysimeters that the actual evaporation rates from the grass are indeed much lower than the Penman rates. Figures 3.2.2 shows the water storage in one of the lysimeters plotted against time for early May 1987. The negative slope over the first nine days has a gradient of 0.83 mm a day compared with the Penman rate for the same period of 2.7 mm a day. The plot also shows the response of the lysimeter to rainfall and a spurious diurnal variation caused by the temperature sensitivity of the logging system. The loggers were later enclosed in a constant temperature cabinet which eliminated this effect. The curious peak on 7 May is believed to have been caused by a sheep straying onto the lysimeter. Unfortunately problems with the logging system were encountered for a large part of the operational period of the lysimeters and the more complicated analysis which is required to extract useful data from this period is incomplete.

The summer of 1986 was a wet one and consequently no significant soil moisture deficits were seen in the data from the neutron probe observations. A preliminary analysis of the measurements made in 1987 indicate that there may have been a period when a small deficit was established but there appear to have been no major deficits. This in itself supports the hypothesis of reduced evaporation rates from high altitude grassland.

The results of the biomass measurements are plotted in Fig. 3.2.3 which shows a linear increase in the proportion of live biomass as a function of time. This function was used in a simple daily accounting model to predict the seasonal change in soil moisture and the results compared with observations for the period March to July 1987. The model calculates the soil moisture S_{i+1} on day i+1 from:

$$S_{i+1} = S_i \quad E_i + R_i$$

where S_i is the soil moisture on day i, R_i is the measured rainfall on day i and E_i the evaporation calculated for day, i, as either the Penman E_t, calculated from the Gleann Crotha weather station data, or as the product of E_t and the biomass function b = 0.00466d + 0.176 where, d, is the day number.

The daily evaporation was also calculated as the product of E_t and the temperature function τ given in Appendix 2 and as the product $E_t b \tau$.

The best fit between observed and predicted soil moisture was obtained when the daily evaporation was given by the triple product. Using E_t alone gave the poorest fit followed by the product $E_t T$. Clearly these results do not establish a causal link between temperature, biomass production and evaporation rates. However, they do show again that the soil moisture data are best explained by an evaporation rate significantly less than E_t.

3.2.4 Looking Ahead

The immediate aim is to re-install the weighing lysimeter systems as early as possible in March or April with new Campbell CR10 loggers. This should improve the reliability and precision of the systems and facilitate data handling. Early installation of the lysimeters will ensure that the evaporation from the grass is monitored at the critical period at the end of and following dormancy when new leaves are first produced.

Meteorological data collection and the measurement of soil moisture using the neutron probe will continue. Interception studies using the wet-surface weighing lysimeter will be started and probably continue in 1989.

At present it is planned to finish taking all measurements in summer 1989.

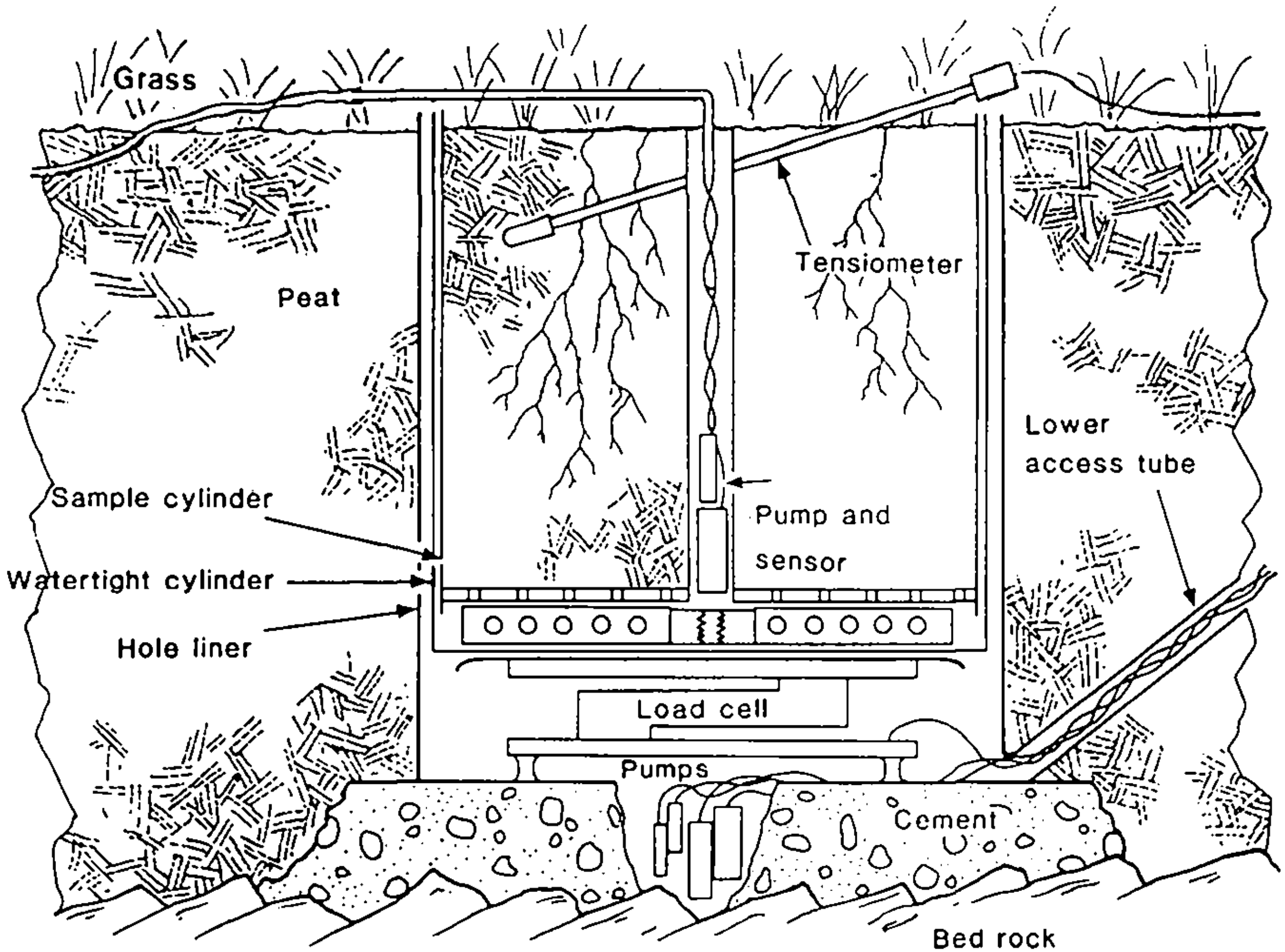


Fig. 3.2.1 Cross-sectional diagram of the weighing lysimeter used in the high altitude grassland study.

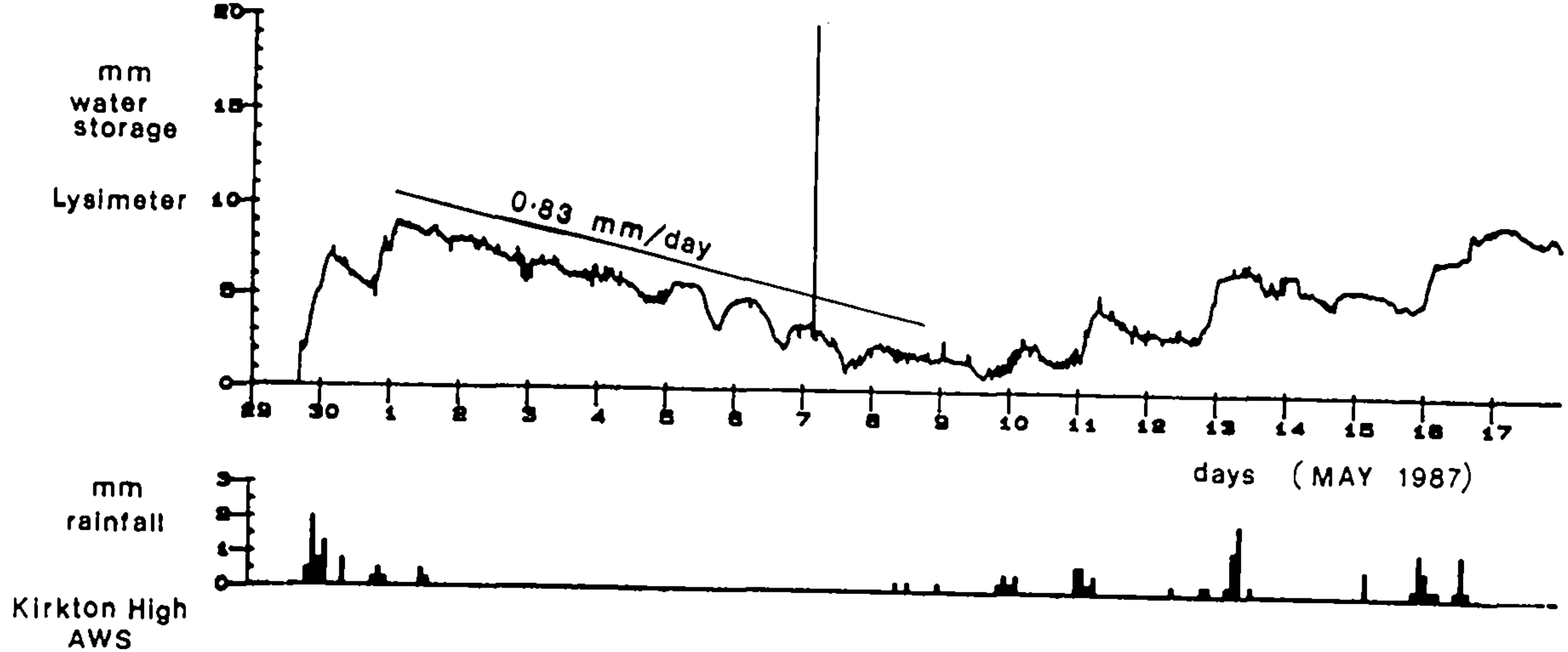


Fig. 3.2.2 Rainfall, and change in mass in mm water equivalent from weighing lysimeter, over the first 18 days of operation.

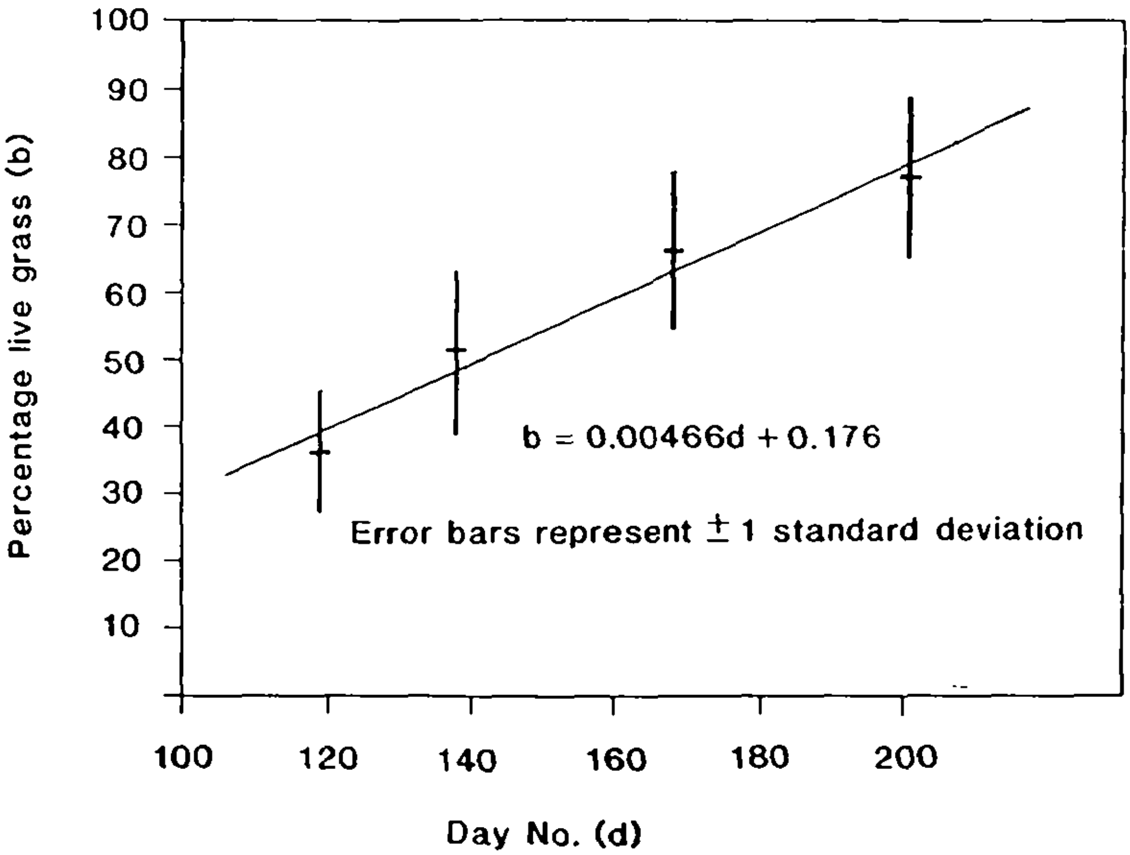


Fig. 3.2.3 Production of biomass from the high altitude grassland site.

3.3 A SIMPLE SEASONAL MODEL OF CATCHMENT EVAPORATION

The main features of this model are noted here but a full description is given in the paper attached as Appendix 4.

The model was developed from the annual model of Calder & Newson (1979) making use of the results of process studies of heather. It is applicable to catchments in which the predominant vegetation is grass and heather. The model requires only daily values of rainfall and Penman potential evaporation E_t, and produces an estimate, E_D, of the daily evaporation from the catchment. Summing the daily values over longer time period reduces percentage random errors. The model is represented by:

$$E_D = f.(T_G + I_G) + (1-f) \quad (T_H + I_H)$$

where f is the fractional area of the catchment under grass and the total daily evaporation from grass (subscript G) and heather (subscript H) are calculated as the sum of the transpiration (T) and interception (I) terms. The transpiration and interception from the grass are calculated using the E_t and rainfall values. Transpiration from the heather is assumed equal to 0.5 E_t, a mean value derived from data collected at a variety of sites in Scotland and England (see Calder, 1986 in Appendix 5). The daily interception loss from the heather is calculated using the exponential function:

$$I_H = \beta(1 - e^{-\delta R})$$

where R is the daily rainfall and β and δ are optimised interception parameters. A modification of the model is possible in which the transpiration from the grass is made a function of temperature such that below 5°C transpiration is put equal to zero, above 10°C it equals E_t and between 5°C and 10°C it is a linear function of temperature.

3.3.1 Application of the Model to an Upland Catchment

The model was applied to the Monachyle catchment which from aerial photographs was estimated to be 67% under heather and 33% under grass. Daily values of rainfall over the grass and heather areas were obtained from the appropriate raingauges after the values had been time distributed on the basis of the daily-read gauge at Tulloch Farm. Daily values of E_t and air temperature (used for the temperature correction) were obtained from the records of the two automatic weather stations in the Monachyle glen. For those periods when snow covered the vegetation, evaporation was assumed to be zero.

Over the period October 1984 to September 1985, the model predicted the total evaporation from the catchment to be 530 mm. This figure was slightly reduced to 516 mmwhen the temperature-restricted transpiration was used in the model. Both figures are less than the precipitation minus runoff measured for the catchment over the same period of 627 mm. However, the difference lies within the likely experimental errors. The difference between the outputs of the two models values was small because most of the grass on the Monachyle catchment grows at low altitudes, less than 450 m. However, extrapolating the model to the high altitude grass on the Kirkton catchment indicated that the reduction in evaporation could be large so that the annual evaporation would be about 60% of the annual Penman potential value.

This modelling study demonstrated the potentially large effect that the low temperature control of transpiration from grass can have. However until results are obtained from the studies of the water use of high altitude grass the magnitude of the temperature effect remains unnkown as does the magnitude of any compensatory effect which may arise from possibly high rates of interception loss.

The simple seasonal catchment model is a step forward from the Calder & Newson model in that it allows a more accurate prediction of evaporative loss on time scales shorter than one year. The cost of this improvement is the requirement of daily data, i.e. rainfall and E_t values. The daily values of evaporation can be accumulated to give weekly, monthly, seasonal or annual evaporative losses, with decreasing percentage random error, as desired.

This model could readily be extended to cover catchments containing coniferous forest provided that snow were not a significant proportion of the preciptation: the appropriate transpiration fraction and interception parameters are already known (see Calder, 1986 in Appendix 5). However, because snow interception loss from coniferous forest can be large (see Section 3.1) the extension of the model to upland Scottish catchments must await the completion of the work on a simplified snow interception model.

3.4 THE ANNUAL CATCHMENT MODEL AND ITS APPLICABILITY TO THE PLYNLIMON CATCHMENT WATER-USE

Calder & Newson (1979) presented a simple model to estimate the water-use of catchments under forest and grassland in upland Britain

$$E \quad (1\text{-}f) \quad E_t + f \quad [(1\text{-}w) \quad E_t + P \cdot \alpha]$$

where: f is the fraction of the catchment under forest,

E_t is the mean annual Penman potential evaporation

w is the proportion of time the forest canopy is wet,

P is the mean annual precipitation, and

α is the interception ration.

This model predicts the annual average evaporation, E.

It is worth considering the experimental evidence on which this formula is based:

1. The interception ratio, α, Calder & Newson use a value of 0.3. Numerous experiments have shown α to be between 0.3 and 0.4 for extensive forests.

2. Forest transpiration = (1 w).$\bar{E}_t$. The primary experimental evidence for this is the result of the forest natural lysimeter operated at Plynlimon 1974-76.

3. Upland grassland evaporation = E_t. The early results from the Wye catchment indicated this result, as do water balances from lowland catchments generally.

4. The early results from the Severn (partly forested) catchment agreed with the overall model.

In the early 1980's a number of limitations in our knowledge of upland evaporation (and in this model) were identified (Calder, 1982):

1. No information could be given on time-scales of less than one year or for drought periods.

2. The results were not applicable for the drier and lowland regions of the UK.

3. The effects of snow were unknown.

4. The evaporation from medium height vegetation was unknown.

In addition, in hindsight, we can now say there was an uncertainty in our knowledge of the evaporation from upland grassland.

Points 1, 3 and 4 have been addressed by the process studies under the Scottish Consortium and these results are described elsewhere.

A large and well validated series of catchment results from Plynlimon is now available, Table 3.4.1 shows the average annual values for 1976-83.

TABLE 3.4.1 Annual Averages from Plynlimon (mm)

	Wye	Severn
P	2415	2469
Q	2050	1908
P-Q	365	561
E_t	476	

Considering the results from the Wye first; the total losses are 77% of the potential value E_t. The most likely explanation of this reduction is a temperature limitation on the grassland transpiration. To illustrate the possible effect a very simple temperature model has been applied to a single year of the Plynlimon data. This model is described in more detail in Appendix 4. Briefly this is the simple daily catchment model which allows no transpiration below 5°C, limited transpiration between 5 and 10°C and transpiration at the Penman rate above 10°C. This model has been applied to meteorological data from 1978 - an average year in terms of rainfall and runoff (Table 3.4.2).

TABLE 3.4.2 Wye Catchment Results for 1978

P	Q	P-Q	E_t	$\frac{(P-Q)}{E_t}$	$E_{(t.corr)}$
2349	2008	341	414	0.82	358

Table 3.4.2 shows that the introduction of the temperature effect can produce the correct water-use. This does not of course prove a causal relationship or validate the form of the temperature model. This must wait until the current work in Balquhidder is completed. This analysis does show that a realistic temperature effect may produce the correct evaporation.

The application of the annual catchment model to the Severn requires the careful consideration of the component areas of the catchment. Table 3.4.3 shows the estimate of this made by Calder (1976). It should be noted that although the forest area constitutes 62% of the catchment area once the area of rides and immature trees are taken into account the actual proportion with complete canopy coverage is 42%.

Table 3.4.4 shows the application of the annual catchment model to the 1978 catchment data. Model 1 is the original Calder & Newson model, this overestimates the catchment evaporation by 160 mm. Model 2 includes a

TABLE 3.4.3 Component Areas of Catchment

Component area	Percentage of catchment area	Percentage of catchment area with canopy coverage
Grassland	38	
Roads, rides, river channels, river banks, gaps in forest	12	
Immature forest plantation with 33% canopy coverage	12	
Mature forest plantation with 100% canopy coverage	38	38
TOTAL	100	42

temperature effect on the grassland part of the catchment, this overestimates by 137 mm. Finally Model 3 also includes a temperature correction the the forest transpiration, this model is within 69 mm of the catchment results. Given storage effects and errors in the catchment results, Model 3 is a reasonable approximation.

TABLE 3.4.4 Obvserved and predicted lossed for the Severn catchment in 1978.

		P-Q	Model 1	Model 2	Model 3
2452	1931	520	681	647	589

The process evidence for a temperature influence on the transpiration from forest is however limited and does not agree with the natural lysimeter results from Plynlimon. This aspect requires further investigation.

Progress on the seasonal catchment model is reported elsewhere (see Appendix 2). The components for an improved annual catchment model are discussed here:

1. Following the process studies into *Calluna vulgaris* a formulation for heather is now available (α = 0.17, k = 0.5).

2. The work on snow interception has shown evaporation from a snow covered forest canopy is at least as large as a rain-wetted canopy. More work will be required to generalise the snow results but in

most areas the assumption of $\alpha = 0.3 - 0.4$ for all preciptation will not introduce large errors.

3. The work on the influence of temperature on grass transpiration must be completed before final conclusions can be reached. However, the simple formulation described here agrees with the Wye catchment results. This can be generalised into an annual model, for example see Fig. 3.4.1.

4. More investigation is required on forest transpiration and in particular its generalisation into a daily model.

An important result from the Balquhidder weather stations is the high potential evaporation rates observed at high altitude. The average value for the Kirkton High weather station (1983-1987) is 531 mm per year (see Table 2.4.1) , with good evidence of an increase with altitude. The MAFF (1967) quotes 354 mm per year for Perthshire for the average county height (394 m). MAFF (1967) also suggest a decrease with altitude, with this correction the predicted potential evaporation for Kirkton High is 292 mm. Thus it is evident that in the light of these results the E_t map of Scotland needs to be revised.

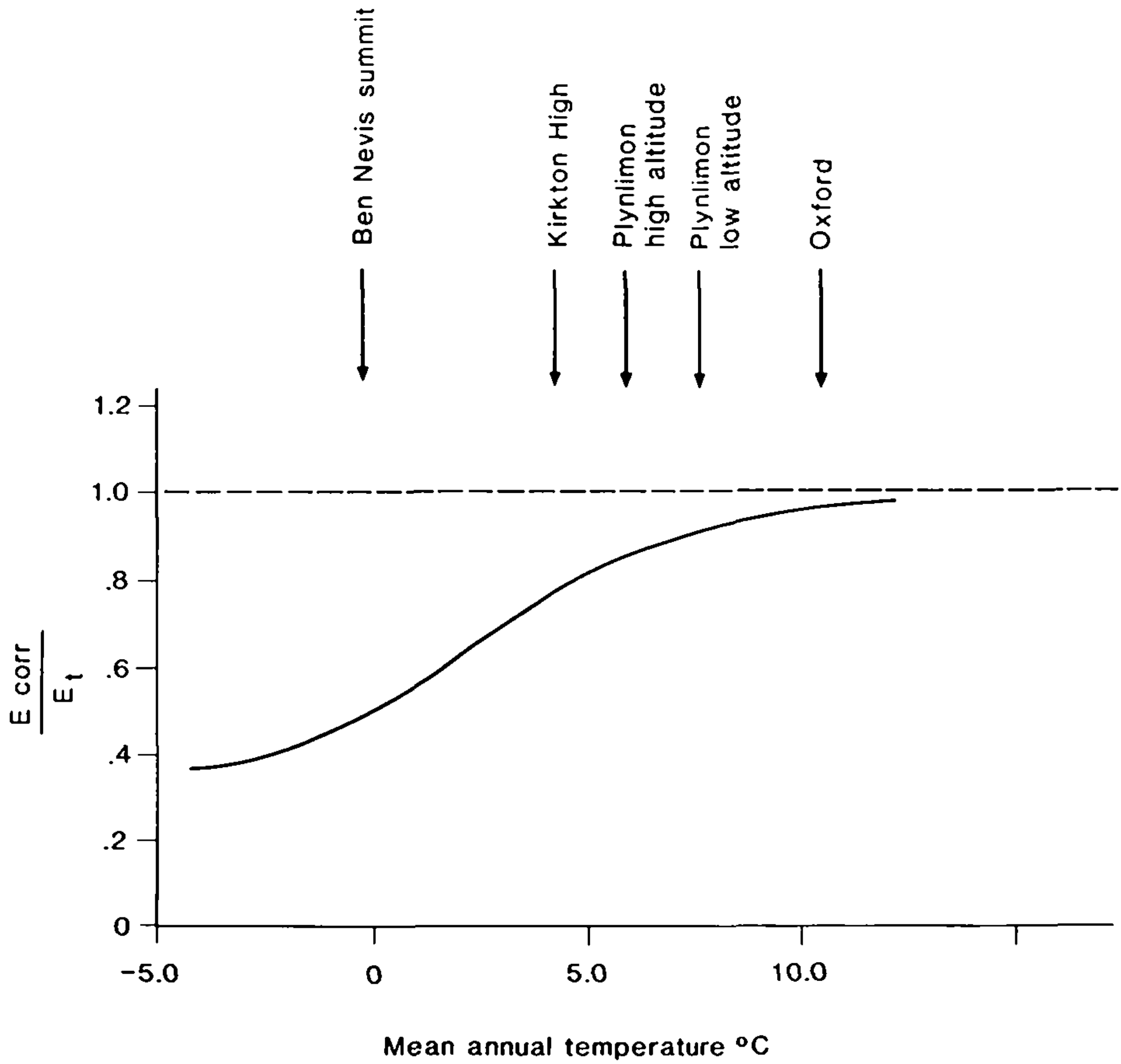


Fig. 3.4.1 The effect of applying the simple temperature model on a daily basis to the annual total of potential evaporation for a variety of temperature regimes.

3.5 THE EFFECT OF LINE THINNING SITKA SPRUCE ON FOREST INTERCEPTION LOSSES AT HAFREN FOREST, POWYS

3.5.1 Introduction

The importance of rainfall interception loss from coniferous forests is now well know as a significant part of the hydrological cycle and has been reported by many workers. The significance of this upon catchment losses has been recognised and, depending upon the prevailing climatic conditions, the losses can be as high as twice that from a grassland catchment, (Calder, 1979).

In the present study the effects of line thinning upon interception loss from Sitka spruce was investigated. Most previous studies of the interception process from Sitka spruce have not considered the effects of thinning. One exception is Anderson & Pyatt (1986) who measured interception from a 63-year old mature Sitka spruce stand which had been thinned in 1960.

3.5.2 Method

The site of the present study was located in Hafren Forest, Powys, Grid reference SN 874903 at an altitude of 305 m. The trees were planted in 1950 at a stocking density of 3000 stems ha^{-1}. Two plastic-sheet net-rainfall gauges (Calder & Rosier, 1976) were installed in March 1980. Data from the two gauges were recorded daily (initially using mechanical counters) and from December 1984 daily using electromechanical counters. Rainfall was measured daily at the Dolydd meteorological site, about 200 m away from the two gauges. Continuity of data collection during the winter was maintained by heating one of the gauges by use of soil warming cables laid beneath the plastic sheet and around the large tipping-bucket flowmeter.

Line thinning of the block was carried out during February and March 1984 by the removal of every third row. This was the first thinning for this block of trees. The two plastic-sheet net-rainfall gauges were removed during the thinning operation and reinstalled into their original positions as soon as thinning was completed.

No systematic canopy coverage surveys were carried out prior to thinning, but visual observations confirmed that the canopy was completely closed. Three surveys (using an anascope) after the thinning operation were made at two sites 50 m apart within the block. The surveys were point observations on a quadrat (size 20 m long by 6 m wide and with a spacing of 1 m), giving the results shown in Table 3. 5.1.

TABLE 3.5.1 Results of Canopy Coverage Surveys using an Anascope

Date	Number of Observations		Number of 'open sky' observations		Canopy Coverage		Free throughfall coefficient (p)
	Site 1	Site 2	Site 1	Site 2	Site 1	Site 2	
1.11.1984	147	147	37	36	0.748	0.755	0.249
18.12.1985	147	147	21	24	0.847	0.837	0.153
6.10.1986	147	147	9	13	0.038	0.911	0.075

TABLE 3.5.2 Annual Interception Ratios

Period	Rain	Net Rain		
01.01.81-31.12.81	2099.6	1295.93	0.38	
01.01.82-01.01.83	1967.2	1138.49	0.42	
02.01.83-31.12.83	2116.0	1238.73	0.40	PRE-THINNING
02.03.84-28.02.85	1389.2	832.91	0.40	POST-THINNING
01.03.85-01.01.86	1577.4	989.96	0.37	
01.01.86-31.12.86	1952.4	1250.66	0.36	

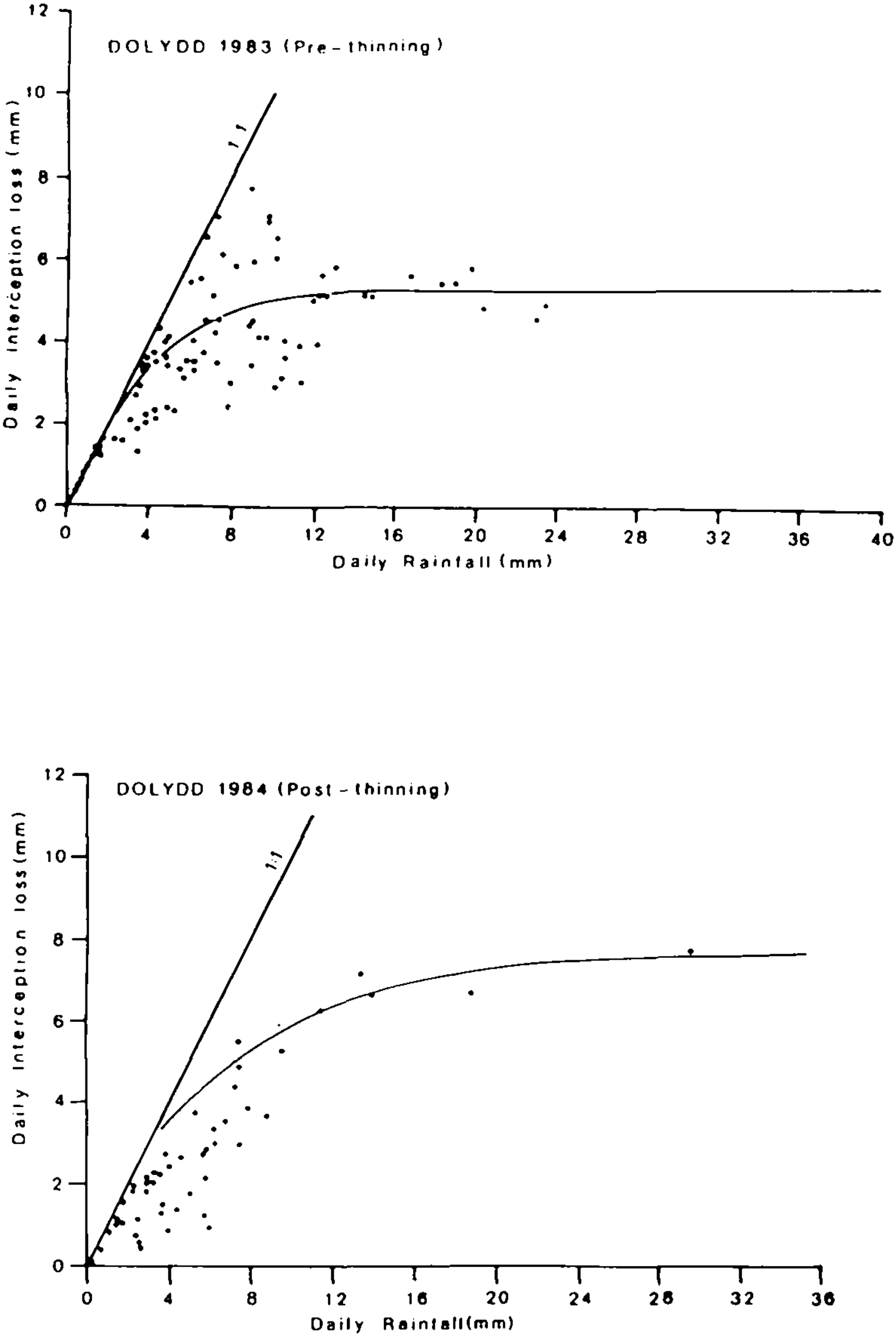
* α = Interception ratio.

NOTE. Line thinning by one-third took place during February and early March, 1984.

3.5.3 Results and Discussion

Forest thinning would be expected to do two things: 1, increase the free-throughfall component (p) and 2, increase the surface roughness and the penetration of turbulence through the canopy. These two changes should be mutually compensating, i.e. an increased free-throughfall component would decrease the total interception loss, while increases surface roughness should increase the total interception loss.

The results in Table 3.5.2 show that when averaged over a year, this compensation is approximately equal. Within the random experimental errors the annual interception ratios are the same before and after thinning. More information is given in the plots in Fig. 3.5.1. These show that for small storms the interception loss is reduced immediately after thinning: the likely result of the increased free-throughfall coefficient. Whereas the interception loss from large storms, represented by the maximum daily interception loss line, fitted by a least squares method, increased immediately after thinning from 5 mm to 7.5 mm: the likely result of the increased surface roughness.



ig. 3.5.1 The effect of line thinning on the daily interception loss at he Dolydd site in mid-Wales.

3.6 SOIL MOISTURE OBSERVATIONS

Transpiration and interception losses from upland vegetation types, can be inferred from the development of the soil moisture deficit and the rate of 'wetting up' of the soil. The relative infrequency of the soil moisture neutron probe observations (rarely more than once a week) and the variability between soil moisture neutron probe measuring tubes at one site limit the precision of the method. However, this is compensated for by the long run of records generally available.

TABLE 3.6.1 Details of soil moisture data available from Crinan and Balquhidder

	VEGETATION TYPE	NO. OF TUBES	PERIOD OF OBSERVATIONS
CRINAN			
	Myrtle	3	1979-1987
	Mature forest	4	1979-1987
	Heather (A)	6	1981-1984
	Heather (B)	6	1981-1987
	Immature forest	3	1984-1987
BALQUHIDDER			
	Mature forest		1983-1987
	Mature forest (original interception site)		1984-1986
	Mature forest (Kirkton Tower)		1987-1987
	Heather (Upper Monachyle)		1983-1987
	Grass (Lower Monachyle)		1984-1987
	Upland grass (Glen Croetha)	3	1986-1987

Neutron probe soil moisture observations have been taken in the Crinan Canal catchments since 1979 and at Balquhidder since 1983, see Table 3.6.1 for details. Observations are continuing both at Crinan, where data are being taken beneath the immature forest, mature forest and heather, and at Balquhidder where observations are continuing beneath the mature forest, heather and upland grass sites. There are now very good data sets available for validating daily water use models. Preliminary work on modelling these data is reported in the annual progress reports (Calder et al., 1984 and Hall et al., 1986). It is planned in the next few months to complete this modelling with the enlarged data set and improved models.

3.7 CHLORIDE BALANCE STUDY OF THE CRINAN CATCHMENTS

This study was initiated in June 1985 and lasted for one year. Its objective was to produce an estimate of evaporation from different vegetation types from the chloride concentration found in rain and stream water. This method assumes that (as chloride is an inert tracer) the chloride input to a catchment will equal chloride output from a catchment via the streams.

The effect of evaporation from a catchment will be to increase the chloride concentration in the streams. This means that to obtain a long term average concentration for the streams the chloride concentrations (found from spot samples) must be weighted using the stream flow.

Weekly water samples were taken from the following:

Storage raingauge at Clac Connaidh
Clac Connaidh Burn - draining an area of heather
Dhaill Farm Burn - draining an area of immature spruce forest
Achantheanbhaile Burn - draining an area of mature spruce forest.

The chloride concentrations of each sample was determined at the Institute of Hydrology within six weeks of the sample being taken.

Flow measurements from Cam Dubh Burn were used as no measurements were made of flow from the three streams sampled. The analysis showed the following:

1. Chloride concentration is variable, particularly in rainfall (see Fig. 3.7.1).

2. Chloride concentration follows a seasonal pattern in the streams (see Fig. 3.7.2).

3. No correlation was established between chloride concentrations found in the streams and the chloride concentration found in the rainfall.

4. No correlation was established between chloride concentrations found in the streams and streamflow.

   The flow weighted mean chloride concentrations are 10.95 (heather), 11.34 (immature forest), 18.41 (mature forest) and 11.51 (rainfall) mg l^{-1}.

The study showed that the heather and immature forest streams show similar chloride concentrations to the rainfall, which suggests very little (or negative) evaporation, whereas the mature forest stream shows an unrealistically large evaporation.

The method failed to produce realistic estimates of evaporation which may be due to two causes. Firstly, the length of the experiment may have been too short to remove any storage effects and, secondly, dry and occult deposition may have occurred.

To improve the estimate of the chloride balance of a catchment a longer sampling period and measurement of dry and occult deposition would be required.

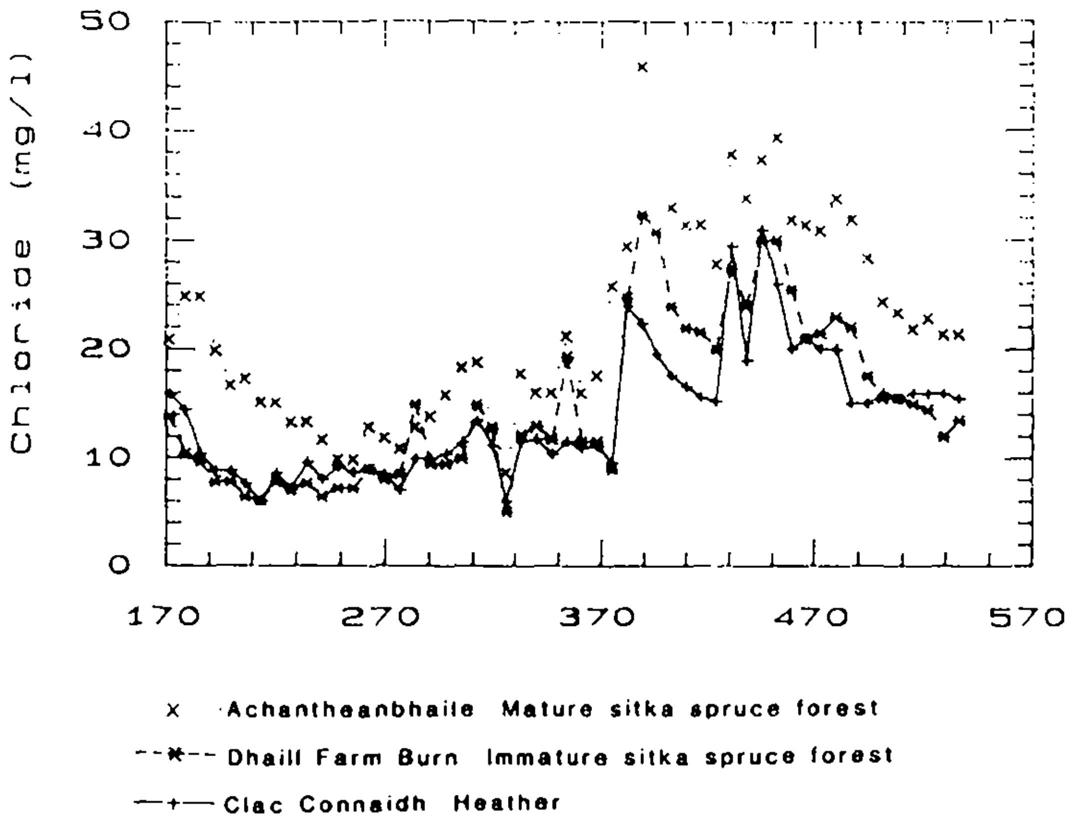


Fig 3.7.1 Chloride concentration versus day No.

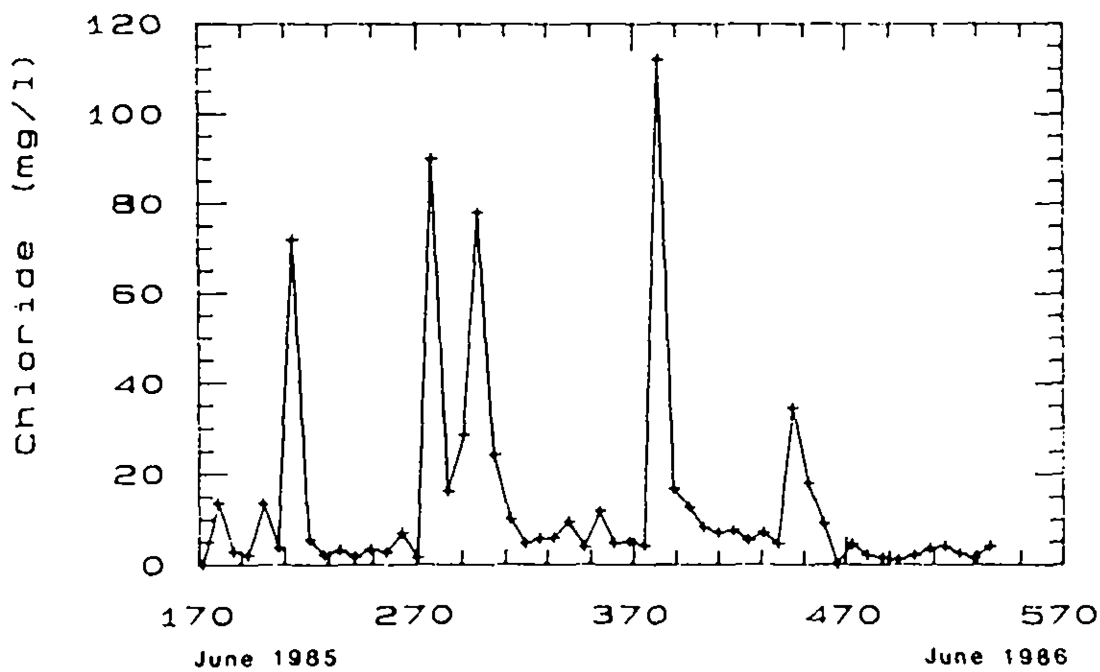


Fig 3.7.2 Chloride concentration in the rainfall versus day No.

3.8 A PRELIMINARY INVESTIGATION INTO THE RELATIONSHIP BETWEEN LOW STREAM FLOW AND SOIL MOISTURE DEFICIT (SMD)

To establish the form of relationship between low stream flows and SMD, records of daily rainfall and flows from the Wye (rough pasture) and Severn (62% afforested) catchments at Plynlimon for the years 1982 to 1972 were used. The rainfall was used in a daily accounting SMD model which included evaporation models for grass, the simple layer model described in Calder at al. (1983), and for forest, the model described in Calder et al. (1984). The SMD model generates a time series of daily predicted SMD values and these were plotted for deficiencies greater than 10 mm against flow for each year for both catchments. Figures 3.8.1 and 3.8.2 show a summary of the results for the readily available data (1972-1979) for the Severn and Wye catchments respectively. For both catchments there is a consistent form of relationship with the flow approaching a minimum value usually about 0.55 mm day^{-1} at a predicted deficit which ranges from 22 mm to 55 mm for the Wye and from 22 mm to 70 mm for the Severn. The greater variability among the Severn results is mostly associated with the atypical drought years of 1975 and 1976. There are also more curves on Fig. 3.8.1 than Fig. 3.8.2 showing that for forest there were more occasions when the predicted deficit exceeded 10 mm than there were for grass. Apart from these differences the two sets of curves are very similar.

This preliminary study has shown the existence of a relationship between flow and SMD in dry periods for the upland Severn and Wye catchments. It would be necessary to examine data from more upland catchments to establish the generality of this relationship. Once the functional form were found for a catchment it should be possible to relate the effects of afforestation to low flows through SMDs which are relatively easily calculated.

However, before any predictive modelling could even by contemplated it would be necessary to establish a causal relationship between SMDs and low flows. This would only be possible for catchments having no ground water storage and would require process studies of the mechanisms controlling low flows..

Taking this work further would be a large undertaking requiring major funding.

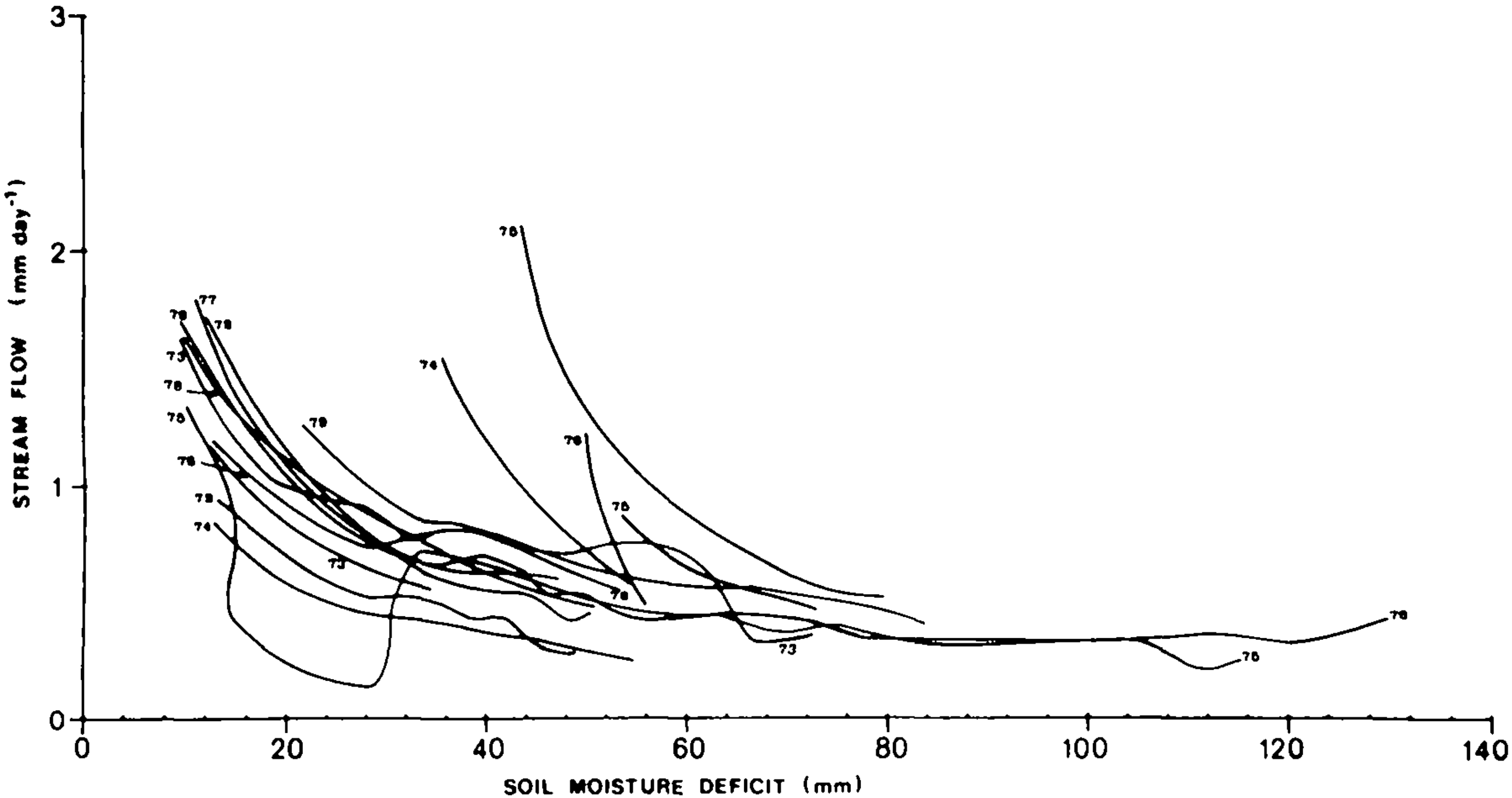


Figure 3.8.1
The relationship between streamflow and predicted SMD for deficits greater than 10 mm for the Severn catchment (62% afforested) over the period 1972 to 1979.

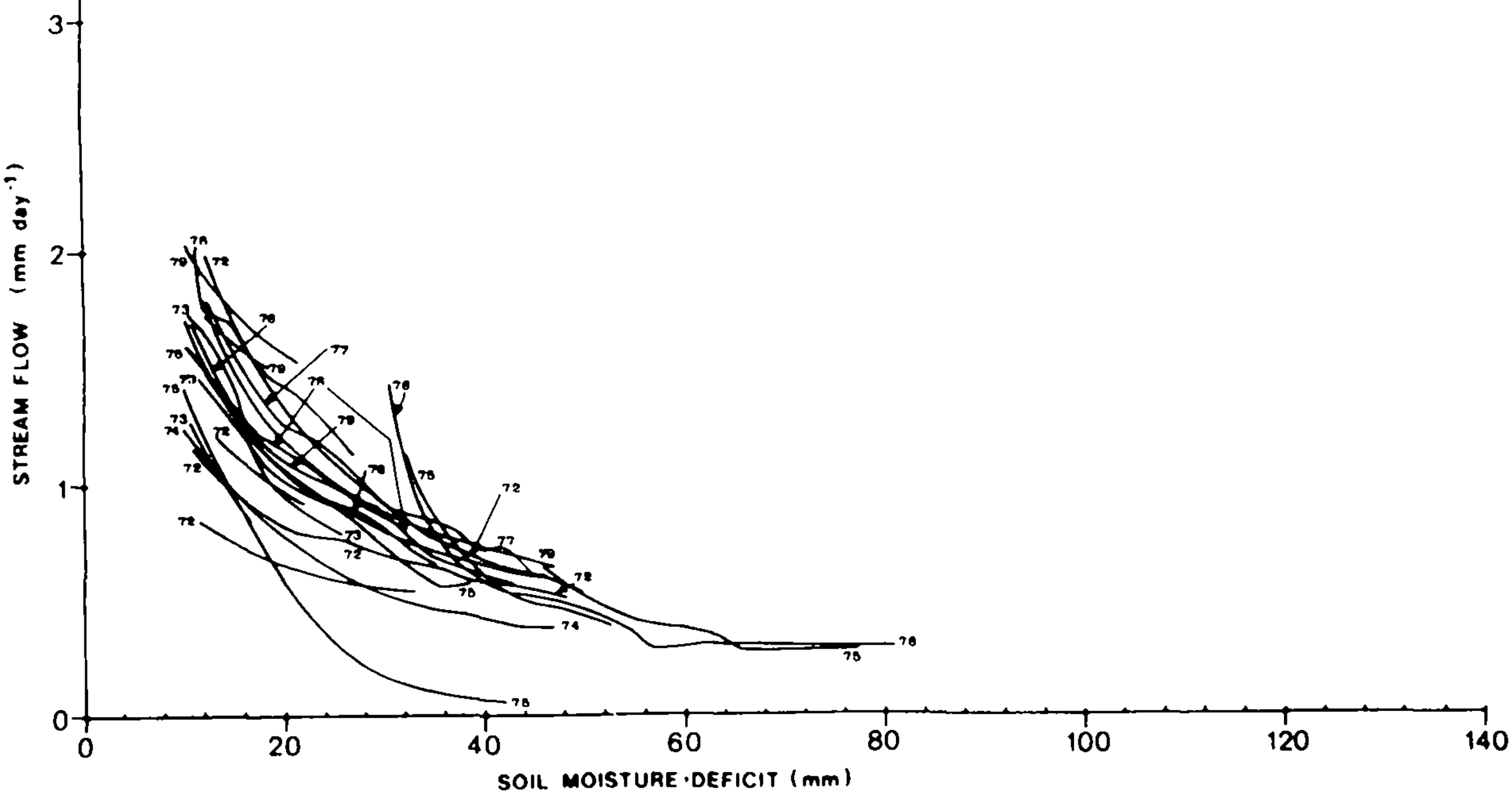


Figure 3.8.2
The relationship between streamflow and predicted SMD for deficits greater than 10 mm for the Wye catchment (rough pasture) over the period 1972 to 1979.

4. Conclusions and Future Work

The strategy of combining an intensive study of the responses of two representative catchments with detailed studies of the hydrological processes identified as being the key factors controlling these responses has yielded much new information and a better understanding of land use and hydrology in the more extreme upland areas of Britain. This information is being used to extend and improve existing hydrological models. Those improvements already implemented and tested on the Balquhidder catchment data have been shown to be equally valid when applied to less extreme areas elsewhere in Britain. There is every indication that further useful information will emerge from the present phase of clear-felling and initial afforestation on the catchments and the extension of the process studies found necessary as a result of the initial catchment findings.

4.1 CATCHMENT STUDIES

The intensive instrumentation of two catchments at Balquhidder to obtain information on water use by the existing vegetation covers, a heather/grass mix on the Monachyle and 35% mature forest with high altitude grassland above it in the Kirkton, has produced much useful information and some unexpected results. The dense networks of precipitation gauges have given useful insights into the spatial variability of precipitation within this type of rugged terrain. A method of estimating snow input has also been evolved. Accurate, continuous measurement of streamflow over the wide range of flows experienced in the steep flashy streams presented a challenge which has been met successfully and has also provided useful data on the performance of standard structures operating close to or beyond their design limits. Apart from its immediate application in defining water use from the catchments, the flow data obtained will provide valuable information on the flood and low flow characteristics of this type of terrain. Despite a relatively poor data capture rate, the network of Automatic Weather Stations installed to provide estimates of Penman potential evaporation, ET, in the catchments have yielded valuable information on the magnitude and variation with altitude and exposure of ET in these upland conditions. It has been shown that, contrary to previous assumptions, ET is significantly greater in summer on the high altitude exposed areas of the catchments than in the valley bottoms. This suggests that the methods presently employed to obtain regional ET values by extrapolation from low level sites may be significantly underestimating ET for upland areas. Initial analysis of the data on radiation, humidity, temperature and windspeed suggests that the main factors leading to these higher ET values are windspeed and net radiation. The data acquired provide an opportunity to develop a much better understanding of the factors controlling climate in upland areas.

The conclusions from the water balance analyses of the two catchments under their existing vegetation covers were surprising and appeared to contradict existing concepts and model predictions. The heather/grass covered Monachyle was found to have a mean annual water use of 634 mm, relative to an ET estimate of 540 mm and the part forested, part grassland Kirkton a water use of 425 mm relative to an ET of 540 mm. Exhaustive checks on the data, the methods of computing catchment means and the geology of the catchments revealed no sources of systematic error large enough to cast doubt on the conclusions that the water use of the Monachyle was certainly not less than ET whereas that of the Kirkton was significantly lower than ET. An indication of the unexpectedness of the latter result is that the application of the previously accepted Calder & Newson model to the Kirkton would have predicted a water use of 710 mm.

A study of interception loss from the forested area of the Kirkton found that this was within the range found elsewhere in upland Britain, suggesting that the low overall water use of the catchment was due to the high altitude grassland areas. To determine whether water use by these grasses was significantly lower than the Penman ET figures an additional process study was proposed, approved and initiated. This study is not yet completed but initial results suggest that water use by grassland at altitudes above 400 m is indeed lower than Penman ET.

Sediment studies in the Balquhidder catchments during the initial phase of the study were aimed primarily at developing sediment ratings for the catchments under their existing vegetation cover, so that changes in erosion rates resulting from the subsequent operations of land preparation and planting in the Monachyle and clear felling in the Kirkton could be quantified. During the initial phase prior to the felling and planting, mean annual losses of 37 t km^{-2} and 57 t km^{-2} of suspended sediment and 0.1 t km^{-2} and 0.8 t km^{-2} of bedload were observed from the Monachyle and Kirkton respectively. The main sources were the steep tributary streams. The reason for the 50% greater loss from the Kirkton, despite its lower precipitation and flow, was not positively established but most of the material appeared to come from the lower, forested, areas which also contained an established but lightly used network of forestry roads.

Following the start of planting and clear felling in 1986 a marked change in the sediment responses was observed in both catchments. In both cases the range of concentrations occurring at low flows increased dramatically and the maximum concentrations also increased significantly during the second year, the latter occurring in the mid-range of flows rather than at the highest flows.

Concentrations now appear to correlate more readily with rainfall events than with major changes in flow, indicating that much greater quantities of sediment are freely available for transport to the streams in both catchments. Sources of this additional material have been identified as the 6% of the Monachyle ploughed and the road system in the Kirkton. Material from the plough lines in the Monachyle concentrates in the cut-off ditches and is transported from these to the streams. Heavy usage and regular maintenance of the Kirkton road system has inevitably increased the supply of loose material.

Provisional estimates suggest increases in the range 3-5 times during these initial two years of the planting and felling operations. It will be necessary to continue monitoring through Phase II to determine the duration of these present loss rates and the levels at which they subsequently stabilise.

4.2 PROCESS STUDIES

The primary areas of study in the physical processes have been in the evaporative characteristics of heather, the interception losses from a snow covered forest and, recently, the evaporation from high altitude grassland. In addition a number of smaller studies have been completed including a study of the relationship of low flows to land-use and a study of the effects of forest line thinning on the interception characteristics. The latter found no significant difference in the annual interception losses before and after thinning.

The work on heather moors in Scotland has shown that the interception losses can be large (on average 17% of rainfall). However the transpiration losses are small, smaller than those expected from lowland grassland or forest. As a result of these opposing tendencies, heather will be expected to have an overall evaporation higher than the Penman potential only in the wetter areas (when the rainfall exceeds 1500 mm).

The studies of evaporation from snow intercepted on a forest canopy, undertaken at Aviemore, have shown that potentially large interception losses can occur. Although a snow covered canopy is smoother than a rain wetted one, the large canopy storage capacity means that evaporation can continue long after the snowfall has finished. At Aviemore the proportion of precipitation lost through interception is larger for snow than for rainfall. However there is evidence that this proportion depends on the stand density and for older and less dense forest, such as that at Balquhidder, the interception losses for rain and snow may be similar.

An increasing effort has been devoted to using the process results to calibrate models which will enable the extrapolation of the catchment results to other regions of the UK. Both annual and seasonal models are being produced. The models of forest and heather are now complete (although that for a snow covered forest needs further work). In the light of the Balquhidder catchment results the original model for grass is now felt to be inadequate in high altitude areas and its further development awaits the completion of the high altitude grassland study.

The application of the models to the Monachyle catchment reproduces the high losses observed from this catchment. The application of the models to the Plynlimon catchments shows a good agreement with the grassland Wye catchment (provided a simple temperature correction is applied). In the part forested Severn catchment there is a small discrepancy between the model and catchment results but this is within the expected errors in the two estimates. The application of the models to the Kirkton catchment cannot be made until the grassland study is complete.

4.3 FUTURE WORK

Subject to funding continuing to be available from DOE and the other sponsoring agencies, it is proposed to continue utilising the instrument networks established on the Balquhidder catchments to accumulate high quality data at least until the present phase of land use changes has been completed.

This will yield further valuable information on the changes in water use resulting from the complete felling of the forested area in the Kirkton catchment and from the planting and initial growth stages of forest in the Monachyle. Continuation of the sediment sampling through this period also will reveal whether losses increase further or begin to stabilise. An extension of the meteorological observations, hopefully with a better capture rate using new loggers scheduled to become available late in 1988, will provide an opportunity to investigate further the relationships between altitude, exposure and the climatic variables and lead to improved methods of estimating catchment scale and regional values of Penman ET.

Extension of the data collection programme through Phase II will also make it possible to analyse the effects of the land use changes on the flood responses and on the flow recessions of the catchments, those having been determined from the undisturbed phase.

The future aim of the process studies will be to fill in the gaps in the seasonal and annual water-use models. The immediate priorities will be to complete the field measurement program of the high altitude grassland study and to incorporate these measurements (and those of the snow interception measurements) into the simple water-use models.

Beyond these immediate priorities there are a number of topics which could be considered for future funding:

The evaporative climate of the Highlands. The Balquhidder weather stations have shown a much higher evaporative demand than was previously thought. Data for the rest of Highland Scotland is sparse although some exists for the Cairngorm region and a few other isolated areas. To provide a more comprehensive view the existing observations will need careful analysis and the establishment of additional weather stations in the north-west highlands, should be considered.

2. Snow melt and evaporative processes from open snow areas in the highlands. A complete hydrological model will require a comprehensive description of these processes.

3. The evaporative characteristics of larch. A proposed study of the interception and transpiration characteristics of this deciduous conifer had to be postponed during the present contract. This information would be valuable, however, in extending the range of the water use models to cover the effects of this widely grown species.

4. The development of models to predict the effects on seasonal streamflow of forestry operations. The present modelling work and its immediate extension relates to annual and seasonal water use and the effects thereon of forestry practices. The relationship between water use and seasonal flow is dependent on site conditions as well as vegetation cover. Phase II of the catchment studies will identify changes arising on these particular sites. Modelling of these changes will give some indication of whether a generalised method of predicting effects on seasonal flow can be developed. Subject to these findings it may then be desirable to examine data from other representative catchments.

5. The water use of forest in the intermediate growth stages up to and including canopy closure for both first and second crop planting. The existing instrumented catchments at Balquhidder could be used to monitor these parts of the forestry cycle either continuously, with rationalised instrumentation networks, or intermittently at intervals of, say, 5 years.

REFERENCES

Ackers, P., White, W.R., Perkins, J.A. & Harrison, A.J.M. 1978. Weirs and flumes for flow measurement. London: Wiley.

Anderson, A.R. & Pyatt, D.G.. 1986. Interception of precipitation by pole-stage Sitka spruce and lodgepole pine and mature Sitka spruce at Kielder Forest. *Northumberland Forestry, 59, No.1, 29-37.*

Ayer, G.R. 1959. The effect of snowcover on snowmelt runoff. *ESCP, 119-127.*

Blackie, J.R. 1987. The Balquhidder catchments, Scotland: the first four years. *Trans. Roy. Soc. Edinburgh : Earth Sciences, 78, 227-239.*

British Standards Institution. 1969. Methods of measurement of liquid flow in open channels; Part 4B, Long based weirs. BS3680. London: British Standards Institution.

Calder, I.R. 1976. The measurement of water losses from a forested area using a "natural" lysimeter. *J. Hydrol., 30, 311-325.*

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

Calder, I.R. 1982. Forest Evaporation. *In: Proc. Can. Hydrol. Symp. 1982. Nat. Res. Counc. Can. Ottawa. Ont. 173-193.*

Calder, I.R., Hall, R.L., Harding, R.J., Rosier, P.T.W. & Wright, I.R. Upland afforestation progress report. *Process Studies 1983-1984.*

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

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

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

Edwards, K.E. & Rodda, J.C. 1970. A preliminary study of the water balance of a small clay catchment. *J. Hydrol. (N.Z.), 9, 202-218.*

Eschner, A.R. & Leonard, R.E. 1969. Disposition of intercepted snow. *ESCP, 73-81.*

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

Hall, R.L., Harding, R.J., Rosier, P.T.W. & Wright, I.R. Upland afforestation and water resources: Process studies progress report 1986/87.

Jeffrey, W.W. 1968. Snow hydrology in a forest environment. *Proc. Workshop Sc., Canadian National Committee of IHD.*

Johnson, R.C. 1985. Mountain and glen: climatic contrasts at Balquhidder. *J. Meteorol., 10, 105-108.*

Meiman, J.R. 1968. Snow accumulation related to elevation, aspect and forest canopy. *Proc. Workshop Sem., Canadian National Committee of IHD.*

Monteith, J.L. 1965. Evaporation and environment. *Symp. Soc. Exo. Biol., 19, 105-234.*

Newson, M.D. 1980. The erosion of drainage ditches and its effect on bedload yields in mid-Wales: Reconnaissance Case Studies. *Earth Surf. Proc., 5, 275-290.*

Olitnik, V.S. 1979. Features of snow accumulation and thawing in Carpathian spruce forests. *Lesovedenie, 4, 85-88 (FA).*

Olszyczka, B. 1979. Gamma ray determinations of surface water storage and stem water content for coniferous forests. Ph.D. Thesis, Department of Applied Physics, University of Strathclyde.

Penman, H.L. 1948. Natural evaporation from open water, bare soil and grass. *Proc. Roy. Soc., London, A193, 120-145.*

Ministry of Agriculture, Fisheries and Food. 1967. Potential transpiration. *Tech. Bull. 16.* London. HMSO.

Roberts, J. 1977. The use of tree cutting techniques in the study of the water relations of mature *Pinus sylvestris* L. 1. The technique and survey of the results. *J. Exp. Bot., 28, 751-767.*

Robins, N.S. & Mendum, J.R. 1987. Geology and hydrogeology of Kirkton Glen, Balquhidder. *Hydrogeol. in Scotland. Report 87.* Edinburgh. Bristol.

Robinson, M. and Blyth, K. 1982. The effect of forestry drainage operations on upland sediment yields: a case study. *Earth Surf. Proc., 7, 55-90.*

Rodda, J.C. 1967. The systematic error in rainfall measurement. *J. Inst. Water Eng., 21, 173-177.*

Satterlund, D.R. & Haupt, H.F. 1970. The deposition of snow caught by conifer crowns. *Wat. Resour. Res., 6, 649-652.*

Swanson, R.H. & Hillman, G.R. 1977. Predicted increased water yield after clearcutting verified in west-central Alberta. *Canadian For. Ser. NOR-X-198, 40p.*

Appendix 1

CONTRACT OBJECTIVES AND PROGRAMME OF WORK PECD 7/7/133.

This contract was originally set out to cover the period 1984-86 during which the DOE undertook to contribute 22.5% of the cost of the agreed programme subject to a maximum of £28,000 in each year. The contract was modified and extended in 1986 to cover a further two year period, with the DOE contribution remaining at 22.5% subject to an upper limit of £31,000 per annum. To help to cover necessary additional work the contract was modified again later in 1986 to raise the DOE contribution to 25% of the costs subject to upper limits of up to £43,700 in 1986/87 and £40,600 in 1987/88.

This contract was originally set out to cover the period 1984-86, subsequently extended to include the years 1986/87 and 1987/88 and then modified again in 1986 when the contribution was increased, to cover additional work. The original objectives and work programme were those agreed between DOE and the other 'consortium' funding agencies in 1983/84, based on proposals submitted by IH and the results already achieved at Balquhidder and elsewhere in the period 1981-1984.

Objectives 1984/86

To investigate:

1. The seasonal differences in evaporation rates between forest, heaths and pasture.

2. The transpiration and interception characteristics of intermediate height upland heath vegetation.

3. The relative evaporations from forests, heaths and pastures in snow conditions.

4. The spatial variability of the upland meteorological parameters which control evaporation rates.

Programme of Work 1984/86

1. To determine transpiration characteristics of forest/upland vegetation and its seasonal differences.

   To determine interception characteristics of intermediate height upland vegetation.

3. To determine snow interception and snow melt characteristics of forests.

4. To develop and improve current research and applied evaporation models.

5. To determine, in typical Scottish Highland conditions of climate, topography and soils, the integrated effects of two different forms of land use (plantation forestry/rough grazing) on the volume of streamflow emerging, its distribution in time and its sediment loading.

These objectives represented the best guess, at that time, as to which were likely to be the key processes in determining the effects of upland afforestation in the extreme conditions of Highland Scotland. It was recognised that these objectives and the programme of work might have to be modified as information began to emerge from the programme.

By 1986 it had been agreed in consortium discussions of the results emerging that the duration of the catchment studies should be extended to gather information on the effects of initial planting in one catchment and of a forest clear felling in the other. The process studies findings on interception resulted also in requests that these studies be extended to include the effects of line thinning on interception and the interception of characteristics of larch. Modelling development was also to explore methods of predicting the effects of vegetation changes on low flows.

The modified and extended objectives and work programme to cover the two-year extension to the contract were

Objectives, 1986/88

To investigate:

1. The seasonal differences in evaporation ratio between forest, heaths and pasture with particular reference to low flow conditions.

2. The effect of forest thinning on interception losses.

3. The relative evaporations from forests, heaths and pasture in snow conditions with a view to developing detailed predictive models.

4. The spatial variability of the upland meteorological parameters which control evaporation rates with particular reference to evaporation/atmosphere interactions.

   Interception losses from larch.

6. Using the existing fully instrumented Balquhidder catchments, the effects of clear felling and of initial planting in snow prone upland conditions.

Programme of work to be carried out by the Contractor, 1986/88

1. To develop models of the relationships between evaporation rates, soil moisture deficits and seasonal flow patterns.

2. To measure and compare interception losses for thinned plots with those from standard planting density.

3. To develop predictive models from the data on snow interception obtained in the initial studies.

4. To analyse meteorological data from Balquhidder and elsewhere to determine the spatial and altitudinal variability of evaporation rates.

5. To apply the gamma-ray and other techniques already proven in spruce to determine interception losses from larch.

6. To continue to operate the streamflow, precipitation, meteorological and sediment sampling networks on the Balquhidder catchments through the period of clear-felling of the forested catchment and initial planting on the present control to determine the hydrological effects of these phases of the forestry cycle.

This process of evolution and modification of the objectives and work programme has continued.

Since the 1986 extension the most notable modification resulted from the presentation of the results of Phase I of the catchment studies in May 1986. These implied that the water use of high altitude grassland may be much lower than previously assumed. Consequently it was agreed by DOE and the other funding agencies that the objectives and work programme would be modified to include a detailed study of the transpiration and interception losses from this grassland in the Kirkton catchment at Balquhidder. To accommodate this additional study the proposed work on larch interception has been postponed.

Appendix 2

Transactions of the Royal Society of Edinburgh: Earth Sciences, **78**, 227–239, 1987

The Balquhidder catchments, Scotland: the first four years

J. R. Blackie

ABSTRACT: Results emerging from the long-term forestry versus upland grassland paired catchment study conducted by the Institute of Hydrology at Plynlimon, mid-Wales, and from studies of the processes controlling the hydrological responses of areas under forest and grassland, have been accepted by the water and forestry industries as a means of determining the probable effects of afforestation in other areas of Britain. When considering proposals in the late 1970s for a further major expansion of forestry, mainly in Highland Scotland, it became apparent that insufficient information was available to predict with confidence the effects in areas where forestry would replace medium height vegetation (heather sp., bracken) or in areas where a significant proportion of the precipitation falls as snow. Against this background a consortium of interested parties (see Hall 1987), agreed in 1981 to fund parallel systems and process studies of the effects in appropriate areas of Scotland. In this paper the initial stages of the systems study, on two catchments in the Balquhidder area of Central Region, are described. Some preliminary results from phase I, in which the catchment water balances under a mature forest and a mixed heather, bracken, grass cover were obtained, are presented. These water balances suggest that water use by the partly forested catchment is lower than that by the control and also lower than Penman *ET*. These findings are discussed in relation to the Plynlimon results and to information gained in the current process studies. Plans for phase II of the study, in which the mature forest will be clear-felled and part of the heather, bracken, grass control will be planted, are outlined.

KEY WORDS: catchment water balance, forestry, heather, high altitude grassland, snow

Since its inception in the late 1960s, the Institute of Hydrology has been conducting research into the hydrological effects of afforestation in upland Britain. Results emerging from the long-term forestry versus grassland paired catchment study at Plynlimon, mid-Wales and from studies of the processes controlling the hydrological responses of areas under forest and grassland have indicated that, in high rainfall upland areas, the rapid loss rates of water intercepted by the aerodynamically rough forest canopy results in much higher total water use by forest than by grassland.

Models of varying degrees of complexity, based on the knowledge gained of the processes and tested on catchment scale data from Plynlimon and elsewhere, have been used to predict the effects of afforestation on water use and hence on streamflow yield in other areas of Britain (Calder & Newson 1979). Predictions of this nature are particularly relevant for catchments already exploited for water supply and hydropower, in that they provide a basis for cost-benefit analysis of the probable effects of varying degrees of afforestation within the catchments.

Other effects of afforestation which have been quantified in studies at Coalburn, Cumbria and at Plynlimon are those arising from the practice of pre-planting surface drainage which is considered to be essential to the establishment of plantation softwoods on poor upland soils. This surface drainage system has been shown to reduce the time to peak and increase the magnitude of the flood peaks and to increase the sediment loads in the streams (Robinson 1980). The latter effect has been shown to persist throughout the first tree crop lifetime at Plynlimon, where total sediment losses are up to five times greater than from the grassland in the adjacent catchment (Robinson & Newson 1986).

However, this information base was considered to be inadequate to estimate the probable effects of the major expansion of forestry in Highland Scotland being proposed in the late 1970s. Two factors in particular were of concern, namely heather and snow. In many areas in the Highlands, forestry would be replacing a vegetation complex consisting of heather, bracken and other medium height vegetation. Little information was available on the interception and water use characteristics of this complex, or on the sediment loss rates from such areas. Climatic conditions, particularly those in the central and eastern Highlands, are more extreme than those encountered in mid-Wales and at Coalburn. A much higher proportion of the total precipitation falls as snow and accumulations of considerable depth can be expected. The effects of forestry establishment in these conditions on water use, on time distribution of streamflow and on erosion and sediment loads required detailed investigation.

From discussion of these inadequacies in existing knowledge a research project proposal was evolved. This comprised a systems study of the catchment scale hydrological responses of the heather, grass, bracken complex and of plantation forestry in typical Highland conditions and a parallel series of studies of the key processes involved, namely the interception and transpiration characteristics of heather and the interception of snow by forest canopies. A consortium of interested parties, including the Scottish Development Department, the Department of the Environment, the Forestry Commission, the North of Scotland Hydro Electric Board, the Water Research Centre representing Scottish water supply interests, the British Waterways Board and the Natural Environment Research Council agreed in 1981 to fund this project.

In this paper the catchments chosen for the systems part of the project are described, together with the instrumentation networks installed in them and the experimental plan for phases I and II of what is anticipated to be a ten year minimum study period. Some preliminary results from phase I of the study are summarised and discussed in relation to the adequacy of the network designs. While no firm conclusions can be drawn at this stage, the possible implications of these results are considered.

1. Experimental design

The classical paired catchment approach to quantifying the hydrological effects of a change in land use was impractical in this case since it would involve monitoring for some sixty years to cover the complete forestry cycle. Instead, the proposed experimental design called for three adjacent, physically similar, catchments typical of the central and eastern Highlands. One of these should have a mature forest cover, while the other two would be under a mixed heather, grass, bracken cover. In phase I of the study the hydrological responses of these three would be monitored and compared for a period of, say, five years. In phase II the mature forest catchment would be felled, one of the heather catchments would be planted and the other remain as the control. This design would yield data on the hydrological characteristics of the heather, grass, bracken cover and of the three critical periods of the forestry cycle in a total time of ten to fifteen years.

It proved impossible to find sites which met all of the requirements of this design while also meeting the practical requirements. The best compromise found was two catchments in the Balquhidder area of Central Region (Fig. 1). One of these, the Kirkton Glen, was partially under mature forest cover due for felling within five years, while the other, the Monachyle Glen, was under a mixed heather, grass, bracken and scrub forest cover. The lower part of this catchment had been acquired by Forestry Commission for planting. Access to these catchments was reasonably good and they appeared technically feasible. From an experimental viewpoint it would have been desirable to have had larger proportions of the catchments under forest and due for planting. However, the figures of 40% and 30% respectively are not untypical of the proportions of many Highland glens which it would be practical to afforest. Soils and temperatures make growth rates uneconomic above approximately 500 m throughout most of this area. Given that these sites come reasonably close to the original specification the design was modified slightly to utilise them.

This modified experimental design called for the two catchments to be monitored under their existing covers over the period 1981/82 to 1985/86 as phase I. In phase II, from 1986 onwards, the Kirkton forest would be progressively clear-felled and the lower part of the Monachyle would be afforested. To compensate for the absence of a third catchment, it was proposed that the upper part of the Monachyle, which was not scheduled for planting, should be gauged as a 'nested' sub-catchment to provide reference data during phase II.

Monitoring in each catchment was to consist of measurement of precipitation inputs (P), of streamflow

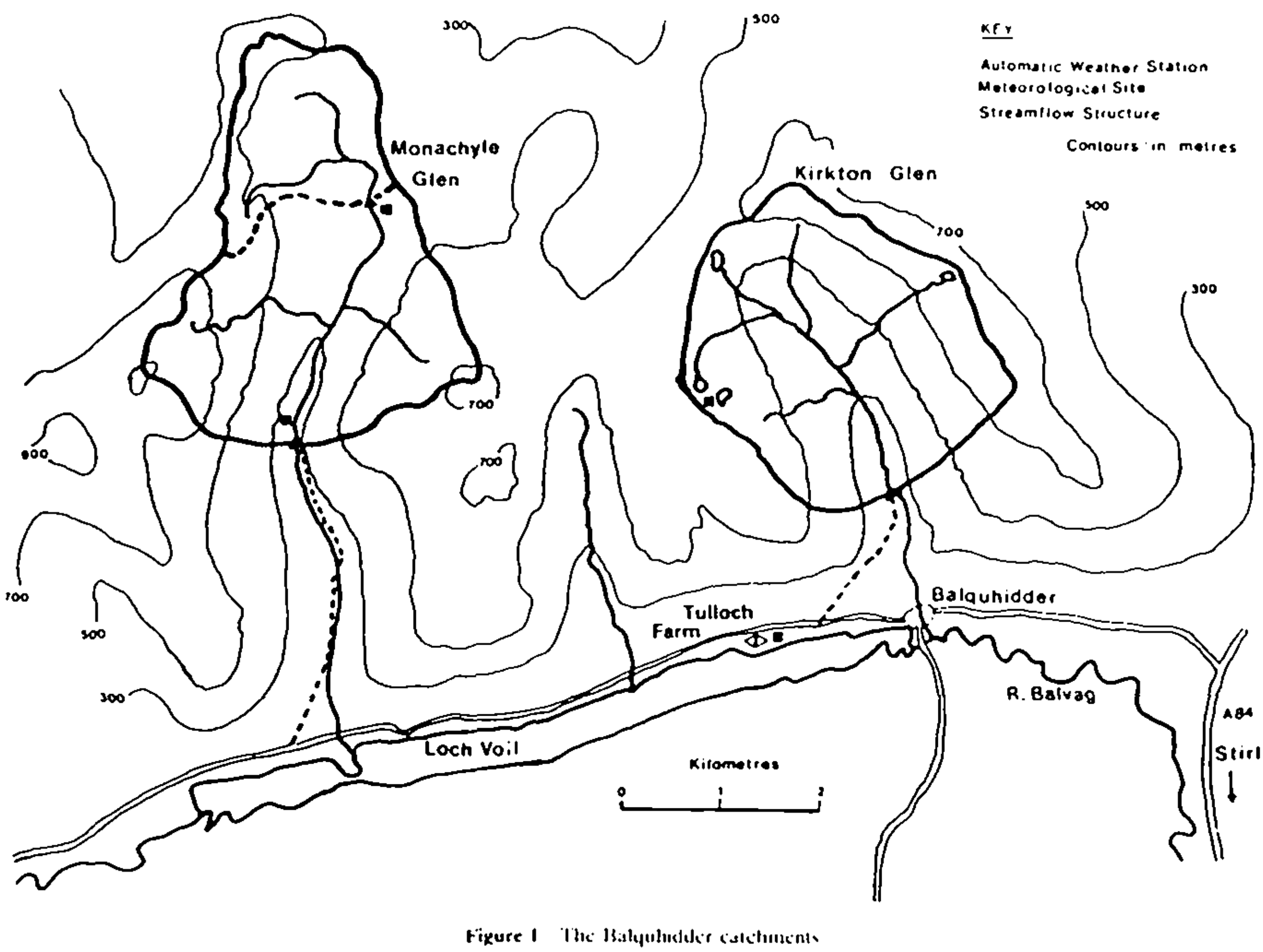


Figure 1 The Balquhidder catchments

outputs (Q), of the meteorological variables necessary to estimate potential evapotranspiration (Et) and of the sediment loads being transported out of the catchment by the stream. From these measurements estimates of water use or actual evapotranspiration (AE) by each catchment in each phase could be determined and related to potential evapotranspiration. Precipitation/runoff relationships would be established from fine time-scale measurements and the effects of the land use changes in each catchment evaluated. Similarly sediment ratings would be established during phase I and changes in these during phase II identified.

Since measurement of changes in catchment moisture storage (ΔS), was not feasible in these catchments because of the highly variable depths of soil and underlying glacial debris, it was recognised that it would be possible to obtain water use estimates only for periods over which ΔS was small relative to $P - Q$, i.e. for periods where the water balance expression

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

could be acceptably approximated as

$$AE = P - Q.$$

Effectively this would mean periods of twelve months or more.

The resources available from the consortium could not cover the incorporation of monitoring of nutrient concentrations or of biological activity in the experimental design. At a later stage, however, groups wishing to study these and other environmental factors likely to be modified by the land use changes have been encouraged to work within the catchments and coordinate their activities.

2. The catchments

Both catchments are steep-sided glaciated valleys aligned approximately N–S with shallow peats, peaty gleys and upland brown earths overlying mica-schists and variable depths of glacial debris in the valley bottoms. The only detailed geological information available consisted of some field notes and sketches dating from 1895. Some areas of deeper peat are present in the more gently sloping upper basin of the Monachyle and a few lochans provide localised storage on the relatively flat upper ridges of the Kirkton Glen. The geology and topography of the area suggested that, despite the presence of some fault lines and of a band of Loch Tay limestone which outcrops in the Kirkton catchment, no significant groundwater movement across the well-defined catchment boundaries was likely to occur. This assumption has been verified subsequently by a hydrogeological survey of the Kirkton catchment (Robins & Mendum 1987). Exposed bedrock stream channel sections at the catchment outfalls and at a convenient point in the upper Monachyle provided sites for stream gauging structures unlikely to be by-passed by sub-surface flows (Fig. 1).

The more westerly Monachyle catchment, with an area of 7.70 km^2 and altitude ranging from 300 m to 900 m, is under a mixed heather and grass cover. Heather dominates the vegetation on the ridges and in the upper basin, and there are considerable areas of exposed rock on the western ridge. Heather is present throughout the lower basin, but grasses predominate with, also, significant areas of bracken and some patches of scrub forest below the crags on the western side.

The Kirkton catchment with an area of 6.85 km^2 and an altitude range from 250 m to 850 m had, in 1981, a cover of mature forest up to approximately the 500 m contour. This forest was predominantly Sitka spruce but included some blocks of Scots pine, larch and other species. The Forestry Commission fence enclosed 44% of the catchment area but, with allowance for unplanted area, roads and clearings, the actual forest cover was estimated to be 35%. Above the forest, grasses are dominant on the main valley slopes, giving way to heather on the relatively flat ridge tops. Rock exposure is limited to a few small areas on the ridge tops and in some of the steep tributary gullies.

3. Data acquisition

The experimental design required instrumentation, capable of producing accurate estimates of catchment mean precipitation, streamflow and the meteorological variables, to be installed as rapidly as possible in this difficult terrain. Consideration of the probable values of P and Q suggested that measurements would have to be accurate to better than 5% of annual totals if meaningful estimates of AE were to be obtained. The instrumentation installed, the philosophy behind the network designs and the methods of utilisation of the data are described briefly in the following paragraphs.

3.1. Precipitation

The measurement of precipitation in mountainous terrain subject to high windspeeds presents considerable difficulties. These are exacerbated where a significant proportion falls as snow, particularly when snow accumulation events are interspersed by periods of total melting on all, or parts only, of the catchment.

3.1.1 Rainfall. The approach adopted at Balquhidder was to design networks of storage raingauges which sampled each significant combination of altitude, aspect and slope in each catchment. The locations of the two resulting networks, each with eleven gauges, are shown in Figures 2 and 3. Installation of these networks was completed in 1981. The gauges are mounted in pits with their orifices and surrounding anti-splash grids at ground level and parallel to the local slope. Cosine corrections are applied to give the equivalent catch on a horizontal surface. These basic networks are read at approximately monthly intervals and the period totals distributed in time as described below. Ground level gauges are known to minimise the aerodynamically induced undercatch of rain by standard gauges in exposed areas subject to high windspeeds (Rodda 1967; Rodda & Smith 1986) but the presence of the pit and anti-splash grid has the reverse effect during snow accumulation periods.

3.1.2. Snowfall. High windspeeds and drift make it almost impossible to measure snow inputs accurately in exposed areas of this very rough terrain. While depth density surveys have some value in determining the water equivalent of snow lying at a given time, they are of little value as a means of estimating inputs to these catchments. Altitudinally-varying melt rates frequently cause such estimates to be biased towards the upper levels. With one man on the ground, systematic surveys are not possible in any case.

The approach adopted to precipitation estimation during snow periods is based on the presence of five small clearings distributed through the forested area of the Kirkton. Within these clearings, drifting is minimal. Standard Meteorological Office raingauges mounted at 30 cm height and 1 m high snow gauges have been installed in each. Comparisons of snow catches by these gauges with depth density measurements in the clearings have shown close agreement

All five clearings are reasonably accessible in snow conditions. Acceptable estimates of snow inputs can thus be obtained at five sites within the catchment after each snow event.

Five of the eleven ground level gauges in the Kirkton network are also mounted in these clearings. During the course of phase 1 the relationships between these five sites and the networks in both catchments have been determined for periods subjected to rainfall inputs only. These relationships, expressed in terms of the catchment means, are summarised in Tables 1 and 2. They are remarkably consistent in each of the three periods used. As a working

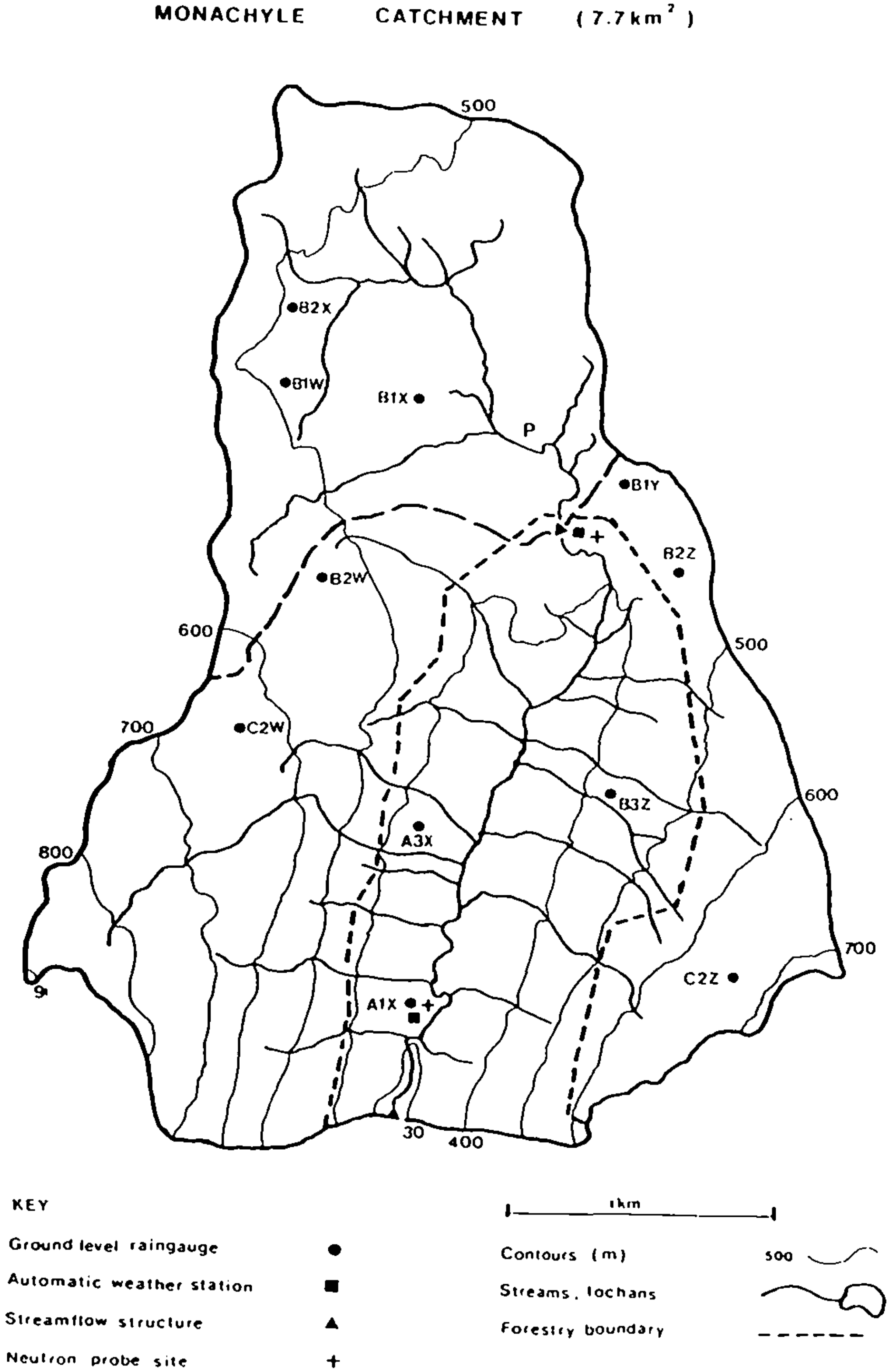


Figure 2 Monachyle instrument networks

hypothesis it is assumed that the distribution of snow inputs within the catchment will, on average, be the same as that observed during rainfall periods. Using the 'rainfall' relationships, estimates of the inputs at each site outside the forest have been derived from the snow measurements made in the clearings. This approach has been applied only during the few winter months when major snow accumulation has occurred. During autumn and spring periods, when only the high altitude storage gauges are affected by snow, estimates for these sites have been derived from the within-network relationships determined during snow-free periods.

3.1.3. Time distribution. Time distribution of each

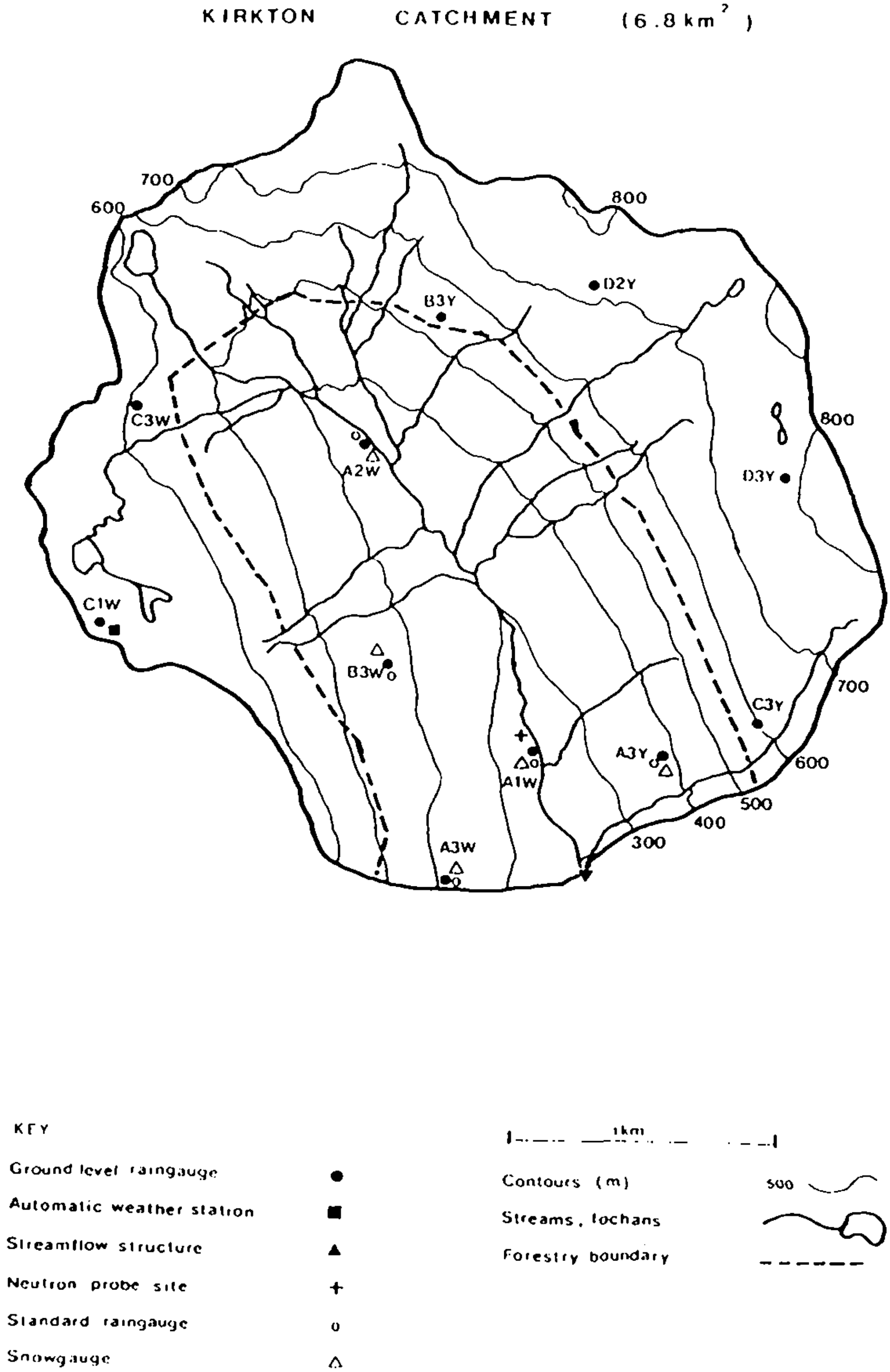


Figure 3 Kirkton instrument network

Table 1 Precipitation distribution within the Kirkton catchment during rainfall only periods when all gauges were operational

	Ground level gauges											Kirkton catchment mean (KM)	Kirkton clearing mean (CM)
	A1W	A2W	A3W	A3Y	B3W	B3Y	C1W	C3W	C3Y	D2Y	D3Y		
Altitude (*m*)	275	370	370	380	420	540	670	580	600	710	780		
Totals, 7·83–11·83	822	849	826	809	910	872	977	936	726	933	949	874	843
Ratios, Gauge/KM	0·94	0·97	0·95	0·93	1·04	1·00	1·12	1·07	0·83	1·07	1·09		0·965
Ratios, Gauge/CM	0·97	1·01	0·98	0·96	1·08	1·03	1·16	1·11	0·86	1·11	1·13	1·036	
Totals, 6·84–12·84	1363	1455	1373	1324	1439	1421	1553	1504	1082	1483	1497	1409	1391
Ratios, Gauge/KM	0·97	1·03	0·97	0·94	1·02	1·01	1·10	1·07	0·77	1·05	1·06		0·987
Ratios, Gauge/CM	0·98	1·05	0·99	0·95	1·03	1·02	1·12	1·08	0·78	1·07	1·08	1·013	
Totals, 4·85–10·85	1322	1477	1334	1319	1447	1477	1504	1531	1180	1567	1586	1431	1382
Ratios, Gauge/KM	0·92	1·03	0·93	0·92	1·01	1·03	1·05	1·07	0·82	1·09	1·11		0·965
Ratios, Gauge/CM	0·96	1·07	0·97	0·95	1·05	1·07	1·09	1·11	0·85	1·13	1·15	1·036	
Totals, above periods	3507	3781	3533	3452	3797	3770	4034	3972	2988	3983	4032	3713	3616
Ratios, Gauge/KM	0·94	1·02	0·95	0·93	1·02	1·02	1·09	1·07	0·81	1·07	1·09		0·974
Ratios, Gauge/CM	0·97	1·05	0·98	0·95	1·05	1·04	1·12	1·10	0·83	1·10	1·12	1·027	

Table 2 Precipitation distribution within the Monachyle catchment during rainfall only periods when all gauges were operational

	Ground level gauges											Monachyle catchment mean (MM)	Kirkton clearing mean (CM)
	A1X	A3X	B1W	B1X	B1Y	B2W	B2X	B2Z	B3Z	C2W	C2Z		
Altitude (*m*)	305	360	480	455	445	520	495	435	420	635	655		
Totals, 7·83–11·83	994	1069	1075	1035	953	1049	1019	821	1021	1183	1067	1026	843
Ratios, Gauge/MM	0·97	1·04	1·05	1·01	0·93	1·02	0·99	0·80	0·99	1·15	1·04		0·822
Ratios, Gauge/CM	1·18	1·27	1·27	1·23	1·13	1·24	1·21	0·97	1·19	1·40	1·27	1·216	
Totals, 6·84–12·84	1650	1744	1825	1741	1580	1757	1741	1445	1665	1902	1741	1708	1391
Ratios, Gauge/MM	0·97	1·02	1·07	1·02	0·93	1·03	1·02	0·85	0·97	1·11	1·02		0·814
Ratios, Gauge/CM	1·19	1·25	1·31	1·25	1·14	1·26	1·25	1·04	1·20	1·37	1·25	1·228	
Totals, 4·85–10·85	1554	1622	1666	1622	1495	1686	1658	1429	1564	1800	1695	1617	1382
Ratios, Gauge/MM	0·96	1·00	1·03	1·00	0·92	1·04	1·02	0·88	0·97	1·11	1·05		0·854
Ratios, Gauge/CM	1·13	1·17	1·21	1·17	1·08	1·22	1·20	1·03	1·13	1·30	1·23	1·171	
Totals, above periods	4198	4435	4565	4398	4028	4492	4417	3695	4229	4885	4503	4351	3616
Ratios, Gauge/MM	0·97	1·02	1·05	1·01	0·93	1·03	1·01	0·85	0·97	1·12	1·04		0·831
Ratios, Gauge/CM	1·16	1·23	1·26	1·22	1·11	1·24	1·22	1·02	1·17	1·35	1·25	1·203	

storage gauge total is achieved by reference to the nearest recording gauge. Six of these are distributed through the area, one attached to each of the four automatic weather stations and one independent one in each catchment (Figs 2, 3). In freezing conditions these recording gauges frequently malfunction and time distribution on a daily basis is then achieved by reference to the daily read standard gauge at Tulloch Farm Meteorological Site, 1.5 km W of Balquhidder.

The original intention was to assemble a complete array of hourly values for all twenty-two gauge sites from which catchment means at hourly intervals or any multiples thereof could be computed. Experience has shown that there will always be some gaps in this array. Consequently, for water balance computation and site comparison purposes, a second array has been assembled which has a monthly time base, these values being accumulated from an approximate daily time distribution with reference to the Tulloch Farm standard gauge.

3.2. Streamflow

The experimental design called for continuous monitoring of discharge from the two main catchments and from the Upper Monachyle sub-catchment. To obtain cumulative totals with an accuracy of 5% or better meant that flumes or weirs would have to be installed and water level recorded continuously. Finding sites on these steep rocky streams where the hydraulic conditions were likely to be compatible with the constraints of acceptable structure designs throughout the expected discharge ranges was time-consuming, but such sites were identified during 1981.

3.2.1. The structures. The sites on the Kirkton and the Monachyle streams came reasonably close to the specifications required to operate simple Crump weirs (British Standards Institution 1969). Both were also reasonably accessible and on sound, watertight bedrock. Design work progressed rapidly, but severe winter weather and other practical problems delayed construction work until 1982. The Kirkton structure, with a 7 m crest width, is capable of containing the estimated fifty year return period discharge of 30 $m^3 s^{-1}$. It became operational in July 1982 and the 5 m width Monachyle structure, designed to contain a 26 $m^3 s^{-1}$ flood, in November 1982. These structures have theoretical lower discharge limits of reliable gauging of 0.076 $m^3 s^{-1}$ and 0.051 $m^3 s^{-1}$, respectively. To gauge lower discharges which could be anticipated in prolonged dry summer conditions, short-throated trapezoidal flumes prefabricated in fibre glass were also installed at each site. Their dimensions were chosen to ensure a reasonable overlap in the discharge ranges with the Crumps.

A rock bar site suitable for a range of possible structure designs was identified in the Upper Monachyle in 1981. The 2 km of difficult terrain between it and the road head (Fig. 1) presented practical constraints on design choice, construction methods and materials. The solution evolved was a flat vee weir (White 1971) constructed entirely from light alloy and keyed into the rock bar at its downstream end. Prefabricated sections were transported from the road head by helicopter. The hydraulic profile is a 1 : 10 flat vee with 1 : 2 approach and 1 : 5 downstream slopes. A width of 3.2 m between vertical sidewalls and a containable head of 1.2 m gives a theoretical discharge range from 0.002 to 9.0 $m^3 s^{-1}$. This is sufficient to cover the estimated 1 in 20 year return period high and low flows. The structure became operational in July 1983.

3.2.2. Water level recording. The equipment used on all five structures is a battery operated magnetic tape recorder which logs, at five-minute intervals, the input received from a float-operated potentiometric water level sensor. Theoretical discrimination is 1 mm throughout the water level range. This design has been in use on Institute of Hydrology sites for many years and, given regular maintenance, has good reliability. Back-up paper chart recorders are operated on the two Crump structures with paper tape recorders on the others. Data loss has been minimal, except during periods of prolonged freezing conditions in winter. Discharges are usually low and steady during such conditions. Interpolation between spot readings, obtained by breaking the ice in the float wells and on the weir crests, results in minimal errors. Problems can arise, however, when a rapid thaw occurs and water level begins to rise before the float well thaws. Anticipation of such conditions by the field observer can minimise the problem. Difficulty of access during the winter means that the Upper Monachyle cannot receive this remedial treatment with the same regularity. The installation of a recording pressure transducer in the approach section of the structure has now reduced winter data loss from this structure. During some winter periods this high altitude reach of the stream freezes up completely, so that flow rates reduce to zero.

3.2.3. Stage-discharge relationships. Using the established hydraulic theory for each structure (Ackers *et al.* 1978), together with its dimensions and assumed approach velocities, relationships between observed water level (stage) and discharge were derived. These ratings were used initially to compute discharges from the observed water levels. It was recognised, however, that checks on their validity were necessary. Spot checks using the dilution gauging technique gave no evidence of significant departures from the theoretical values at low discharges on all structures. Good agreement was found between the low flow flumes and the Crumps in their overlapping discharge ranges. The few spot checks obtained at medium discharges on the Monachyle and the Upper Monachyle sites also gave no cause for concern. However, dilution gauging at medium to high discharges on the Kirkton revealed significant departures from the theoretical values. These indicated a progressive underestimate by the theoretical rating with increasing stage. Though disappointing, this was not altogether unexpected, since the approach channel configuration was at the upper limit of slope and roughness acceptable by the theory.

Following the installation of a bridge across the approach section of the structure, a programme of multipoint current metering was initiated in the Kirkton. By December 1985 a reasonably representative range of discharges had been sampled and the suite of cross-section velocity profiles and water levels was analysed. The revised rating derived from these data is compared with the original in Figure 4. Also plotted are the spot discharge values computed from each current metering run. Observations during the current metering exercise identified two factors other than the upstream channel slope which were contributing to the departure. These were the establishment of a sediment level in the approach section during high flows which reduced the effective crest height to 0.4 m as compared to its design height of 0.7 m and progressively greater asymmetry in velocity distribution with increasing stage caused by a rock intrusion on the right bank. The accumulated water level observations from 1982 have now been re-processed using the revised rating. While departures of this magnitude are not anticipated at high flows on the Monachyle, a bridge has been installed on this structure and a programme of current metering initiated. Current metering is not a practical proportion in the flat-vee Upper Monachyle structure except at high discharge. More detailed dilution gauging tests are being carried out at this site.

3.3. Meteorological data

Recognising that meteorological conditions could differ significantly between catchments, the decision was taken to instal meteorological instrumentation in both. The instrumentation chosen was the Institute of Hydrology-designed Automatic Weather Station. Using the same battery operated magnetic tape logger as the water level recording system, this records five-minute values of solar and net radiation, air temperature, humidity, windspeed and wind direction. From these data, estimates of potential evapotranspiration, *ET*, are computed (Penman 1948). Also attached to the logger is a tipping bucket recording raingauge. In choosing locations for these automatic weather stations within the catchments, costs and accessibility had to be considered as well as the need to sample possible variations due to altitude and topography. As shown in Figure 2, a valley bottom site at 300 m and a site at 450 m whose exposure was typical of most of the upper part of the catchment were selected for the Monachyle. In the Kirkton a site at 670 m on the western ridge which typified the exposure conditions on both ridges was selected (Fig. 3). The cost of installing a second automatic weather station over forest in the valley bottom was considered to be too great. Subsequent events have shown that this was a mistake and a canopy level automatic weather station was mounted in the Kirkton in summer 1986. To provide reference data as a precaution against data loss from the catchment sites a fourth automatic weather station was mounted on a site at

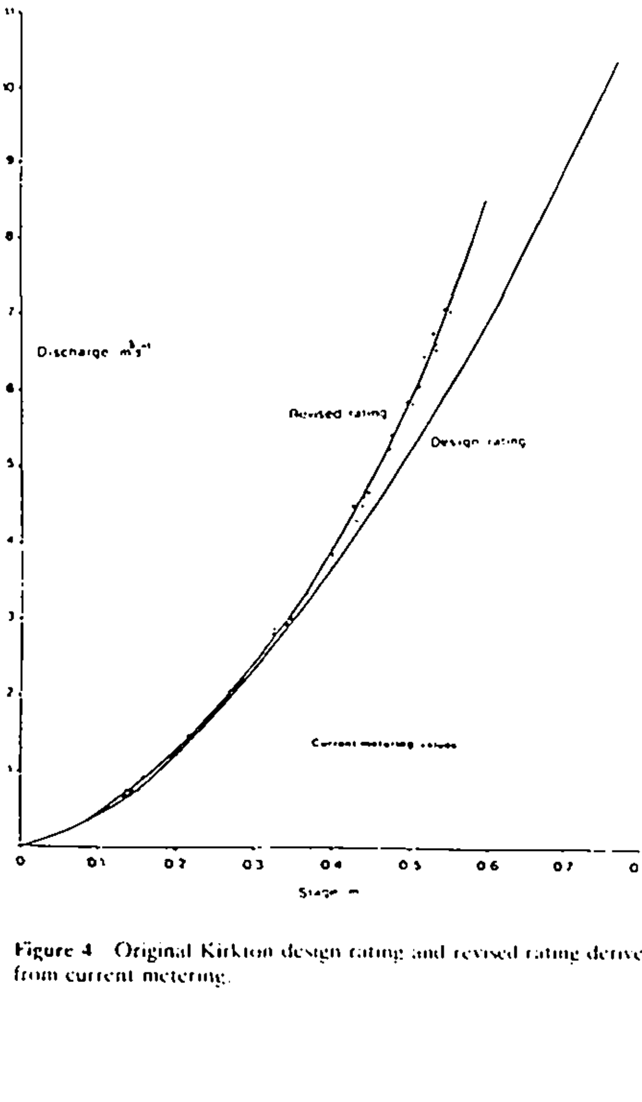


Figure 4 Original Kirkton design rating and revised rating derived from current metering.

Table 3 Summary of regression relationships between monthly mean daily *ET* estimates from the AWS sites for months when complete data were available

Kirkton (KH) *and Tulloch Farm* (TF)

KH = 1·179 TF + 0·047 TF = 0·831 KH − 0·015
$n = 21$, $r^2 = 0·9799$

Monachyle (MG) *and Tulloch Farm*

MG = 1·086 TF + 0·035 TF = 0·897 MG − 0·006
$n = 28$, $r^2 = 0·9740$

Upper Monachyle (UM) *and Tulloch Farm*

UM = 1·326 TF − 0·067 TF = 0·736 UM + 0·069
$n = 15$, $r^2 = 0·9768$

Upper Monachyle and Monachyle

UM = 1·186 MG − 0·058 MG = 0·833 UM + 0·064
$n = 15$, $r^2 = 0·9877$

Upper Monachyle and Kirkton

UM = 1·004 KH + 0·001 KH = 0·953 UM + 0·055
$n = 10$, $r^2 = 0·9567$

Kirkton and Monachyle

KH = 1·056 MG − 0·100 MG = 0·726 KH + 0·398
$n = 24$, $r^2 = 0·7669$

Tulloch Farm (Fig. 1), which was easily accessible in all weather conditions. Manually-read meteorological equipment was also installed at this site for comparison purposes.

All four automatic weather stations were mounted so that the dominant vegetation 'seen' by the net radiation sensor was grass. Consequently the *ET* values computed for each site relate to grass. Data capture was poor from the high altitude sites at first but the installation of a solar panel at Kirkton and a wind generator at the Upper Monachyle site to maintain battery power improved matters considerably. Recently data capture has been exceeding 90% from all sites, though intermittent problems have been experienced with individual sensors. The windspeed sensors at the high level stations have given most trouble and, as has already been indicated, the recording raingauges frequently malfunction during freezing conditions. Work is continuing on studying the between-site relationships of the individual variables. Some initial comparisons of the Kirkton site with Tulloch Farm (Johnson 1985) indicated a mean temperature lapse rate of 8.9°C per km between these two sites and much higher radiation and windspeeds at the upper site. Pending completion of this work and its application to estimate catchment *ET* means, the relationships between *ET* at the four sites have been investigated using monthly mean daily values from months with complete records. These relationships, summarised in Table 3, have been utilised to fill gaps in the records so that provisional long-term totals for the sites could be estimated and compared.

3.4. Sediment transport

Sediment movement through the outfalls of both catchments has been monitored since the summer of 1982. Suspended material is sampled continuously using vacuum-operated automatic samplers. During storm events, spot samples are taken at a much higher frequency. During storm events also, specialised equipment is used to sample the movement of heavier bed load material and surveys of the deposition within the approaches to the flow gauging structures are carried out after each major event. Initial results were described by Scott *et al.* (1986). During 1984 the Department of Environmental Sciences at Stirling University agreed to extend the range of the sediment studies to include detailed work on identifying sediment sources and transport methods within the catchments. These studies are described in detail by Ferguson and Stott (1987).

4. Data analysis and provisional results

4.1. Water balance

Phase 1 of the study was completed in December 1985. While some precipitation and meteorological data were acquired during 1981 and early 1982, the acquisition of full data sets for water balance purposes effectively began in autumn 1982 for the two main catchments and in August 1983 for the Upper Monachyle sub-catchment. As will be appreciated from the comments on data acquisition in the previous section, considerable retrospective analysis was required to convert the field readings to usable data, to estimate values to infill gaps and to correct the initial values obtained in the case of the Kirkton streamflow. Much of this is still incomplete, but a provisional set of monthly precipitation, streamflow and *ET* values for the two main catchments covering the period December 1982 to November 1985 has been assembled to give an initial indication of the water use of each catchment. Within this set, the Kirkton streamflow data are considered to be in their final form following their re-computation using the revised rating. The Monachyle streamflow data are still subject to possible revision following the current metering checks presently in hand. Preliminary figures indicate that the present rating may be overestimating high flows by 3–5%.

The precipitation data have been derived from the ground level networks using the Tulloch Farm daily standard gauge for time distribution and the relationships in Tables 1 and 2 to estimate missing values during snow periods. For this provisional set, arithmetic means of each catchment network have been calculated. As illustrated in Table 4, the mean differences between arithmetic and domain-weighted means for snow-free periods when all gauges were operational are less than 1% in both catchments. The greatest departure occurred in the period June 1984 to December 1984 in the Kirkton Catchment, when the difference was 1.6%. As can be seen from Table 1, this coincided with a period when gauge C3Y was giving consistently lower readings, relative to the catchment mean, than in either of the other periods. The apparently low rainfall in this domain is discussed further in Section 4.2. While individual monthly totals may be in error as a result of the method of time distribution, the effect on the cumulative totals will be insignificant.

Table 4 Precipitation totals for rainfall only periods estimated by the arithmetic mean (*AM*) and domain weighted mean (*DM*) methods

	Monachyle			Kirkton		
Period	*AM*	(mm)	*DM*	*AM*	(mm)	*DM*
7·83–11·83	1026		1021	874		866
6·84–12·84	1708		1703	1409		1386
4·85–10·85	1617		1615	1431		1428
Totals	4351		4339	3714		3680

The *ET* values for the four automatic weather station sites have been assembled using the relatively crude method described in Section 3.3 to infill gaps. So far no attempt has been made to estimate catchment mean *ET* values. The annual totals plotted against altitude in Figure 5 demonstrate a marked increase between the valley bottom sites and the exposed high altitude sites in Kirkton and the Upper Monachyle. This increase with altitude is contrary to the normal presumption (see e.g. MAFF 1967). Figure 6 indicates that the increase is greatest during summer. Figure 5 also demonstrates consistent relationships between all the sites and close agreement between Upper Monachyle and Kirkton despite the 250 m altitude difference. The latter suggests that similarity in exposure rather than altitude *per se* may be the key factor. Subject to further evidence from the automatic weather station recently installed over forest in the Kirkton catchment, it would appear that *ET* differences are likely to be greater within catchments than between them.

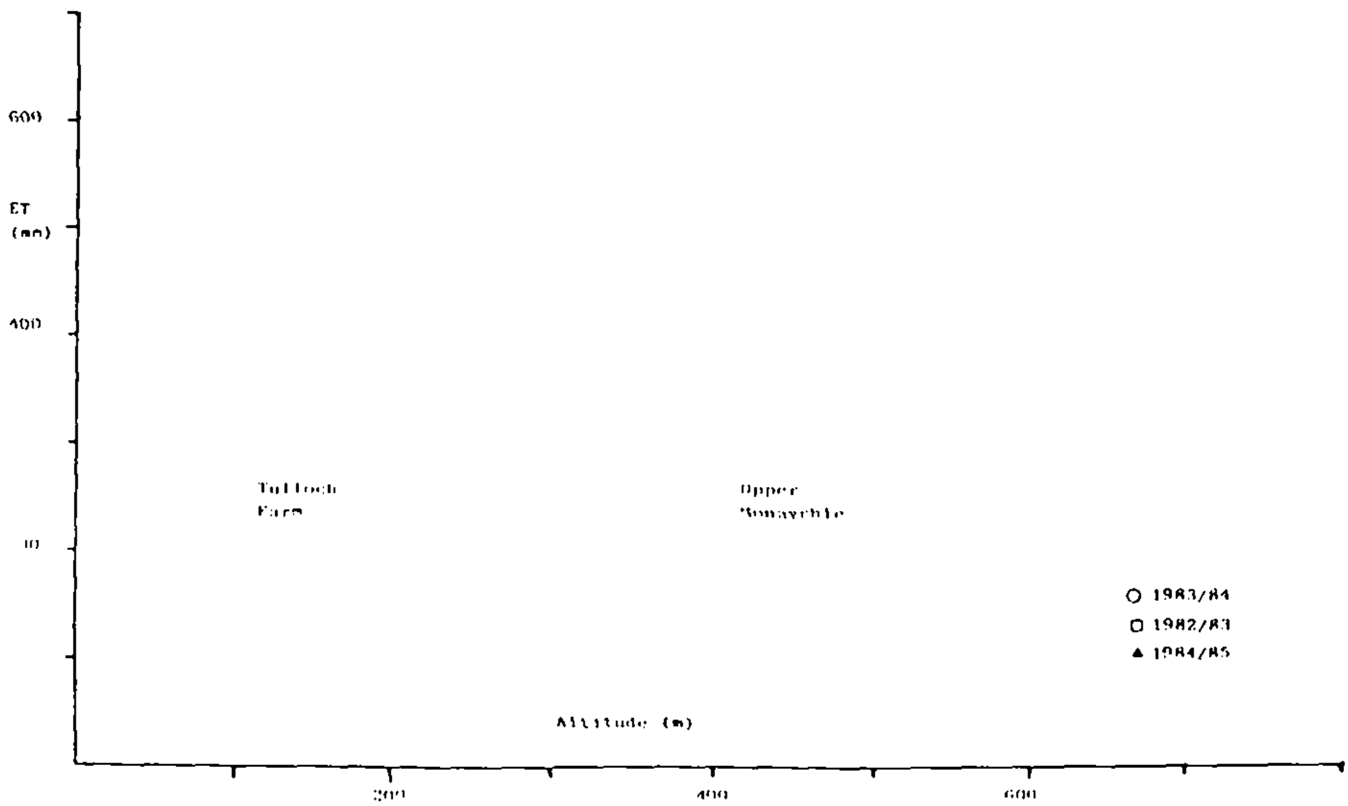


Figure 5 October–September estimates of *ET* from each automatic weather station site

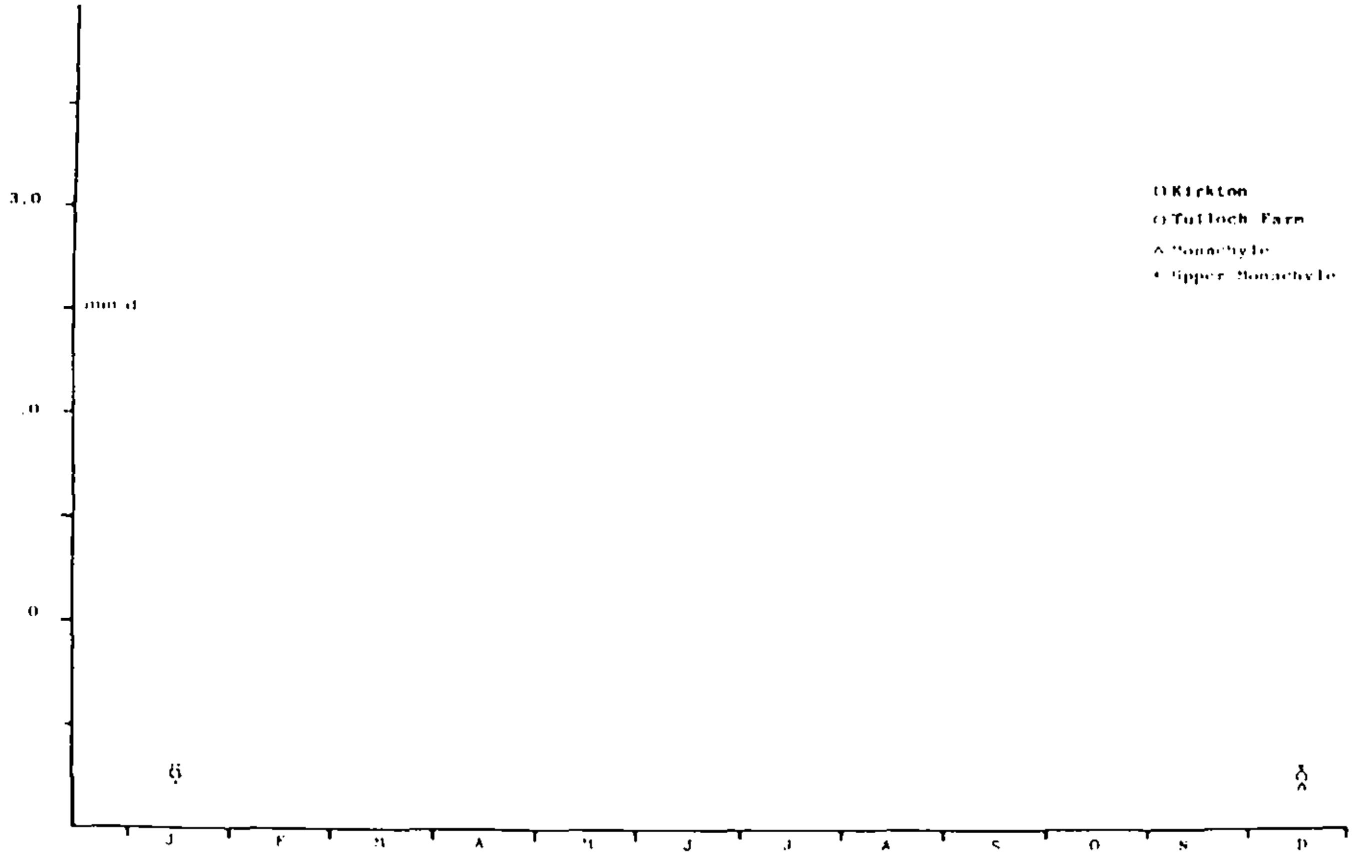


Figure 6 Monthly mean daily estimates of *ET* from each automatic weather station site for 1984

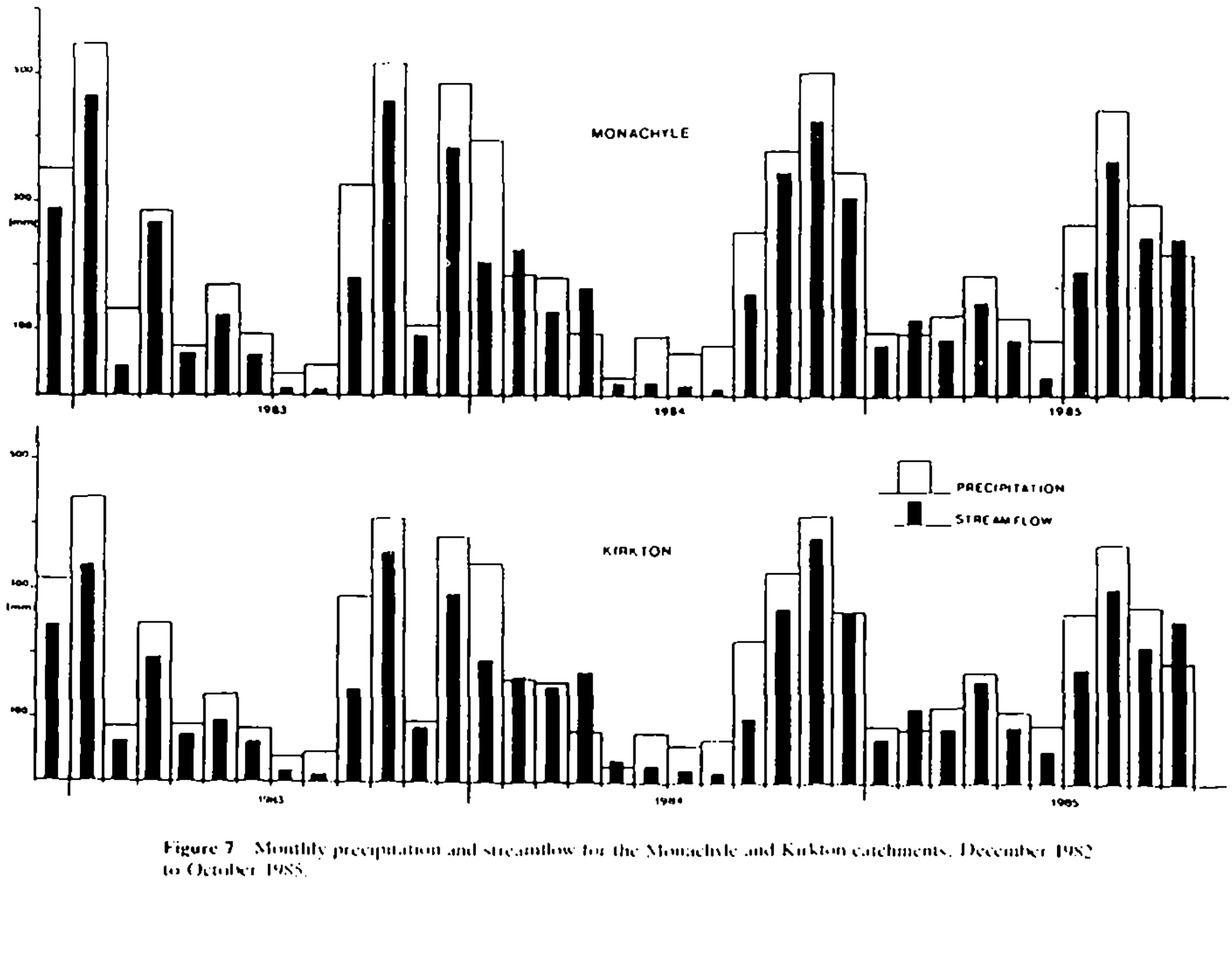


Figure 7 Monthly precipitation and streamflow for the Monachyle and Kirkton catchments, December 1982 to October 1985.

Table 5. December 1982 to October 1985 provisional totals and equivalent 12 month means of precipitation, streamflow, potential evaporation and estimated water use, $P-Q$

	Monachyle		Kirkton	
	Total	12 month mean	Total	12 month mean
Precipitation (P)	7688	2630	6520	2236
Streamflow (Q)	6058	2077	5246	1798
$P-Q$	1630	558	1274	437
Penman (ET) (Kirkton)			1586	543

The provisional monthly totals of precipitation and streamflow are plotted as a time series in Figure 7 and the cumulative totals, together with those of $P-Q$ and ET from the Kirkton site, are listed in Table 5. Despite the similarity in their altitude ranges, Monachyle consistently receives the greater precipitation. This is mirrored in the flow during the wetter months, but in dry periods Kirkton produces higher flows. The longest periods of snow accumulation occurred in January and February 1984, and January and February 1985.

The average twelve-month precipitation difference of 18% or 400 mm, together with the 15.5% or 278 mm difference in streamflow, results in a mean twelve-month $P-Q$ value for the Monachyle of 558 mm that is 121 mm higher than the 437 mm for the Kirkton. These compare with an ET figure of 543 mm for the exposed upper area of Kirkton and, by implication from Figure 5, a similar figure from the upper areas of the Monachyle. The plot of twelve months moving totals in Figure 8 indicates that the between-catchment differences are remarkably consistent, particularly from April 1983 onwards, suggesting that if any errors are present in the data they are systematic rather than random. The consistently lower $P-Q$ value from the partly forested Kirkton and its low value relative to ET are remarkable in that they would not have been predicted by current theory.

4.2. Possible sources of error

$P-Q$ is, of course, only a crude estimate of water use, AE, which neglects storage change over the period considered. While storage changes cannot be monitored accurately in these catchments, it is instructive to consider their possible magnitude as a means of assessing error in the above water use estimates. If it is assumed that the twelve-month AE values follow the general trend of ET then Figure 8 gives an indication of the magnitudes of ΔS. Extreme values of +280 mm and −240 mm for Monachyle in the twelve-month periods ending in January 1984 and January 1985 are obtained, with similar values for Kirkton.

The components of catchment storage can be summarised as soil moisture, "gravitational" water which eventually emerges as streamflow and, in this case, snow accumulation. Within the period of record, maximum snow accumulation occurred in Balquhidder in January, February and March 1984. A series of depth/density samples taken in a settled period in late January gave water equivalent figures in the range 100 mm to 180 mm for both catchments. Accumulation in the 1985 snow period was only of the order of 20–30 mm. It is reasonable to assume, therefore, that the 1984 snow accumulation was the major factor in the $P-Q$ departures from the norms in the twelve- month periods either ending or starting in January 1984 to March 1984. This suggests that the departures from the norms arising from the other two components of storage are considerably less than 200 mm.

An indication of the possible magnitudes of the soil moisture component is given by the results of a soil moisture depletion study at three deeper soil sites in the catchments (Calder 1986). After the prolonged dry spell in 1984, maximum deficits recorded were 50 mm, 80 mm and 100 mm under heather, grass and spruce.

Gravitational storage is more difficult to assess. Storm

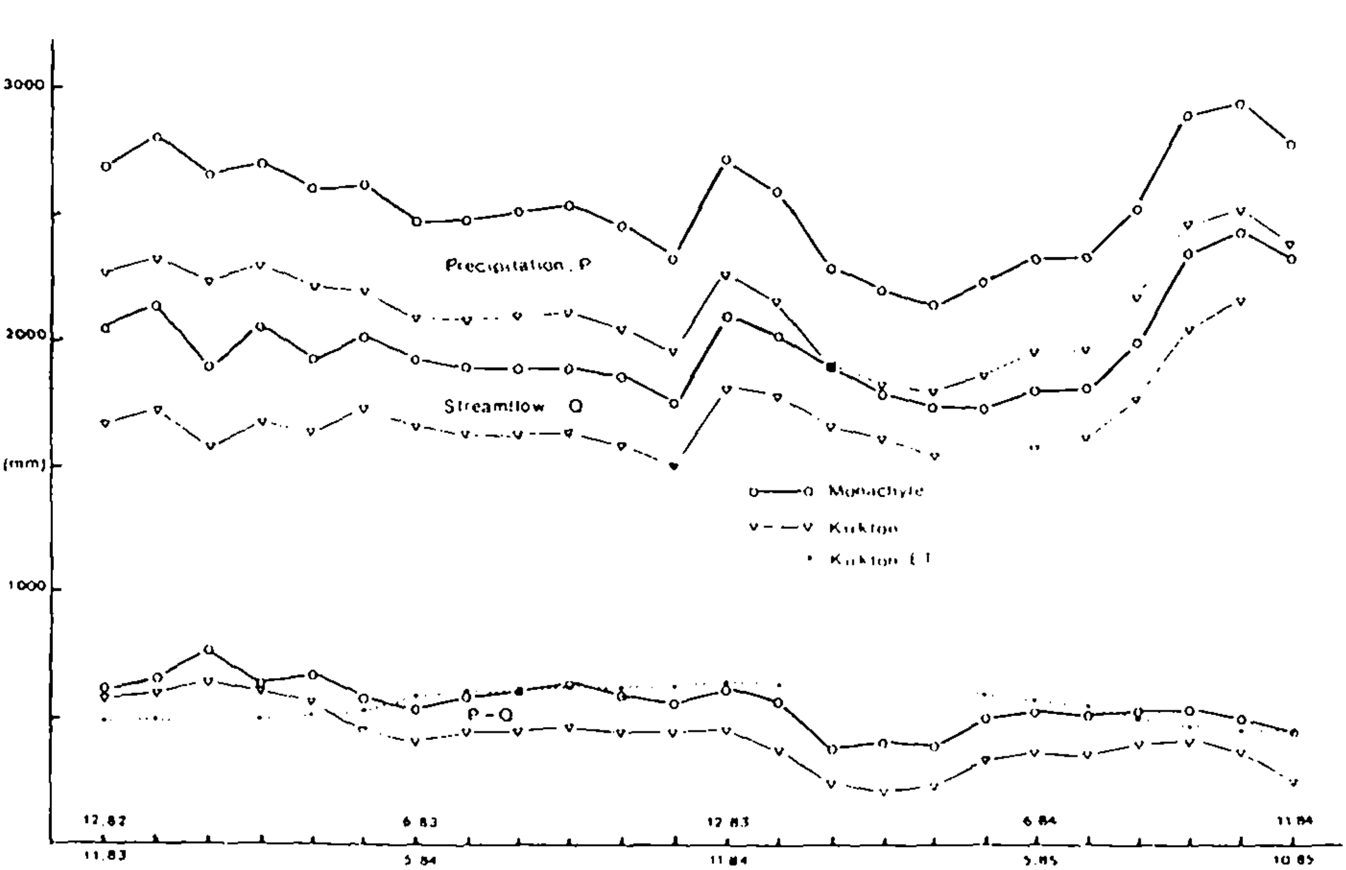


Figure 8. Moving twelve-month totals of precipitation, streamflow, $P-Q$ and ET for the Balquhidder catchments; dates on the horizontal axis are those for each successive twelve month period

water leaves these 'flashy' catchments very rapidly. Flows of 82 mm and 60 mm per day have been recorded from the Monachyle and Kirkton catchments. After storm events, flow rates drop very rapidly to 2–3 mm/day. Thereafter recession is much slower. During the dry summer of 1984 both streams were effectively in recession from the cessation of snowmelt in April till the end of August. Total flows over this period were only 57 mm and 93 mm from the Monachyle and Kirkton catchments, respectively. Flow rates at the end of the period were 0.2 mm/day and 0.4 mm/day, respectively.

These indications of the likely ranges of soil moisture and gravitational storage are consistent with the above estimate of ΔS being considerably less than 200 mm except when snow is present or storm water is in transit. Examining the start and end dates of the cumulative totals in Table 5 in this context indicates that no storm water was in transit, no snow was present and preceding wet spells would suggest very low soil moisture deficits on both dates. Baseflows were higher in both catchments on the start date in December 1982, but crude estimates of the recession rates suggest that the storage differences arising from this are unlikely to exceed 50 mm. Thus the storage changes, ΔS, over this thirty-five month period are likely to be in the range −50 to −100 mm in both catchments. The error this introduces in the mean twelve-month $P-Q$ estimates of AE is therefore −17 to −34 mm.

Other possible sources of systematic error in the $P-Q$ values relate to the streamflow and precipitation data. If the rating check on the Monachyle structure verifies the initial indications, then the flow data presented will be in error by +3% to +5%, i.e. the $P-Q$ values for Monachyle will be 10–15% too low.

Precipitation presents the greatest difficulty in terms of identifying sources of error. Regarding the eleven gauges in each network as independent estimates of the catchment means gives standard errors of 2.6% and 2.1% for the cumulative values in Tables 1 and 2. As indicated in Section 4.1, however, much of the variation about the mean in each case is domain related and persistent. Checks on the representativeness of gauges such as C3Y in Kirkton and B2Z in Monachyle which show the most extreme departures from the mean are under way, with additional gauges installed in the domains.

While the method of estimating snow input is open to question, it was used to give complete catchment estimates only in January and February 1984, and January and February 1985, giving 772 mm and 659 mm, respectively, of the Monachyle and Kirkton totals of 7688 mm and 6520 mm over the thirty-five months. If the method introduces errors even as high as 20%, the effects on the cumulative totals would be only 2%. These in turn would result in errors of 10% in the equivalent twelve-month mean values of $P-Q$.

4.3. Discussion

Accepting the present $P-Q$ estimates, the value for Monachyle relative to ET is broadly in line with model predictions based on process studies carried out concurrently with these catchment studies (Hall 1985) and reported in a contemporary paper (Hall 1987). The estimate of AE for the Kirkton is, however, much lower relative to ET than expected from current knowledge of forest and grass water use. Early results from Plynlimon for 1969–1975 (Institute of Hydrology 1976) gave the following mean annual values for catchments experiencing comparable mean annual precipitation of some 2400 mm.

	$P-Q$ (mm)	ET grass
Wye (grassland)	431	442
Severn (62% forested)	690	
Severn (forested area only)	856	

From his lysimeter study of the water use of spruce forest within the Plynlimon catchments, Calder (1976) obtained estimates which were consistent with the catchment water balance figures. Calder and Newson (1979) evolved from these and other data a simple prediction model which has been widely used to estimate the water use of partly forested catchments in upland Britain. Applying the above Plynlimon data, in the form of ratios of water use for each vegetation type relative to ET, and the Calder and Newson model to the Kirkton data gives the following estimates of water use, AE, by this catchment.

	Plynlimon based estimate	C and N estimate	Water balance
Kirkton AE	713 mm	711 mm	~437 mm

Given the probable range of uncertainty in the water balance figure discussed above there is clearly a need to identify the reasons for this discrepancy.

A plot study of interception losses within the Kirkton forest has produced figures in the range 26–28% of precipitation which are only marginally lower than those observed elsewhere in Britain (Calder & Newson 1979). These suggest that total water use by the forested area is likely to be in excess of 700 mm per annum, comparable to that determined for the Hafren forest at Plynlimon. With some 35% of the Kirkton under forest and assuming that the 10% dominated by heather would have a similar water use to the Monachyle, this would suggest a water use rate of 248 mm by the grass-dominated remainder of the catchment. This is some 40% lower, relative to ET, than the Plynlimon results would suggest. If, therefore, the water balance results stand up to the detailed scrutiny presently under way, there would seem to be a case for some intensive study of the water use of high altitude grassland.

5. Future work

The proposed time span for the monitoring of the effects of the land use changes in phase II, as discussed in Section 1, is a minimum of five years. During this time work will continue also on assessing and refining the estimates of precipitation obtained from the networks. This work must include the development and testing of alternative methods of snow input estimation, since the sheltered clearings within the Kirkton catchment which are the basis of the present method will disappear as clear felling progresses. Much work still has to be done also on the automatic weather station data, on the analysis of the storm hydrographs and storage discharge relationships for both phases of the study and on the data from the Upper Monachyle sub-catchment.

The objective of these systems studies and the parallel series of process studies is to obtain the information necessary to develop and test mathematical models which can be used to predict the effects on streamflow of any combination of upland vegetation. The preliminary results from the Kirkton catchment have identified the need to study the water use of high altitude grassland in greater detail so that this objective can be achieved.

6. References

Ackers, P., White, W. R., Perkins, J. A. & Harrison, A. J. M. 1978. *Weirs and flumes for flow measurement.* London: Wiley.

British Standards Institution 1969. *Methods of measurement of liquid flow in open channels, Part 4B, Long based weirs.* BS3680. London: British Standards Institution.

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

Calder, I. R. 1986. The influence of land use on water yield in upland areas of the U.K. J HYDROL **88**, 201–211.

Calder, I. R. & Newson, M. D. 1979. Land use and upland water resources in Britain—a strategic look. WATER RESOUR BULL **16**, 1628–1639.

Ferguson, R. I. & Stott, T. A. 1987. Forestry effects on suspended sediment and bedload yields in the Balquhidder catchments, Central Scotland. TRANS R SOC EDINBURGH EARTH SCI **78**, 379–384.

Hall, R. L. 1985. Interception studies of heather using a wet-surface weighing lysimeter. J HYDROL **81**, 193–210.

Hall, R. J. 1987. Processes of evaporation from vegetation of the uplands of Scotland. TRANS R SOC EDINBURGH EARTH SCI **78**, 327–334.

Institute of Hydrology 1976. *Water balance of the headwater catchments of the Wye and Severn 1969–75.* IH REP 33. Wallingford: Institute of Hydrology.

Johnson, R. C. 1985. Mountain and glen: Climatic Contrasts at Balquhidder. J METEOROL **10**, 105–108.

Ministry of Agriculture, Fisheries and Food 1967. *Potential transpiration.* TECH BULL 16. London: Her Majesty's Stationery Office.

Newson, M. D. 1980. The erosion of drainage ditches and its effect on bedload yields in mid-Wales: Reconnaissance Case Studies. EARTH SURF PROC **5**, 275–290.

Penman, H. L. 1948. Natural evaporation from open water, bare soil and grass. PROC R SOC LONDON **A193**, 120–145.

Robins, N. S. & Mendum, J. R. 1987. Geology and hydrogeology of Kirkton Glen, Balquhidder. HYDROGEOL IN SCOTLAND, REP 87. Edinburgh: British Geological Survey.

Robinson, M. 1980. *The effect of pre-afforestation drainage on the streamflow and water quality of a small upland catchment.* IH REP 73. Wallingford: Institute of Hydrology.

Robinson, M. & Newson, M. D. 1986. Comparison of moorland hydrology in an upland area with peat soils. INT PEAT J **1**, 49–68.

Rodda, J. C. 1967. The systematic error in rainfall measurement. J INST WATER ENG **21**, 173–177.

Rodda, J. C. & Smith, S. W. 1986. The significance of the systematic error in rainfall measurement for assessing wet deposition. ATMOS ENVIRON **20**, 1059–1064.

Stott, T. A., Ferguson, R. I., Johnson, R. C. & Newson, M. D. 1986. Sediment budgets in forested and unforested basins in upland Scotland. *In* Hadley, R. F. (ed.) *Drainage Basin Sediment Delivery.* INT ASSOC HYDROL SCI PUBL **159**, 57–68.

White W. R. 1971. *The design and calibration of flat-vee weirs.* HRS REP INT 88. Wallingford: Hydraulics Research.

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MS received 16 October 1986. Accepted for publication 31 July 1987.

Appendix 3

JOURNAL OF METEOROLOGY
"An international journal for everyone interested in climate and weather, and in their influence on man."

Editor: Dr. G. T. Meaden Vol. 10, no. 98, April 1985

MOUNTAIN AND GLEN CLIMATIC CONTRASTS AT BALQUHIDDER

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Abstract: Using the automatic weather stations at Tulloch Farm (altitude 135m above ordnance datum) and Kirkton (2.3km NNW of Tulloch Farm, altitude 673m AoD) contrasts are drawn between the 1983 records of temperature, radiation, wind, and precipitation.

In the Highlands of Scotland the three major industries of tourism, forestry and farming are increasingly looking to the high, rugged areas for future development. The steepness of the topography hinders each one and combines with the altitude differences to create contrasting climatic environments within short distances.

The Tulloch Farm and Kirkton automatic weather stations (AWS) are in the Balquhidder area of the Highlands; they are operated by the Institute of Hydrology as part of a paired catchment study.

Tulloch Farm AWS (altitude 135m AoD) is in the bottom of a deep glaciated glen, orientated east-west, containing Loch Voil and Loch Doine. In contrast Kirkton AWS (altitude 673m) is on the top of a broad north-south orientated ridge, 2.3km NNW of Tulloch Farm.

The automatic weather stations record the following meteorological parameters at 5-minute intervals: solar radiation, net radiation, temperature, temperature depression, wind run, wind direction, rainfall.

These data are recorded on to Microdata loggers, battery-powered at Tulloch Farm and solar-powered at Kirkton.

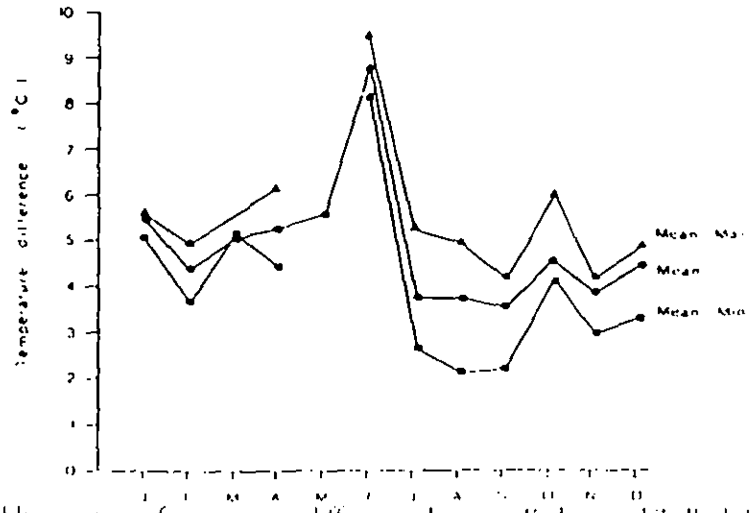

Fig. 1 Monthly variation of temperature differences between Kirkton and Tulloch Farm, 1983

As an indication of temperature differences in 1983, the number of days when the mean temperature was below 0°C for the Kirkton AWS was 95, but only 9 for Tulloch Farm AWS. Daily mean temperatures of 20°C or more occurred only once at Kirkton but 14 times at Tulloch Farm.

Fig.1 shows monthly mean temperature differences between the stations. The greatest differences in temperature occur in the early summer and the smallest differences in late summer or early autumn. These results are however only for one year. Taylor (1976) showed that lapse-rates have great variability in time.

Table 1 shows the two stations' annual mean temperatures and also the lapse rates calculated from these values.

TABLE 1

Annual mean temperature	Tulloch Farm	9.0°C
	Kirkton	4.2°C
Lapse rate: 8.9 deg C km^{-1}		
Annual mean maximum temperature	Tulloch Farm	12.4°C
	Kirkton	6.9°C
Lapse rate: 10.2 deg C km^{-1}		
Annual mean minimum temperature	Tulloch Farm	5.7°C
	Kirkton	1.7°C
Lapse rate: 7.3 deg C km^{-1}		

These lapse-rates are much greater than those found in Wales by Smith (1950), the northern Pennines by Harding (1979), and the Ben Nevis observatory by Buchan and Omond (1905), due mainly to the greater sheltering in this case of the lower station by the surrounding mountains. There is also a greater difference between the lapse-rates derived from maximum and minimum temperatures due to the nocturnal drainage of cold air to the valley bottom.

Temperature inversions, deep enough to extend beyond the height of the Kirkton AWS occurred on 10 days in the year, with the most extreme in February, persisting for 16 hours with a maximum temperature difference of −4.5 deg C.

Annual mean temperature depressions were found to be 0.7 deg C less at the Kirkton AWS, confirming that this station lies in the moist mid-altitude atmospheric layer.

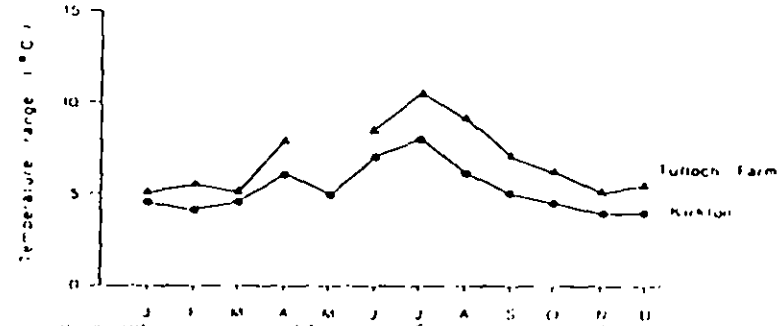

Fig.2: The mean monthly range of temperature at the two sites.

Fig.2 shows the monthly temperature ranges for the two stations. The patterns are similar over the year but the range is always greater at the lower altitude station. Linacre (1982) showed that the daily range in temperature changes nonuniformly with height, and the 200-700m altitude range is one of transition from the lower altitude band where daily range increases with height to higher altitudes where daily range decreases with height.

Wind differences between the two stations were found to be caused by local topography. The Tulloch Farm wind direction is dominated by the east-west orientation of the glen with the most frequent being 271-315 degrees. In contrast, the Kirkton wind direction shows a more typical frequency for the British Isles with directions of 181-270 degrees being the dominant. Speeds were found to be much greater at the Kirkton AWS (mean 5.7ms^{-1}) compared to the Tulloch Farm AWS (mean 2.7ms^{-1}).

Precipitation, especially at Kirkton, contains a large proportion of snow which presents problems in accurate measurement. 1983 was a relatively snow-free year for the Balquhidder area. There were 33 days when snow was lying at the Tulloch Farm AWS at 0900 GMT and an estimated 93 days at the Kirkton AWS. Precipitation in the British Isles increases with altitude although aspect and slope are usually assumed to have some influence. The two stations have large altitude differences, the ground at each is almost horizontal, so slope and aspect here play a minor role. Fig.3 shows the monthly totals for each station. In some months the higher altitude station has a lower total; in winter this could indicate an undercatch of snow. The annual precipitation totals for 1983 were Tulloch Farm 1917.7mm, Kirkton 2490.8mm.

Fig.4 of the monthly mean values of net radiation shows that Kirkton net radiation is usually greater than Tulloch Farm. The 1983 mean values were

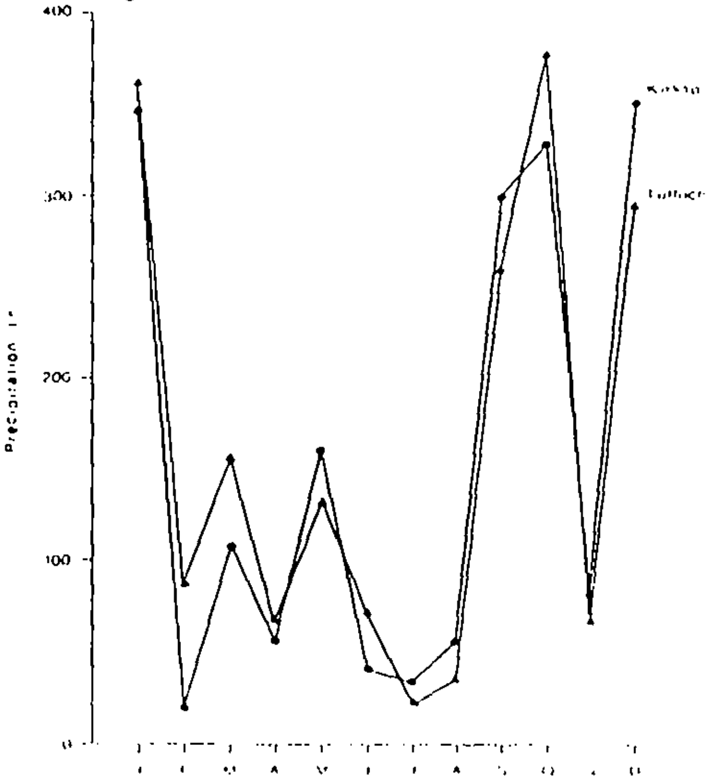

Fig.3 Monthly precipitation values for the two sites, 1983

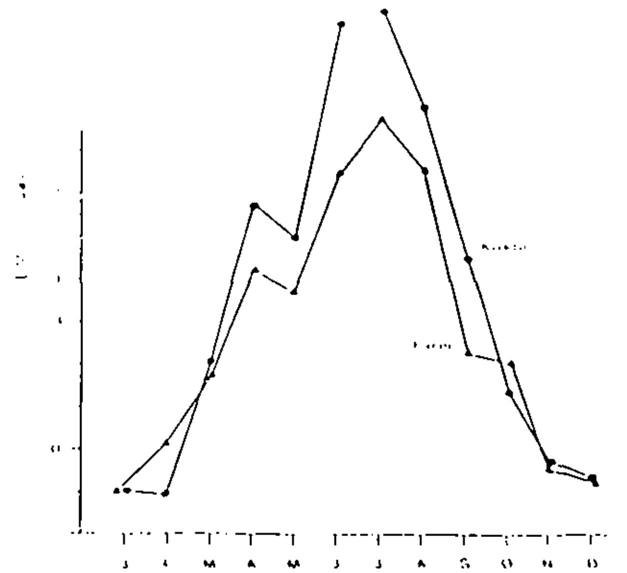

Fig.4: Monthly net radiation totals for the two sites, 1983.

Tulloch Farm 2.6 MJ M^{-2} day^{-1} and Kirkton 3.6 MJ m^{-2} day^{-1} implying a gradient of 1.9 MJ m^{-2} day^{-1} km^{-1}.

Harding (1979) found that there was a change from a decrease of radiation with height to an increase at about 500m, this change being attributed to cloud thickness, high-altitude stations being near or above the cloud tops. The Kirkton AWS is rarely above the cloud top and when the cloud base lies between the stations the cloud is usually so thick that no differences can be observed. The increase in net radiation is therefore attributed to a combination of several factors. Tulloch Farm in winter does not receive direct solar radiation for six weeks due to the shading of the mountains south of the station. Also, in winter, snow lying at the stations will affect the measurement of net radiation; this is a more common occurrence at the Kirkton AWS. Haze is not common in this area but when it is present it will be much thinner above the high-altitude station. Finally, nocturnal cooling reduces net radiation; this will affect Kirkton less because of the greater atmospheric stirring at the higher altitude.

The 1983 data from these two weather stations has therefore shown that the climatic contrasts are very pronounced. Exploitation of the Highlands is tempting but limits imposed by the climate must be recognised by farming and forestry for economic reasons and for safety in tourism.

REFERENCES

BUCHAN, A. and OMOND, R. T. (1905): The Ben Nevis observations, 1893-1897. *Trans Roy. Soc. Edin.*, *63*, 481-504.

HARDING, R. J. (1979): Altitudinal gradients of temperature in the northern Pennines, *Weather*, Vol.34, No.5.

HARDING, R. J. (1979): Radiation in the British uplands, *Journal of Applied Ecology*, *16*, 161-170.

LINACRE, E. (1982): The effect of altitude on the daily range of temperature, *Journal of Climatology*, Vol.2, 375-382.

SMITH, L. P. (1950): Variations of mean air temperature and hours of sunshine on the weather slope of a hill, *Met. Mag.*, *79*, 231-233.

TAYLOR, J. A. (1976): Upland Climates. In Chandler T. J. and Gregory S. (eds.) *The climate of the British Isles*, Longmans London.

Appendix 4

Transactions of the Royal Society of Edinburgh: Earth Sciences, 78, 327–334, 1987

Processes of evaporation from vegetation of the uplands of Scotland

R. L. Hall

ABSTRACT: The results of a series of experiments to study the physical processes governing the evaporation from upland vegetation in Scotland, i.e. coniferous forest, heather and grass, are described. Particular attention is given to the interception process occurring in heather, one of the dominant indigenous species in Scottish upland catchments. Attention is also given to the interception of snow precipitation which in the Scottish uplands is a significant proportion of the total precipitation. A comparison of the parameters describing the efficiency of the transport process of water vapour for coniferous forest and heather indicates that the process is more efficient than predicted by classical diffusion theory; additional transport mechanisms are considered. A simple model, based upon the results of the process studies, was applied to data from the Monachyle catchment (Balquhidder) and the model predictions compared with observations. This study, in conjunction with recent results from the Balquhidder catchment experiment, illustrates the necessity of further investigations to give a fuller understanding of the evaporation from high altitude grassland.

KEY WORDS: catchment model, heather, high altitude grass, interception, Scottish, simple seasonal model, spruce, transpiration, transport mechanisms.

Results from the catchment study at Plynlimon in central Wales, quoted by Calder and Newson (1979), showed that the water use of the forested Severn catchment exceeded that of the grassland Wye catchment by approximately 20% of the annual rainfall. This difference was shown through evaporation studies (Calder 1976) to be the result of high evaporation rates of intercepted water from the forest canopy combined with long-duration low-intensity rainfall. The successful explanation of the catchment results through these evaporation studies was a clear demonstration of the importance of process studies in hydrology.

Describing physical processes in terms of mathematical models provides a means of explaining catchment results and extrapolating them to different times and locations. However, because of vegetative and climatic differences, the results of evaporation studies carried out in Wales cannot be incorporated directly into models to assess the impact of afforestation in Scotland. In particular, the dominant indigenous vegetation in Scottish catchments is often heather rather than grass and in Scotland a much larger proportion of the annual precipitation falls as snow.

The necessity of evaporation studies in the Scottish environment was recognised by the Consortium on Upland Afforestation and Water Resources (see the Acknowledgements for a list of the constituent organisations) and a series of experiments was undertaken to study the relevant processes. The results of these experiments, described below, have been incorporated into research models developed to give a fuller understanding of the processes. The new information gained from these has in turn been used to derive simple seasonal models requiring minimal input data. Such models, suitable for application to water resource studies, make it possible to estimate catchment evaporation on time scales shorter than the customary year.

To date, the most successful description of evaporation from vegetation is that given by the Penman-Monteith equation (Monteith 1965). A physically-based equation, it estimates the one-dimensional (vertical) flux of water vapour from a vegetative canopy considered as a single homogeneous layer. The rate of evaporation, E, is related to the prevailing weather through two parameters which are functions of the canopy: r_c, the surface resistance and r_a, the aerodynamic resistance to water vapour transport from the vegetation surface to some observation height above the vegetation. In dry conditions, when the plants are transpiring r_c is the parallel weighted sum of the stomatal resistances (Jarvis 1981) and the sum of r_c and r_a controls the rate of evaporation, E, through

$$E = \frac{\Delta A + \rho c_p(q' - q)/r_a}{\lambda\Delta + c_p(1 + r_c/r_a)}, \qquad (1)$$

where A is the total available energy; λ is the latent heat of vaporisation of water; Δ is the slope of the saturated specific humidity versus temperature curve for water at air temperature; ρ is the density of moist air; c_p is the specific heat of air at constant pressure; and q' and q are the saturated specific humidity and the specific humidity of the air, respectively. When the canopy is completely wet $r_c = 0$ and the evaporation of intercepted water is constrained by r_a only. Measurement of these resistances is thus necessary for any model or estimate of evaporation from vegetation which is based on Equation (1).

Estimates of evaporation which do not require information about resistances are also available. For short lowland grass the evaporative loss is estimated well by the Penman (1948) potential evaporation E_t. This is defined as the potential rate of evaporation from short green vegetation completely covering the ground and well supplied with water. It is calculated using

$$E_t = \frac{\Delta Q_n + \gamma E_a}{\Delta + \gamma}. \qquad (2)$$

where Q_n is the net radiative energy input to the vegetation, E_a is a ventilation term which is a function of windspeed and vapour pressure deficit and γ is the psychrometric constant.

The Penman equation is a special case of the more general Equation (1) and implicitly includes aerodynamic and surface resistances appropriate to the surfaces for which the equation was originally derived. It will not, therefore, accurately estimate evaporation rates from vegetation which has a different atmospheric coupling. However, with care it can be used if multiplied by empirical "transpiration factors". Although this practice is hard to justify on physical grounds it does provide estimates having empirical support of the average transpiration from vegetation other than lowland grass. As such its use is of practical importance to those wishing to estimate transpiration from different vegetation without having to resort to complicated research models.

Both the approaches characterised by Equations (1) and (2) have been used in the evaporation studies described below.

1. A review of the results of a series of process experiments

1.1. Transpiration

Transpiration of spruce, heather and grass has been studied using the neutron soil moisture probe (Bell 1976) to measure the soil moisture content beneath the vegetation. (In a drought period the transpiration rate is reflected in the rate of development of a soil moisture deficit.) Measurements were made at several sites, four at the Knapdale forest, Kintyre peninsula, beneath spruce and heather, and three at Balquhidder, beneath spruce, heather and upland grass.

The soil moisture studies have supported the results of earlier work by Calder (1976) showing that E_t can be used to estimate transpiration from spruce when multiplied by a transpiration factor (Calder 1986) of 0·9. A daily accounting model developed by Calder *et al.* (1983b), requiring only daily values of rainfall and E_t in addition to the soil moisture measurements, was used to determine a transpiration factor for heather of 0·5. The same value was indicated from the results of an analysis by Calder *et al.* (1983a) of historical data from Law's lysimeters at Stocks Reservoir, Lancashire; Wallace *et al.* (1982) found the value to range from 0·2 to 0·5 for the months May to July for heather growing on Sneaton Moor, Yorkshire.

1.2. Interception

The Plynlimon studies showed that in the wet western climate of the British Isles the interception component of annual evaporation from coniferous forest is twice the transpiration component (Calder 1976) with an average annual loss by interception of about 37% of the gross precipitation. Interception measurements at Knapdale forest using plastic-sheet, net-rainfall gauges (Calder & Rosier 1976), gave a figure of 36%. Similarly a figure of 45% was measured at Queens Forest, near Aviemore, for periods when there was no snow. Large interception losses result from high evaporation rates consequent upon the turbulence-driven transport processes associated with the aerodynamically rough forest canopy. This is reflected in the low values of r_a.

Further confirmation of high rates of interception loss has come from measurements of the attenuation of gamma-rays traversing a 40 m stretch of forest to determine the amount of water stored on the canopy (Calder & Wright 1986, Olszyczka 1979). These measurements also showed that the rates of interception loss were consistent with an r_a of 3·5 s m^{-1}, which was the value obtained by Calder (1977).

The gamma-ray equipment has also been used, in conjunction with a tree-weighing experiment and net-rainfall gauges, to measure the interception of snow. Very good agreement was found between the measurements made by these separate methods. Spruce canopies quite regularly hold in excess of 20 mm water equivalent of snow and storages in excess of 28 mm were sometimes observed. Evaporation rates from melting snow were typical of rates from a wet spruce canopy (rates up to 0·5 mm h^{-1}) and were consistent with r_a = 3·5 s m^{-1}. Sublimation rates were lower, even allowing for the effect of condensation and the additional energy required by the molecules to move from the solid phase into the vapour phase. The low sublimation rates measured during periods when condensation was not occurring gave an optimised r_a of 35 s m^{-1} which may reflect the aerodynamically smoother surface presented by a thickly snow-covered canopy. Despite lower loss rates sublimation can result in significant interception loss of snow by coniferous forests when large amounts of intercepted snow coincide with long periods of sub-zero temperatures. Large total interception losses of between 80% and 100% of gross precipitation, were observed for individual snow-storms. An average annual interception ratio for snow has yet to be determined.

The interception characteristics of heather were studied using a wet-surface weighing lysimeter system (Calder *et al.* 1984; Hall 1985, 1986) at sites in Scotland and Norfolk. Whereas the transpiration rates from heather are generally lower than from grass, the rates of interception loss are higher, a direct consequence of smaller r_a. Measurements of r_a as a function of windspeed at different sites by Hall (1986) indicated a correlation between the topography around the sites and the magnitude and form of the r_a-windspeed function: the lower values of r_a were measured at the aerodynamically rougher sites.

After some modifications, the lysimetric method was used by Hall (1985) to determine the other canopy parameters required for operating a Rutter interception model on heather. The drainage rate, D in mm h^{-1}, from heather was found to be well described by

$$D = k(\exp[bC] - 1), \qquad (3)$$

where C, the canopy storage, is in mm and the drainage parameters k and b have the values 0·0085 mm h^{-1} and 5·13 mm. The intricate small-scale structure of the heather foliage and its highly wettable cuticle result in water readily forming a continuous film over it which is not easily shaken off. 0·85 mm of water were required for a continuous film to form and significant drainage did not occur until a depth of more than 1·1 mm was on the canopy. These depths coupled with measurements of leaf area, on a projected leaf area basis, indicated that for unit area of foliage, heather is able to store a large depth of water: 0·6 mm m^{-2} as compared with 0·2 mm m^{-2} for spruce. The free throughfall coefficient was found to equal 0·13.

The lysimetric method was also used to compare evaporation rates from dry and rain-wetted grass with estimates of Penman potential evaporation. No systematic difference was observed within the limits of experimental scatter. This supports the use of the Penman equation to estimate evaporation rates from grass after rainfall and during dry conditions. However, similar interception studies at Wallingford, Oxfordshire, with samples of grass sprayed with weak (0·1%) solutions of surfactant, on days when the surrounding grass was thoroughly wetted by rain, indicated that evaporation rates from totally wet grass may exceed E_t (Calder *et al.* 1986). Aerodynamic resistances calculated from this experiment are plotted against windspeed in Figure 1 and compared with values obtained at Balquhidder for wet grass not sprayed with surfactant. These results suggest that the r_a values from the surfactant-sprayed grass are lower, implying higher evaporation rates.

A convenient summary of most of the above results is tabulated by Calder (1986).

1.2.1. Evidence of the inadequacy of conventional eddy-diffusion theory from the interception studies. According to conventional eddy-diffusion theory the aerodynamic resistance to vapour transfer can be equated to the aerodynamic resistance to momentum transfer after corrections are applied to allow for bluff-body forces and atmospheric stability effects. However, this gives r_a values which are higher than those determined from the spruce and heather interception experiments described above. Moreover, the eddy-diffusion theory predicts an r_a inversely related to mean windspeed, whereas the gamma-ray attenuation experiment produced evidence of a lack of dependence of r_a on windspeed for spruce. For heather, r_a was found to be a function of windspeed but with a smaller coefficient than predicted by theory. Moreover, at a hillside site in mountainous topography near Killin, Calder *et al.*

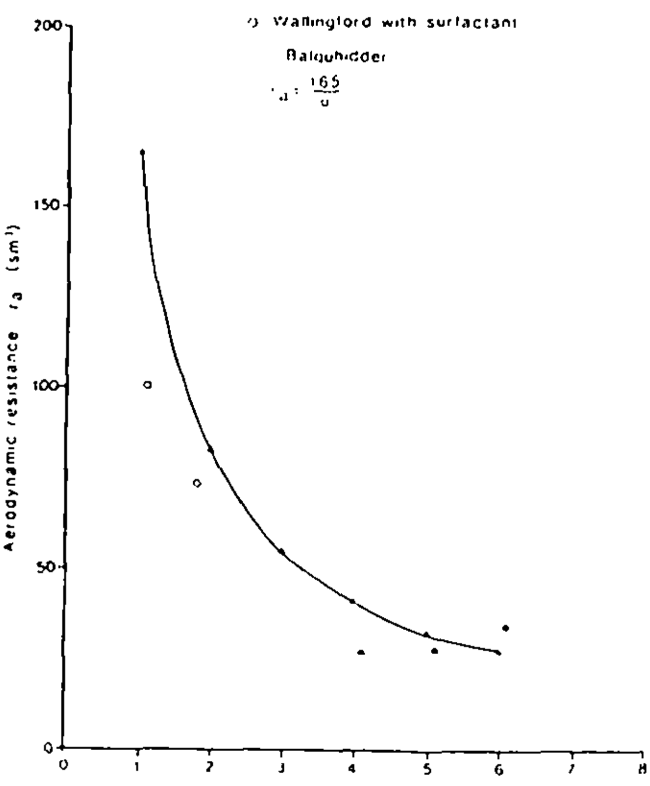

Figure 1 Comparison of the aerodynamic resistance as a function of windspeed, u, for rain-wetted grass (measured at Balquhidder), totally wet surfactant-sprayed grass (measured at Wallingford) and the theoretical r_a, the theoretical function, $r_a = 165/u$, was calculated using

$$r_a = \frac{1}{u}\left(\frac{1}{k}\ln\frac{(z-d)}{z_0}\right)^2$$

based on classical eddy diffusion theory (Monteith & Szeicz 1962), parameters used were $z = 2$ m, $d = 0{\cdot}075$ m and $z_0 = 0{\cdot}01$ m with von Karman's constant, $k = 0{\cdot}41$

(1984) found that r_a was not a simple inverse function of the mean windspeed as predicted by eddy diffusion theory.

Several studies (e.g. Finnigan 1979; Denmead 1984; Crowther & Hutchings 1985; Grant *et al.* 1986) have shown that large scale turbulence in the form of intermittent energetic gusts are a major mechanism in transporting momentum, heat and water vapour between vegetation and atmosphere. The low r_a values found for spruce and heather give further support for this additional transport mechanism, as does the lack of dependence of r_a on mean windspeed for spruce, if the additional mechanism is not a simple function of windspeed. Larger differences between measured and predicted values of r_a for heather observed at Killin compared with a flatter site in Norfolk (see Hall 1986) are probably the result of the large-scale turbulence generated by the upland topography.

There are now both experimental observations and, due to the work of Finnigan (1979), Raupach and Legg (1984) and others, theoretical reasons for expecting evaporation rates from vegetation often to exceed rates predicted on the basis of flux-gradient relationships, particularly in the uplands.

2. A simple model of catchment evaporation

2.1. The model

The information gathered from the process studies has been used to develop a simple model which calculates daily evaporation E_D (transpiration plus interception loss) from a catchment under grass and heather. This model has the same form as the Calder and Newson (1979) annual model from which it is derived; likewise it requires few inputs, only rainfall and Penman potential evaporation, E_t, although on a daily basis. E_t is used to estimate evaporation from grass and, using a transpiration factor of 0·5, to estimate transpiration from heather. Interception loss from the heather is estimated from an exponential relationship between the daily rainfall and interception loss. The model is represented by

$$E_D = f \cdot E_t + (1-f)[0{\cdot}5 \quad E_t \quad (1-w) + \beta(1-\exp(-\delta R))]. \tag{4}$$

where f is fractional area under grass; R is the daily rainfall and w is the fraction of the day that the heather is wet where $w = 0{\cdot}068R$ or $w = 1$ for $R > 14{\cdot}5$ mm, a relationship derived from modelling studies referred to below.

The interception parameter, β is the maximum predicted interception loss on one day. The interception parameter δ has no simple physical interpretation, but when the rainfall is very small the product $\beta\delta$ is the slope of the interception loss versus rainfall curve; if $\beta = 1/\delta$, then for low rainfall the predicted interception loss will equal the rainfall. Values of β and δ of 2·65 mm and 0·36 mm^{-1}, respectively, were obtained using a least squares optimisation computer program on daily values of rainfall and interception loss. Because of the lack of any measurements of interception loss from heather, values of daily interception loss were calculated using a Rutter interception model (Rutter *et al* 1971) with Plynlimon meteorological data collected over forest and adjusted using the technique of McNaughton and Jarvis (1984). (Forest data were used because at the time high quality meteorological measurements over heather were not available.) The Rutter model incorporated the canopy parameters for heather found by Hall (1985) and the aerodynamic resistance function measured at a Scottish upland site (near Killin) by Calder *et al.* (1984).

The daily exponential model of interception loss has not been tested against any observed interception loss data for heather because none is known to exist. However, Calder (1986) has shown the same model, using parameters for coniferous forest, to be very successful in predicting interception loss from forest.

2.1.1. A temperature-dependent transpiration function. A modified form of Equation (4) was developed to investigate the magnitude of possible temperature effects in reducing evaporative loss from a catchment. Since plant growth does not generally occur until air temperatures reach 5°C, for grasslands transpiration will be insignificant until mean air temperatures exceed that temperature. To model this effect, the estimate of the transpiration rate from grass in equation (4) was made a function of temperature. When the air temperature was less than 5°C the transpiration was put equal to zero; between 5°C and 10°C transpiration was a linear function of temperature such that at 10°C it was equal to E_t; above 10°C E_t was used. Estimation of the transpiration from heather was not altered as the transpiration factor of 0·5 was determined from data collected throughout the year and thus implicitly includes any temperature effects. A full mathematical formulation of both versions of the model is given in the Appendix.

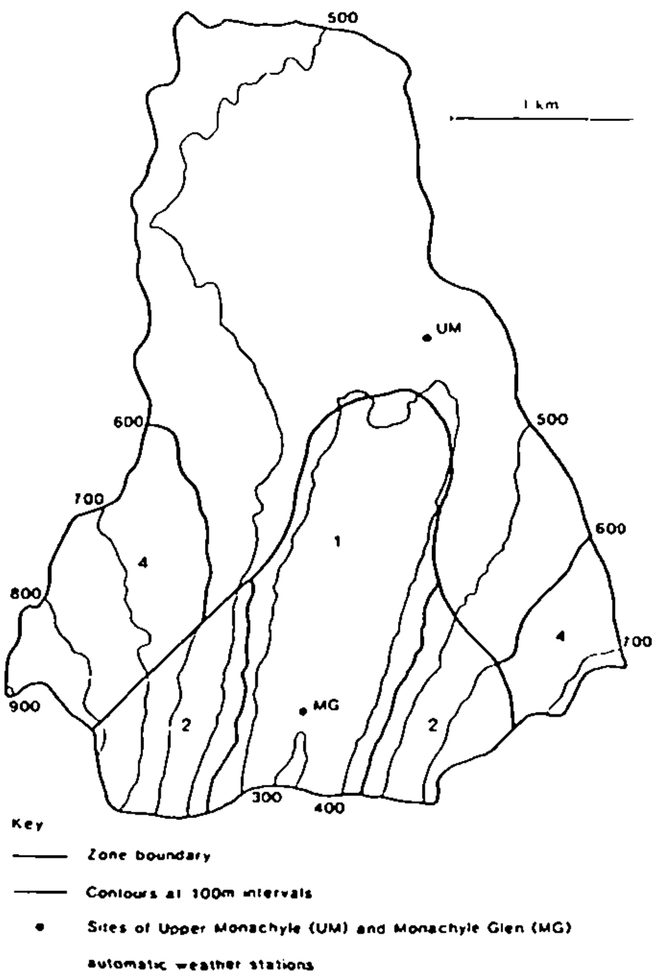

Figure 2 Monachyle catchment showing the four zones used in the model and described in Table 1: (1) lower grass, (2) upper grass, (3) lower heather and (4) upper heather zones.

2.2. Application of the model

2.2.1. Monachyle catchment. The Monachyle catchment (56°18'N, 4°15'W) in the Grampian mountains has an area of 7·7 km² and is one of a pair of instrumented catchments, the other being the Kirkton catchment, which form the basis of the Balquhidder catchment experiment operated by the Institute of Hydrology (Blackie 1987). A sketch map of the Monachyle catchment is shown in Figure 2. The southern part of the catchment is a steep-sided glaciated valley, predominantly grass covered, with an altitude range of 300 m to 900 m. To the N the land flattens to a predominantly heather-covered area which ranges approximately in altitude from 450 m to 500 m. Other vegetation includes bilberry, bracken and patches of scrub forest. Peat is the main soil type throughout the catchment and overlies mica-schist. Annual rainfall ranges from more than 3100 mm in the SW to 2400 mm in the NE with a mean annual value for the catchment of 2636 mm.

The simple catchment model was used to produce estimates of daily transpiration and interception loss from the grass and heather areas of the Monachyle catchment with and without the temperature adjustment to the estimate of the transpiration of grass. In applying the model to the Monachyle catchment several simplifying assumptions were made. These were:

(i) The entire catchment was assumed to be under heather or grass. Although other species are present and there are significant areas of bare rock and bare peat, most of the catchment is covered by heather or grass or a mixture of the two. Aerial photographs were used to identify which parts of the catchment were predominantly covered with heather and which with grass.

(ii) Evaporation from snow-covered parts of the catchment was assumed to be zero. Falls of snow occur annually on the Monachyle catchment but, whereas significant evaporation has been shown to occur from snow-covered forest, the turbulence generated over the much smoother snow-covered heather and grass is less vigorous so that evaporation will be much less. Additionally the much higher albedo of the snow pack coupled with the energy required to melt the snow mean that less energy is available for evaporation. Experimental studies of smooth snow pack in Norway (Harding 1986) showed that evaporation rates were very small and the total evaporation over a three week period was less than 1 mm. Moreover, the amount of snow required to cover grass and heather smoothly is small because of the height of the grass and because the structure of the heather readily allows bridging between leaves and twigs. Hence the evaporation from snow-covered parts of the catchment was equated to zero.

(iii) To simplify modelling the effects of altitude on temperature and snow cover, the catchment was considered as having the four zones marked in Figure 2 and classified in Table 1. The evaporation predicted from the catchment was then the sum of the evaporation calculated using Equation (4) applied to each of these four zones in conjunction with daily snow observations.

(iv) Daily snow observations took the form of estimates of the altitude of the snow lines and the assumption was made that all the vegetation above that was snow covered.

Table 1 A description of the four zones of the catchment (area = 770 ha) used in the model and shown in Figure 2

Zone No.	Dominant Vegetation	Lower altitude limit *m*	Mean altitude *m*	Fraction of catchment area
1	grass	300	350	0·19
2	grass	450	600	0·14
3	heather	400	450	0·52
4	heather	600	700	0·15

2.2.2. Kirkton catchment (high altitude part). Evaporation from the grass growing on the upper part of the nearby Kirkton catchment was also modelled to estimate the reduction in evaporative loss due to restricted transpiration at low ambient temperatures. Whereas most of the grass on the Monachyle catchment grows below 450 m, in the Kirkton catchment all of the upper part, between altitudes of 500 m and 850 m, is grassed except for small areas of exposed rock and heather.

2.3. Input data

Daily estimates of E_t and air temperature for 1984 and 1985 were taken from the Upper Monachyle and Monachyle Glen automatic weather station records, missing periods were infilled from the nearby Tulloch Farm automatic weather station or failing that, from the Tulloch Farm manual observations using regression relationships. The air temperatures were corrected for the mean altitude of each of the four zones. The daily rainfall over the heather and grass areas was calculated as the mean of the rainfall recorded by the raingauges relevant to those areas after these had been time distributed on the basis of a daily-read gauge at Tulloch Farm.

The same data were used, after altitudinal-correction of the air temperature, in modelling the evaporative loss from grass growing in the Kirkton catchment at a representative altitude of 680 m.

2.4. Results of the modelling exercise

The model produced daily estimates of transpiration, T, and interception loss, I, from the grass and heather on a catchment-area basis (see Appendix). The cumulative values of these estimates are plotted in Figure 3, where the subscripts G and H denote grass and heather, respectively. Likewise, the evaporation from grass, $E_G = T_G + I_G$ and heather, $E_H = T_H + I_H$ are plotted in Figure 4 with evaporation calculated using the temperature dependent transpiration function denoted by a prime i.e. E'_G. Figure 5 compares the estimated evaporative loss with observed values of rainfall minus runoff. The annual estimates shown in Tables 2 to 4 were obtained by summing the daily estimates.

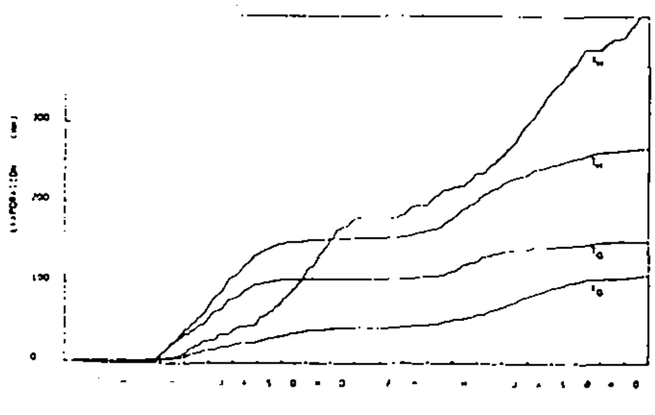

Figure 3 Calculated cumulative evaporation from the Monachyle catchment (67% heather, 33% grass) over two years; transpiration (T) and interception (I) components are shown separately for grass (subscript G) and heather (subscript H)

As expected, because of its very efficient interception, the evaporation from the heather is greater than that from the grass. The figures given in Table 2 show that in 1985 the predicted interception loss for heather is more than twice the predicted transpiration. Although the precipitation for the two years differed by 5·5% (2489 mm in 1984 and 2632 mm in 1985) the total predicted loss for the catchment (heather 67%) differed by only 2%. This is the result of a compensatory effect attributable to heather interception loss exceeding grass interception loss and grass transpiration exceeding heather transpiration. The model predicts that, in the dry summer in 1984, enhanced transpiration from the grass would have compensated for reduced interception loss from heather, whereas in the wet summer of 1985 enhanced interception loss from the heather would have compensated for reduced grass transpiration (see Table 2).

This compensatory effect also makes output from the model insensitive to changes in the relative areas of the grass and heather. Changing the fractional area of the grass

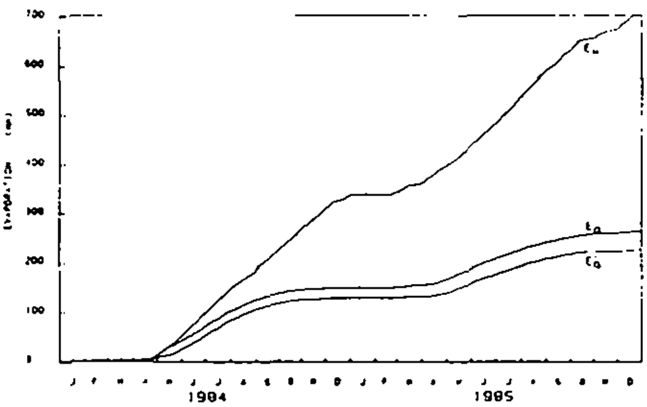

Figure 4 Calculated cumulative evaporation (E) from the Monachyle catchment over two years from the grass (subscript G) and heather (subscript H); also shown, denoted by a prime ('), is the cumulative evaporation from the grass calculated using the temperature function described in the Appendix.

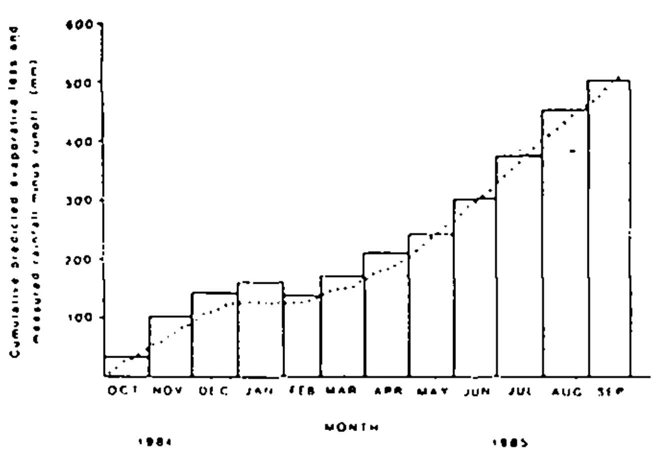

Figure 5 Comparison of cumulative monthly, measured rainfall-minus-runoff, for the Monachyle catchment, with the cumulative evaporative loss calculated using the simple model incorporating the temperature-dependent transpiration function for grass; dots represent calculated values at five-day intervals

Table 2 The effect of changing the relative areas of the grass and heather on the components of the annual total evaporation from the catchment; all values in mm depth of water over the entire catchment area, annual interception (I) and transpiration (T) components of the evaporation (E) given separately and were obtained from daily values calculated using the method described in the Appendix; subscript G denotes grass, H heather and A the annual total

Grass : Heather Ratio	Year			I_H	T_H	E_G	E_H	E_A
0 : 100	1984			280	230		510	510
	1985			381	161		542	542
18 : 82	1984	26	59	224	195	85	419	504
	1985	38	27	309	141	65	450	515
33 : 67	1984	48	107	183	160	155	343	498
	1985	70	49	254	116	119	370	489
48 : 52	1984	70	155	143	124	225	267	492
	1985	101	72	199	91	173	290	463
100 : 0	1984	149	339			488		488
	1985	243	162			405		405

Table 3 The effect of restricting transpiration from grass according to the function given in the Appendix for the Monachyle catchment, 33% grass and 67% heather; all values are in mm depth over the entire catchment area, primes denote that the temperature function was applied, otherwise the notation is as in Table 2

Year	I_G	T_G	T'_G	E_G	E'_G	E_H	E_A	E'_A
1984	48	107	86	155	134	343	498	477
1985	70	49	32	119	102	370	489	472

Table 4 The effect on the predicted evaporation from grass growing at 680 m of applying the temperature function described in the Appendix, notation as in Table 2; all values in mm a^{-1}

Year	I_G	T_G	T'_G	E_G	E'_G	$\frac{E_G - E'_G}{E_G}$
1984	146	361	210	507	356	0·297
1985	242	177	52	420	294	0·298

by ±0·15, the maximum uncertainty in the relative areas, produced only a 3% change in the total evaporation averaged over the two years. The difference in evaporative losses predicted for catchments with 100% grass and 100% heather cover is 137 mm for the wetter 1985 compared with 22 mm for 1984.

Putting to zero the evaporation from snow-covered parts of the catchment reduced the accumulated E_t by about 5% in 1985. However, the large snowfalls in 1984 resulted in the accumulated E_t being reduced by 8% and 18% for the Monachyle Glen and Upper Monachyle respectively.

The consequences of transpiration from the grass being a function of temperature are shown in Figure 4 and Table 3. The predicted reduction in evaporation from the grass on the catchment averaged over the two years is 14%.

Model (temperature function included) predictions of the evaporative loss for the catchment are compared with measurements of rainfall minus runoff (see Blackie *et al.* 1986) for the twelve months October 1984 to September 1985 in cumulative form in Figure 5. The agreement is remarkably good, particularly since no allowance has been made for seasonal storage within the catchment which comprises three main reservoirs: accumulated snow, soil water and shallow aquifers. The observed monthly values of rainfall minus runoff can only be considered to provide a very crude measure of the evaporative loss as the storages may be of the same magnitude as the monthly values which themselves contain uncertainties associated with the rainfall and runoff figures. The effect of snow storage during the period November to January is clearly shown; a negative monthly value for February produces a decrease in the cumulative value. Agreement between the predicted evaporative loss and the observed values is best during the summer months when the effects of storage are minimal. Despite the limited value of the individual monthly figures, for comparative purposes the cumulative values do provide an increasingly good check. A comparison of the annual figures shows exceptionally good agreement which is fortuitous given the uncertainties in the model and in the rainfall and runoff figures: 516 mm predicted, versus 505 mm observed.

Table 4 shows the predicted effect of temperature-restricted transpiration on annual evaporative loss from high altitude grassland; the annual evaporative loss predicted from grass growing on the upper parts of the Kirkton catchment is less than that for grass growing at lower altitudes on the Monachyle. The evaporation, based on days when there was no snow cover, was reduced by 30% in both years compared with the reduction of 14% over the same period for the Monachyle. The reduced evaporation when compared with the mean annual (1984–1985) E_t for the Kirkton catchment of 543 mm, based on data from an automatic weather situation at 680 m, implies that the annual E_t for the high altitude grass-covered part of the Kirkton should have a temperature correction factor of 0·6.

3. Discussion

The application of the simple model to the Monachyle catchment has demonstrated that its annual evaporation is a remarkably constant quantity because of the compensatory effect of the high interception loss and low transpiration from heather. For the same reason uncertainties in the predicted catchment evaporation, associated with the rather crude estimate of the relative areas of grass and heather, are small.

Less easy to dismiss is the uncertainty arising from snow cover on the catchment. It was assumed (see Section 2.2.1) that all points above the observed snow line were snow covered. Clearly this overestimates the extent of snow cover which at times was patchy. It was also assumed that evaporation from snow-covered grass and heather is zero: this must underestimate the evaporation rate, certainly as the snow begins to melt and the cover becomes incomplete. Evaporation of rain fallen upon snow was also ignored. The total effect of these assumptions is that evaporation is underestimated by the model by an amount which may be significant in a year of high snowfall like 1984. Hence the reduction in the annual E_t for the two automatic weather stations resulting from these assumptions represents a maximum reduction.

The assumption that the entire catchment was under either grass or heather also gives rise to uncertainties in the total evaporation. Evaporation from the areas of exposed rock is likely to be at rates lower than from grass or heather, whereas evaporation rates from patches of bracken and bilberry which occur in the grass area are likely to be at rates higher than those from grass. The net effect is that total uncertainties due to this assumption are small.

The recent advances in our understanding of evaporation from heather and coniferous forest have resulted in the evaporation from upland grass being the least fully understood. A simple model of catchment evaporation shows that low-temperature control of grass transpiration can result in a significant reduction in the loss from upland grass particularly for grass growing at the highest altitudes; 40% in the example given. If these temperature effects exist, then direct application of the annual Penman E_t to catchments containing a significant proportion of high altitude grass will overestimate evaporation. However, it is not known to what extent a reduction in transpiration may be offset by enhanced interception loss during the months when the grass leaves are senescent. Interception loss rates are affected by the way water is held on the vegetation and as senescent leaves lose the epicuticular wax (Siva Fernandes 1964), present on many species, rain will tend to form a film over the leaves rather than discrete droplets. This effect coupled with high windspeeds and low rainfall intensities may result in relatively high interception loss rates. However, at high altitudes the grass will often be above or near the cloud base and in these conditions evaporation will be suppressed. Clearly, understanding of evaporation from high altitude grassland is very incomplete and there is much scope for further research.

Application of the simple catchment model to upland Scottish catchments containing coniferous forests awaits the development of a successful model of snow interception from coniferous forest. Work on this is in progress.

4. Conclusions

The experimental studies described in this paper have led to a much fuller understanding of the processes involved in evaporation from upland vegetation, in particular heather and coniferous forest. This new knowledge has made it possible to operate interception models of a research type: the Rutter model, and to develop simpler models, with less exacting data requirements, which can, however, be used successfully for estimating evaporation from catchments on a seasonal basis.

To improve upon our present ability to predict losses from high altitude grassland, research is required to investigate the effects of temperature upon growth and transpiration rates. Interception experiments are also needed to determine if enhanced evaporation from totally wet grass, which may occur during the dormant periods, is able to offset any reduction in transpiration.

Further improvements in the model predictions of catchment evaporation would be achieved as a result of studies of snow interception from short to medium height vegetation and through the use of areal estimates of snow cover.

5. Acknowledgements

The work described in this paper has been carried out by a team: Richard Harding, Ivan Wright, Paul Rosier and the author, under the leadership of Ian Calder. Thanks are also due to Jim Hudson and Jim Blackie for helpful discussions and to Dick Johnson whose careful industry provided the data used in the catchment model. Financial support from the Scottish Consortium on Upland Afforestation and Water Resources (British Waterways Board, Department of Energy, Department of the Environment, Forestry Commission, North of Scotland Hydro Electric Board, Scottish Development Department, Water Research Centre) is gratefully acknowledged.

6. Appendix

The daily evaporation, E_D in mm, from the catchment is given by equation (4) which in a modified notation is

$$E_D = T_G + I_G + T_H + I_H = E_G + E_H. \qquad \text{(A1)}$$

The daily transpiration (T) and interception loss (I) components from grass (subscript G) and heather (subscript H) are calculated in accord with the rules given below and on the basis of catchment area. In the equations below R denotes daily rainfall, T_D the daily mean air temperature and E_t the Penman potential evaporation

a) Unmodified form

(i) Grass

$$\text{If } R \geqq E_t \text{ then } T_G = 0 \text{ and } I_G = E_t$$
$$\text{If } R < E_t \text{ then } I_G = R \text{ and } T_G = E_t - I_G \qquad \text{(A2)}$$

(ii) Heather

The fraction of the day that the heather is wet, w, is given by

$$w = 1 \quad \text{if} \quad R \geqq 14{\cdot}5 \text{ mm}$$
$$w = 0{\cdot}068 \cdot R \quad \text{if} \quad R < 14{\cdot}5 \text{ mm}. \qquad \text{(A3)}$$

Then

$$T_H = 0{\cdot}5 \; (1 - w) \; E_t \qquad \text{(A4)}$$

and

$$I_H = \beta(1 - \exp(-\delta R)), \qquad \text{(A5)}$$

where β and δ are optimised parameters; $\beta = 2{\cdot}65$ mm is the maximum predicted interception loss on one day and $\delta = 0{\cdot}36 \text{ mm}^{-1}$ has no simple physical interpretation.

b) Temperature function

(i) Grass

$$\text{If } R \geqq E_t \text{ then } T_G = 0 \text{ and } I_G = E_t$$
$$\text{If } R < E_t \text{ then } T_G = \tau \text{ and } I_G = R \qquad \text{(A6)}$$

where the transpiration function τ is defined as

$$\tau = 0 \quad \text{for} \quad T_D < 5°\text{C}$$
$$= E_t \quad \text{for} \quad T_D > 10°\text{C}$$
$$= E_t \quad (T_D - 5)/5 \quad \text{for} \quad 5°\text{C} \leqq T_D \leqq 10°\text{C}, \qquad \text{(A7)}$$

but if $T_G + I_G > E_t$, then $T_G = E_t - I_G$.

(ii) Heather

T_H and I_H are the same as for the unmodified form.

7. Notation

Symbol	Description	Units
A	available energy	W m^{-2}
b	drainage parameter	mm
c_p	specific heat of air at constant pressure	$\text{J kg}^{-1}\,\text{K}^{-1}$
C	canopy storage	mm
D	drainage rate	mm h^{-1}
E	rate of evaporation	$\text{kg m}^{-2}\,\text{s}^{-1}$
subscripts:		
a	Penman ventilation term	mm d^{-1}
A	annual, catchment	mm a^{-1}
D	daily, catchment	mm d^{-1}
G	grass	mm d^{-1}; mm a^{-1}
H	heather	mm d^{-1}; mm a^{-1}
t	Penman potential	mm d^{-1}; mm a^{-1}
	fractional area	

Symbol	Description	Units
I	interception loss rate	mm d^{-1}; mm a^{-1}
subscripts:		
	G grass	
	H heather	
k	drainage parameter	mm h^{-1}
q	specific humidity of the air	kg kg^{-1}
q'	saturated specific humidity of the air	kg kg^{-1}
Q	Penman net radiative energy input	mm d^{-1}
	aerodynamic resistance to water vapour transport	s m^{-1}
	surface resistance to water vapour transport	s m^{-1}
R	daily rainfall	mm d^{-1}
T_D	mean daily air temperature	°C
T	transpiration rate	mm d^{-1}; mm a^{-1}
subscripts		
	G grass	
	H heather	
	temporal wetness fraction	
β	interception parameter	mm
γ	psychrometric constant	kg kg^{-1} K^{-1}
δ	interception parameter	mm^{-1}
Δ	slope of the saturated specific humidity versus temperature curve for water at air temperature	kg kg^{-1} K^{-1}
	latent heat of vaporisation of water	J kg^{-1}
	density of moist air	kg m^{-3}
	temperature dependent transpiration function	mm d^{-1}

8. References

Bell, J. P. 1976. *Neutron probe practice.* Wallingford: Institute of Hydrology. REP **19**

Blackie, J. R. 1987. The Balquhidder catchments, Scotland: the first four years. TRANS R SOC EDINBURGH EARTH SCI **78**, 227–239.

Blackie, J. R., Hudson, J. A. & Johnson, R. C. 1986. *Upland afforestation and water resources. Preliminary analysis of phase I of the Balquhidder catchment studies.* Wallingford: Institute of Hydrology.

Calder, I. R. 1976. The measurement of water losses from a forested area using a "natural lysimeter". J HYDROL **30**, 311–25.

Calder, I. R. 1977. A model of transpiration and interception loss from a spruce forest in Plynlimon, central Wales. J HYDROL **33**, 247–65.

Calder, I. R. 1986. The influence of land use change on water yield in upland areas of the U.K. J HYDROL **88**, 201–211.

Calder, I. R., Hall, R. L., Harding, R. J. & Rosier, P. T. W. 1983a. *Upland afforestation progress report. Process studies 1982–1983.* Wallingford: Institute of Hydrology.

Calder, I. R., Harding, R. J. & Rosier, P. T. W. 1983b. An objective assessment of soil-moisture deficit models. J HYDROL **60**, 329–55.

Calder, I. R., Hall, R. L., Harding, R. J. & Wright, I. R. 1984. The use of a wet-surface weighing lysimeter system in rainfall interception studies of heather (*Calluna vulgaris*). J CLIMATE APPLIED METEOR **23**, 461–74.

Calder, I. R., Hall, R. L., Harding, R. J., Rosier, P. T. W. & Wright, I. R. 1986. *Upland afforestation and water resources. Progress report 1985–1986. Process studies, Phase I.* Wallingford: Institute of Hydrology.

Calder, I. R. & Newson, M. D. 1979. Land-use and upland water resources in Britain—a strategic look. WATER RES BULL **15**, 1628–39.

Calder, I. R. & Rosier, P. T. W. 1976. The design of large plastic-sheet net-rainfall gauges. J HYDROL **30**, 403–05.

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

Crowther, J. M. & Hutchings, N. J. 1985. Correlated vertical wind speeds in a spruce canopy. *In* Hutchinson, B. A. & Hicks, B. B. (eds) *The Forest-Atmosphere Interaction*, 534–61. Dordrecht: D. Reidel.

Denmead, O. T. 1984. Plant physiological methods for studying evapotranspiration: problems of telling the forest from the trees. AGRIC WATER MANAGE **8**, 167–89.

Finnigan, J. J. 1979. Turbulence in waving wheat II. Structure of momentum transfer. BOUNDARY-LAYER METEOR **16**, 213–36.

Grant, R. H., Bertolin, G. E. & Herrington, L. P. 1986. The intermittent vertical heat flux over a spruce forest canopy. BOUNDARY-LAYER METEOR **35**, 317–30.

Hall, R. L. 1985. Further interception studies of heather using a wet-surface weighing lysimeter system. J HYDROL **81**, 193–210.

Hall, R. L. 1986. The use of a PET microcomputer in rainfall interception studies of heathland. *In* Clark, J. A., Gregson, K. & Saffell, R. A. (eds) *Computer Applications in Agricultural Environments*, 45–56. London: Butterworths.

Harding, R. J. 1986. Exchanges of energy and mass associated with a melting snowpack. *In* Morris, E. M. (ed.) *Modelling Snowmelt-induced Processes*, Proceedings of the Budapest Symposium, July 1986. IAHS PUBL 155.

Jarvis, P. G. 1981. Stomatal conductance, gaseous exchange and transpiration. *In* Grace, J., Ford, E. D. & P. G. Jarvis (eds) *Plants and their atmospheric environment*, 21st Symposium of the British Ecological Society, 175–204. Oxford: Blackwell.

McNaughton, K. G. & Jarvis, P. G. 1984. Using the Penman–Monteith equation predictively. AGRIC WATER MANAGE **8**, 263–78.

Monteith, J. L. 1965. Evaporation and the environment. *In The State and Movement of Water in Living Organisms.* SYMP SOC EXP BIOL **19**, 205–34. London: Cambridge University Press.

Monteith, J. L. & Szeicz, G. 1962. Radiative temperature in the heat balance of natural surfaces. Q J R METEOR SOC **88**, 496–507.

Olszyczka, B. 1979. *Gamma ray determinations of surface water storage and stem water content for coniferous forests.* Ph.D. Thesis, University of Strathclyde.

Penman, H. L. 1948. Natural evaporation from open water, bare soil and grass. PROC R SOC LONDON **A193**, 120–45.

Raupach, M. R. & Legg, B. J. 1984. The uses and limitations of flux-gradient relationships in micrometeorology. AGRIC WATER MANAGE **8**, 119–32.

Rutter, A. J., Kershaw, K. A., Robins, P. C., & Morton, A. J. 1971. A predictive model of rainfall interception in forests. I. Derivation of the model from observations in a plantation of Corsican pine. AGRIC METEOR **9**, 367–84.

Siva Fernandes, A. M. S. 1964. Studies on plant cuticle, surface waxes in relation to water-repellency. ANN APPL BIOL **56**, 297–304.

Wallace, J. S., Roberts, J. M. & Roberts, A. M. 1982. Evaporation from heather moorland in North Yorkshire, England. *In Proceedings of a Symposium on Hyrological Research Basins, Sonderheft, Landeshydrologie, Bern (1982)*, 397–405.

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MS received 28 November 1986. Accepted for publication 23 June 1987.

Appendix 5

Journal of Hydrology, 88 (1986) 201–211
Elsevier Science Publishers B.V., Amsterdam — Printed in The Netherlands

[3]

THE INFLUENCE OF LAND USE ON WATER YIELD IN UPLAND AREAS OF THE U.K.*

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(Received December 12, 1985; accepted after revision July 15, 1986)

ABSTRACT

Calder, I.R., 1986. The influence of land use on water yield in upland areas of the U.K. J. Hydrol., 88: 201–211.

A series of experiments, designed to investigate the seasonal differences in evaporation from the major upland vegetation types, is described together with preliminary results. These results were used to calibrate a simple (minimal data requirement) seasonal model which relates transpiration to the local climatological Penman E_t estimate and interception, via an exponential relationship, to the daily precipitation. The model adequately describes currently available observations of soil moisture deficit, interception loss and runoff in the uplands. A practical application of the model, to investigate the effects of the recent program of afforestation on the seasonal runoff from the Crinan canal catchments, is outlined. Although differences in the evaporative characteristics of the major upland vegetation types are now fairly well understood, further studies are needed both to investigate the effects of afforestation on "low flows" in rivers and to answer questions concerning the effects of evaporation from large scale forests on the atmosphere.

INTRODUCTION

By the late nineteen-seventies the gross effects on water resources of afforesting grass moorland in the wet upland areas of the U.K., that annual evaporative losses would be almost doubled and annual runoff reduced by about 20%, were well recognised (Calder and Newson, 1979). These results were of sufficient significance, to many water supply and hydroelectric power interests, to warrant further research. This research was directed, not only to quantify the effects better, but also to investigate whether these observations were directly applicable to the Scottish uplands where heather rather than grass moorland predominates and where snow forms a significant component of the annual precipitation. The questions then being posed can be summarized as "what are the effects on water resources when: (1) forests replace heather moorland? (2) snow is a significant component of the annual precipitation?" and "what are the seasonal differences in evaporation (and runoff) from the different upland vegetation types?"

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*Based on a paper presented to the British Hydrological Society meeting on "Evaporation theory and practice", London, 9 December 1985.

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0022-1694/86/$03.50

A research programme, involving process studies and catchment experiments was initiated by the Institute of Hydrology to investigate these topics and preliminary results from the process studies are now available.

METHOD

The philosophy adopted to interpret the results of the process studies was first to understand the basic exchange mechanisms involved, using as a framework "research" models based on the Penman-Monteith (Monteith, 1965) equation and then to develop and calibrate simpler, more empirical, models of evaporation which require only minimal data. Central to the simpler methods is the Penman (1948) evaporation equation and, in particular, the Penman E_t potential transpiration estimate for short grass which, for the practical purpose of predicting evaporative losses from grassland (when well supplied with water and when not subject to low temperatures which may inhibit growth) has stood the test of time and remains unsurpassed. The Penman equation, when used in conjunction with a "transpiration factor", the ratio of actual transpiration to the Penman E_t (short grass) estimate, also has value in estimating transpiration losses from upland forests and heather (see e.g. Calder and Newson, 1979; Calder, 1982, 1985). Interception losses from tall vegetation are not, however, well described by the Penman approach and it is advantageous to consider these separately (see e.g. Calder and Newson, 1979; Shuttleworth and Calder, 1979).

EXPERIMENTAL STUDIES

Four new research projects were initiated to determine the evaporative characteristics of upland vegetation under different climatic conditions; these involved neutron probe observations of soil moisture (following standard Institute of Hydrology procedures; Bell, 1976; Calder, 1979) to determine relative transpiration rates, a wet-surface portable lysimeter system to investigate the interception of rainfall by short and medium height vegetation, studies of the mass and energy transport over a smooth snow surface and complementary studies of snow interception from an aerodynamically rough forest surface.

Soil moisture studies

The soil moisture observations were made under heather moorland and young and mature forest on the catchments of the Crinan canal reservoirs, Strathclyde Region, Scotland (Calder et al., 1982) and under heather and grass moorland and mature forest on the Institute of Hydrology's experimental catchments at Balquhidder, Central Region, Scotland. The Crinan studies, which are operated in collaboration with the British Waterways Board, were begun in 1979 and are still continuing, and will continue, hopefully, until the young forest reaches maturity, to show the transition in evaporation rates as the forest develops. The results already obtained show clearly the large differences that are to be expected in soil moisture deficits beneath the mature forest as compared with the heather and grass moorland (Fig. 1) at both the Balquhidder and Crinan sites.

Wet-surface lysimeter

A portable weighing lysimeter system, incorporating an electronic balance, together with meteorological and surface temperature sensors linked to a microcomputer, was developed to investigate the interception characteristics of intermediate height vegetation. The system was operated at a number of Scottish upland sites including Crinan, Balquhidder, Killin and Aviemore. It was also operated on a heather moor near Thetford in East Anglia (Hall, 1985, 1986) in conjunction with micrometeorological studies being carried out by the Institute of Hydrology. From these studies (Calder et al., 1984a) and also from studies carried out on Sneaton moor, Yorkshire, using fixed lysimeters (Wallace et al., 1982, 1984), the interception characteristics were determined and information was also obtained on the transpiration characteristics of heather.

"Smooth" snow pack studies

When snow covers short vegetation the resulting surface generally becomes, aerodynamically, very much smoother. It would therefore be expected that the turbulent transport of both heat and vapour from the new surface would be inhibited. Furthermore, because the albedo of the snow surface is generally much higher and there is an extra energy requirement in terms of the latent heat of fusion, it is reasonable to assume that evaporation rates will be much reduced as compared with a wet vegetated surface experiencing the same external meteorological conditions. Experiments carried out at Finse, Norway, to study the exchange processes, mainly for improving snow melt models have, indeed, confirmed this general view (Harding et al., 1986). The studies, which involved neutron probe measurements of the equivalent water content of the pack, the use of the portable lysimeter to measure evaporation and condensation rates and measurements of the temperature and wind profiles above the pack showed that evaporation rates never exceeded 0.06 mm h^{-1} and, over time periods of the order of one day, evaporative losses were generally counterbalanced by periods when condensation occurred. Measurements from the lysimeter of aerodynamic resistance of the pack to water vapour transport and wind profile measurements of the aerodynamic resistance to momentum transport were usually consistent with the aerodynamic resistance function:

$$r_a = 300 \cdot U^{-1} \mathrm{s\,m}^{-1}$$

where U is the windspeed (m s^{-1}) recorded at a height of 2 m. (Resistances significantly higher than those given by this equation were however recorded from the very smooth surface produced immediately after snowfall (Harding et al., 1986).) Despite the relatively high aerodynamic resistance of the snow

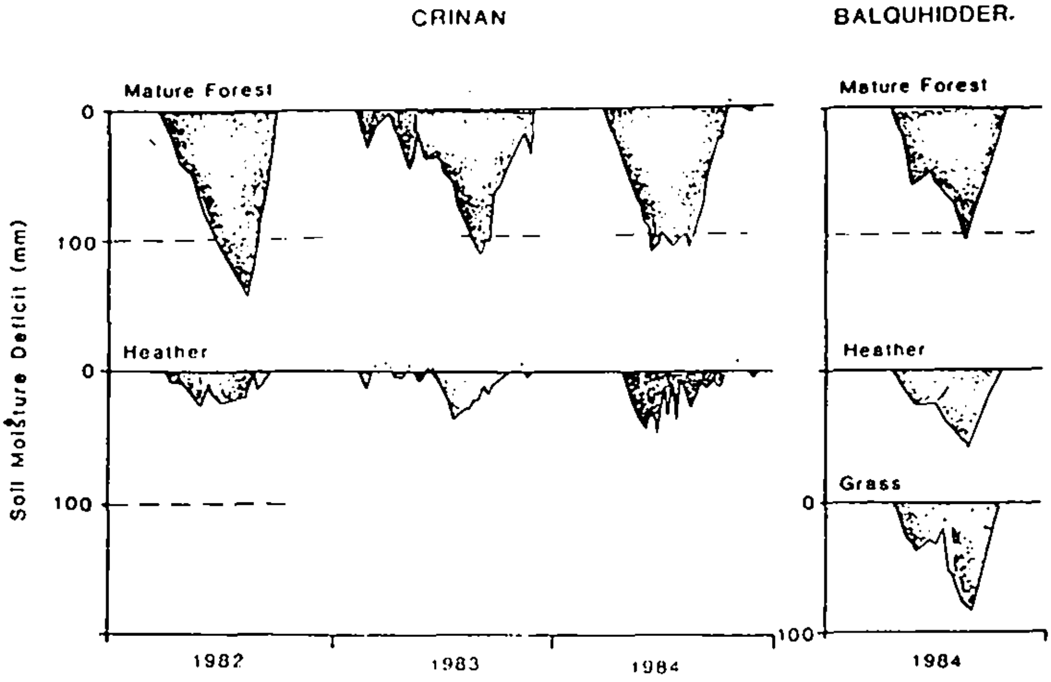
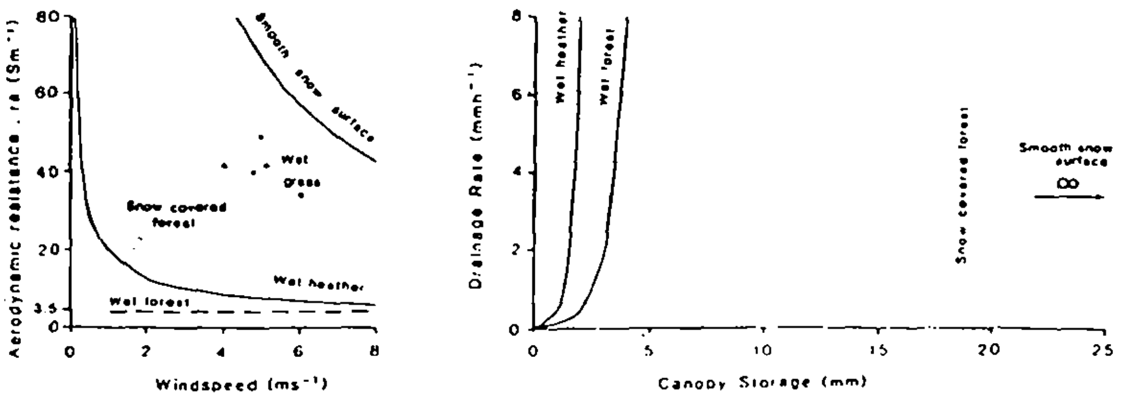


Fig. 1. Soil moisture deficits measured beneath mature spruce forest, heather and grass moorland at Crinan and Balquhidder.

surface, about half of the energy for melting the pack in spring was, nevertheless, supplied by sensible heat transport (usually during stormy periods), the rest being accounted for by radiant energy inputs.

Snow interception from forests

The complementary studies, designed to investigate the transfer mechanisms from snow covered rough vegetation, were carried out at a site in the Queens forest near Aviemore, in the Highland Region of Scotland. Three principal experiments were conducted: a gamma-ray attenuation rig (developed from a system originally devised by Strathclyde Applied Physics Department, see Olszyczka, 1979) was used to measure the change in density, and hence infer changes in water content, of a 40-m transect of the canopy; a "tree weighing" experiment was used to measure directly the canopy storage of a single tree; and heated plastic-sheet net-rainfall gauges were used to measure the net precipitation, whether in the form of snow or water, dropping off the canopy. These studies, although not complete, have demonstrated the importance of snow interception from forests; they show that evaporative losses from trees in snow conditions may be similar, if not greater, than those in wet conditions whereas a snow cover on short vegetation will tend to reduce evaporative losses compared with those in wet conditions. The reasons for this are that the much larger storage capacity of snow on the canopy (> 20 mm water equivalent) may, in terms of overall loss, compensate for, if not outweigh,



Typical Evaporation Rates (mmh⁻¹)		
	Wet Conditions	Snow Conditions
Forest	0.25	0-0.5
Heather	0.15	–
Grass	<0.1	<0.06 (evap ≈ condensation)

Fig. 2. Aerodynamic resistance as a function of windspeed, drainage rates as a function of canopy storage and typical evaporation rates determined for the different vegetation types in rain and snow conditions.

the effects of the higher aerodynamic resistance (boundary layer resistance) brought about by a reduction in both surface roughness and a reduced evaporating surface area. The gamma-ray studies (Calder and Wright, 1986) have also confirmed the parameter values in a previously derived drainage function for spruce forest in wet conditions (Calder, 1977).

The results of these and other studies of interception from the different vegetation types under both rain and snowfall conditions are shown in Fig. 2. A summary of the transpiration results, relating measurements of actual evaporation in dry conditions to the Penman E_t estimate for grass via the ratio β, is shown in Table 1.

EVOLUTION OF THE SIMPLE SEASONAL MODEL

Calder and Newson (1979) proposed a method, involving a minimal data requirement, for calculating the effects on annual water losses brought about by afforesting upland grassland catchments. This involved the assumption that evaporation losses from grassland and transpiration losses from forests could be estimated from the annual Penman estimate (E_{ta}) whilst the annual interception loss from the forest could be obtained from a simple function involving annual rainfall (P_a), i.e.:

$$\text{annual evap.} = E_{ta} + f(P_a \cdot \alpha - w_a \cdot E_{ta}) \quad (1)$$

where α is the interception fraction (35–40% for regions of the U.K. where annual rainfall exceeds 1000 mm), w_a is the fraction of the year when the canopy is wet ($\approx P_a \times 1.22 \cdot 10^{-4}$) and f is the fraction of the catchment under canopy coverage. Use of aerial photographs has shown that, typically, for areas marked on maps as extensive forests, the f value is 0.66, the remainder comprising roads, rides, riverbanks, clearings and immature plantation with unclosed canopies. (For catchments with a high proportion of immature forest it may be worthwhile to obtain a more accurate estimate. Binns (pers. commun., 1983) suggested that an "S"-shaped function may be appropriate and such a relationship has been tentatively assumed and used in the water resource investigation outlined below with f values, for trees aged between 0 and 5 yrs as 0.1, 6–10 as

TABLE 1

Interception and transpiration observations summarized in terms of the average interception ratio, α, the daily interception model parameters, γ, δ, and the ratio of actual to Penman E_t evaporation, β

Source	Period	Interception parameters			Transpiration fraction β
		α	γ (mm)	δ (mm^{-1})	
Forest					
All sites interception: Plynlimon, Dolydd, Crinan and Aviemore		0.35	6.99	0.099	
Plynlimon forest lysimeter	1974–1976	0.30	6.[illegible]	0.099	
Dolydd	1981–1983	0.39	7.6	0.099	
Crinan	1978–1980	0.36	6.6	0.099	
Aviemore	1982–1984*	0.45	7.1	0.099	
Heather					
Model estimate derived using automatic weather station data and measured interception parameters (Calder et al., 1986)	1981		2.65	0.36	
Crinan, neutron probe (Calder et al., 1982, 1984b)	1981–1983				0.58–0.67
Laws's heather lysimeters (Calder et al., 1983b)	1964–1968	0.16			0.47
Sneaton moor lysimeter (Wallace et al., 1982)	1980	0.19			0.25–0.5
Grass					
Wye Catchment Plynlimon indicates total annual evaporation consistent with					

* Not including snow periods.

0.33, 11-15 as 0.75, 16–20 as 0.95 and 20 + as 1.0. The results of further studies are awaited to test the validity of this assumption.)

Research on the evaporative characteristics of heather has established that transpiration losses are smaller but interception losses greater than those from grassland. These observations suggest (Calder, 1985; see Table 1) that the annual interception losses from heather can be estimated with an equation of the form:

$$\text{annual evap.} = \beta \cdot E_{ta}(1 - w_a) + \alpha \cdot P_a \qquad (2)$$

where $\beta = 0.5$ and $\alpha = 0.2$.

Two further assumptions need to be made (and tested) to arrive at the simple seasonal model. These are that seasonal estimates of evaporation can be obtained by "bulking up" daily estimates of both transpiration, obtained as the product of the β parameter, a climatologically derived daily Penman E_t estimate and a term $(1 - w)$ which represents the fraction of the day that the canopy is dry, and interception, derived from an exponential relationship involving daily precipitation $[P(\text{mm})]$, i.e.,

$$\text{daily evap.} = \beta \cdot E_t(1 - w) + \gamma [1 - \exp(-\delta \cdot P)] \qquad (3)$$

where w is the fraction of the day the canopy is wet ($= 0.045P$ for $P < 22$; $= 1$ for $P \geqslant 22$, after Calder and Newson, 1979) and the parameters γ and δ define the form of the interception relationship.

Some support for the former assumption is provided by soil moisture deficit modelling studies beneath heather and forest in Scotland (Calder et al., 1984b) and grassland in lowland Britain (Calder et al., 1983a). The second assumption has been tested by comparing model predictions of cumulative interception loss, using a value optimized over data collected at a number of sites (in mid-Wales at Dolydd and Hore, the west coast of Scotland at Crinan and the central Highlands of Scotland at Aviemore), with observations at an individual site (Fig. 3). The agreement is as good as, if not better than, that expected with the more sophisticated "research" models using a Rutter type (Rutter et al., 1971) interception model and a Penman-Monteith evaporation term. The inaccuracy of the research model arises because, even with the best local, short-term meteorological measurements currently available (from automatic weather stations) the model sensitivity to errors in the atmospheric humidity deficit term is such that large errors may result, e.g. uncertainties in the measurement of the wet bulb depression of 0.2°C have been shown to produce errors in the predicted interception loss of 15–20% (Calder, 1977).

Estimates of the γ and β parameters for the different vegetation types and the sources from which they were derived are shown in Table 1. At present, and until the detailed analysis of the results from the snow interception study have been completed, it is assumed that the interception losses from forests in both snow and rain conditions are the same proportion of the gross precipitation (the data from which the parameters were derived includes some snow periods). The equivalent "working assumption" for snow interception from heather or grass is that the average daily evaporation rate is zero.

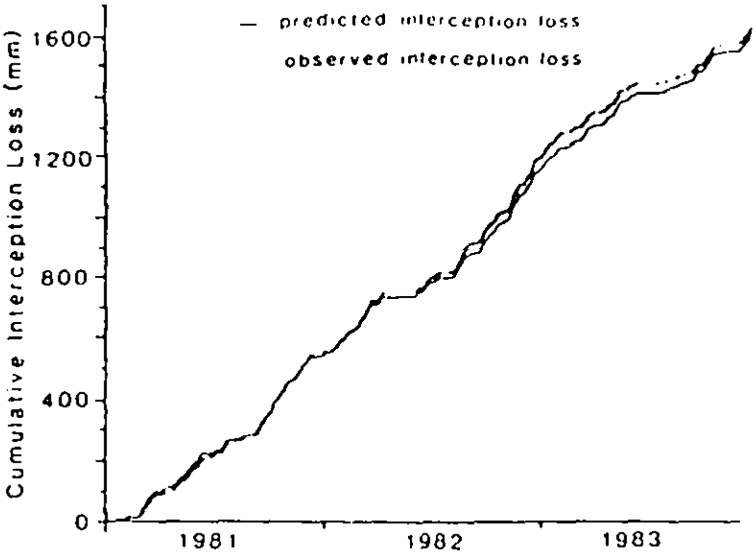


Fig. 3. Cumulative interception losses predicted with the "daily" interception model together with observations at the Dolydd site.

APPLICATION OF THE MODEL

The first practical application of the simple seasonal model was the prediction of the effects of afforestation on the seasonal runoff from the catchments that feed the Crinan canal. Historically the water supply to the canal has always been critical during dry summers and restrictions on the use of the canal have at times been necessary. Earlier studies carried out for the British Waterways Board, based on the application of the simple annual model (Calder et al., 1982) had indicated that the recent afforestation program, initiated in 1970, would, on reaching maturity by the year 2000, have reduced the runoff from the reservoired catchments by about 22%. It was perhaps then not surprising that during 1984, a year with about average annual rainfall but having a dry summer period, difficulties were experienced in meeting demand; back pumping of water from the lower reaches to the summit section had to be carried out to keep the canal in operation. To provide information for engineering decisions to augment and conserve water resources, the rainfall distribution during 1984 was chosen as an example of what in supply terms might be considered to be about a "one in ten drought year". Using this rainfall record the effects on seasonal runoff were calculated for a heather moorland with the proportions of forest canopy coverage, f, equal to 0.03, 0.16, 0.56, corresponding to those expected on the catchments in the years 1970, 1985, and 2000, respectively. The predictions from the runoff model, which operated essentially by predicting the difference between rainfall and evaporation for periods when areas of the catchments were not experiencing a soil moisture deficit, are shown in Fig. 4. The measured demand curve of the canal in 1984 for lockage and seepage is also shown in Fig. 4 together with the predicted changes in reservoir storage (assuming this demand curve). Although this treatment of the

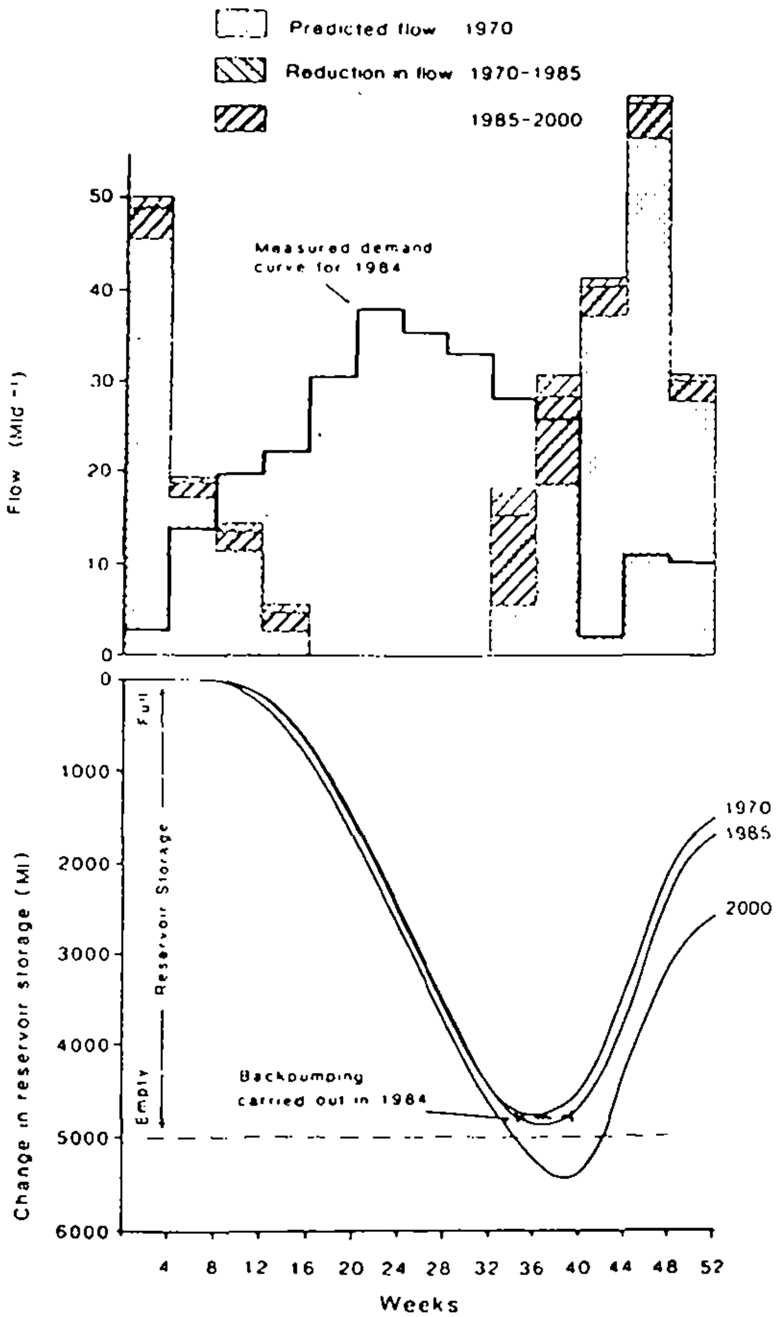


Fig. 4. Seasonal distribution of runoff and reservoir storage predicted for the Crinan canal reservoir catchments with different proportions of afforestation, corresponding to the years 1970, 1985 and 2000, given a year with a rainfall distribution equal to that recorded in 1984. The measured demand curve for the reservoir in 1984 is also shown

water supply requirements for the canal is a gross simplification of a complex operational problem the general features it shows are, probably, none the less valid. The pattern of afforestation on the catchments in 1970 would not have been sufficient to require additional backpumping, but by the year 2000 with the forestry at its most mature phase, the backpumping requirement will have more than doubled and, perhaps more importantly, it is unlikely that the reservoir would refill following a winter of average rainfall.

CONCLUSIONS

For practical purposes, the requirement for further research to investigate differences in evaporative losses from different upland vegetation types is probably now diminishing. However, as a result of the recent intensive studies into forest and heather evaporation, grass evaporation, now, is least well understood and there is a case for further studies to redress the balance. In particular, few detailed studies of grass evaporation have been carried out in the very high altitude (say > 550 m) regions of the U.K. where, for much of the year, daily average temperatures will be less than the threshold temperature of about 5°C, below which both growth and transpiration may be severely curtailed by physiological controls. Actual evaporation rates, as a consequence, may differ significantly from the Penman E_t estimate. Other areas which remain poorly understood and warrant further research, both for scientific and practical purposes, are illustrated by the present difficulty in answering questions such as: (1) How does afforestation effect "low flows" in rivers? (2) If the typical scale size of Scottish forests were increased, say by a factor of two, would interception losses (as a proportion of the annual rainfall) be reduced?.

Although these are simple questions their solution requires the application of techniques and methods which have yet to be developed. The first question involves not only a knowledge of evaporation but also of the link between evaporation, soil moisture deficit, recharge and river flow; the second requires a knowledge of the large scale interaction between the exchange of heat and water vapour from the wet surface of forests and the atmosphere.

The urgency of these questions and the availability of the necessary funding will determine if and when they are to be tackled.

ACKNOWLEDGEMENTS

The majority of the recent studies reported here were carried out for, and funded by, a consortium comprising the Natural Environment Research Council, British Waterways Board, Department of Energy, Scottish Development Department, North of Scotland Hydroelectric Board, Department of the Environment, Forestry Commission and the Water Research Centre; this support is gratefully acknowledged.

REFERENCES

Bell, J.P., 1976. Neutron probe practice. Institute of Hydrology, Wallingford, Rep. No. 19.

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

Calder, I.R., 1979. The theory of the neutron probe method. Projeto PNUD/UNESCO/BRA/75/007, Publicacao no. 4., Instituto de Pesquisas Hidraulicas, Porto Alegre, Brazil.

Calder, I.R., 1982. Forest evaporation. Proc. Can. Hydrol. Symp., 1982. Nat. Res. Counc. Can., Ottawa, Ont., pp. 173-193.

Calder, I.R., 1985. Influence of woodlands on water quantity. Inst. Biol. Proc. Environ. Div. Symp on: Weather, Woodlands and Water, Edinburgh, 23 March 1984.

Calder, I.R. and Newson, M.D., 1979. Land use and upland water resources in Britain — a strategic look. Water Resour. Bull., 16: 1628-1639.

Calder, I.R. and Wright, I.R., 1986. Gamma-ray attenuation studies of rainfall interception from Sitka spruce — some evidence for an additional transport mechanism. Water Resour. Res., 22: 409–417.

Calder, I.R., Hall, R.L., Harding, R.J., Rosier, P.T.W. and Wright, I.R. 1982. Report on collaborative project with the British Waterways Board on the effects of afforestation on the runoff from the catchments supplying the Crinan canal reservoirs. Institute of Hydrology Report, Wallingford.

Calder, I.R., Hall, R.L., Harding, R.J. and Rosier, P.T.W. 1983a. Upland afforestation and water resources progress report. Process studies 1982-1983. Institute of Hydrology Report, Wallingford.

Calder, I.R., Harding, R.J. and Rosier, P.T.W., 1983b. An objective assessment of soil moisture deficit models. J. Hydrol., 60: 329-355.

Calder, I.R., Hall, R.L., Harding, R.J. and Wright, I.R. 1984a. The use of a wet-surface weighing lysimeter system in rainfall interception studies of heather (*Calluna vulgaris*). J. Climatol. Appl. Meteorol., 23: 461–474.

Calder, I.R., Hall, R.L., Harding, R.J., Wright, I.R. and Rosier, P.T.W. 1984b. Upland afforestation and water resources progress report. Process studies 1983-1984. Institute of Hydrology Report, Wallingford.

Calder, I.R., Hall, R.L., Harding, R.J., Wright, I.R. and Rosier, P.T.W., 1986. Upland afforestation and water resources progress report. Process studies 1985-1986. Institute of Hydrology Report, Wallingford.

Hall, R.L., 1985. Further interception studies of heather using a wet-surface weighing lysimeter system. J. Hydrol., 81: 193-210.

Hall, R.L., 1986. The use of a Pet microcomputer in rainfall interception studies of heathland. In: J.A. Clark, K. Gregson and R.A. Saffell (Editors), Computer Applications in Agricultural Environments. Proc. 42nd Nottingham Easter School in Agricultural Science. Butterworths.

Harding, R.J., Calder, I.R., Moore, C.J. and Morris, E.M., 1986. A comparison of techniques for the estimation of snow melt and evaporation from a snow surface. J. Hydrol., submitted.

Monteith, J.L., 1965. Evaporation and the environment. Symp. Soc. Exp. Biol., 19: 205-234.

Olszyczka, B., 1979. Gamma-ray determinations of surface water storage and stem water content for coniferous forests. Ph.D. thesis, Department of Applied Physics, Univ. of Strathclyde.

Penman, H.L., 1948. Natural evaporation from open water, bare soil and grass. Proc. R. Soc. Lond., Ser. A, 193: 120-145.

Rutter, A.J., Kershaw, K.A., Robins, P.C. and Morton, A.J., 1971. A predictive model of rainfall interception in forests. I: Derivation of the model from observations in a plantation of Corsican Pine. Agric. Meteorol., 9: 367-384.

Shuttleworth, W.J. and Calder, I.R., 1979. Has the Priestley-Taylor equation any relevance to forest evaporation? J. Appl. Meteorol., 18: 639-646.

Wallace, J.S., Roberts, J.M. and Roberts, A.M., 1982. Evaporation from heather moorland in North Yorkshire, England. Proc. Symp. Hydrol. Res. Basins, Bern 1982, pp. 397-405.

Wallace, J.S., Lloyd, C.R., Roberts, J.M. and Shuttleworth, W.J. 1984. A comparison of methods for estimating aerodynamic resistance of heather (*Calluna vulgaris* (L.) Hull) in the field. Agric. Forest Meteorol., 32: 289-305.

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