INSTITUTE of
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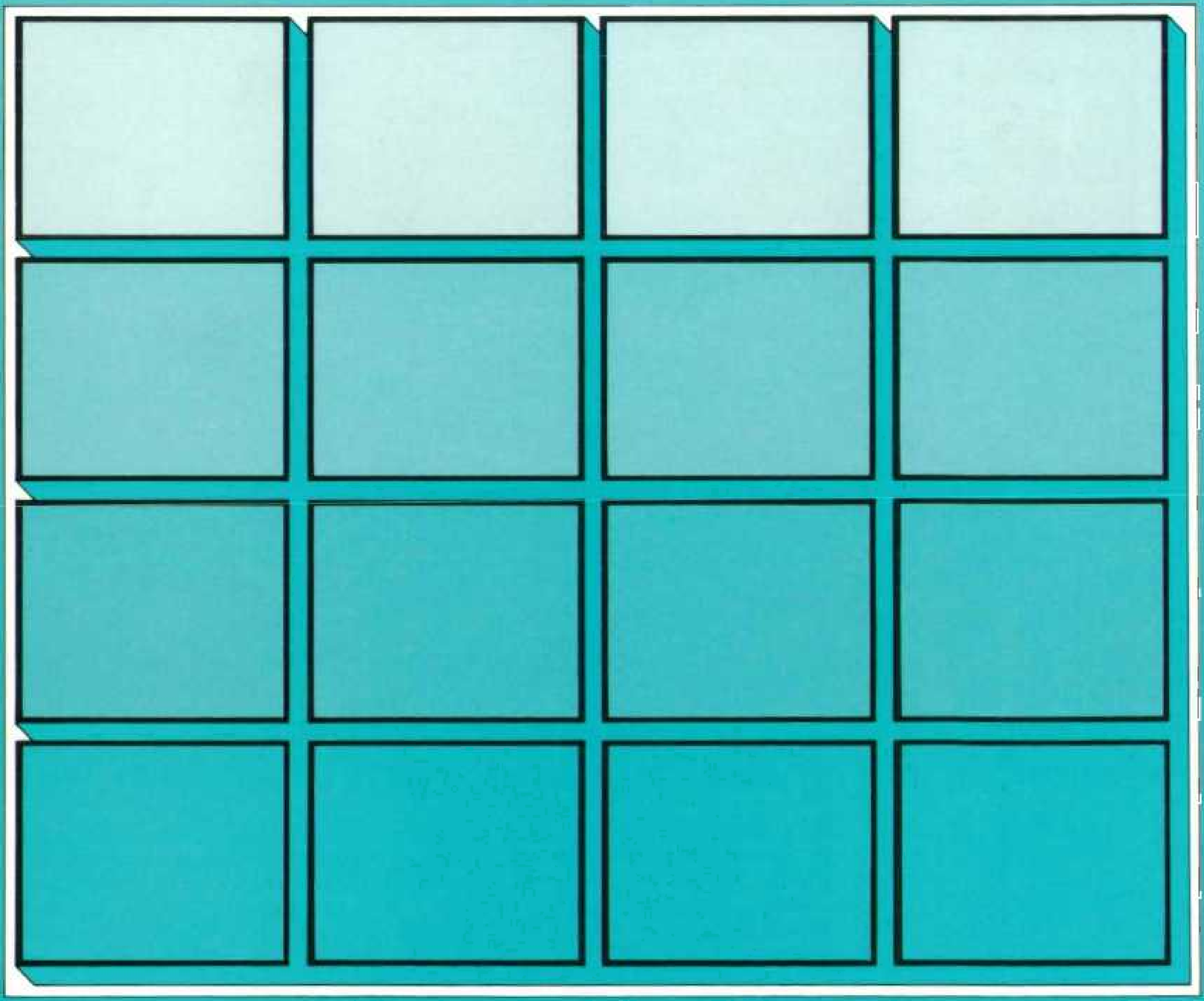


INSTITUTE of HYDROLOGY

The **Institute of Hydrology** is a component establishment of the UK Natural Environment Research Council, grant-aided from Government by the Department of Education and Science. For over 20 years the Institute has been at the forefront of research exploration of hydrological systems within complete catchment areas and into the physical processes by which rain or snow is transformed into flow in rivers. Applied studies, undertaken both in the UK and overseas, ensures that research activities are closely related to practical needs and that newly developed methods and instruments are tested for a wide range of environmental conditions.

The Institute, based at Wallingford, employs 140 staff, some 100 of whom are graduates. Staff structure is multidisciplinary involving physicists, geographers, geologists, computer scientists, mathematicians, chemists, environmental scientists, soil scientists and botanists. Research departments include catchment research, remote sensing, instrumentation, data processing, mathematical modelling, hydrogeology, hydrochemistry, soil hydrology, evaporation flux studies, vegetation-atmospheric interactions, flood and low-flow predictions, catchment response and engineering hydrology.

The budget of the Institute comprises £4.5 million per year. About 50 percent relates to research programmes funded directly by the Natural Environment Research Council. Extensive commissioned research is also carried out on behalf of government departments (both UK and overseas), various international agencies, environmental organisations and private sector clients. The Institute is also responsible for nationally archived hydrological data and for publishing annually HYDROLOGICAL DATA: UNITED KINGDOM.

Research on Forestry and Water Resources
1987-88

A Report on work funded in part by WRC Contract CS 4139 RX

by

THE CATCHMENT STUDIES AND PHYSICAL PROCESS
STUDIES SECTIONS

of

THE INSTITUTE OF HYDROLOGY

Executive Summary

This report has been prepared in response to a one year contract from Water Research Centre relating to specific aspects of the ongoing consortium funded studies of the effects of upland afforestation on water resources in Highland Scotland. It covers results obtained during 1987/88 in the catchment studies at Balquhidder and in the physical process studies which are relevant to the specific points raised in the contract.

In the catchment studies the re-calibration of the streamflow structures on the heather/grass Monachyle catchment was completed and the accumulated flow data re-computed. Checks on catchment precipitation using additional gauges in key domains have revealed no significant sources of error resulting from the location of the present network in the part forested Kirkton catchment. The Monachyle precipitation may be underestimated marginally because of the absence of a gauge in one small domain. A gauge has now been installed in it but insufficient data have been obtained so far to check this suggestion.

Further work on the data from the Automatic Weather Stations has confirmed that Penman ET is higher overall in both catchments than regional estimates would suggest. This work has indicated that the apparent increase in ET from valley bottom to high altitude exposed sites is due to higher net radiation and wind-speed at the upper sites in summer.

A hydro-geological survey has confirmed that cross-boundary movement of groundwater into the Kirkton is insignificant.

The above work has confirmed the preliminary results for the pre-treatment phase of the water balance study. At a mean of 425 mm per annum the water use of the 35% forested Kirkton catchment is significantly lower than the 634 mm per annum for the heather/grass/bracken covered Monachyle catchment. Methods of determining catchment mean ET values are still evolving. The annual means from the high altitude sites for the pre-treatment phase are similar at 540 mm per annum, suggesting that water use exceeded Penman ET in the Monachyle and was considerably lower in the Kirkton catchment.

Methods have been evolved to overcome the problems of winter flow measurement at the Upper Monachyle sub-catchment structure. Data now available indicate close similarity in water use between this and the main catchment.

Analysis of the flow response characteristics confirms that the Monachyle was the flashier catchment during the pre-treatment phase with consistently higher peaks and more rapid baseflow recession.

No firm conclusions on water use or flow response changes can be derived from the data obtained so far in the second phase of the study. To date 10% of the Monachyle has been planted out of a target of 25-30% and 14% of the Kirkton has been felled out of a target of 25%.

Sediment ratings for the pre-treatment phase have been prepared. These

indicate mean annual losses of 37 t km^{-2} and 57 t km^{-2} from the Monachyle and Kirkton respectively. Losses have increased by 3-5 times in both catchments during the initial stages of planting and felling.

In the physical process studies the major effort has gone into the study of high altitude grass water use but progress has also been made on incorporating earlier fundings into useable models.

Preliminary analysis of data from the high altitude grassland study indicates that during early summer the transpiration rate from high altitude grass is typically only one third to one half of the potential rate. Transpiration rates throughout the summer are typically only 1-2 mm a day.

Modelling studies have shown that improvements in accuracy to the annual catchment model (Calder & Newson, 1976) are possible when the influence of temperature on transpiration from upland grass is taken into account.

A physically-based research model has been developed, requiring only meteorological data as inputs, which satisfactorily describes the evaporation and melt processes of snow intercepted by a coniferous forest canopy. Ultimately, after simplification, this model will be incorporated into the simple seasonal catchment model.

3.1.1 Background

3.1.2 Experimental details

3.1.3 Results and discussion

3.2 The use of E_t in estimating evaporation from upland catchments

3.2.1 Altitudinal variation of E_t

3.3 Modelling of snow interception by coniferous forest

3.3.1 Results so far

PROPOSED WORK FOR 1988-89

1. Introduction

The Water Research Centre, acting on behalf of the Scottish Water Authorities, has been one of the main supporters of the programme of research on the effects of upland afforestation on water resources in Highland Scotland since the programme was agreed by a consortium of funding agencies in 1981. The Institute of Hydrology as the main contractors has presented detailed progress reports on the programme to an annual meeting of the consortium each year. In 1986 this report took the form of a presentation of preliminary results from the work over the period 1982-85. Whilst uncertainty remained regarding some aspects of the data, the results emerging appeared to indicate that the prediction models developed from previous work in upland Wales were inadequate for application in the more extreme conditions of Highland Scotland. These preliminary results sparked off a series of discussions which lead to modifications and extensions of the research programme. In 1987 W.R.C. presented the contractors with a list of aspects of the work on which they felt that further clarification was required. This list was framed as a formal one year contract and this response is therefore presented as a contract report. The points raised in the contract were:

Complete (as far as practicable by 31 March 1988) the investigation of possible sources of error in the data from the Balquhidder catchment studies, and report.

2. Continue to examine the water relations of high altitude grassland (interception, transpiration and evaporation), particularly providing a preliminary analysis of the situation in summer and early autumn 1987.

3. Complete the analysis of field data gathered up to 31 March and report.

Define the base-line rapid-response characteristics of both catchments to short-term events in the period ending 31 December 1984, prior to land-use change.

5. Prepare an interim report on sediment ratings and the origins of sediment in relation to forest practices observed to 31 March 1987.

6. Report on the performance of the raingauge networks.

Report on the studies of the rating of the lower Monachyle flow gauge and the consequences of re-rating this gauge on the comparison between Monachyle and Kirkton water yields.

8. Present a preliminary analysis of the hydrological behaviour of the upper Monachyle sub-catchment.

9. Investigate further and report on the Penman anomaly.

10. Prepare a list of recommendations for work proposed for the period 1 April 1988 to 31 March 1989 so that those organisations for whom WRC acts as an agent can discuss and comment on the relevance of the future programme to the water industry.

In the report which follows, responses and comments on these points have been grouped under the headings of catchment studies and physical processes rather than being presented in the above sequence.

Much of the detail was presented during a two day workshop on the results of the research programme held in Edinburgh in December 1987. Notes on these presentations were subsequently circulated in February 1988. These findings are summarised in this report and details are given of further work completed since the December meeting.

2. Catchment Studies

The preliminary results from Phase I of the catchment studies presented in 1986 suggested that water use by the part forested, part grassland Kirkton catchment was considerably less than that by the heather/grass covered Monachyle catchment. Furthermore, the Kirkton water use appeared to be lower than the Penman potential evaporation calculated from the automatic weather station data whilst that of the Monachyle was comparable with Penman. These preliminary findings caused concern since the Calder and Newson model, derived from catchment and process studies at Plynlimon and elsewhere, would have predicted water use by the Kirkton considerably in excess of Penman.

This unexpected result gave rise to a number of queries concerning possible systematic errors in the water balance data and the water-tightness of the Kirkton catchment in particular.

During 1987 considerable progress was made in investigating these possible sources of error. A hydrogeological study of the Kirkton catchment was commissioned and the subsequent report (Robins and Mendum, 1987) concluded that no significant movement of groundwater across the catchment boundary was occurring. The results emerging from investigations of possible sources of error in the terms of the water balance and in the Penman estimates are discussed in the following sections. Progress in the analysis of the sediment transport data is described. A preliminary balance analysis of the upper Monachyle sub-catchment is presented. The water balances of the main catchments are updated to include the first two years of Phase II of the study in which the forest in the Kirkton is being felled and the lower 30% of the Monachyle is being afforested.

2.1 PRECIPITATION

The design of the original networks of 11 ground level gauges in each catchment and the sub-network of snow measurement sites has been described exhaustively in previous reports.

In discussion of the preliminary results the remarkable stability of the between-site relationships within the networks was noted and the use of these relationships to infill gaps in the data during rainfall only periods was generally agreed to be reasonable. Queries were raised, however, concerning a number of sites and the extent to which they were fully representative of their 'domains'. As a check on these, five additional gauges were installed during 1986 and 1987. In the Kirkton two were installed in domain C3Y (see Fig. 2.1.1) to check on the original gauge which had given consistent readings throughout the 1982/85 period at 81% of the catchment mean. A third gauge was installed close to the southern end of the long narrow domain C3W on the western slopes. This was placed immediately adjacent to a long term Meteorological Office storage gauge (not part of the network) to obtain also comparative readings between a ground level and a 30 cm high gauge. In the Monachyle two additional gauges were installed, one in domain B3Z on the eastern side which had been consistently the lowest reading domain and the other in the previously ungauged domain D2W covering the area above 700 m on the western side. The latter was not installed until early autumn 1987 and prolonged snow coverage during the winter has resulted in no useful data from it to date.

Whilst some scatter is apparent in the comparative readings in domains C3Y, C3W and B3Z the regressions and the cumulative totals in Table 2.1.1 give no indication that the original gauges were unrepresentative of these domains. It is interesting to note, however, that the standard 30 cm high gauge, MO, gives consistently lower readings that the adjacent ground level gauge C3W(2).

From the initial results of these ongoing comparisons it would appear that no systematic error is being introduced into the catchment precipitation estimates by 'the existing gauges in domains C3Y, C3W and B3Z. Confirmation of the existing readings in these domains reinforces the distribution pattern emerging from the data. This indicates a steep uniform gradient with altitude on the east facing slopes of both catchments with a more complex pattern on the west facing slopes. The minimum precipitation in both catchments occurs midway up these slopes. The gradient on the east facing slopes suggests that the D2W domain on the SW of Monachyle above 700 m should have the highest precipitation. Readings on the new gauge during 1988 will reveal whether this is in fact the case. If so, the absence of readings from this small domain in previous years would mean that the catchment rainfall has been underestimated, though consideration of the gradient and the domain area would suggest that the effect on the catchment mean is unlikely to be more than 1-3%. Nevertheless, the implication is that the water use of the catchment may have been underestimated, ie. that the differences between the catchments and between water use and Penman is greater than current figures suggest (Section 2.4).

A second aspect of precipitation which gives rise to some uncertainty is the validity of the method of estimating snow inputs. This assumes that the between-site relationships determined during rainfall periods also apply when the precipitation at some or all of the sites is falling as snow. Results from comparisons with a prototype combined snow and rainfall gauge installed at one low level site in the Monachyle during 1987 have been inconclusive so far since only small inputs of snow were recorded there last winter. Whilst there seems to be no major theoretical flaw in the above assumption regarding snow inputs, practical difficulties arise because of lateral movement of snow in high windspeed conditions. This redistribution makes it difficult to obtain point measurements to verify the assumption, particularly in the steep rough topography of the upper areas of the catchments. It also raises the question of whether there is a net gain or loss resulting from movement over the catchment boundaries. Such errors must be viewed in perspective however. On average snow accounts for 10-30% of the input depending on altitude, the bulk of this being wet snow which either melts soon after falling or coalesces into stable snowpack.

TABLE 2.1.1 Comparison of Precipitation Measurements within Key Domains in the Catchments

DOMAIN C3Y, KIRKTON

Network gauge C3Y, check gauges C3Y(2), C3Y(3)

No. Readings	Cumulative totals (mm)		
	C3Y	C3Y(2)	C3Y(3)
21	3946	3920	-
8	1785		1777

Regressions: C3Y(2) = 0.917 C3Y + 14.3 $r^2 = 0.91$
C3Y(3) = 0.837 C3Y + 35.4 $r^2 = 0.81$

DOMAIN C3W, KIRKTON

Network gauge C3W, check gauge C3W(2), standard gauge, MO

No. Readings	Cumulative totals (mm)		
	C3W	C3W(2)	MO
o	1412	1397	1266

Regressions: C3W(2) = 0.940 C3W + 8.7 $r^2 = 0.90$
MO = 0.890 C3W(2) + 2.8 $r^2 = 0.93$

DOMAIN B3Z, MONACHYLE

Network gauge B3Z, check gauge B3Z(2)

No. Readings	Cumulative totals (mm)	
	B3Z	B3Z(2)
	1472	1433

Regressions: B3Z(2) = 0.879 B3Z + 20.0 $r^2 = 0.95$

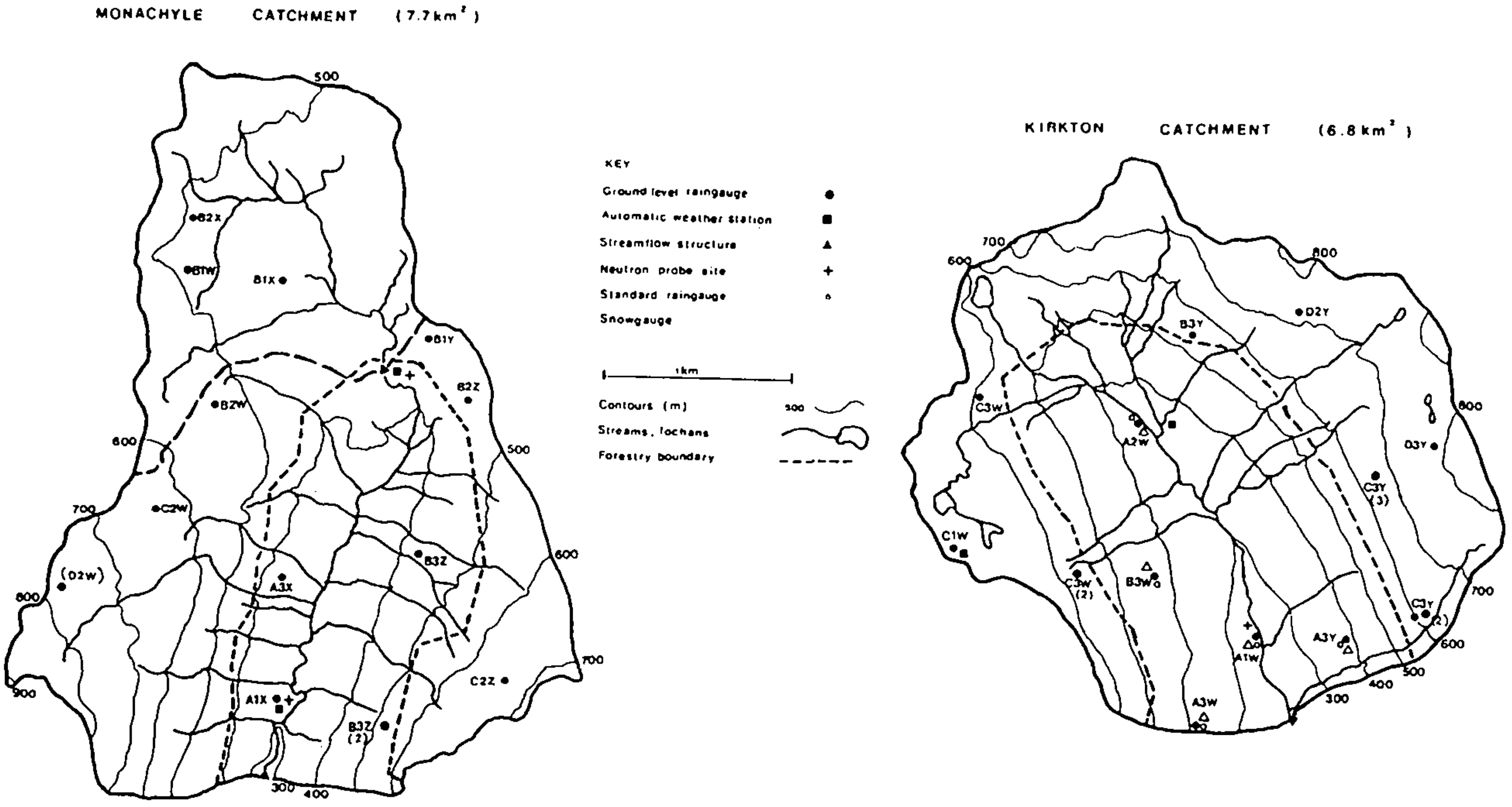


Figure 2.1.1 *Instrument networks in Monachyle and Kirkton catchments*

2.2 STREAMFLOW

Both the main flow structures had question marks over the validity of their theoretical stage/discharge ratings because of the steep rocky conditions in the upstream channels. Details of the results of their recalibrations using data from multi-vertical/multi-point current metering were given for the Kirkton in 1986 and for the Monachyle at the December 1987 discussion meeting. The revised flow figures from both are now considered to be accurate to within 1-3% on annual totals. The net effect of the revised rating of the Monachyle structure was to reduce the annual flows by some 5-6% compared to those calculated from the original rating. Monthly and annual flows are presented in Section 2.4.

Apart from early spot checks using dilution gauging, no further work has been undertaken in checking the rating of the flat-vee structure on the Upper Monachyle sub-catchment. Approach conditions there are ideal and the theoretical rating of these structures is well established (Ackers et al., 1978). Frequent freezing of the float well meant that records from this structure were incomplete for winters prior to 1986. However, after much intercomparison, a system of using pressure transducers to obtain water levels when the float system was inoperative was evolved. As a result continuous flow records are now available from April 1986. These are discussed further in Section 2.4.

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. 2.2.1 and 2.2.2 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. 2.2.3.. 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.

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 between the catchments. Such information must come from before and after comparisons within the catchments when the planting in the Monachyle and the felling in the Kirkton are completed.

During the initial stages of the Phase II land use changes data are being accumulated for future comparisons but little can be gained from them during this transition period.

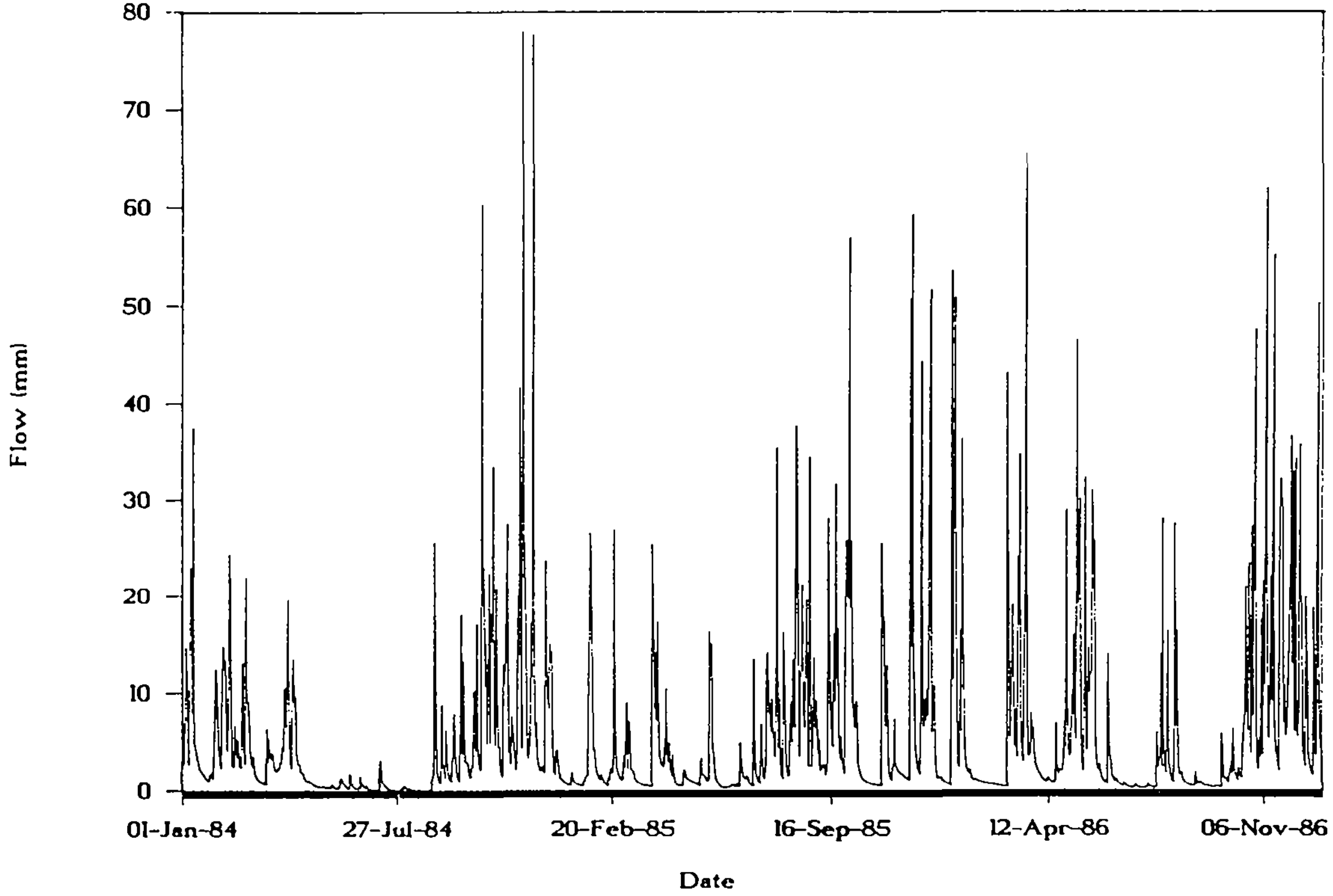


Figure 2.2.1 *Monachyle daily flows*

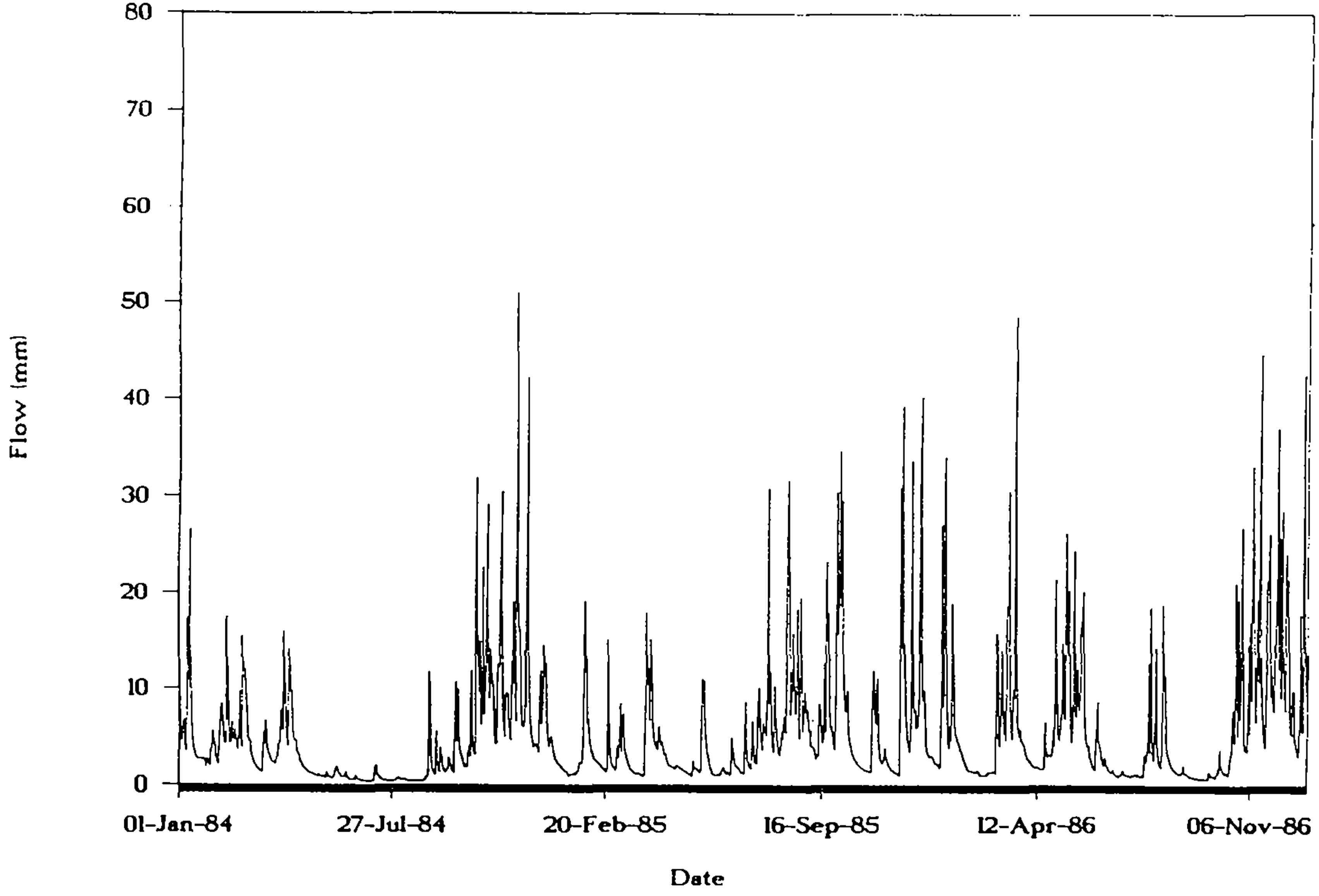


Figure 2.2.2 Kirkton daily flows

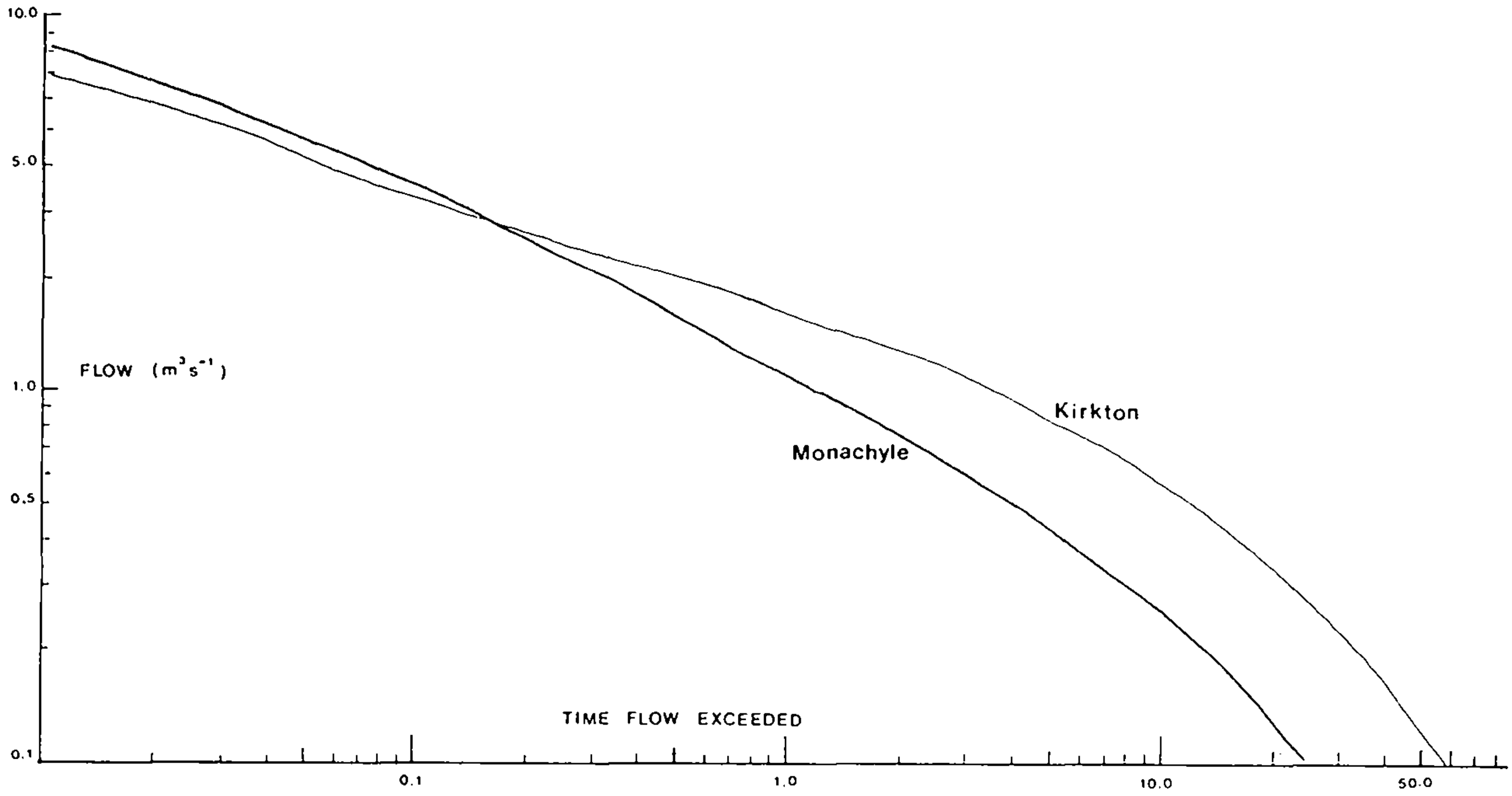


Figure 2.2.3 *Monachyle and Kirkton flow duration curves*

2.3 PENMAN ESTIMATES

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.

As indicated in Figure 2.1.1 a network of 4 AWS has been 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 Kirkton Forest at 380 m. In topographical terms the upper two stations are sampling 'ridge top' situations in the Monachyle and Kirkton catchments, while the Monachyle Glen and Kirkton Forest sites sample conditions in the bottom of N-S valleys. A fifth station, Tulloch Farm, was installed at 140 m at an early stage to provide an easily accessible reference station.

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.

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 3.1.3).

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.

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. During the past year, further comparisons of the individual variables have been carried out.

Regressions of monthly mean daily values of solar, net, temperature, saturated humidity deficit and wind speed against the Tulloch Farm values for all complete months for all stations are listed in Table 2.3.1. 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. Comparison of the slopes of the regression lines 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.

This study of the individual variables revealed that a few months previously considered to have good data were suspect. Revised annual estimates of ET from the stations are listed in Table 2.3.2.
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 2.4.

TABLE 2.3.1 Monthly Mean Daily Correlations with Tulloch Farm AWS for Complete Months' data 1985-87.

Site = A x Tulloch Farm + B
N = Number of data pairs
r^2 = Coefficient of determination

SOLAR RADIATION (Wm^{-2})

Site	N	A	B	r^2
Monachyle Glen	22	0.91	1.93	0.98
Upper Monachyle	31	1.0	3.19	0.99
Kirkton High	21	1.03	1.44	0.98
Kirkton Forest	13	0.95	-2.28	0.98

NET RADIATION (Wm^{-2})

Site	N	A	B	r^2
Monachyle Glen	22	1.10	-3.60	0.96
Upper Monachyle	31	1.42	8.94	0.96
Kirkton High	22	1.35	1.66	0.96
Kirkton Forest	14	1.19	-2.63	0.88

TEMPERATURE (°C)

Site	N	A	B	r^2
Monachyle Glen	9	0.98	0.44	0.97
Upper Monachyle	31	0.99	-2.31	0.99
Kirkton High	22	0.94	-4.87	0.97
Kirkton Forest	6	0.94	-2.21	0.98

SATURATED HUMIDITY DEFICIT (gkg^{-1})

Site	N	A	B	r^2
Monachyle Glen	22	1.08	-0.27	0.93
Upper Monachyle	18	0.90	-0.27	0.93
Kirkton High	22	0.76	-0.39	0.85
Kirkton Forest	13	0.57	-0.18	0.78

WINDSPEED ($m\ s^{-1}$)

Site	N	A	B	r^2
Monachyle Glen	19	1.30	0.59	0.83
Upper Monachyle	16	1.81	0.27	0.77
Kirkton High	22	2.08	1.50	0.67
Kirkton Forest	10	0.67	0.44	0.77

TABLE 2.3.2 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

2.4 WATER USE ESTIMATES

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 2.2) 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. 2.4.1. 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 2.2. are also evident.

Cumulative plots of monthly P, Q, P-Q and ET are shown in Fig. 2.4.2 and annual totals of P, Q and P-Q are compared with Penman ET totals in Table 2.4.1. Both of these indicate that water use, AE, 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 2.2 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.

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 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. 2.4.3 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 can be interpreted as indications of ΔS. Thus, for example, when the January-March 1984 period of major snow accumulation enters and leaves the 12 month totals departures of up to 300 mm are seen to occur. 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 2.2.1.

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 2.4.2, 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 2.4.2 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.

From the above the best estimates of mean annual water use by the two catchments during the Phase 1, 'undisturbed' period are seen to be:

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

Consideration 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 2.3.2), 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) appear to rule out the possibility of errors large enough to account for the discrepancy. An on-site interception study giving a mean interception loss of 32% 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. To determine a better basis for the estimation of water use by grass in these extreme conditions, a detailed study was initiated at Balquhidder in 1986. Details of this and preliminary results from it are given in Section 3.1.

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 described in a paper by Hall (1987).

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 2.4.1 and 2.4.2 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 2.5.

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 2.4.1 suggest a downward trend in water use but a longer run of data is required before this can be confirmed.

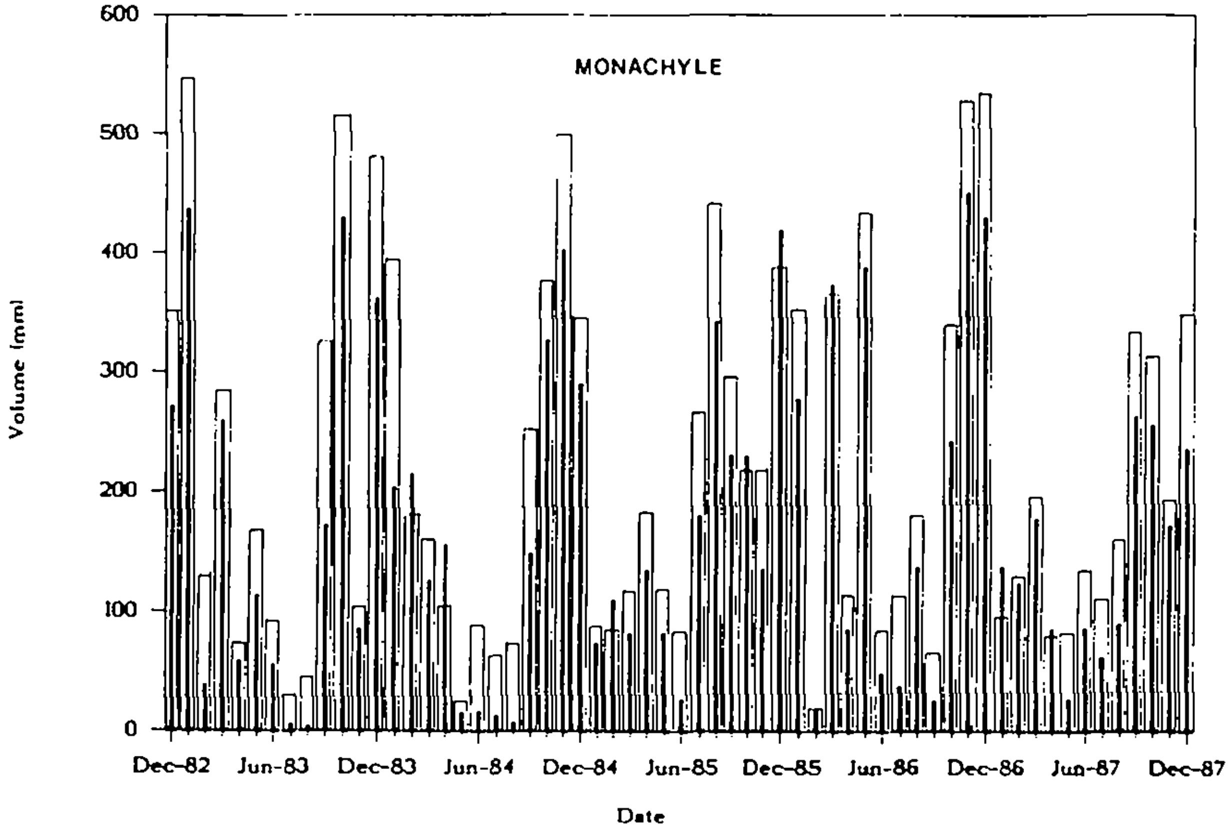
Clearly it is desirable for both studies to be extended through the period of land use changes to determine the full effects of these phases of the forestry cycle on water use and on streamflow response. Already, however, it has become apparent that afforestation in Highland Scotland is likely to result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

TABLE 24.1 *Annual totals (mm) of Precipitation (P), Streamflow (Q), Estimated Water Use (P-Q) and Penman Potential Evaporation (ET))*

Period	MONACHYLE (Heather/grass) P	MONACHYLE (Heather/grass) Q	MONACHYLE (Heather/grass) P-Q	MONACHYLE (Heather/grass) ET	KIRKTON (Forest + Grass) P	KIRKTON (Forest + Grass) Q	KIRKTON (Forest + Grass) P-Q	KIRKTON (Forest + Grass) 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 2.4.2 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



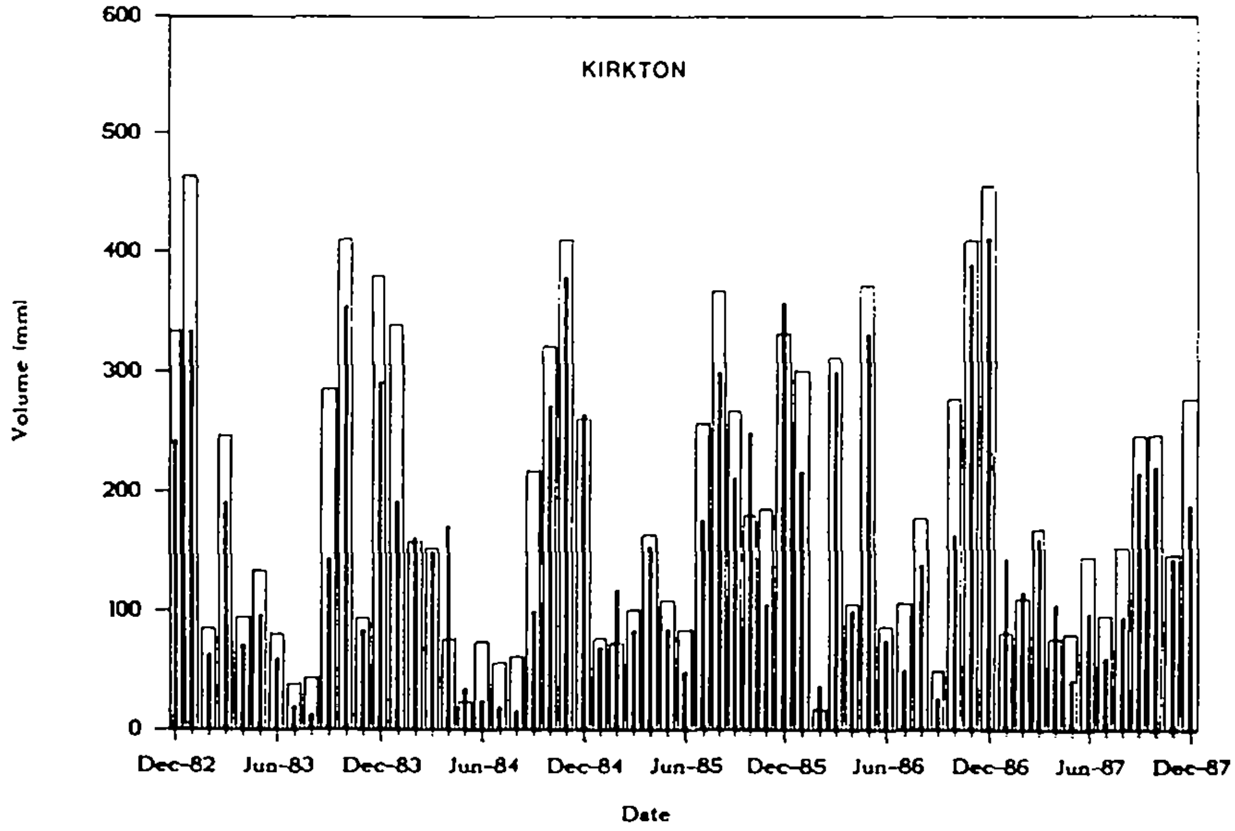


Figure 2.4.1 Monthly precipitation and streamflow

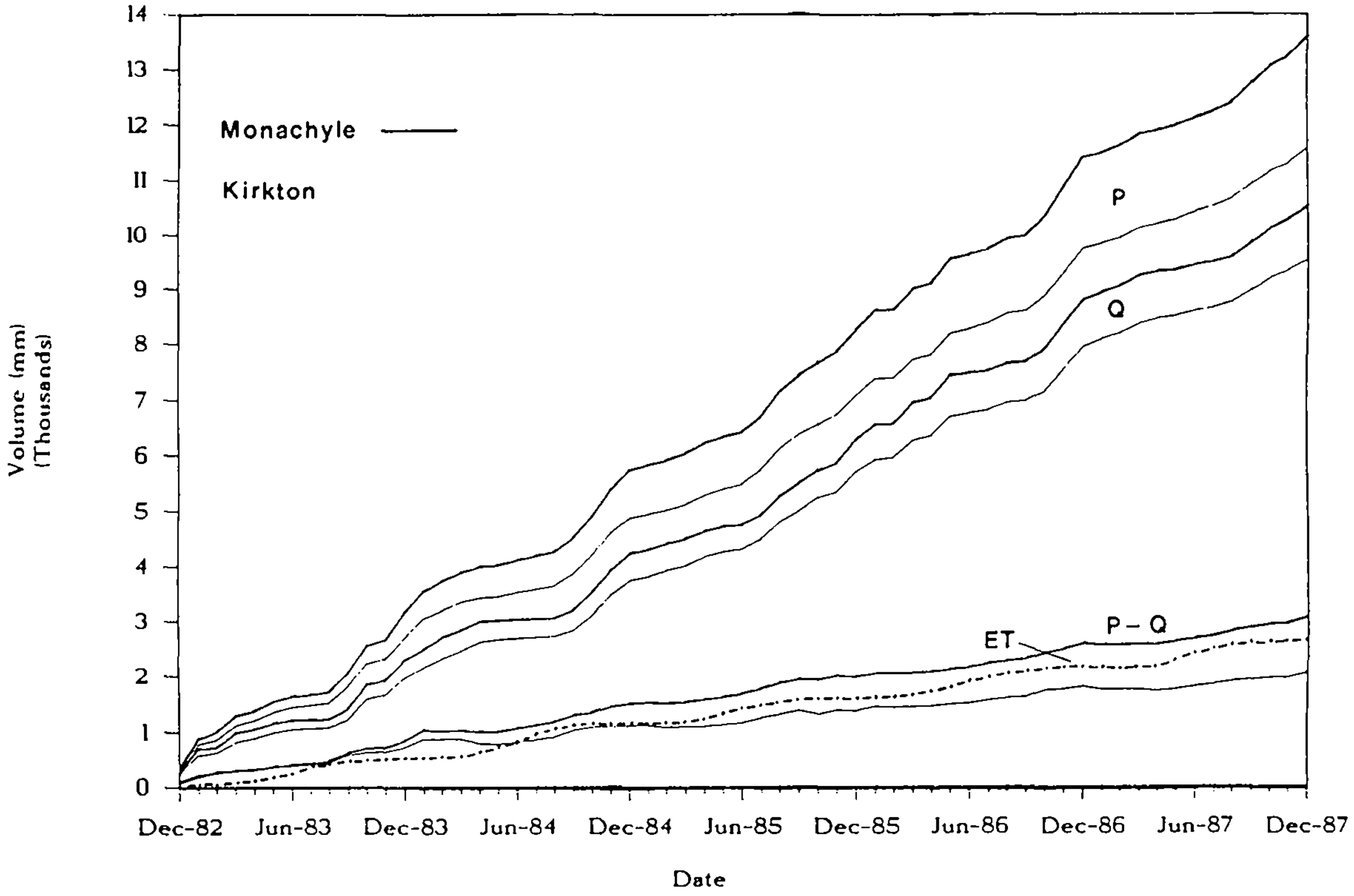
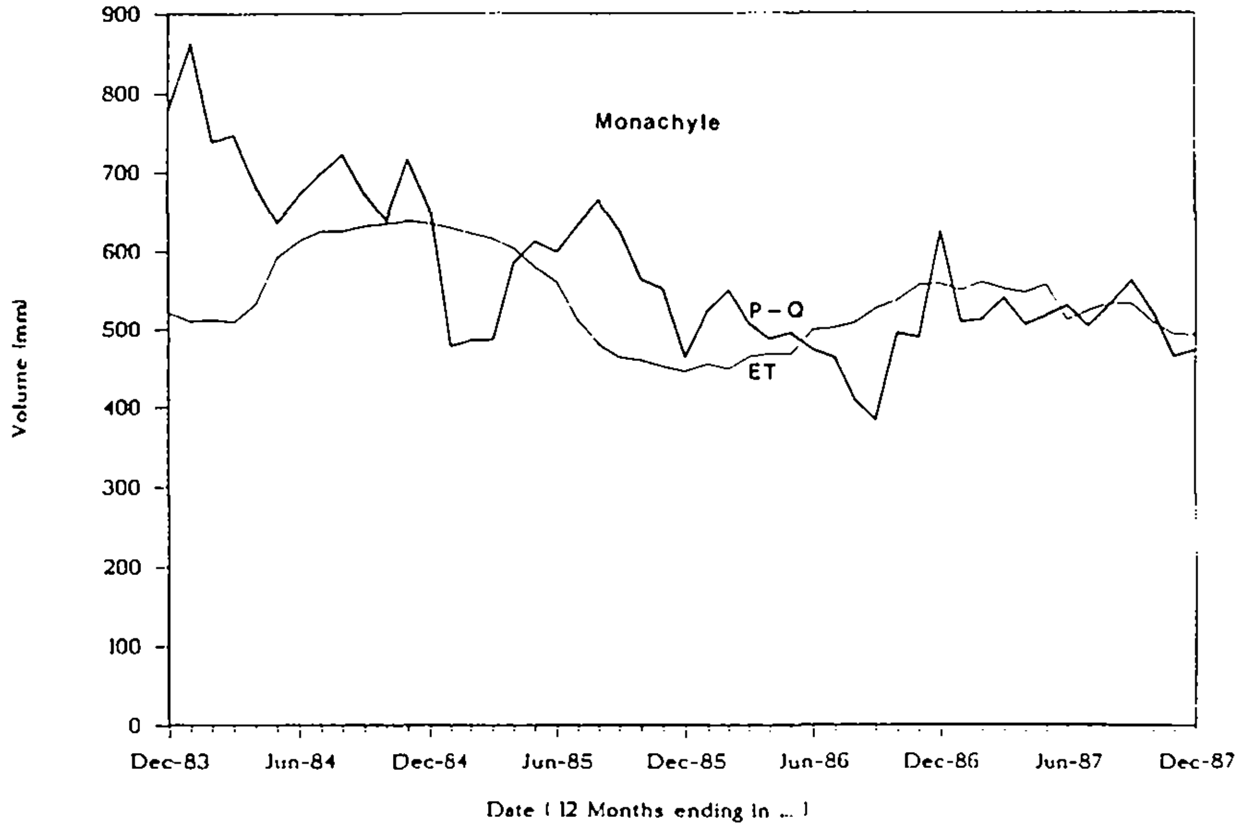


Figure 2.4.2 *Cumulative precipitation (P), streamflow (Q), estimated water use (P-Q) and Penman ET*



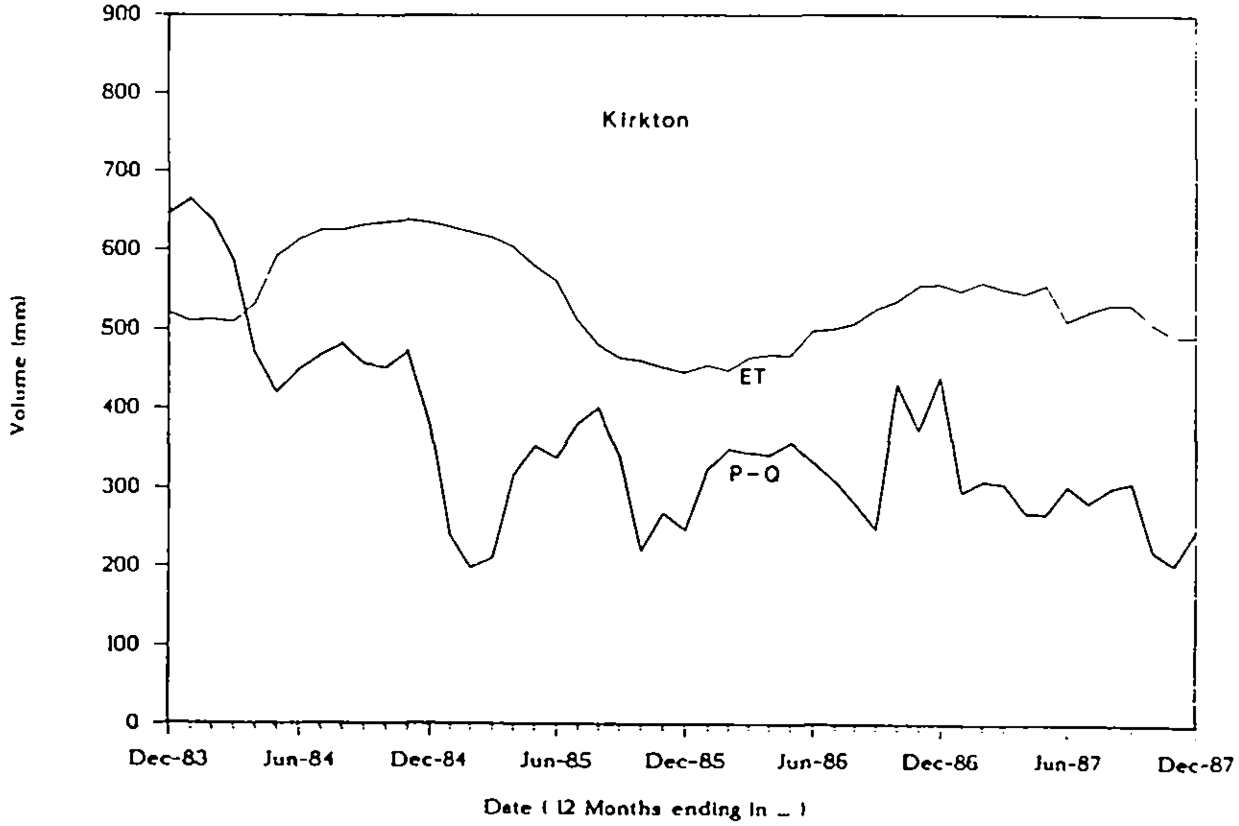


Figure 2.4.3 *Twelve month running totals of estimated water use (P-Q) and Penman ET*

2.5 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.

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.2.5.1 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 2.5.1. 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. 2.5.1C 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 2.5.1). 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 2.5.1 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. 2.5.1 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. 2.5.2, 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 2.5.1 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. 2.4.1) rather than any stabilisation within the catchments.

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 2.5.1. 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.

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 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.

TABLE 2.5.1 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

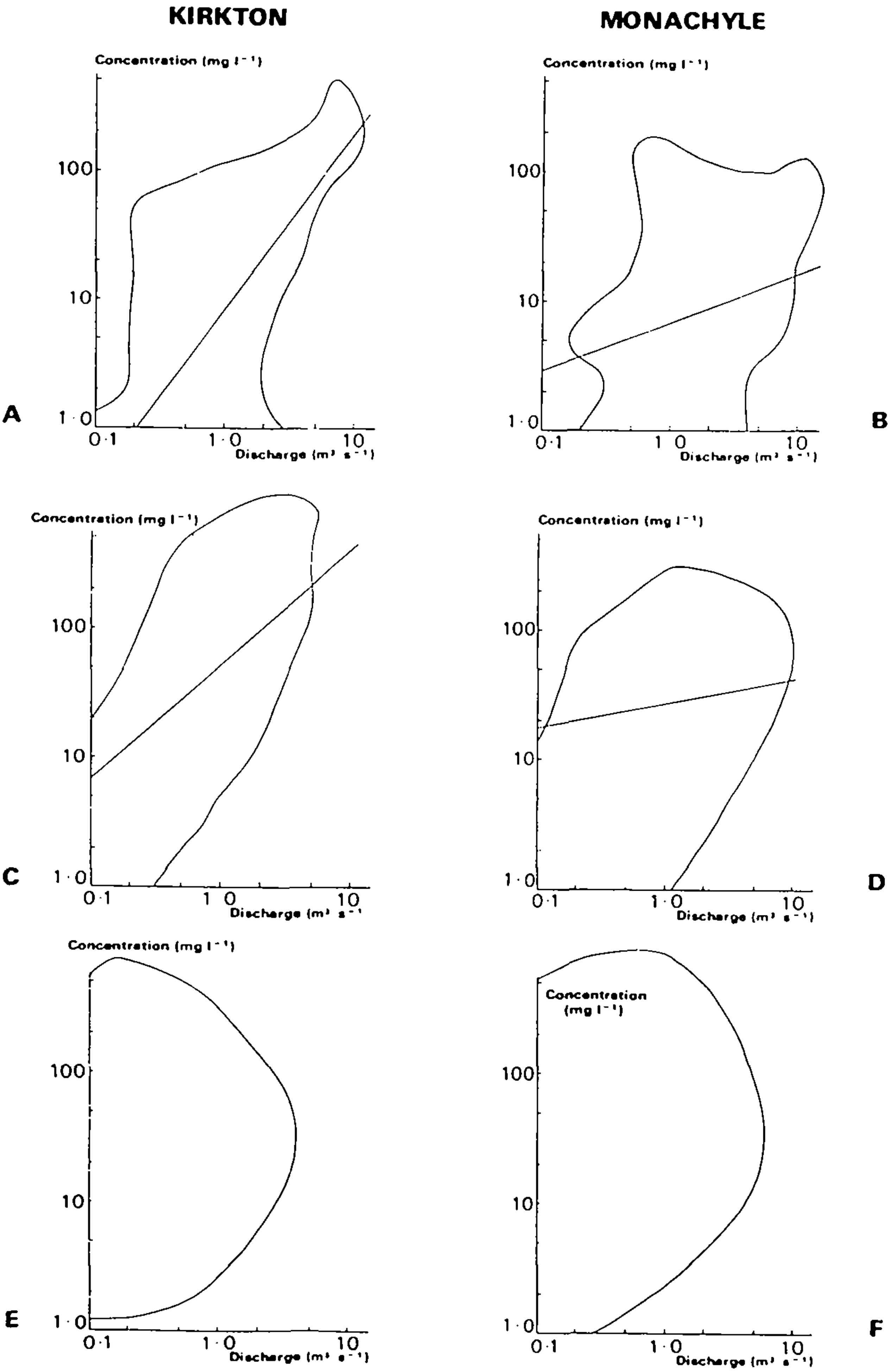


Figure 2.5.1 *Suspended sediment/discharge relationships*
A, B 1983-85; C, D 1986; E, F 1987

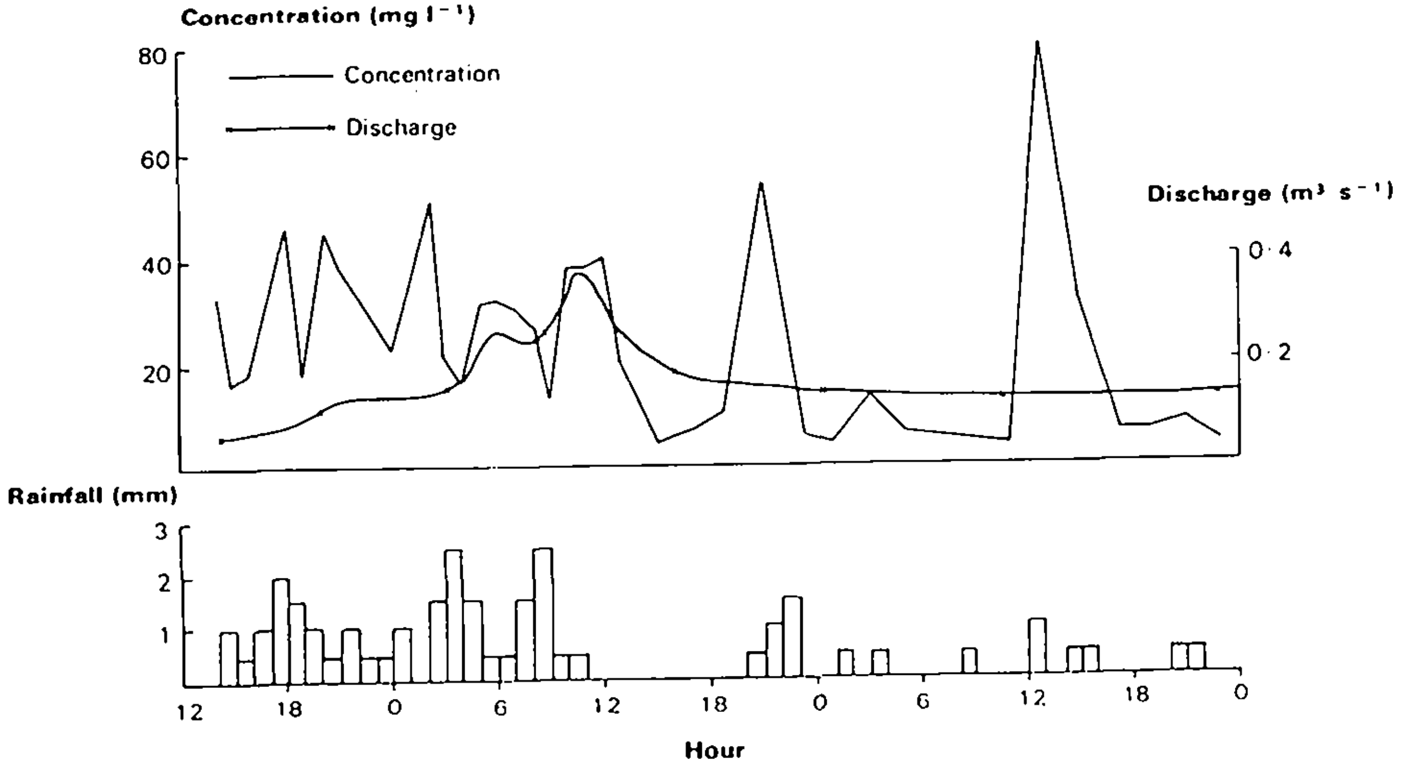


Figure 2.5.2 *Kirkton suspended sediment, flow and rainfall 29-31 May 1987*

3. Physical Processes

Work on the process studies during the past year has been concentrated upon the high altitude grassland experiment. Modelling work has also continued to improve our understanding of the snow interception process by coniferous forest and to extend the applicability of simple water-use models (based on the Penman potential evaporation estimate) to upland grassland. Reports on each of these studies are given in the following sections.

3.1 HIGH ALTITUDE GRASSLAND STUDIES

3.1.1 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.

The results from the first phase of the Balquhidder catchments 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. 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.

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.

3.1.2 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 experiments, biomass measurements (to determine the ratio of live to dead grass) 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. 3.1.1. 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 rod 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.

3.1.3 Results and Discussion

As yet analysis of data from the grassland study is still in its early stages. 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. Figure 3.1.2 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 lysimeter systems have recently (March 1988) been recommissioned for the 1988 growing season and the old loggers have been replaced with two new Campbell CR10 logging systems. These should improve the reliability and precision of the systems and facilitate data handling.

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. The total water contents in mm calculated from observations made in 1987 are plotted with the daily rainfall in Fig. 3.1.3. There was good agreement between the data from the two sets of tubes but there were one or two periods when a more frequent measurement would have been beneficial. A preliminary analysis of the measurements indicate that there may have been a period towards the end of May 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 made from April to July 1987 are plotted in Fig. 3.1.4 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. 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 products of $E_t\tau$ and $E_t b\tau$ where the temperature function τ is that used by Hall (1987). This assumes that below 5°C there is no transpiration, between 5°C and 10°C there is limited transpiration and that above 10°C transpiration occurs at the Penman rate.

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 $E_t\tau$. 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.

The preliminary analysis of the data from the lysimeters and measurements of soil moisture indicates that during the early summer the transpiration rate from high altitude grassland at the Gleann Crotha site is low: typically one third to one half of the E_t rate calculated from the meteorological data also collected at the site. There are also indications from the soil moisture data that transpiration rates throughout the summer are typically only 1-2 mm a day. This is in agreement with expectations but results from continued measurements during 1988 will be needed before firm conclusions can be drawn.

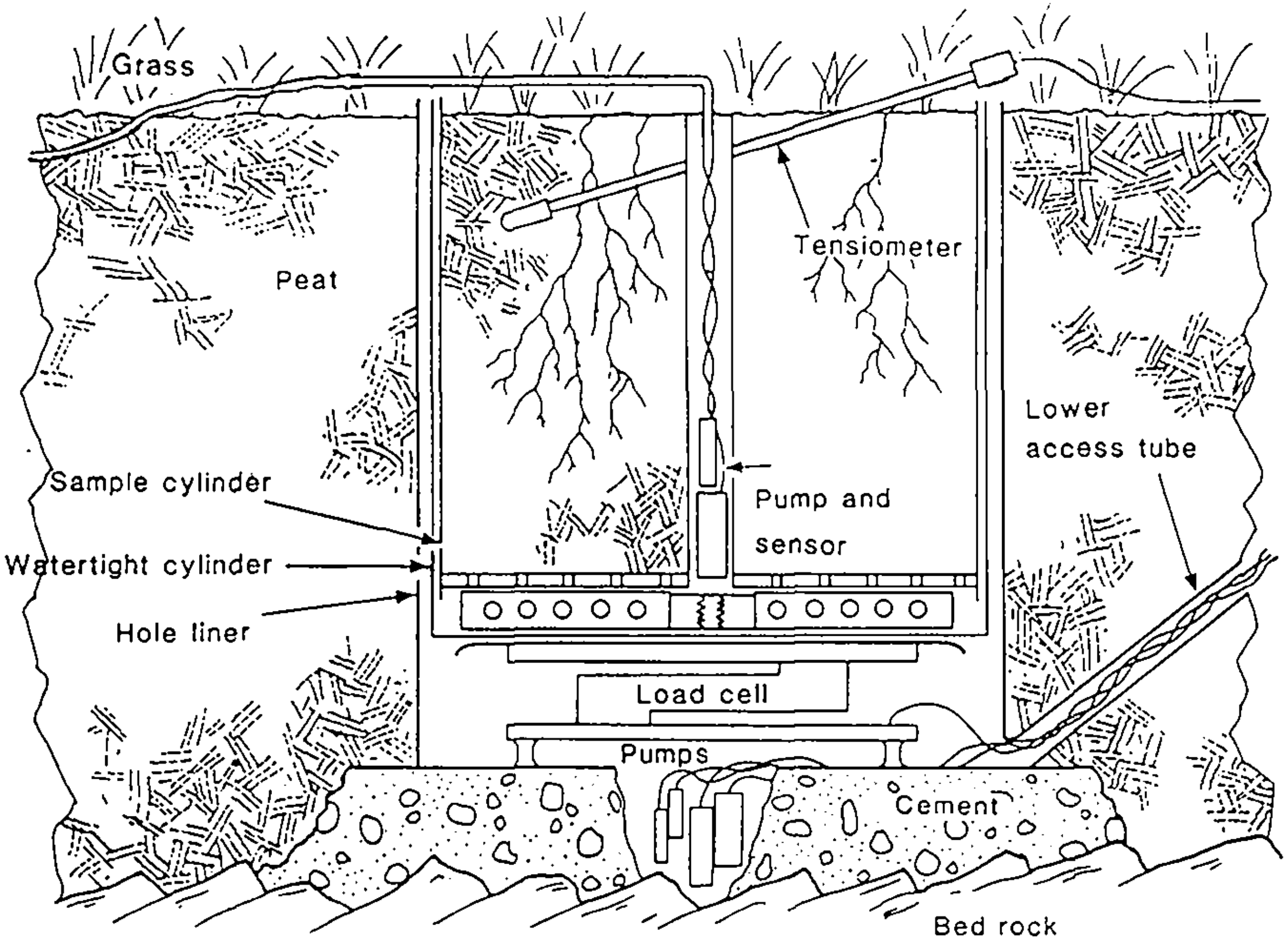


Fig. 3.1.1 Cross-sectional diagram of the weighing lysimeter used in the high altitude grassland study.

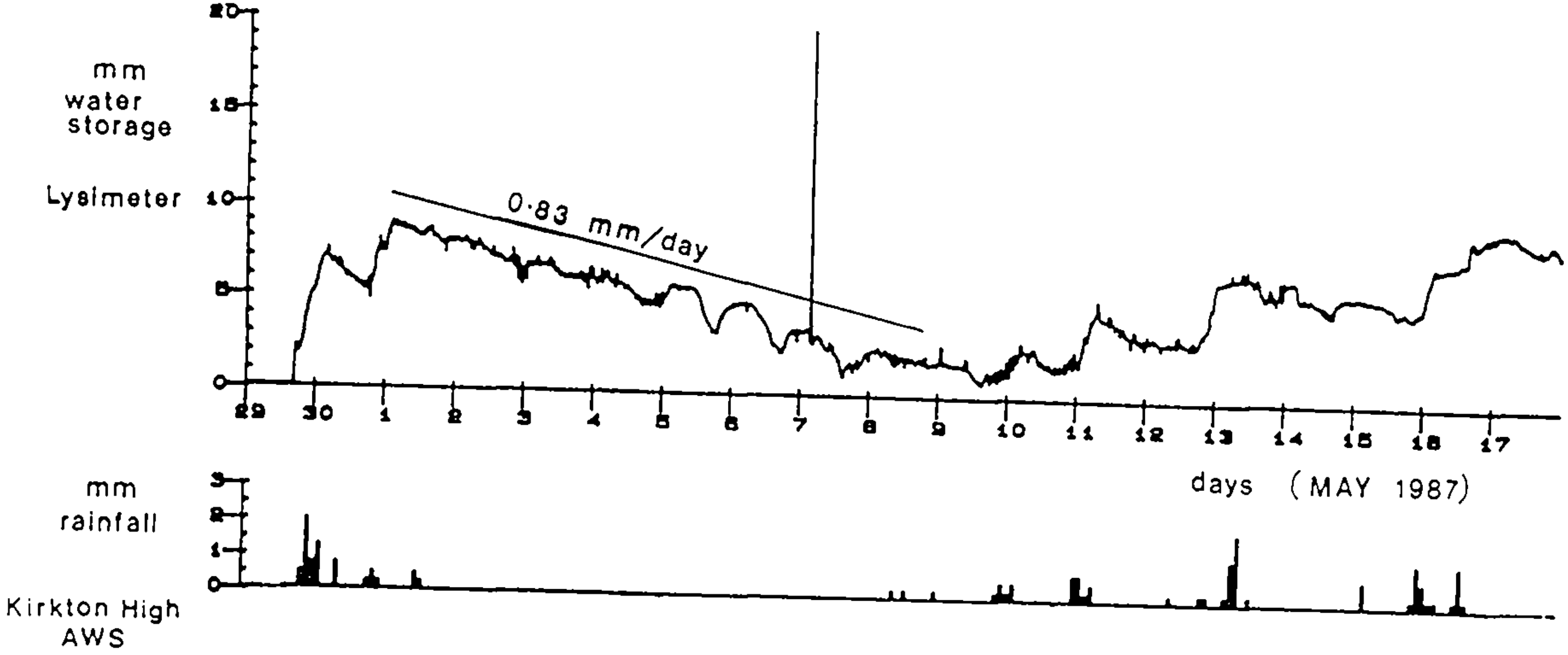


Fig. 3.1.2 Rainfall, and change in mass in mm water equivalent from weighing lysimeter, over the first 18 days of operation.

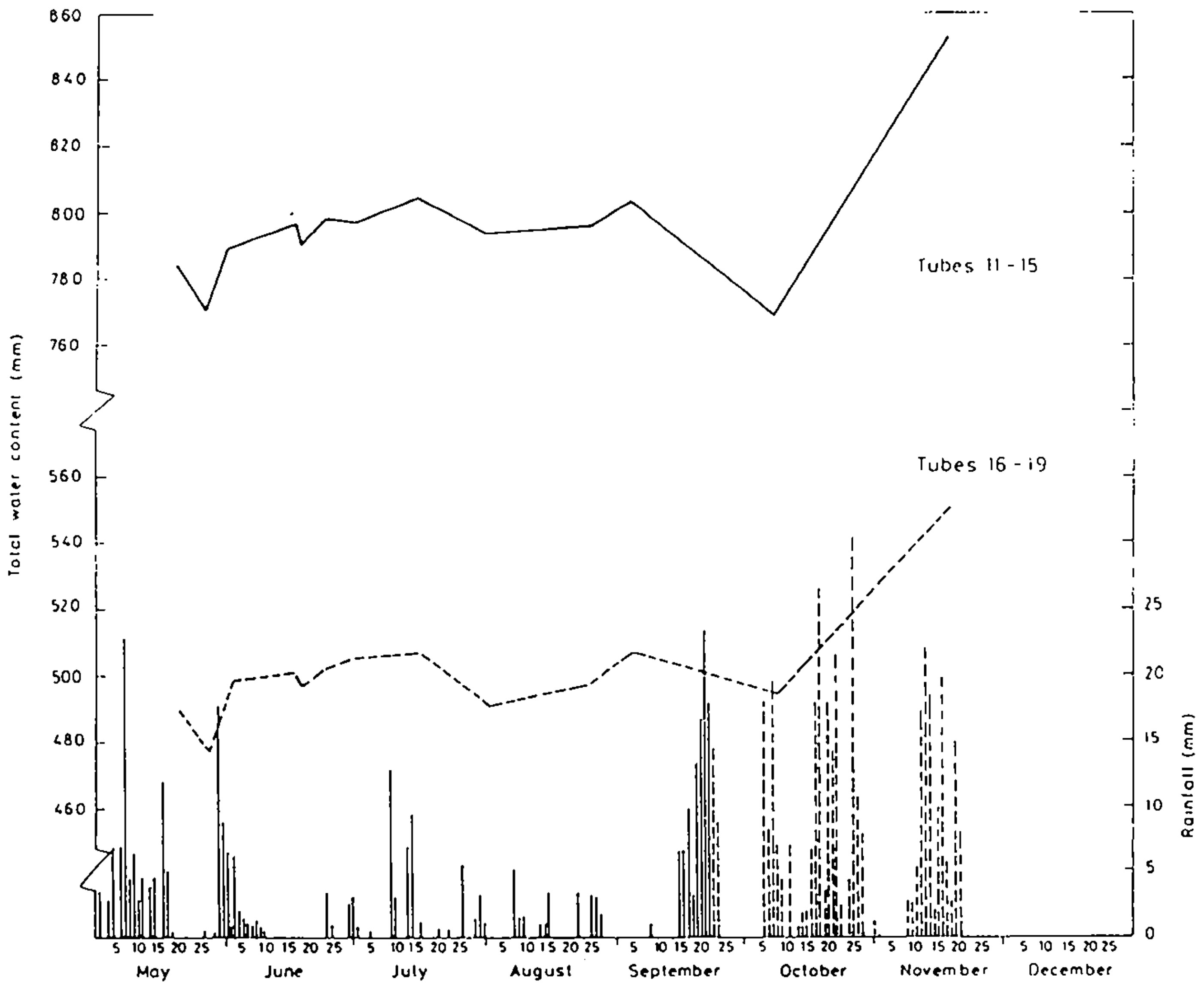


Fig 3·1·3 Soil moisture and rainfall at the high altitude grassland site in 1987. Rainfall values were measured either at the site or Kirkton High or at the Tulloch Farm manual weather station (shown by broken line)

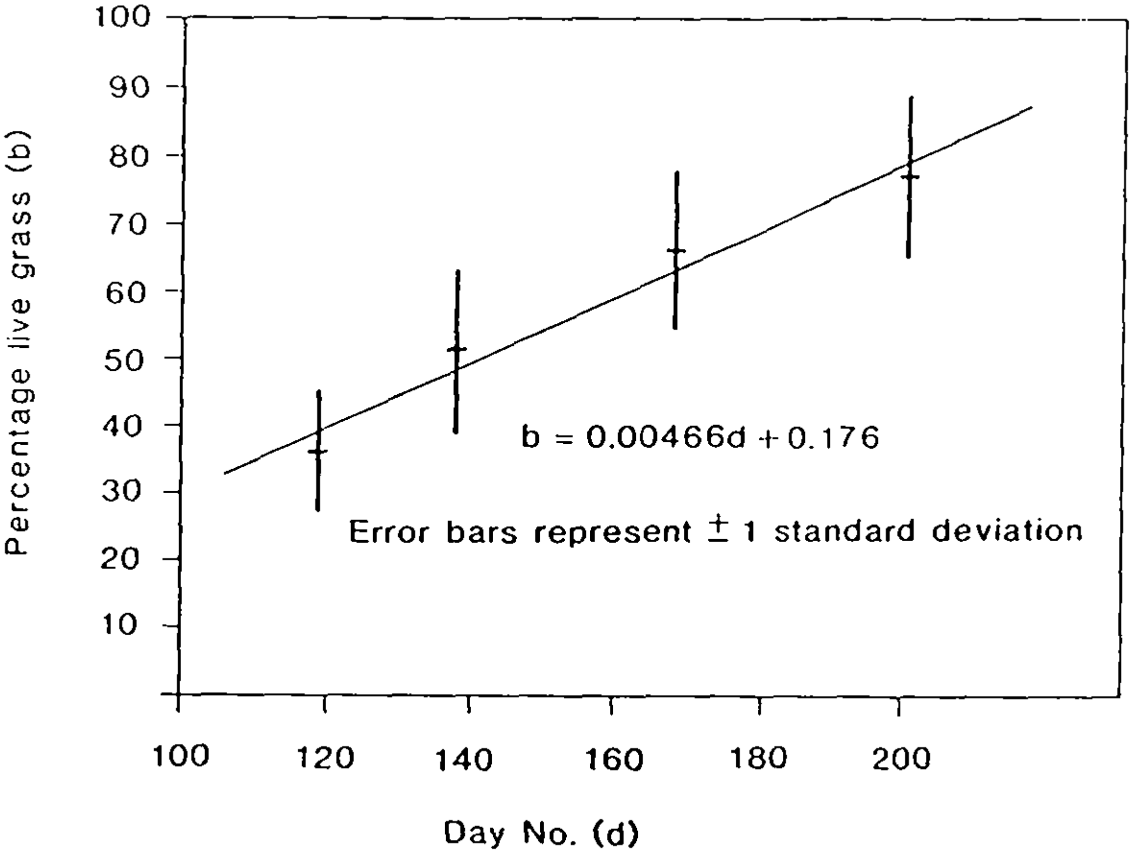


Fig. 3.1.4 Production of biomass from the high altitude grassland site.

3.2. THE USE OF E_t IN ESTIMATING EVAPORATION FROM UPLAND CATCHMENTS

The Penman potential evaporation is used in the Calder & Newson (1979) model which estimates the water-use of catchments under forest and grassland in upland Britain. This model estimates the annual average evaporation from a catchment, E, as

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

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 ratio.

This formula is based upon the following assumptions:

(i) The interception ratio, α has a value of 0.3. Numerous experiments have shown α to be between 0.3 and 0.4 for extensive forests.

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

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

Encouraging agreement was found between the model predictions and the early results from the partly forested Severn catchment. However a comparison of the more recent results with the model predictions indicates some discrepancy. A large and well validated series of catchment results from Plynlimon is now available. Table 3.2.1 shows the average annual values for 1975-83.

TABLE 3.2.1 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 the very simple temperature model referred to in section 3.1.3 and described in detail in Hall (1987), has been applied to a single year of the Plynlimon meteorological data. The year chosen was 1978: a year of average rainfall and runoff.

TABLE 3.2.2 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 3.2.2 shows that the introduction of the temperature effect can produce a water-use in agreement with observation. 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.

The application of the annual catchment model to the Severn requires careful consideration of the component areas of the catchment. Table 3.2.3 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 3.2.3 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		
Immature forest plantation with 33% canopy coverage		
Mature forest plantation with 100% canopy coverage	38	38
TOTAL	100	42

Table 3.2.4 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 temperature effect on the grassland part of the catchment, this overestimates by 137 mm. Finally Model 3 also includes a temperature correction 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. However, there is little experimental evidence generally for a temperature influence on the transpiration from forest and in particular lysimeter results from Plynlimon suggest there is no temperature effect for forest. Clearly this is an area for further research.

TABLE 3.2.4 Obvserved and predicted losses for the Severn catchment in 1978.

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

On the basis of the results of the process studies it is possible to suggest modifications to improve the accuracy of the Calder & Newman annual catchment model. These are:

(i) Where heather occurs on a catchment use an interception ratio α *0.17 and multiply* E_t *by a transpiration fraction of 0.5.*

(ii) 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 α = 0.3 0.4 for all preciptation will not introduce large errors.

(iii) The work on the influence of temperature on grass transpiration must be completed before final conclusions can be reached. However, the simple formulation described above agrees with the Wye catchment results. This can be generalised into an annual model, for example see Fig. 3.2.1.

3.2.1 Altitudinal variation of E_t

As already discussed in Section 3.1.3 Penman E_t values calculated from meteorological data collected by automatic weather stations at high altitude sites at Balquhidder are high and show evidence of an increase with altitude. The average value for Kirkton High weather station is 531 mm a year for 1983-87 whereas MAFF (1967) quotes 354 mm a year for Perthshire for the average county height of 394 m. MAFF (1967) also suggests 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. This is of especial importance for the* annual model since it is generally the MAFF E_t values which are used to calculate the evaporation from uninstrumented catchments.

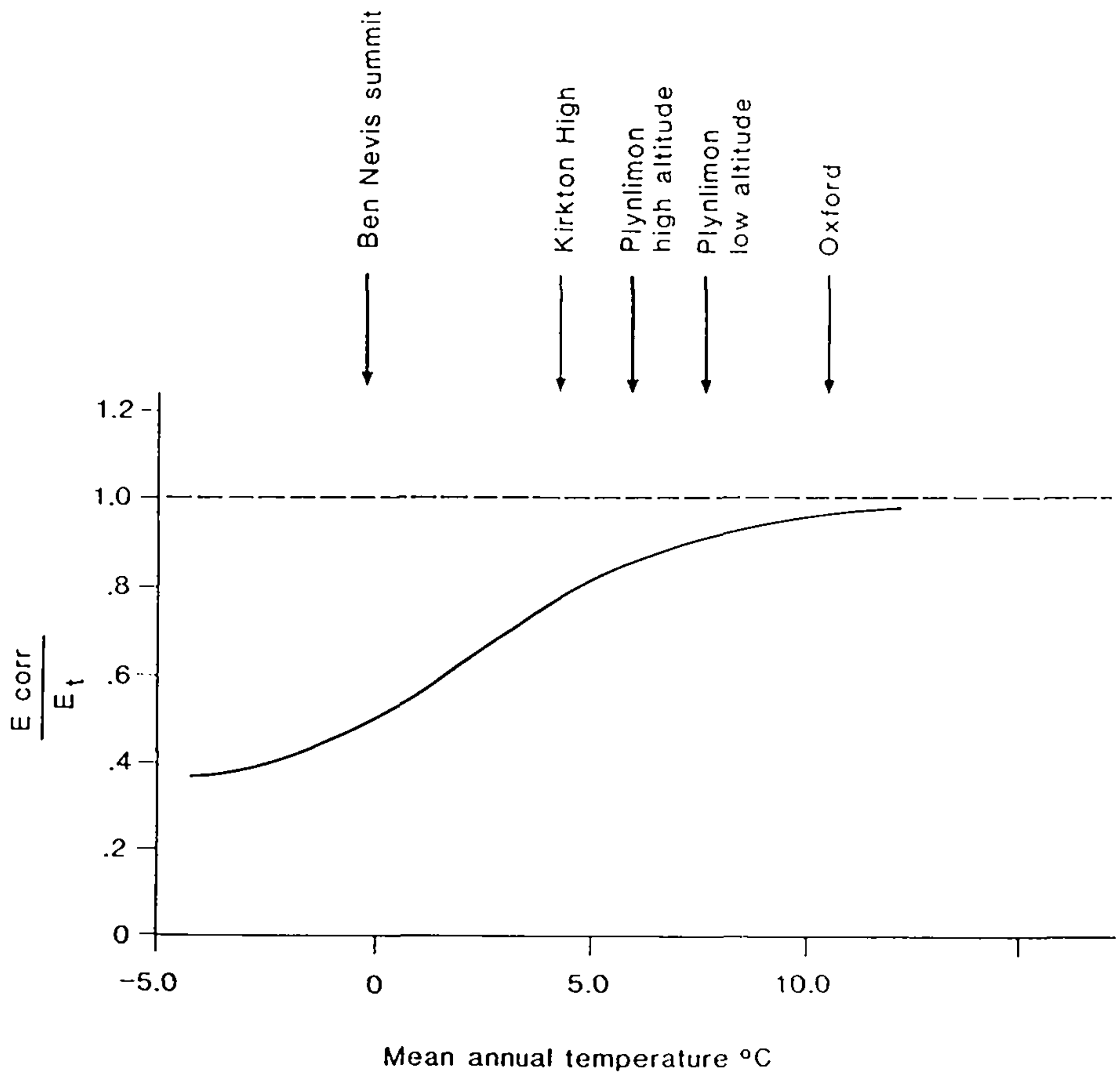


Fig. 3.2.1 The effect of applying the simple temperature model on a daily basis to the annual total of potential evaporation for a variety of temperature regimes.

3.3 MODELLING OF SNOW INTERCEPTION BY CONIFEROUS FOREST

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 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 a more pragmatic perspective has been used to understand the principle processes and produce an effective, physically based model. The model structure is shown schematically in Fig. 3.3.1 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.

The model has been developed using snow interception measurements made at Queens Forest, Aviemore during the winters of 1983/84 and 1984/85 and reported elsewhere.

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.

It is an interesting observation 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 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.

Together with the earlier empirical studies it has highlighted the important features of snow interception by coniferous forest.

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.

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 seasonal catchment model such as that described in Hall (1987).

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. 3.3.2). 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:

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

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).

3.3.1 Results so far

Figure 3.3.3 shows interception ratio data collected at Queens Forest 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, whereas measurements of interception loss made before and after line thinning a forest at Plynlimon suggest that a more open forest structure may not affect the long term rainfall interception loss. Thus 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.

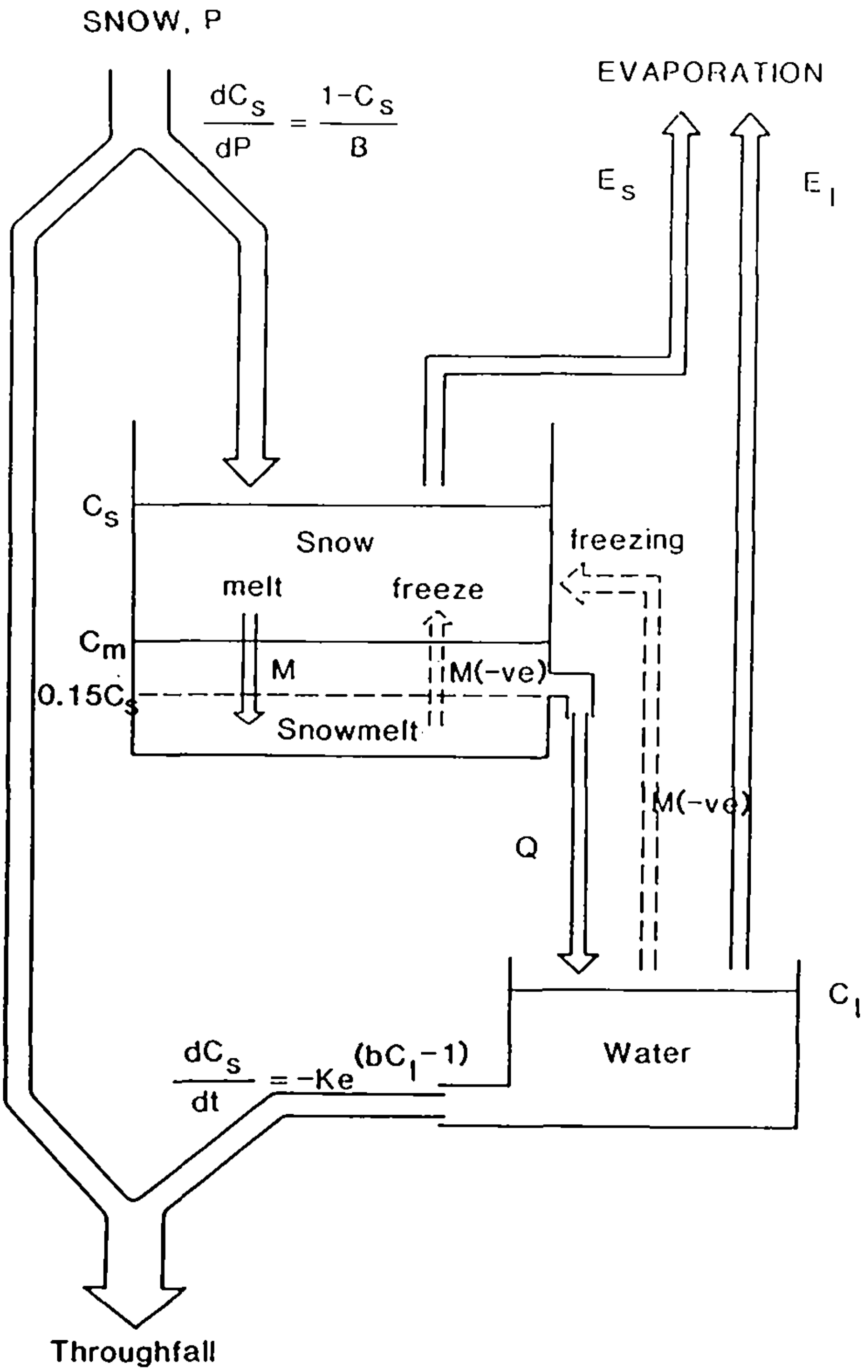


Fig. 3.3.1 Diagrammatic representation of the snow interception model

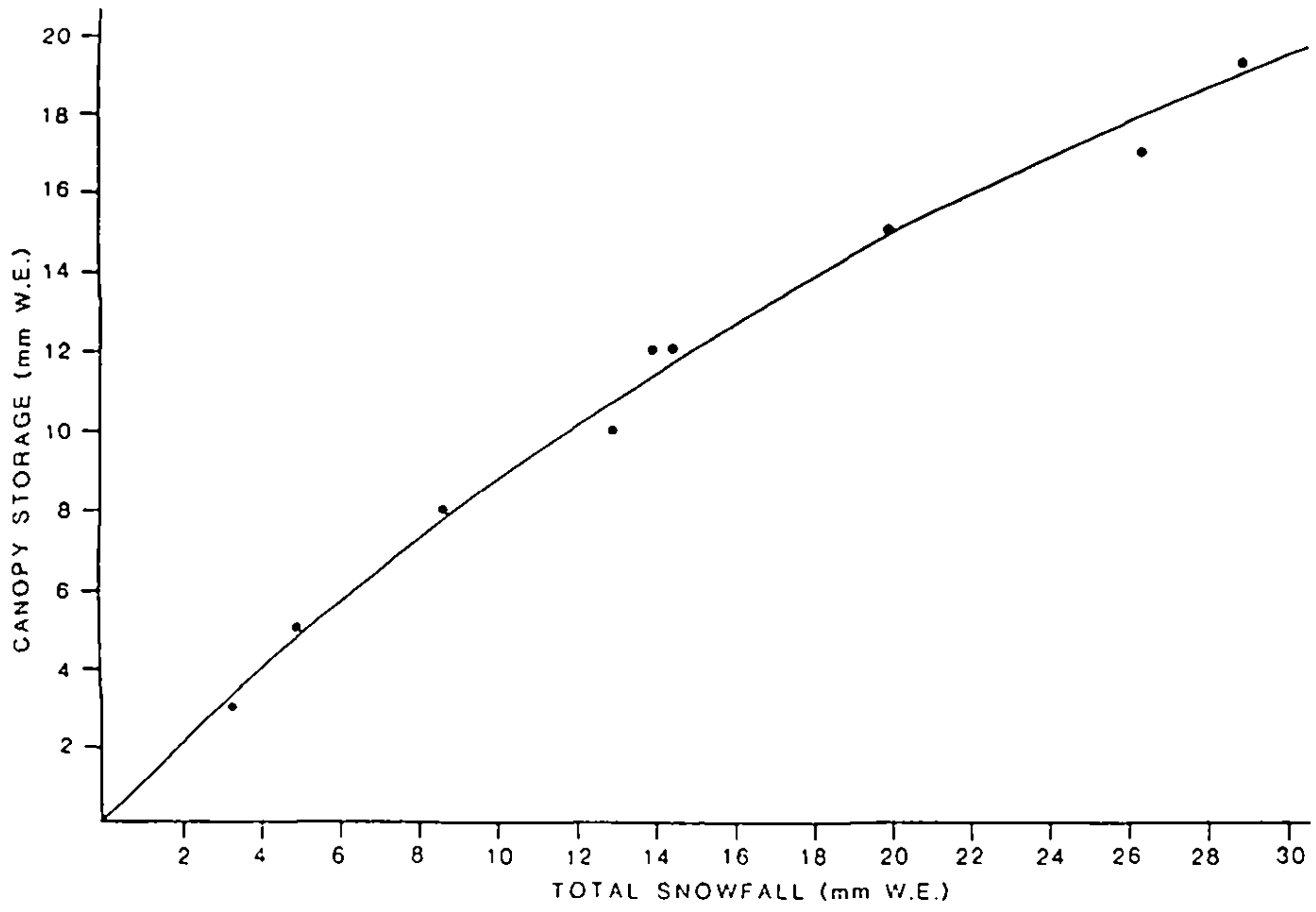


Fig. 3.3.2 Build-up function for snow on the forest canopy.

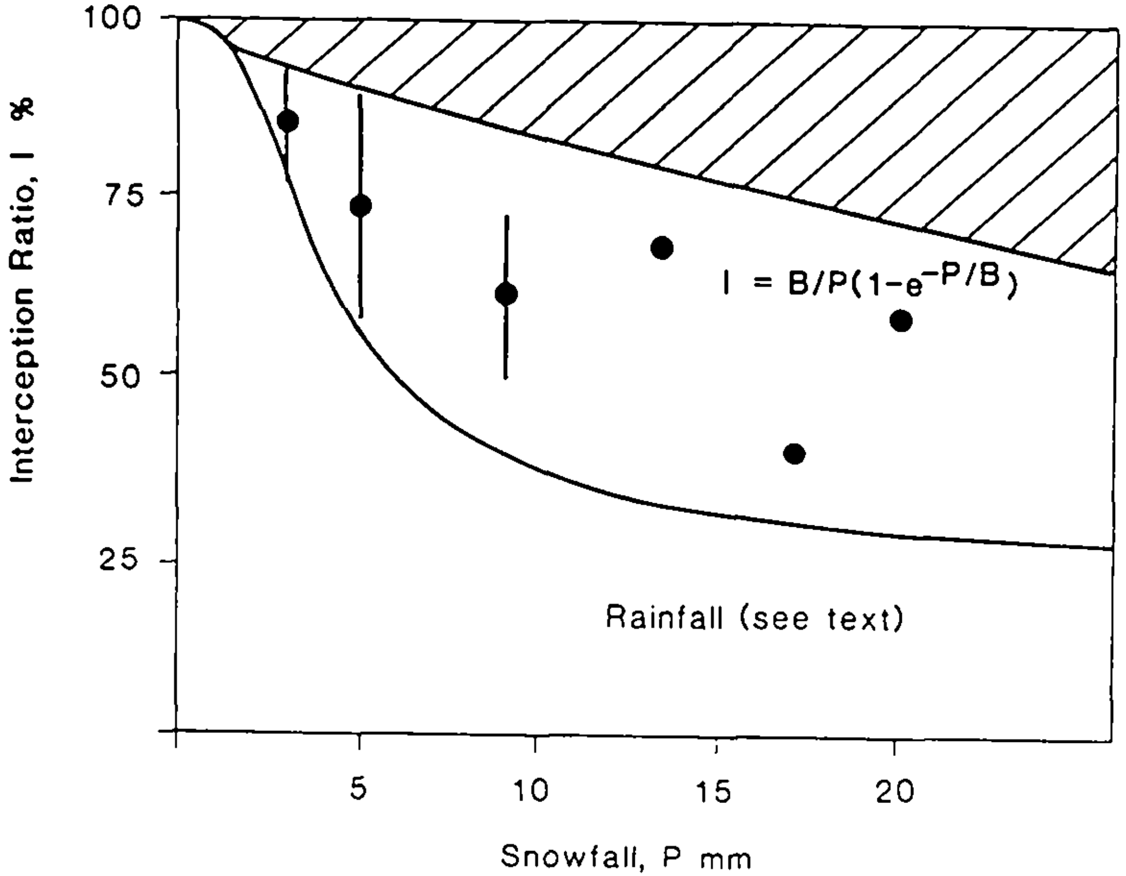


Fig. 3.3.3 Interception ratio for snowfall versus snowfall for individual storms.

4. Proposed Work for 1988-1989

In the catchment studies it is proposed to continue data collection from the networks through 1988/89 and, if funding permits, through to 1990/91 when the programme of planting in the Monachyle and felling in the Kirkton will be completed. This will make if possible to identify the magnitude of changes in water use and comparison with the Phase I data will indicate the extent of changes in streamflow responses resulting from these land changes.

It is proposed also to continue the programme of intensive sediment sampling to determine when and at what levels erosion rates stabilise.

New loggers will be installed on the weather stations in autumn 1988. These should result in better data capture and thus expedite the investigation of the relationships between the individual meterological variables and altitude, aspect and exposure. An understanding of these is necessary for the development of better methods of estimating catchment mean Penman ET and of extrapolating from the present sparse, low altitude network of meteorological stations in Highland Scotland.

During the coming year also it is proposed to start work on modifying existing catchment models, by the inclusion of the new water use elements from the process studies and appropriate snow melt routines, to achieve a greater understanding of the seasonal flow characteristics of the catchments and how these are being modified by the land use changes.

In the process studies it is proposed to continue operating the high altitude grassland experiment. All the measurements made in 1987 will be continued viz:

(i) measurements of soil moisture, if possible at more frequent intervals, which in dry periods allow transpiration rates to be calculated;

(ii) measurements of the total water balance of the grassland using the two lysimeter systems with new Campbell CR10 loggers;

(iii) measurements of meteorological data using an automatic weather station to provide the basis for calculating the potential E_t rate;

(iv) measurements of biomass production.

In addition the interception characteristics of the grassland will be studied using a wet-surface weighing lysimeter system.

Detailed data analysis will continue and the results will form the basis for subsequent developing and testing of mathematical models of evaporation from high altitude grassland.

It is also proposed to continue the snow-modelling work with the aim of producing a simplified model for later incorporation into a general simple seasonal catchment model.

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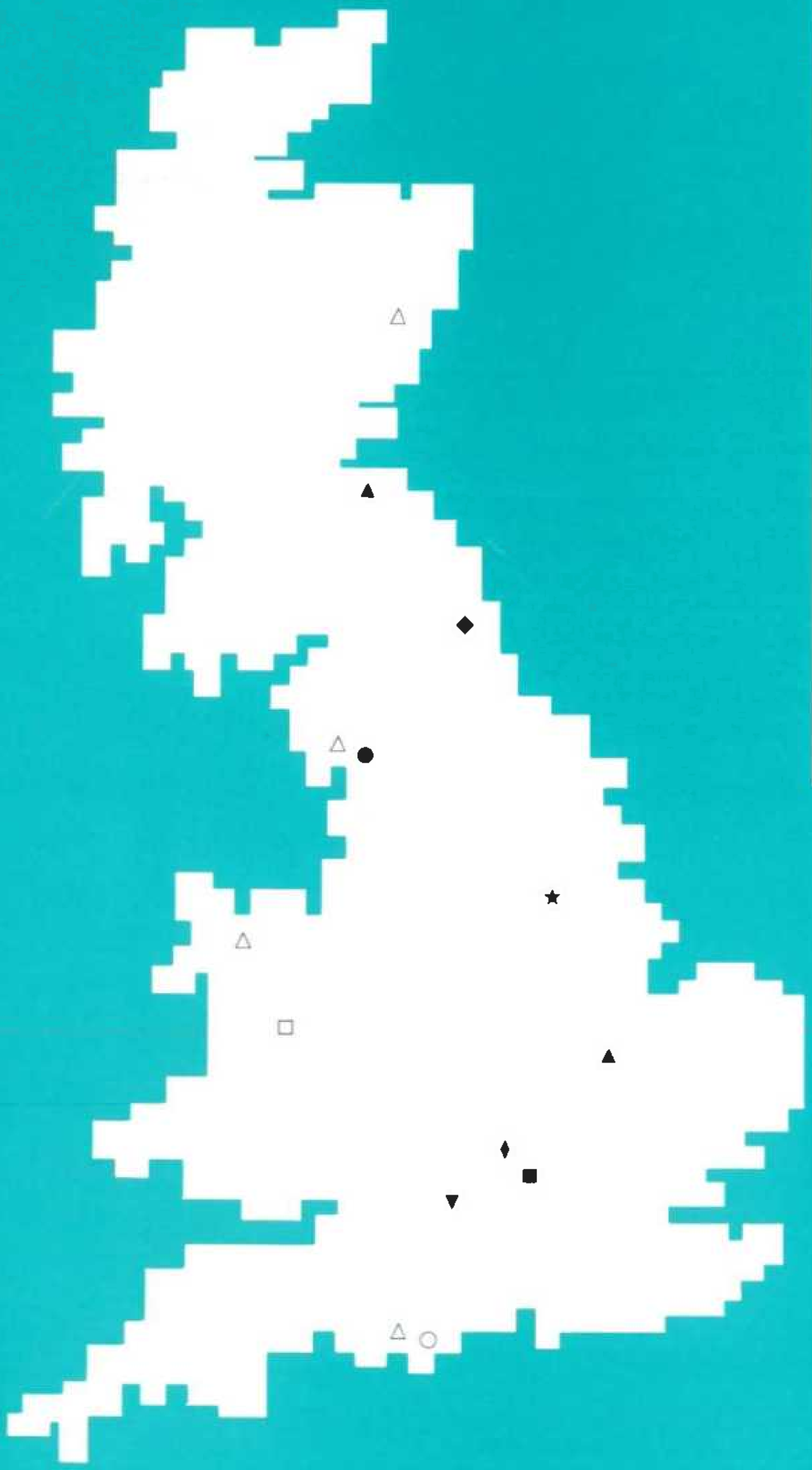

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