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UPLAND AFFORESTATION AND WATER RESOURCES

Progress Report on the Balquhidder Catchment Studies and Process Studies 1988/89

by

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1. Introduction

1988 was the third year of the second phase of the Balquhidder catchment studies, the phase in which land use in both catchments undergoes progressive change. It was also the third year of field work on the study of the water use of high altitude grassland on a site immediately adjacent to the Kirkton catchment.

In this report the activities on both of these aspects of the project are commented on, summaries of the data collected are presented and results obtained are discussed.

The proposed programme of work for 1989-91 is outlined and the use to be made of the catchments beyond that period is discussed.

2. Precipitation gauge performance checks

2.1 PRECIPITATION ESTIMATES

The year 1988 has been the second wettest since the Balquhidder experiment began, and is characterised by a particularly wet summer with maximum monthly rainfall occurring in July. It also had a mild winter and because of the lack of complications due to snow this has made the provision of a complete network record an easier task than in previous years. The index used to assess the impact of snowfall on the performance of the ground level networks in previous years has been the proportional relationship between the paired catchment gauges mounted 30 cm above ground (standard gauges) and ground level gauges in clearings in the Kirkton forest. For rainfall only periods undercatch of the standard gauges relative to the ground level gauges is of the order of 5% and deviations of >10% are considered indicative of snow effects. Where a snow month has been flagged the standard gauge data is used to infill the monthly totals.

1988 has been unusual in that no deviations of >10% have occurred that can solely be attributed to snow (see Table 2.1.1.). January and April just exceed this threshold and in previous years would have been flagged as snow months, however there is a trend in deviations that shows increasing differences between ground level and standard gauges even in rainfall-only months. As a result some doubt now surrounds the validity of -10% as a suitable threshold value. Deviations averaged -7.5% in 1988 compared to -5.3% in 1987 for example. Further analysis is in progress on data from individual clearing sites. First indications are that the trend is real and is probably related to increased exposure following felling of trees in the vicinities of the gauges. For 1988, therefore, it has been assumed that the ground level networks on the lower part of the Kirkton have performed reasonably well. Data from some of the higher gauges have been snow affected and these have been discarded, but it has been possible to infill missing monthly values by using the long-term ratio of individual sites to the catchment mean, in both Kirkton and Monachyle. The ratios of gauge catch to catchment mean for 1988 are shown in Table 2.1.2. where it can be seen that the relationship of each gauge to the catchment mean in both Kirkton and Monachyle has remained similar to the long term ratios.

The existence of this increasing undercatch by the standard gauges renews the debate as to whether precipitation estimates for those winter months infilled by standard gauge data should be increased by 5-10% to compensate. It would seem sensible to introduce this correction retrospectively for previous years, and to increase the magnitude of the correction over the period of the felling to allow for extra gauge exposure. Correction of the data must now wait until next year, when it will be done in conjunction with other changes to the methods of calculating areal precipitation recommended in this report. The impact on the Balquhidder results will be to increase both precipitation and water use totals for both catchments. However, the difference between catchments should not change markedly.

2.2 RESULTS FROM CHECK GAUGES IN SELECTED DOMAINS

In 1987 two domains in each catchment (Fig 2.2) were selected for gauge duplication as part of the general checking of the raingauge networks. This was to give an assessment of both the influence of local topography on gauge performance and the variation of rainfall within the domains.

Check gauges were installed in the following domains:

Kirkton C3Y	noted in previous years as having anomalous readings (20% low) compared to the other Kirkton east gauges. One check gauge was placed 20 metres away on a more gentle slope, and the other 800 metres to the NW.
Kirkton C3W	1000 metres to the SE
Monachyle B3Z	900 metres to the SE
Monachyle D2W -	this domain was previously unsampled because of its inaccessibility with readings from C2W assumed to be adequate.

All the check gauges were installed as ground level gauges and angle corrections were carried out before any comparisons were done.

Excluding period when snow fell in the domain the following totals have been obtained for the 2 year period:

Table 2.1.1 Monthly precipitation totals from the Kirkton clearing gauges and deviations from the ground level totals

	G. Level Mean	Snow Gauges Mean	Snow Gauges % Dev	Standard Gauges Mean	Standard Gauges % Dev
January	305·3 3.05.3	254.9	-16.5	274.6	-10.1
February	202.5	191.3	-5.5	191.2	-5.6
March	230.3	232.3	+0.9	221.5	-.38 −3·8
April	106.9	81.1	-24.1	94.9	-11.2
May	91.1	77.4	-15.0	86.3	-5.3
June	37.1	22.9	-38.3	33.8	-8.9
July	317.9	269.6	-15.2	297.5	-6.4
August	347.6 347·6	213.3	-13.9	234.3	-5.4
September	215.1	186.4	-13.3	203.7	-5.3
October	297.1	251.9	-15.2	272.1	-8.4
November	132.8	99.1	-25.4	121.0	-8.9
December	203.1	179.5	-11.6	190.9	-6.0
Total	2386.8	2059.7	-13.7	2221.8	-6.9

Table 2.1.2 Ratios of annual precipitation for each gauge in the networks with the catchment mean

KIRKTON

	A1W	A2W	A3W	A3Y	B3W	B3Y	C1W	C3W	C3Y	D2Y	D3Y
1982 → 1986	0.95	1.02	0.96	0.92	1.00	1.01	1.10	1.11	0.82	1.06	1.06
1988	0.96	1.03	0.93	0.93	1.01	1.03	1.06	1.02	0.81	1.13	1.10

MONACHYLE

	A1X	A3X	B1W	B1X	B1Y	B2W	B2X	B2Z	B3Z	C2W	C2Z
1982 → 1986	0.96	1.02	1.06	1.01	0.92	1.04	1.03	0.63	0.97	1.12	1.03
1988	0.98	1.04	1.04	1.02	0.92	1.05	1.00	0.87	0.96	1.10	1.03

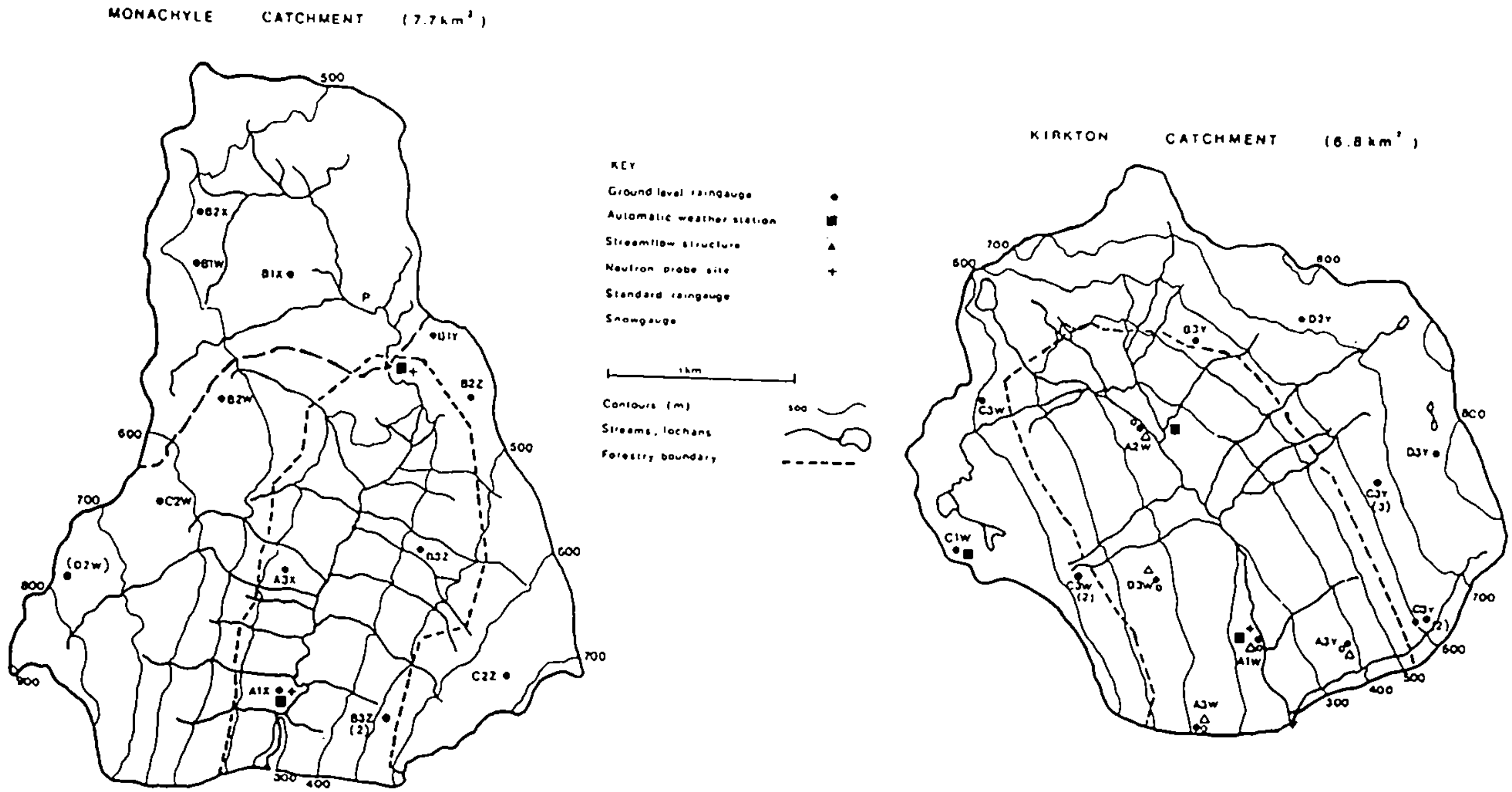

Figure 2.2 The instrument networks on the Balquhidder catchments

	Totals	Percentage difference
C3Y	3670.7	
C3Y check 1	4203.7	+14.5%
C3Y	2751.8	
C3Y check 2	3338.8	+21.3%
C3W	3042.3	
C3W check	3044.4	+0.1%
B3Z	2789.3	
B3Z check	2773.0	-0.6%
C2W	1601.9	
D2W	1726.1	+7.8%

The comparisons throughout the year show very little variability and in regression analyses between the original and check gauges r^2 values are 0.96 or better.

Results from the gauge Kirkton C3Y check 1 confirm that the original gauge was poorly placed in relation to the local topography, but the check gauge only showed a 14.5% increase which still does not compare well with the other Kirkton gauges. C3Y check 2 gave a 21% increase which is very close to the figure expected from this domain. From these results it must be assumed that the original gauge was not representative of the domain C3Y. C3Y check 1 does confirm however that the southern end of this domain receives less rainfall, probably because of its high exposure to westerly winds. Replacing C3Y with C3Y check 2 in the network of gauges increases the arithmetic mean of the Kirkton catchment by 1.6%. In future the domain will have to be divided into two, with the majority of the domain monitored by the gauge C3Y check 2 and the southern end monitored by the gauge C3Y check 1.

Domains C3W and B3Z showed a very close agreement between the original gauges and the check gauges.

The gauge D2W had an 8% difference compared with its neighbour C2W. This domain is one of the larger in the Monachyle and so the gauge will be retained and will form part of the network. Its inclusion will increase the catchment arithmetic mean by 1.7%. All past data will therefore be adjusted.

2.3 THE PERFORMANCE OF THE STANDARD GAUGES IN THE NETWORKS

Octapent gauges with rims 30 cm above the ground (Meteorological Office standard gauges) have been used at all the Kirkton forest clearing sites since 1984. Their main use has been in moderate snow conditions when the ground level gauges become buried. It is well documented that there is an undercatch by a standard gauge compared to a ground level gauge, related to wind speed. Therefore, when a standard gauge is used to infill winter data a known correction must be applied for the undercatch at that site.

Figure 2.3 shows the results from the five clearing sites and the Tulloch farm met site with the undercatch of the standard gauges related to altitude. There is clearly an increasing undercatch with altitude which is particularly uniform when the gauges on the west side of the Kirkton are taken alone. The equation for these gauges is:

$$\text{Undercatch } (\%) = 0.04 \text{ Altitude} - 8.8$$

Most of the Kirkton clearing sites are now more exposed because of the clear-felling, however the change in the relationship between the standard and ground level gauges has only been slight. This is possibly due to the tree brashings which have been left on the felled areas continuing to provide shelter. The standard gauges will therefore continue to be operated at these sites. In the lower Monachyle, where there will be an increasing protection from the new trees, standard gauges are going to be installed.

2.4 RESULTS FROM THE SHIELDED SNOW GAUGE

The snow input to the catchments has always been recognised as very difficult to measure. Various methods have been tried in the past, eg. a snow profiler, but without much success. As mentioned in the previous section the standard gauges in the forest have been used for moderate snow conditions but there is still a need for a gauge to cope with large falls of snow and also any subsequent precipitation which might fall before the site can be visited.

The original tall snow gauges which have been operating in the Kirkton forest were found to have an aerodynamic problem when used on exposed sites. As the clearing sites are now more exposed the gauge is being modified to cope with this and also make it useable on some Monachyle sites. The main modification is the addition of a shield with two rows of flaps which close up on the upwind side but can open allowing any trapped snow to fall away. At rim level an open grid provides a more uniform top to reduce turbulence over the gauge top.

Since 1987 a shielded snow gauge and the original snow gauge have been operating at the exposed lower Monachyle weather station where snow is frequently a problem. Figure 2.4 shows a time series plot of the ratio of the two snow gauges to the ground level gauge. Throughout the year there is a

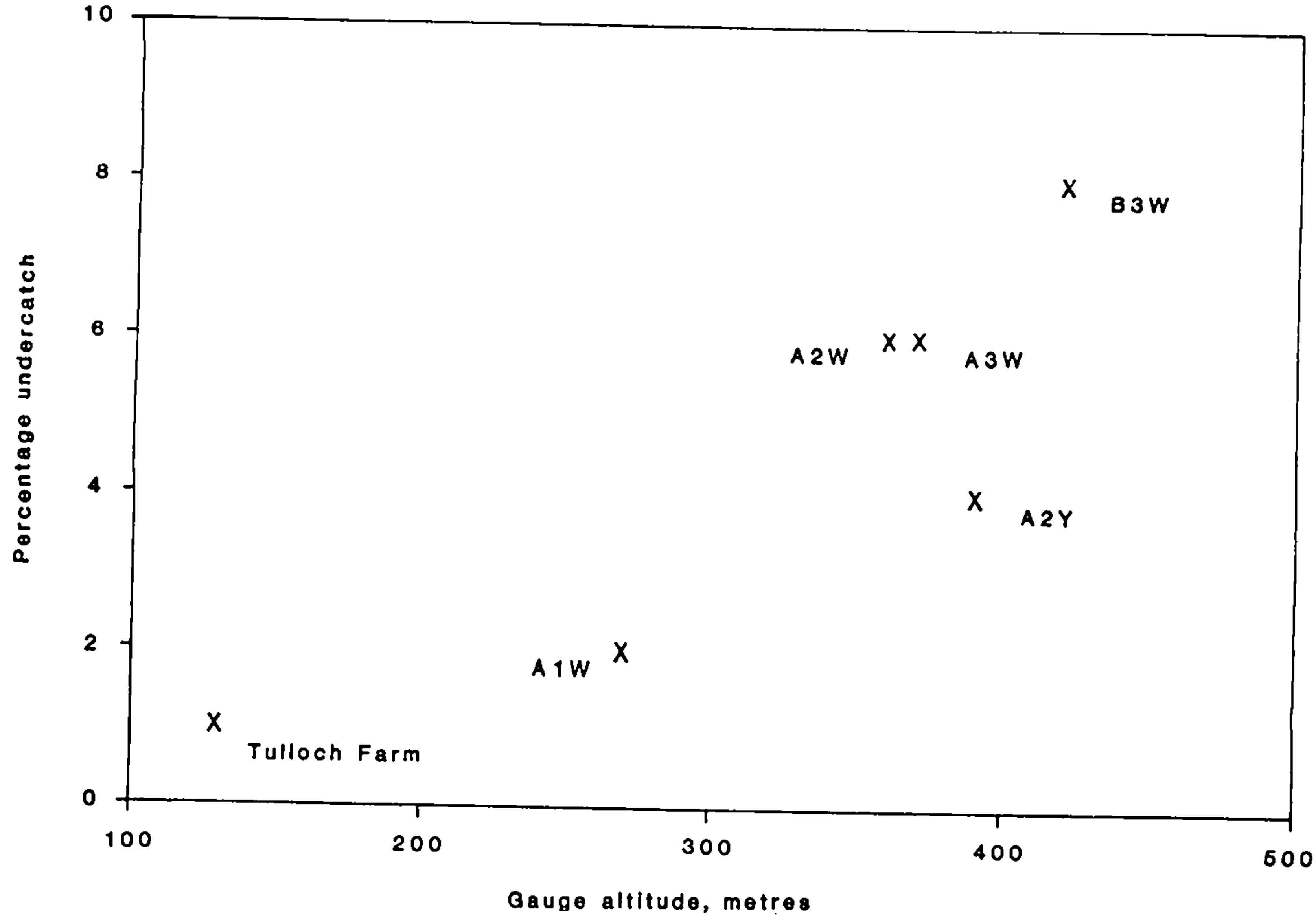

Figure 2.3 *Kirkton standard gauge catch compared to ground gauge catch at different altitudes*

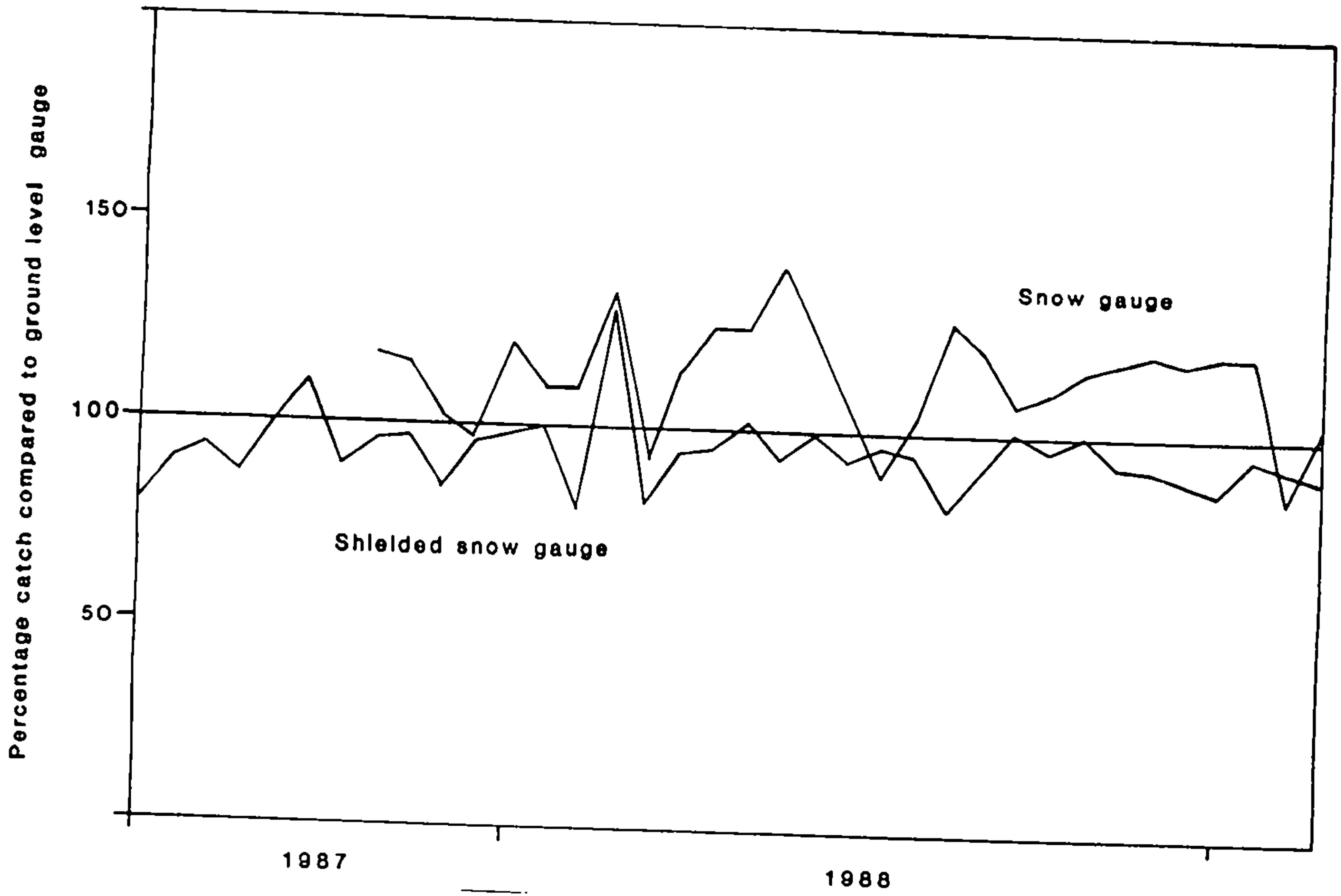

Figure 2.4 *Performance of snow gauges compared to the ground level gauge at the lower Monachyle*

more steady relationship between the shielded gauge and the ground level gauge. When large snowfalls occur with light winds the 2 gauges catch very similar amounts. This implies that, in the sheltered forest clearings, the snow gauge has probably been reliable during heavy snow. But on exposed sites the problem is any subsequent rain which falls before the snow catch is measured. The mixed catch of the snow gauge is not reliable but the shielded snow gauge works well in both snow and rain and is considered to be a much better gauge.

More development is planned on the gauge to make the shield more easy to operate and to improve the gauge rim. If further tests are successful then several of the gauges will be built and installed at key locations in both catchments.

3. Streamflow measurement

The high accuracy of streamflow estimation for both Kirkton and Monachyle has been achieved by using independent calibration by current metering to replace the theoretical ratings which have been shown not to apply in these conditions. Confidence in the use of these ratings has depended on the maintenance of stable bed levels in the approach section to each structure. Sediment in the Kirkton stilling pool has equilibrated at a level 0.4 m down from the crest, giving a reduced weir height from the design value of 0.7 m. In the Monachyle the full design weir height of 0.7 m has been maintained throughout the study. However, a slowly growing shoal upstream of the weir is almost certainly affecting the approach velocity distribution and is implicated in the observed deviation of the current meter rating from theoretical. In both cases, however, it has been possible to assume that the revised ratings have not needed to change with the varying conditions.

Since 1986, the catchments have been subjected to considerable disturbance; felling in Kirkton has changed the nature and volume of sediment coming down the burn, while construction of a water off-take upstream of the weir has also put potentially mobile sediment into the system. There are indications that both sources of sediment have caused a reduction in weir height during 1988 but that this will only have affected low flows (where weir height is less important) and that the original bed level was restored by autumn floods.

The Monachyle is different in that it was always thought that the weir pool could be emptied and that the design approach conditions could be guaranteed for long periods with minimal maintenance. This of course takes no account of increased sediment movement that may occur due to the recent ploughing of the catchment. However, the existing shoal is clearly affecting the rating and this must be quantified before the shoal is removed. Subsequently, the rating should be rechecked to see if it has reverted to the theoretical. The imminent delivery of a set of electromagnetic current meters will serve to improve the precision of the ratings on both structures, particularly in the low flow region where the existing impeller meters are notoriously insensitive.

4. Meteorological Data

1988 was a year of mixed fortunes in terms of data capture from the Automatic Weather Stations in the catchments. Virtually a complete record was obtained for the year from the low level Tulloch Farm site, though interpretation of the data from September onwards created some problems (see below). All the other stations suffered to some extent from combinations of logger and sensor faults for varying intervals during the first half of the year. The greatest loss occurred at the upper Monachyle site where logger faults, a persistently recurring fault in the wet bulb depression channel and subsequently a failure of the windspeed sensor has made it impossible to compute complete monthly Penman data for 10 months of the year for this site.

4.1 NEW DATA LOGGING SYSTEMS

Undoubtedly the highlight of the year was the installation of the new Campbell processor-controlled solid state loggers in September. Since then the data capture has improved dramatically. No failure of these loggers has yet occurred. In addition the ease with which the data can be read, on site, means that the detection and rectification of individual sensor faults occurs more rapidly. This further minimises data loss when compared with the old magnetic tape system.

This step forward in data capture was not without its teething troubles, however. The methods adopted in setting up the calibrations of the temperature sensors were found to be inadequate and this problem was not fully resolved until June 1989. Data for the period from September 1988 onwards had then to be corrected retrospectively and useable Penman data for the period were finally available in August 1989.

4.2 PENMAN ESTIMATES

The Penman potential (ET) estimates obtained from good, complete months of data at each site are plotted in Figure 4.2.1. The complete record for the Tulloch Farm site demonstrates the seasonal pattern for 1988. This was close to normal for the first six months. Thereafter heavy, persistent rainfall in July depressed ET and the very mild, windy conditions in December gave exceptionally high values.

Using the established between-site relationships (Blackie, 1987) the gaps in the Kirkton High and Monachyle Glen records have been infilled to give estimates of the annual totals. These are presented in Table 4.2.2. where they are compared with estimates from previous years, indicating that 1988 values were close to the 1983-87 means.

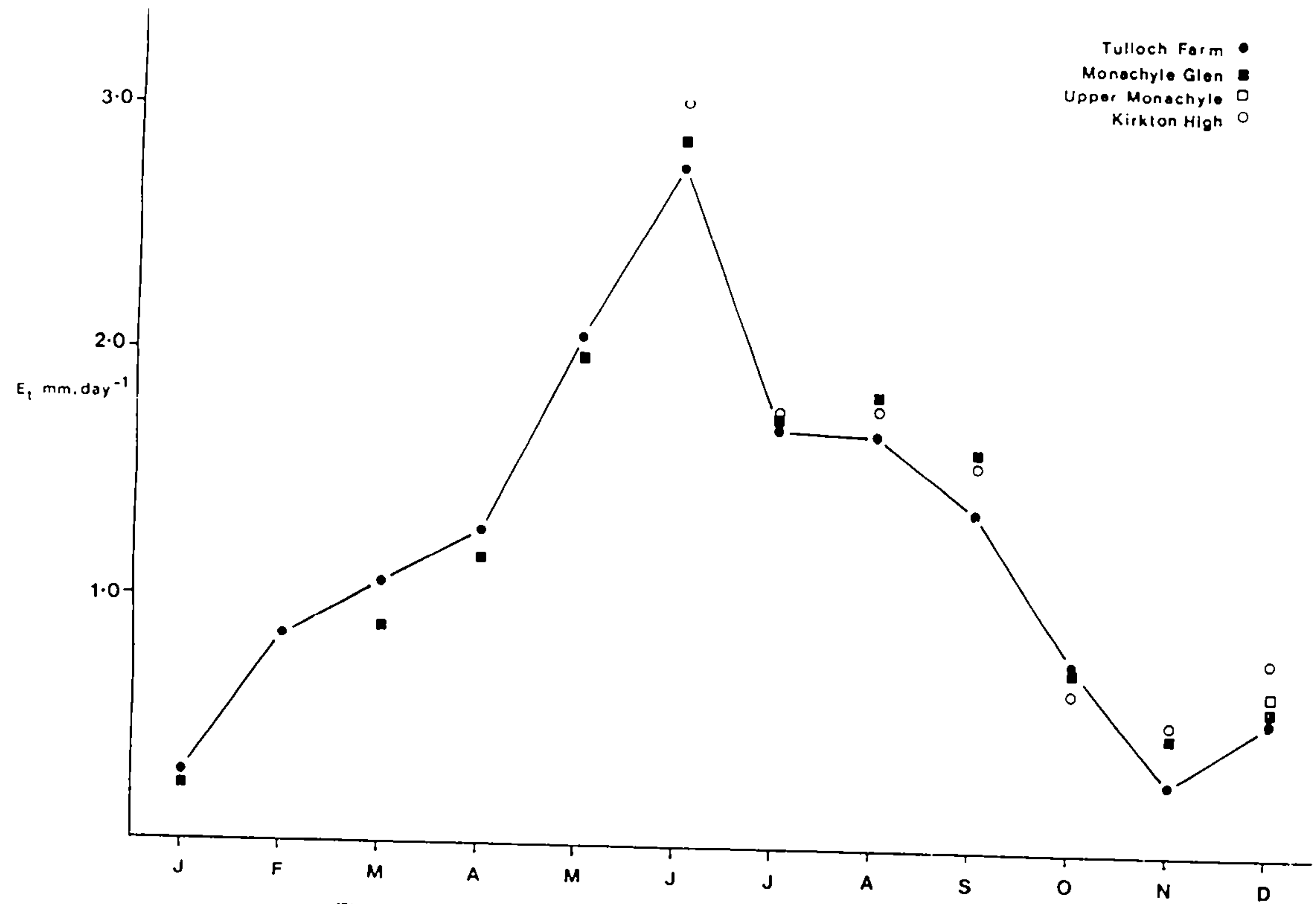

Figure 4.2.1 *Monthly mean daily values of Penman ET for all good, complete months during 1988*

Table 4.2.2. Estimated annual Penman ET totals (mm)

	1983	1984	1985	1986	1987	1983-87 means	1988
Kirkton High (670 m)	522	635	446	558	492	531	516
Upper Monachyle (470 m)	(540)*	634	464	584	492	543	(527)*
Monachyle Glen (300 m)	495	557	392	458	443	469	463
Tulloch Farm (140 m)	438	504	370	415	415	428	447

*Estimated from the other stations

4.3 PENMAN ET RELATIONSHIPS WITH ALTITUDE

The need to establish better-defined relationships between ET and topography, particularly in the upland areas, has been discussed at some length in previous reports. There is an immediate requirement for this in the Balquhidder study to provide a basis for estimating catchment mean ET for comparison with water balance studies of catchment water use. There is also a more general requirement in that the models for estimating upland water use now being developed require local and regional estimates of ET as inputs.

Work to date using the sparse AWS networks on Balquhidder, despite being hampered by data capture problems, has established an apparent upward trend in ET with altitude in this topography. The 1988 figures, quoted in Section 4.2 above, do not disprove this trend.

With the much better data capture from the new logging systems and the installation of an additional AWS in the cleared area in the lower Kirkton (see Figure 4.3.) in June 1989 a more detailed analysis can be undertaken during 1989-90.

4.4 KIRKTON FOREST AWS

Data capture from this station, tower mounted above the forest canopy in the lower Kirkton, was considerably better in 1988 than in previous years, though by no means complete. As with the other sites it has been excellent since

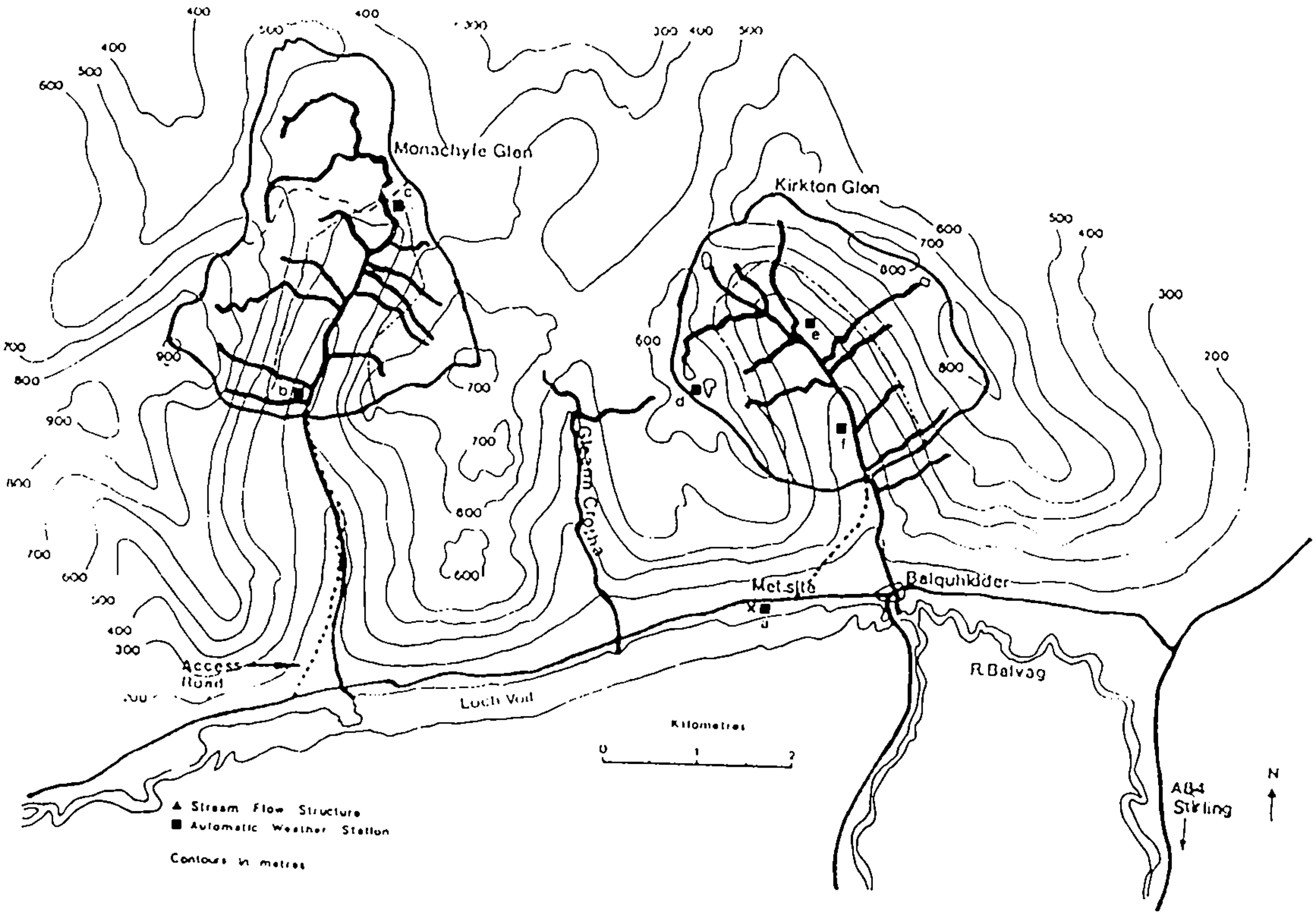

Figure 4.3 The Automatic Weather Stations at Balquhidder:
(a) Tulloch Farm, (b) Monachyle Glen, (c) Upper Monachyle, (d) Kirkton High, (e) Kirkton Forest, (f) Kirkton Cleared Area (installed June 1989)

the installation of the Campbell logger.

Whilst these data are of considerable value they cannot be compared directly with those from the other stations in the altitude sampling network. The net radiation and the wind, temperature and humidity profiles immediately above the forest canopy differ considerably from those above the short grass/heather canopies "seen" by the other stations. A detailed comparison with the new station installed at a comparable altitude in the cleared area of the Kirkton (Figure 4.3.) will be possible during 1989. Thereafter the canopy station will have to be removed in accordance with the felling schedule.

4.5 AWS AND MANUAL STATION ET ESTIMATES

Whilst the AWS samples the meteorological variables at frequencies varying from once per 10 seconds to once per 5 minutes and measures net radiation directly, manual met stations vary in reading frequency from once per three hours to once per day and estimation of net radiation for Penman ET is obtained indirectly from sunshine hours. Recent comparisons of AWS and "manual" estimates of ET at other IH sites have revealed variable levels of agreement. Such a comparison is not possible at present for the Tulloch Farm AWS and manual site since sunshine hours are not recorded there. Past comparisons of temperature, humidity and windspeed (1983 Progress Report) have been reasonably satisfactory but it is proposed that this comparison should be extended to the Penman estimates by installing a sunshine recorder on the site.

These comparisons are relevant to the comparison of Balquhidder ET estimates with regional ones since the regional estimates are based on a sparse network of manual stations.

4.6 TOPOGRAPHY AND THE METEOROLOGICAL VARIABLES

In the 1988 report a summary of the between-site variations in the meteorological variables was given. A further indication of the variations in the meteorological conditions in the catchments is given in Figures 4.6.2 and 4.6.1. These demonstrate the frequency distributions of wind direction and windspeed for the four AWS sites (pre-Campbell data).

Comparison of Figure 4.6.2 with Figure 4.3 demonstrates the constraints topography places on wind direction. Most notable is the contrast between Tulloch Farm in the east-west valley and Monachyle Glen in the north-south valley. This influence is still detectable at the less constrained upper Monachyle site when this is compared with the Kirkton High site which comes closest to unhindered exposure to the regional wind flow.

Figure 4.6.1 demonstrates the increasing range of windspeeds experienced as altitude/exposure increases.

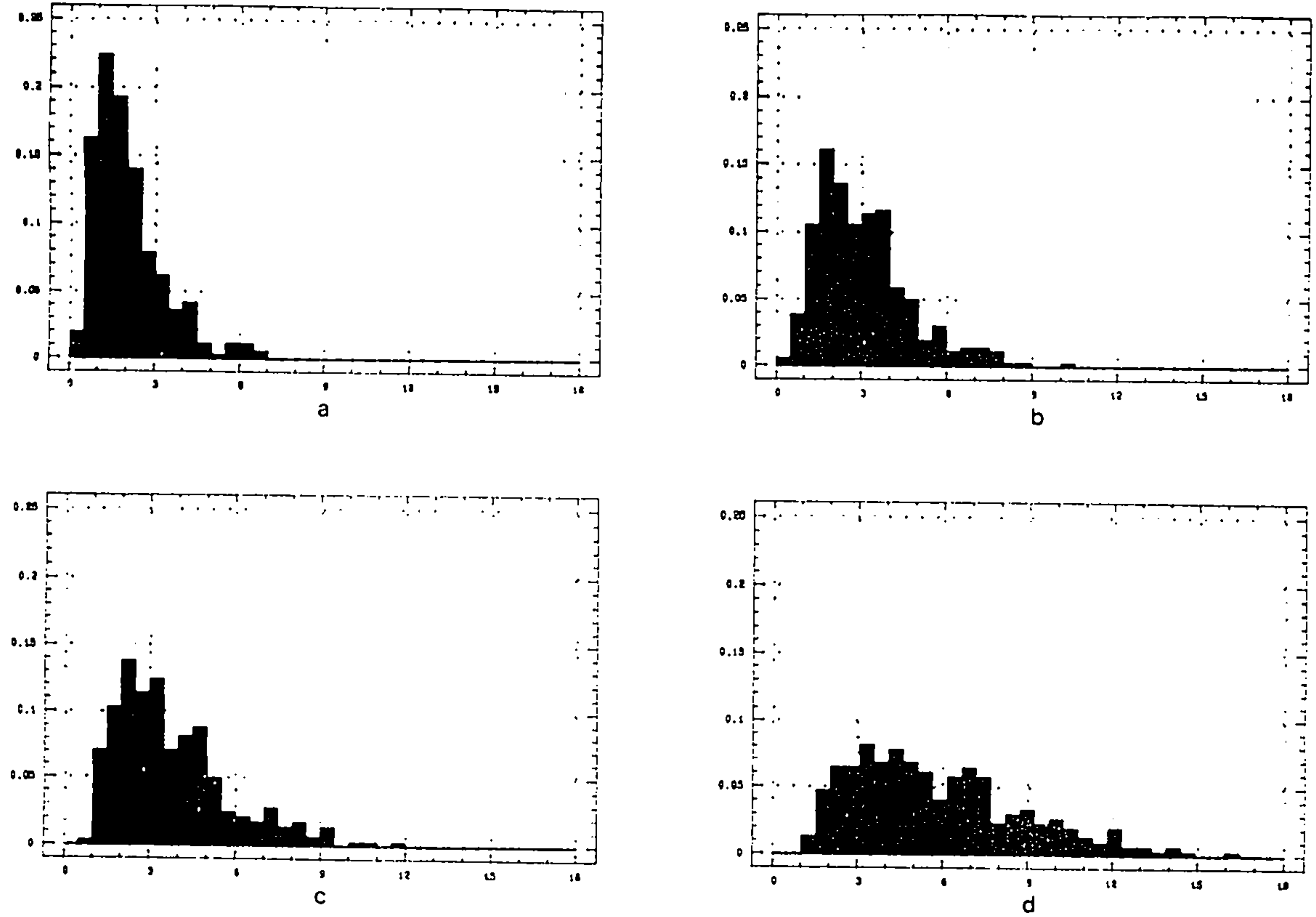

Figure 4.6.1 Frequency distributions of windspeeds (ms^{-1}) from AWS at (a) Tulloch Farm, (b) Monachyle Glen, (c) Upper Monachyle, (d) Kirkton High

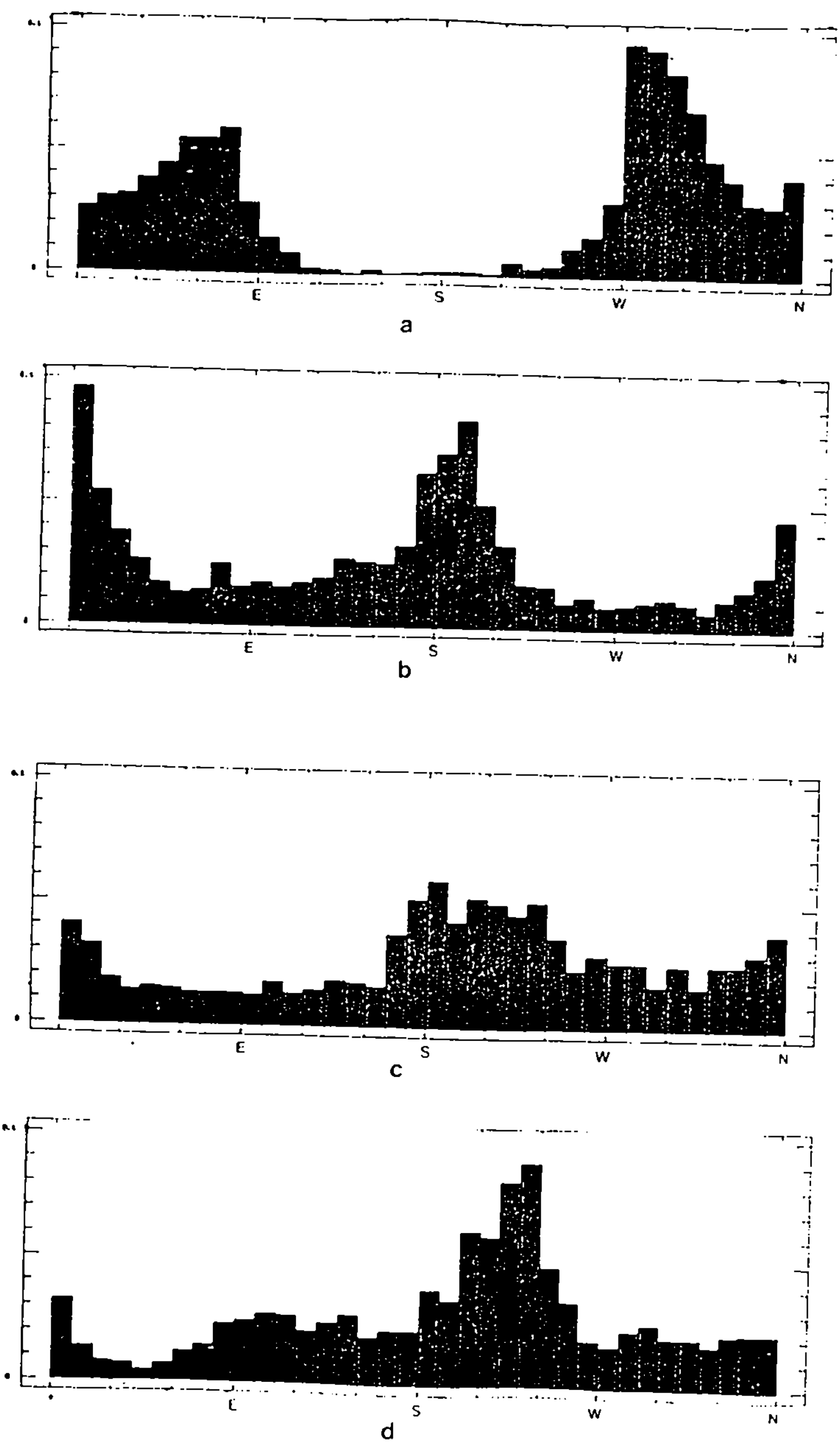

Figure 4.6.2 *Frequency distributions of wind directions from AWS at (a) Tulloch Farm, (b) Monachyle Glen, (c) Upper Monachyle, (d) Kirkton High*

5. Catchment water balances

5.1 PRECIPITATION AND STREAMFLOW

The monthly values of precipitation and streamflow obtained from the networks and the streamflow structures on the Monachyle and Kirkton catchments during 1988 are presented in Figures 5.1.1 and 5.1.2, whilst the annual totals are compared with those from previous years in Figure 5.1.3. The seasonal distributions are very similar in both catchments, with a marked contrast between a very dry June and a very wet July, the wettest month of the year. Figure 5.1.3 shows that the annual totals in 1988 were the second highest recorded during the study.

The excess of streamflow over precipitation in both catchments in February is due to precipitation late in January emerging as streamflow in February, whilst that in April is due to snow accumulation in March emerging as melt flow in early April. The marginal excess in the Kirkton only in June is comment on the much longer, flatter baseflow recession in this catchment. The excess in the Kirkton in October is more difficult to explain. Baseflow levels were similar at the beginning and end of the month and detailed quality control has revealed no obvious errors in the streamflow record. The only possible source of error identified to date is in the precipitation record where gauge C3Y (see Section 2.2) recorded only 59% of the catchment mean as compared to the normal 81%. A correction on this basis would lift the monthly total by some 6 mm.

Another source of some uncertainty is contained in the Kirkton streamflow total for January 1988. During this month 20 days of streamflow record were lost when both the 'front line' and the back-up recorders failed simultaneously. Since the short term response characteristics of the Kirkton and Monachyle are very different and since a short term storm response model is not yet fully developed from the Kirkton it was necessary to use a monthly streamflow regression with the Monachyle to estimate the monthly Kirkton total. The regression, based on the previous 60 months, has the form:

$$\text{Kirkton streamflow} = 0.7956 \cdot \text{Monachyle streamflow} \quad 18.9$$

with an r^2 of 0.969. This method of infilling was chosen in preference to the regression of Kirkton streamflow on precipitation which was less well defined.

5.2 CATCHMENT WATER USE

The crude estimate of water use, P-Q, is of little value on periods shorter than one year in the conditions at Balquhidder where the storage change term, ΔS, in the water balance can frequently exceed 50 mm. Over longer periods it becomes a progressively more accurate estimate however, as its value increases relative to storage change between the beginning and end of the

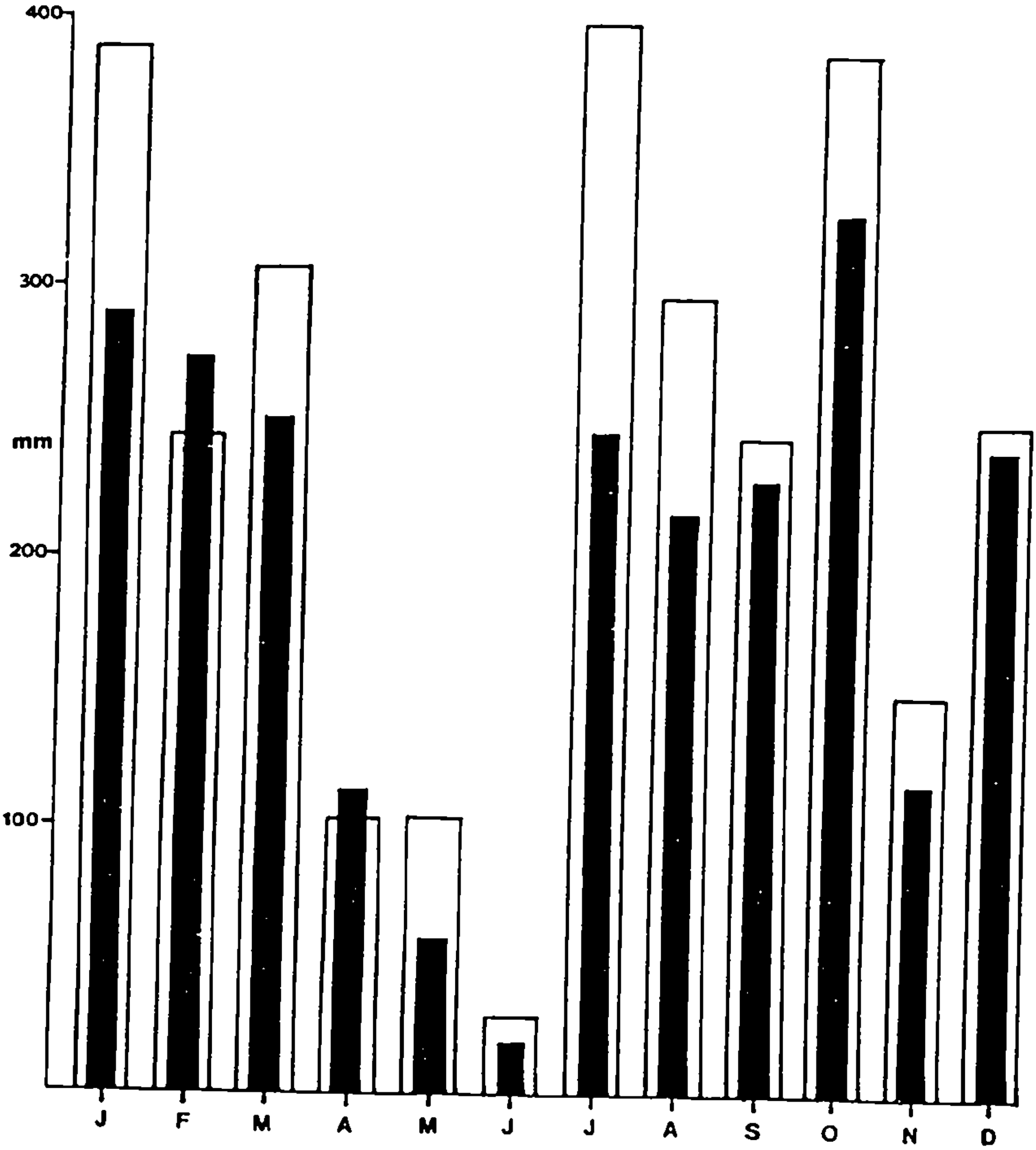

Figure 5.1.1 Monthly catchment means of precipitation and streamflow for the Monachyle catchment for 1988

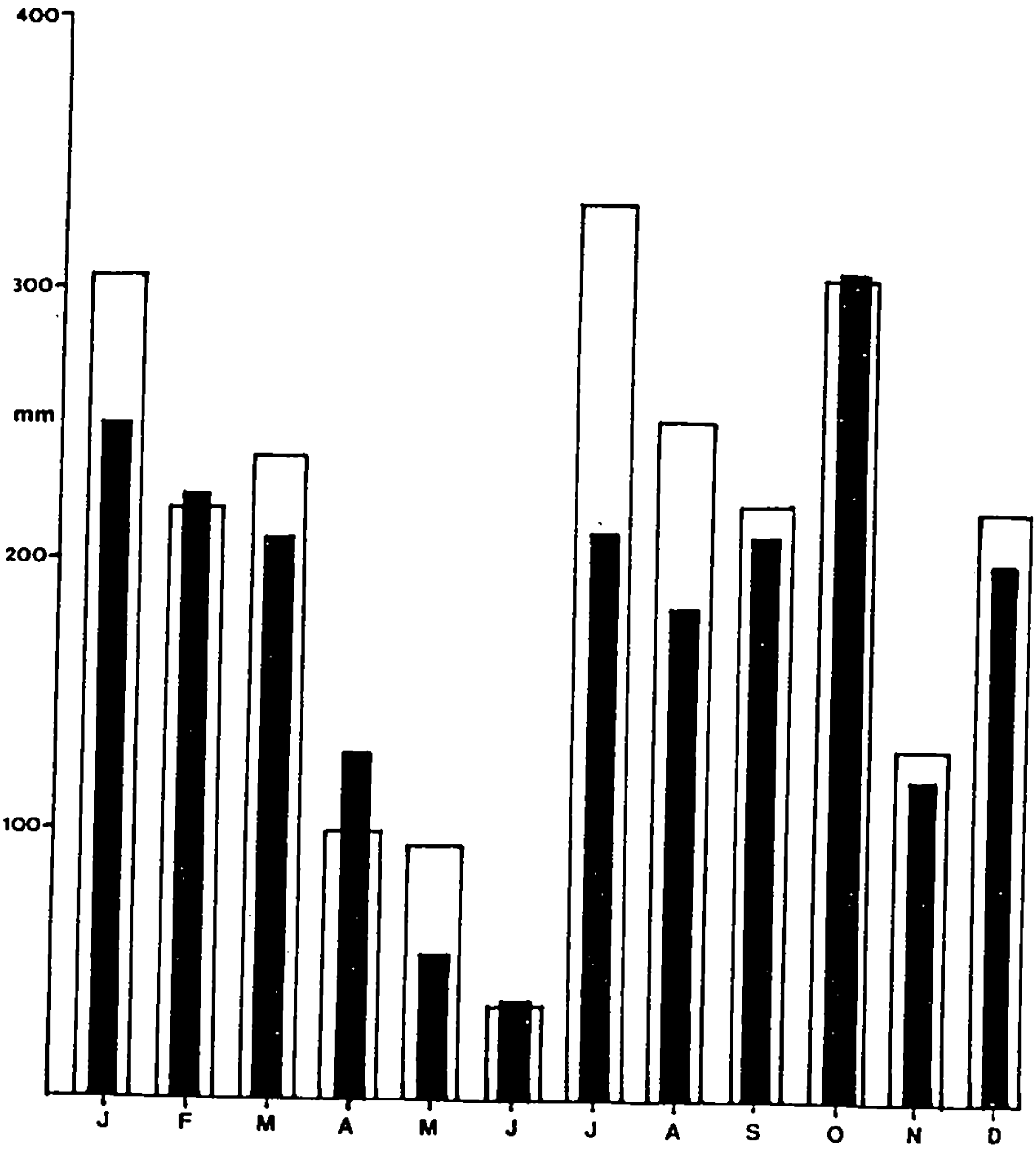

Figure 5.1.2 *Monthly catchment means of precipitation and streamflow for the Kirkton catchment for 1988*

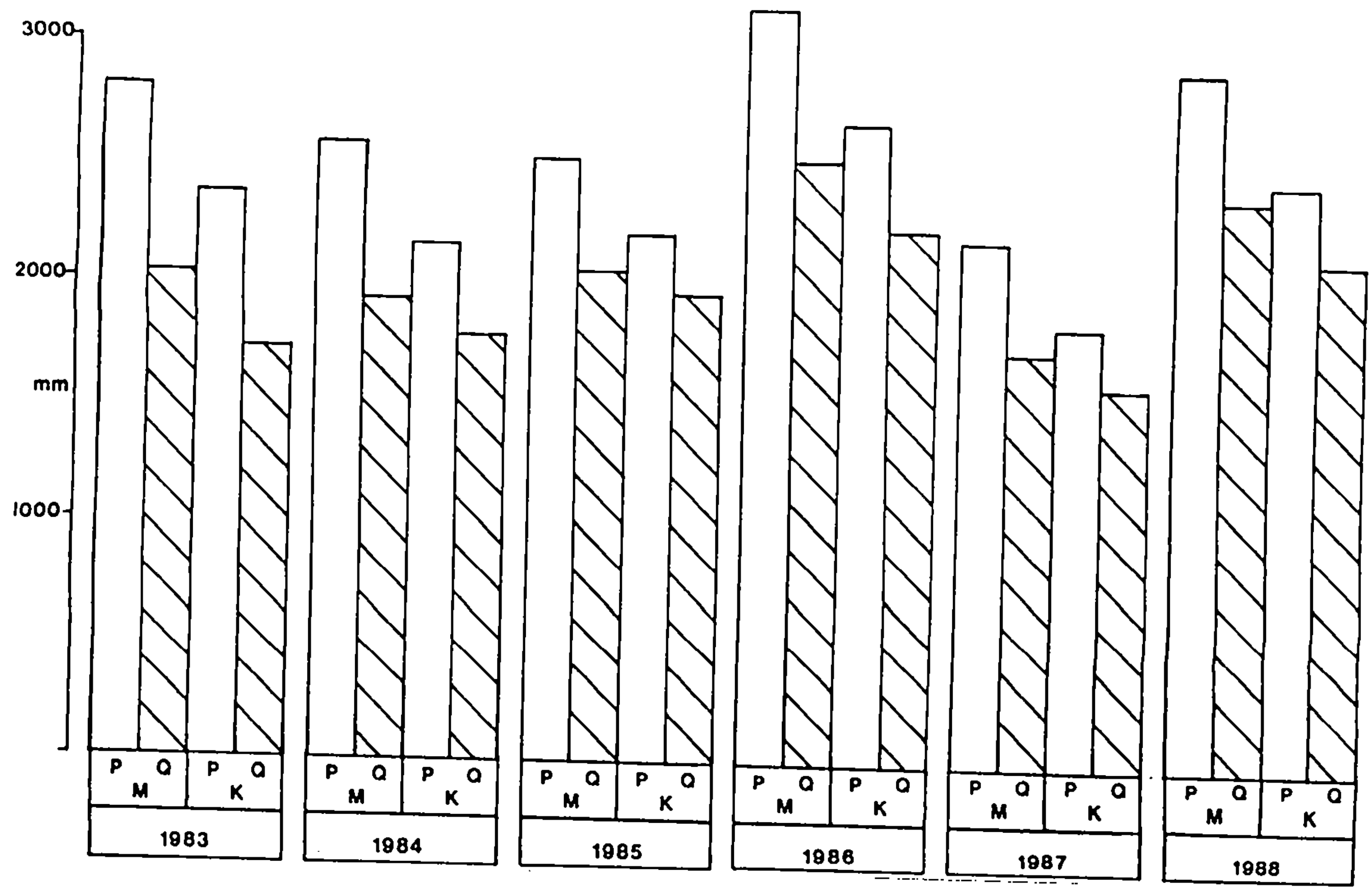

Figure 5.1.3 *Annual precipitation (P) and streamflow (M) totals for the Monachyle (M) and Kirkton (K) catchments*

period.

The P-Q estimates for 1988 are listed in Table 5.2.1 where they are compared with those for previous years and with Penman ET. The relative values between the catchments are similar to those in previous years, within the limits set by the uncertainties due to the unknown ΔS terms.

The cumulative P-Q value for the Monachyle during Phase II of the study remains closer to the estimated ET value for the upper Monachyle site, which is at approximately the mean catchment altitude. That for the Kirkton catchment remains significantly lower than the Kirkton High ET estimate though it must be remembered that Kirkton High at 670 m is well above the mean catchment altitude. No obvious trend in water use is present in the Kirkton annual values despite the progressive felling which has now cleared just under half of the 40% forest cover.

In Table 5.2.2 the 1988 P, Q and P-Q figures for the upper Monachyle subcatchment are compared with previous periods and with estimates for the 'lower' part of the catchment derived for the area weighted differences between the main and sub-catchments. As in 1987, a complete record of flow was obtained from the upper Monachyle structure through the use of pressure transducers to measure water level in the frost-prone winter months. The differences between the two parts of the catchment are small but it is noted that water use in the 'lower' part, containing the area drained and planted in 1986, has been consistently lower that that in the upper sub-catchment since then.

5.3 POSSIBLE SOURCES OF ERROR

The results of checks on various 'domains' within the precipitation networks have been described in Section 2. The preliminary deductions drawn from these are that correction of the undercatch by gauge C3Y in the Kirkton may produce an increase in the catchment precipitation estimate of 1.6% whilst gauging the high level D2W domain in the Monachyle may increase catchment precipitation estimates by 1.7%. If correct, these would increase the mean annual precipitations by 37 mm and 45 mm respectively. These figures are within the uncertainty limits on the present totals and would not significantly alter the relative water use estimates from the two catchments. Baseflow levels at the start of the year were higher than at the end, indicating that this component of ΔS would be negative for the year. No significant snow storage was present at either end of the year and the soil moisture status must have been close to or above field capacity. In the circumstances it is probable that ΔS was small and negative, ~~including~~ indicating a slight overestimate in water use ~~for~~ from using only P-Q.

TABLE 5.2.1 Annual totals (mm) of Precipitation (P), Streamflow (Q), Estimated Water Use (P-Q) and Penman Potential Evaporation (ET)

Period	MONACHYLE (Heather/grass) P	Q	P-Q	ET	KIRKTON (Forest + Grass) 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
1988	2912	2389	523	527*	2459	2126	333	516
Means	2752	2211	541	534	2328	1987	341	522

* Estimated from regressions on other sites

TABLE 5.2.2 Comparison of P, Q and P-Q for periods when Upper Monachyle Flow Data were Avalable (mm)

Period	MONACHYLE P	Q	P-Q	UPPER MONACHYLE P	Q	P-Q	'LOWER' MONACHYLE P	Q	P-Q
8/83-11/83	995	593	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	1443	1815	628	2390	1865	525
1987	2198	1724	474	2236	1757	479	2183	1711	472
1988	2912	2389	523	2931	2376	555	2904	2394	510
Means			517			554			502

6. Kirkton forest interception studies

Reference has been made to the forest interception site in several previous annual reports. The work has now been written-up and in February 1989 a draft paper was submitted to the Journal of Hydrology. As it is still awaiting publication only extracts from the results and discussion sections are presented below:

6.1 RESULTS

The site was operated from October 1983 until June 1986 when this area of the forest was clear-felled. A total of 54 readings were taken, usually at two week intervals but more frequently during prolonged wet or snowy periods. In this period the total interception amount was 28% of the precipitation and throughfall and stemflow constituted 69% and 3% of the precipitation. At this site with an annual average precipitation total of 2130 mm, this implies an annual loss through interception of 596 mm.

Large variations were found in interception loss, throughfall and stemflow totals throughout the period and also between the individual collectors for the two week periods. For example, although the mean throughfall was 69% there were extreme values of 93% and 21%. Also for one two week period the mean of the throughfall collectors was 71% but one caught 53% and another 42% of the rainfall. Equations 1-3 and Figure 6.1.1 show the relationships between precipitation and throughfall, stemflow and derived interception loss.

$$T = 0.71\,P - 2.1 \qquad (r^2 = 0.95 \quad SE = 0.023) \qquad (1)$$

$$S = 0.03\,P + 0.1 \qquad (r^2 = 0.61 \quad SE = 0.003) \qquad (2)$$

$$T = 0.26\,P + 1.9 \qquad (r^2 = 0.69 \quad SE = 0.025) \qquad (3)$$

where:
P = precipitation (mm)
T = throughfall (mm)
S = stemflow (mm)
I = interception (mm)

Figure 6.1.2 shows a time series plot of the interception results. The maximum value of 79% occurred in May 1985 and the minimum value of 0% in January 1985. There is a general trend of high interception in the summer and low interception in the winter but the large variability is the most apparent feature. Some links can be made between the interception rates and synoptic features but usually over the 2 week period several different conditions have prevailed.

The catches of individual throughfall collectors have been related to direction away from the tree stem, canopy density above the collector and distance away from the stem. For the direction a single tree was systematically surrounded

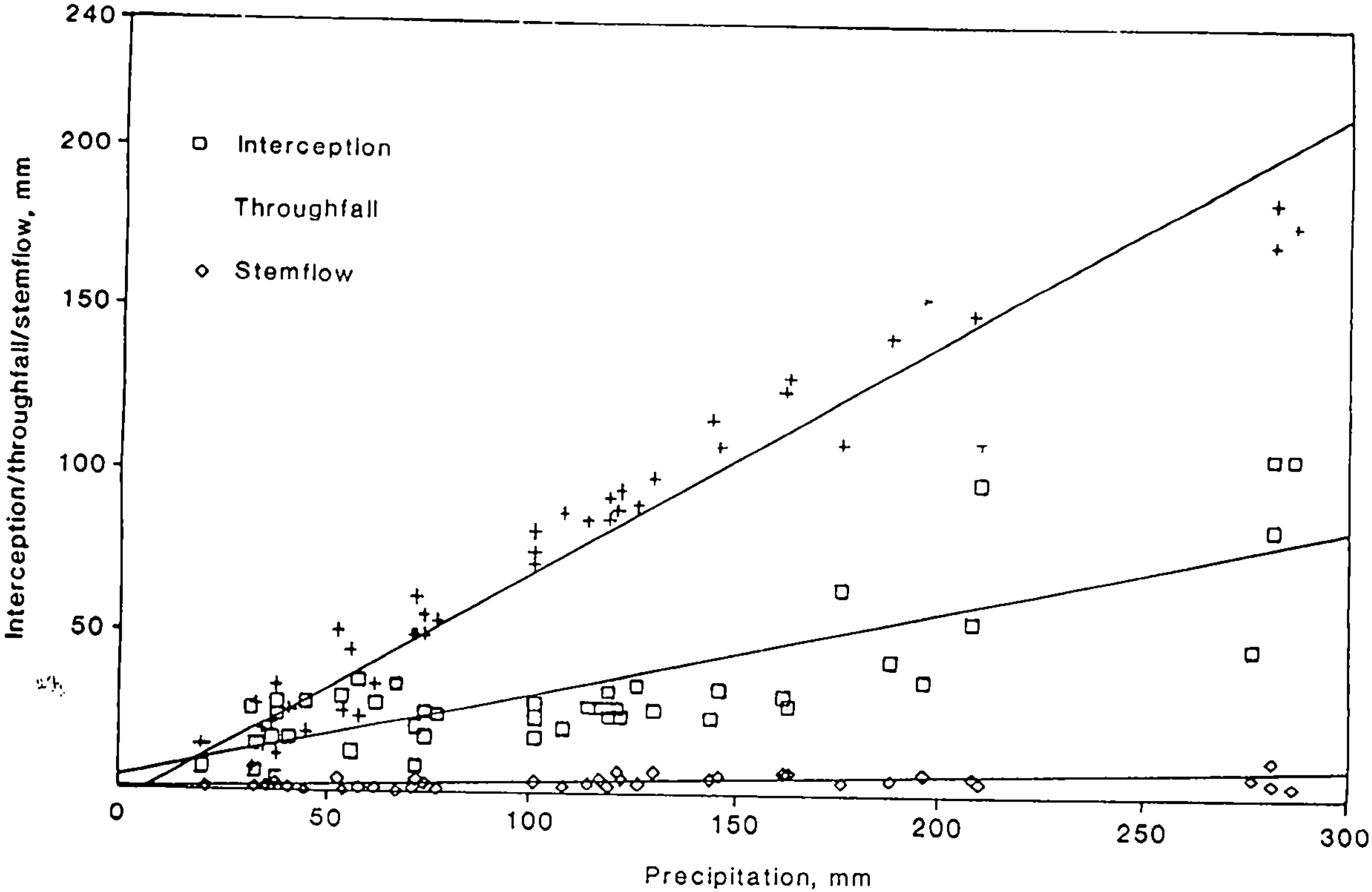

Figure 6.1.1 *Interception, throughfall and stemflow relationships with precipitation*

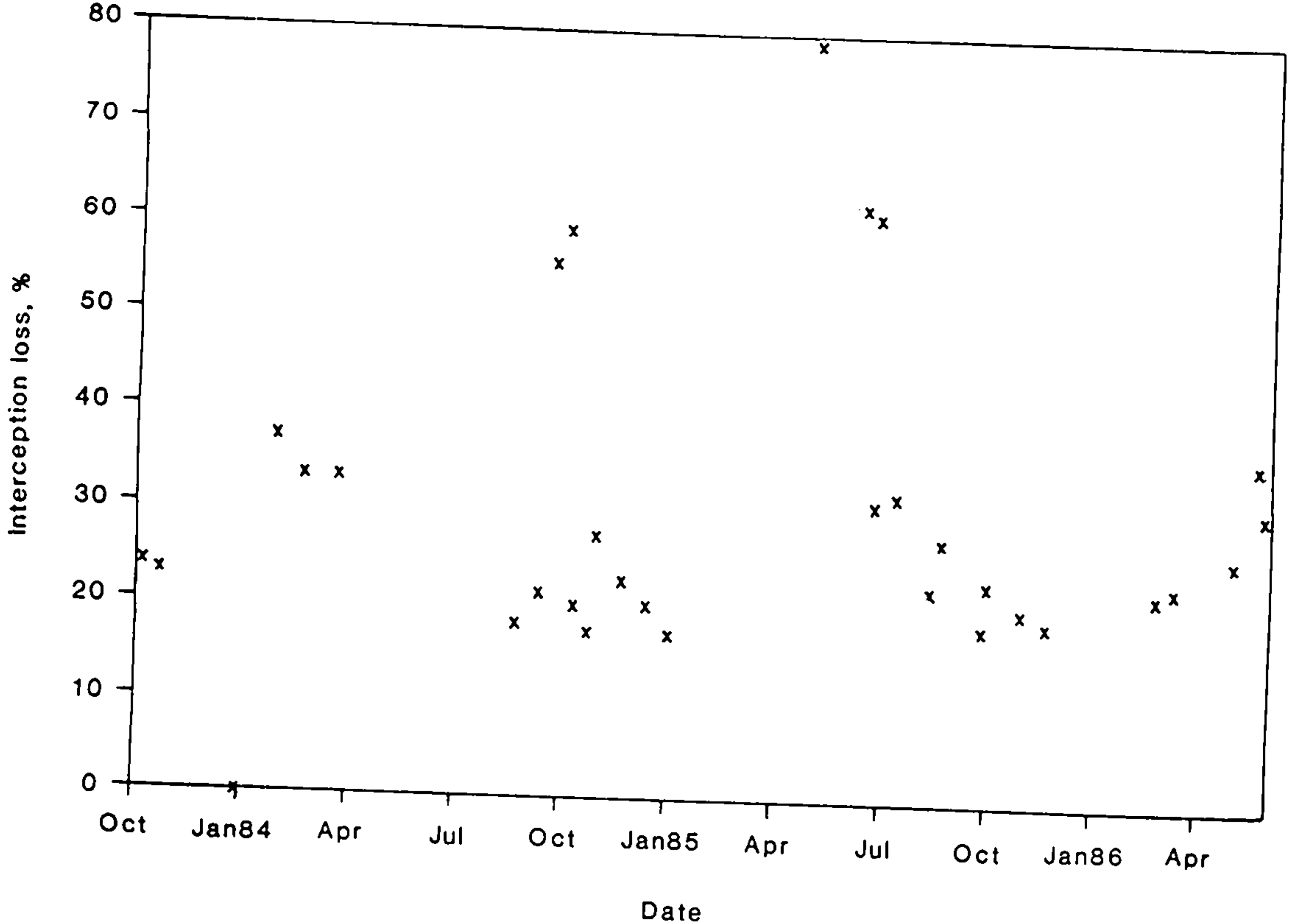

Figure 6.1.2 Interception loss, October 1983-June 1986

by small collectors and measurements taken for 1 year. Only a slight variation was found when all samples in given sectors were averaged, the eastern collectors had a lower catch. Canopy density showed a slight negative relationship but not on a significant level. The best relationships, explaining 65% of the variability, was obtained with the distance away from the stem expressed as a percentage of the distance to the canopy edge (Figure 6.1.3). It is interesting to note that 4 of the 5 collectors near the canopy edge had catches exceeding the precipitation. This is probably due to the longer branches bending near the end and directing some branch drainage outwards.

Stemflow has been show to constitute a very small proportion of the precipitation (3%) but the amounts of water can be significant for nutrient cycling, fine root growth and small scale erosion around the tree base. Amounts have a poor relationship with tree girth and the probable controls are in the canopy where slope angle and shape of the branches become important.

Snow measurement was one of the considerations when designing the site, and the period January to February 1984 had several large falls of snow. During the period the canopy started dry, then accumulated a large snow storage which gradually avalanched, sublimated or melted, eventually returning to a dry state. Figure 6.1.4 shows that the cumulative precipitation during the period reached 283 mm water equivalent in the neighbouring forest clearing where the maximum snow depth was 70 cm. The amount of intercepted precipitation calculated for the middle four readings comprised an amount lost through sublimation and the amount of snow stored on the canopy. Figure 6.1.4 shows this quantity to decrease between the fourth and fifth readings due to a large, but not complete, melt. The final interception loss figure is 37%. If it is assumed that there was a constant loss rate through the 28 day period then the amount of snow held in storage can be estimated. This is shown in Figure 6.1.4 as the area between the loss plus storage and predicted loss curves. The greatest amount estimated to have been stored on the canopy is 22 mm water equivalent.

6.2 DISCUSSION

Interception loss from the Kirkton forest canopy was 28% of the precipitation total. Similar results have been obtained from other British upland forests, at Greskine (Ford & Deans, 1978), Kielder (Anderson & Pyatt, 1986) and Plynlimon (Hudson, 1988) where average losses were 30%, 32% and 25% respectively. However, results from Stocks (Law, 1956) and another Kielder site (Anderson & Pyatt, 1986) show that interception losses can be larger, 38% and 49% respectively. It is possible that site exposure is the reason for these latter 2 results.

The throughfall and stemflow in the 50 year old Kirkton forest were 96% and 4% of the net precipitation. Figure 6.2 shows these with other results from British forests of different age. Without the Stocks results, which are again anomalous, there are remarkably close relationships between throughfall and stemflow as percentages of net precipitation and age of the trees, equations 4

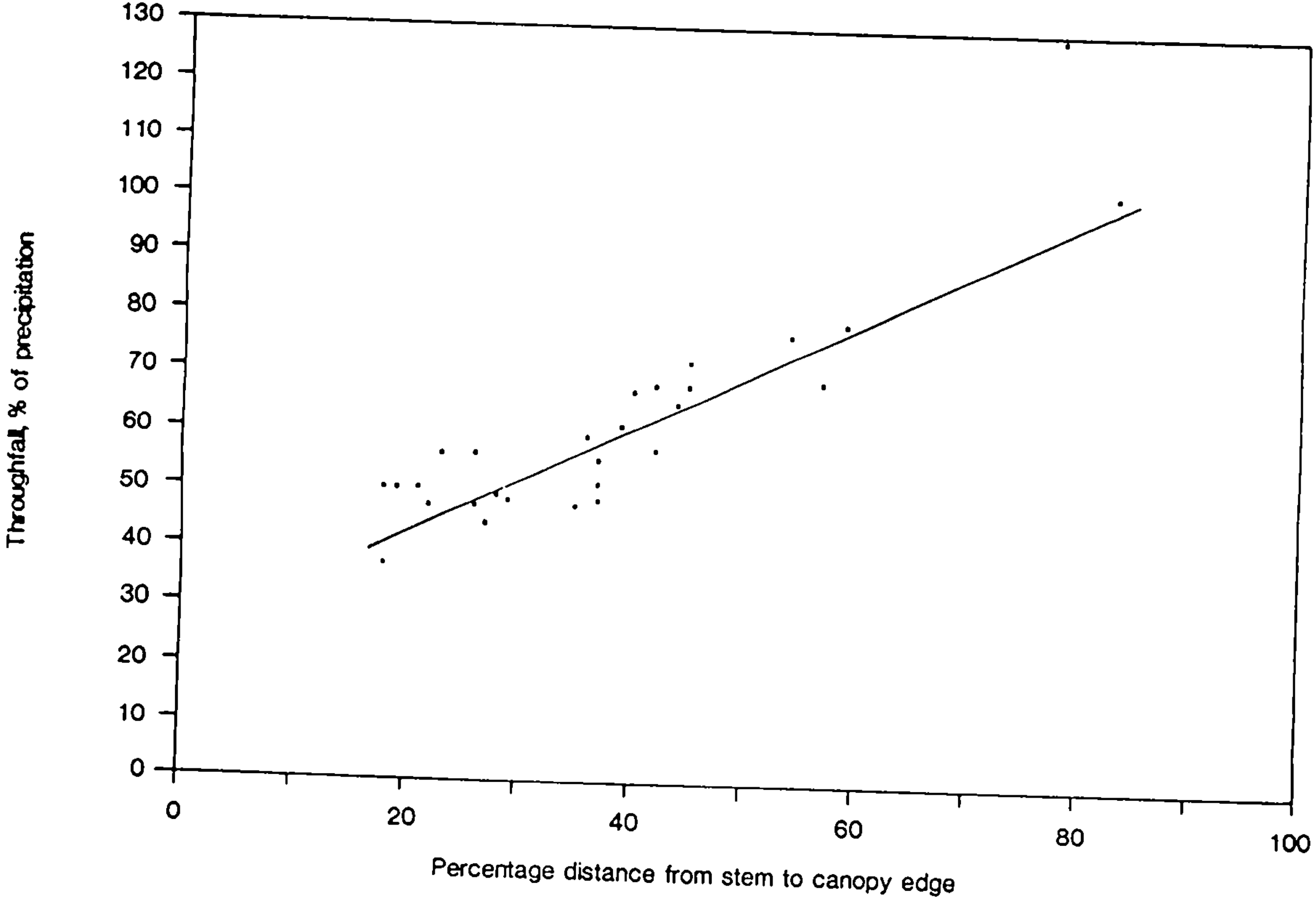

Figure 6.1.3 *Throughfall related to percentage distance away from tree stem*

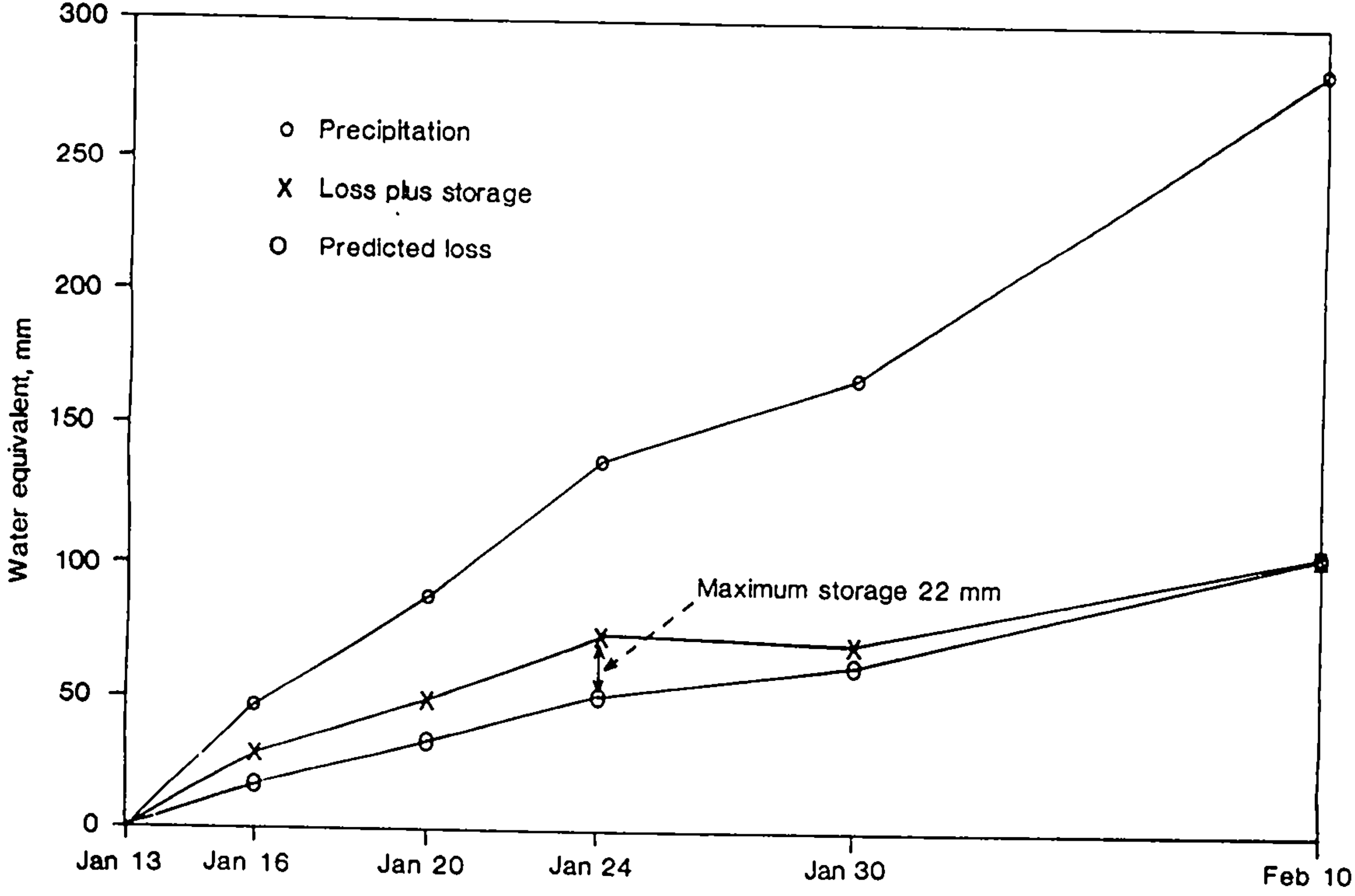

Figure 6.1.4 Snow interception, January-February 1984

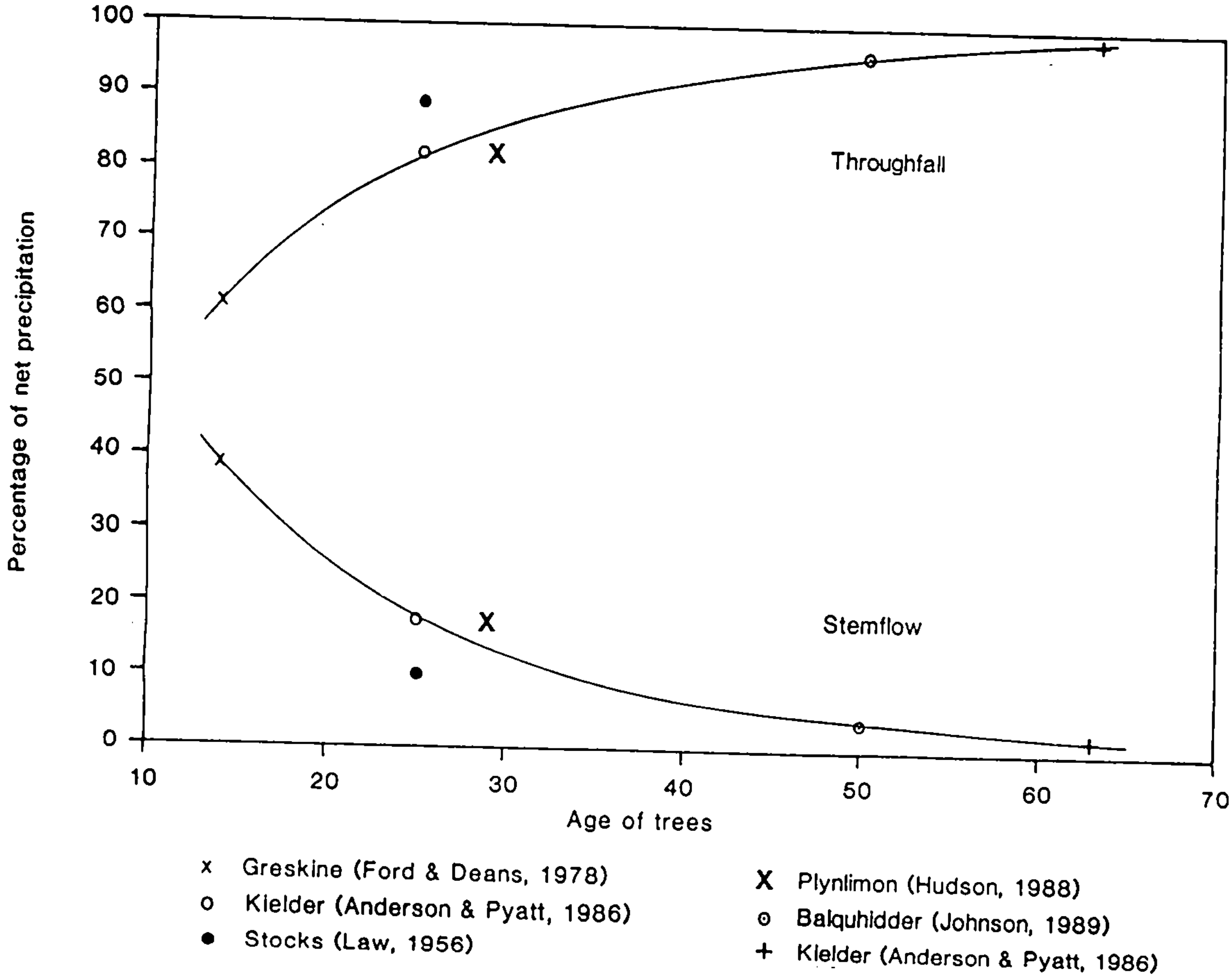

Figure 6.1.5 *Variation with age of the throughfall and stemflow percentages of net precipitation*

and 5. Therefore, although the age of the trees does not appear to influence the interception amount and consequently the total amount of water reaching the ground, the proportion of throughfall increases and the stemflow decreases as the trees grow older. Probably the most important consequence of this is to water quality and nutrient cyling with young trees providing more acidic stemflow than older trees.

$$TF = -50.5 + 140 \log_{10}(age) - 12.9\ (age)^{0.5} \qquad (4)$$

$$r^2 = 0.98$$

$$SF = 151 - 140 \log_{10}(age) + 12.9\ (age)^{0.5} \qquad (5)$$

$$r^2 = 0.98$$

where: TF = throughfall (% of net precipitation)
SF = stemflow (% of net precipitation)
age = age of trees

The seasonal pattern of interception differs from the Kielder and Greskine forest results in winter snow months. The Kirkton forest receives significant falls of snow which have been shown to result in increased winter interception losses.

The spatial variability of throughfall also differs from the result from the Greskine forest. In the Kirkton forest, where the crown was just interlocking, throughfall increased away from the stem. However, in the Greskine forest, where the trees had "a considerable overlap", throughfall was greatest near the stem.

7. Sediment Studies

Previous work in the UK on the effects of forestry on catchment sediment discharges has shown that the land preparation stage before planting is the time when most sediment discharge takes place. The maximum effects appear to be only short lived but the Plynlimon results showed that the suspended sediment concentrations were still above the pre-disturbance level even after 30 years. Also, because of its slow movement, the greatest effects of bedload might not be transmitted to the catchment outfalls for over 50 years.

Recently there have been two changes occurring in the forestry industry which could alter the general results indicated above. The first is that many districts are reaching the end of the first forest cycle, therefore clear-felling is increasing throughout the UK. The second change is the introduction of new recommendations to forest management which put a large emphasis on minimising the impact on the natural environment.

In terms of UK sediment studies, Balquhidder now represents one of the first sites to study the effects of clearing felling and the use of riparian buffer zones. It is also becoming one of only a small group of long term monitored sites in the UK.

Initially the aim of the sediment programme was to monitor sediment movement during flood events when it was considered that most of the fluvial transport took place. Annual loads could then be calculated using a rating curve method. With time the sampling has intensified which is giving more opportunities to devise other analytical methods for load evaluation. Work has been done on the sediment sources and temporary storage areas to determine the factors influencing the supply of material to the main stream.

The aims of the programme therefore are:

1. To assess the effect of pre-planting ground preparation on the Monachyle sediment yield.

2. To assess the effect of the Kirkton clear felling and timber extraction on:

    a. Source areas.
    b. Transport.
    c. Storage.
    d. Catchment yield.

7.1 METHODS

The sampling methods used at the catchment outfalls are:

7.1.1 Suspended sediment

Automatic vacuum samplers positioned close to the Crump weirs set on an 8 hourly sampling interval. Shorter intervals can be selected during major flood events.

The variability which has been found in the samples initiated periods of intensive sampling when series of multiple single point samples and cross sectional profile sampling were carried out. Both automatic and hand samples have shown that there really is a large variability in sediment concentration in very short time intervals. Because of this the cross sectional profiling is taking longer to assess, as many sets of samples will be required to derive the best single point sampling position.

7.1.2 Bedload

A Helley-Smith bedload sampler was initially used to take spot samples over 10 minute time intervals. Operating these samplers is not easy, especially in the largest flood conditions. Therefore, as these were the times when most bedload moved it was considered that the method was probably underestimating the total bedload. Larger volume collecting bags with a large mesh size were therefore made and the samplers tethered in the streams. This resulted in potentially all the bedload movement being sampled. To a certain extent this has worked but in some floods so much material moves that the bags soon fill up and even emptying after each flood is not enough. However the method is an improvement and the size analyses of the catches have led to further insights into bedload movement.

Many different techniques have been used to assess the source areas, storage areas and transport methods. These include:

1. Source areas -	erosion pins road surveys hillslope traps
2. Storage areas -	quantification of natural traps
3. Transport methods -	pebble tracing tributary traps tributary/drain spot samples

7.2 RESULTS

In December 1988 a paper was given at the IAHS conference in Brazil on sediment budgets, the paper (Johnson 1988) is presented in appendix 1. Recently all the sediment data has been transferred onto a PC at Balquhidder enabling much more rigorous analyses to be done.

Figure 2 in Johnson 1988 shows the suspended sediment relationships with discharge for 1983-87. Figures 7.2.1 and 7.2.2 in this report show the 1988 relationships from both catchments. The scatter in the data is probably the most striking feature of the plots, especially since the land-use changes in early 1986.

Time series plots of suspended sediment also show a large scatter and any trends are difficult to find. By smoothing, using a 12 month running mean, a more acceptable plot is produced (Fig. 7.2.3). The land-use change in the Kirkton started in late 1985 when road upgrading was carried out and the Monachyle ploughing started in early 1986. Upward trends in Fig. 7.2.3 are evident around these times which do not appear to correspond with any particularly wet months. However, as both land-use changes occurred at around the same time, it is still not conclusive that the disturbances were responsible for the rises in suspended sediment concentrations.

Load evaluation is very difficult from these data sets but first estimates of the 1988 suspended loads are:

Kirkton 1750 tonnes (255 t km^{-2})
Monachyle 450 tonnes (58 t km^{-2})

i.e. 4.5 and 1.5 times greater than the pre-disturbance figures.

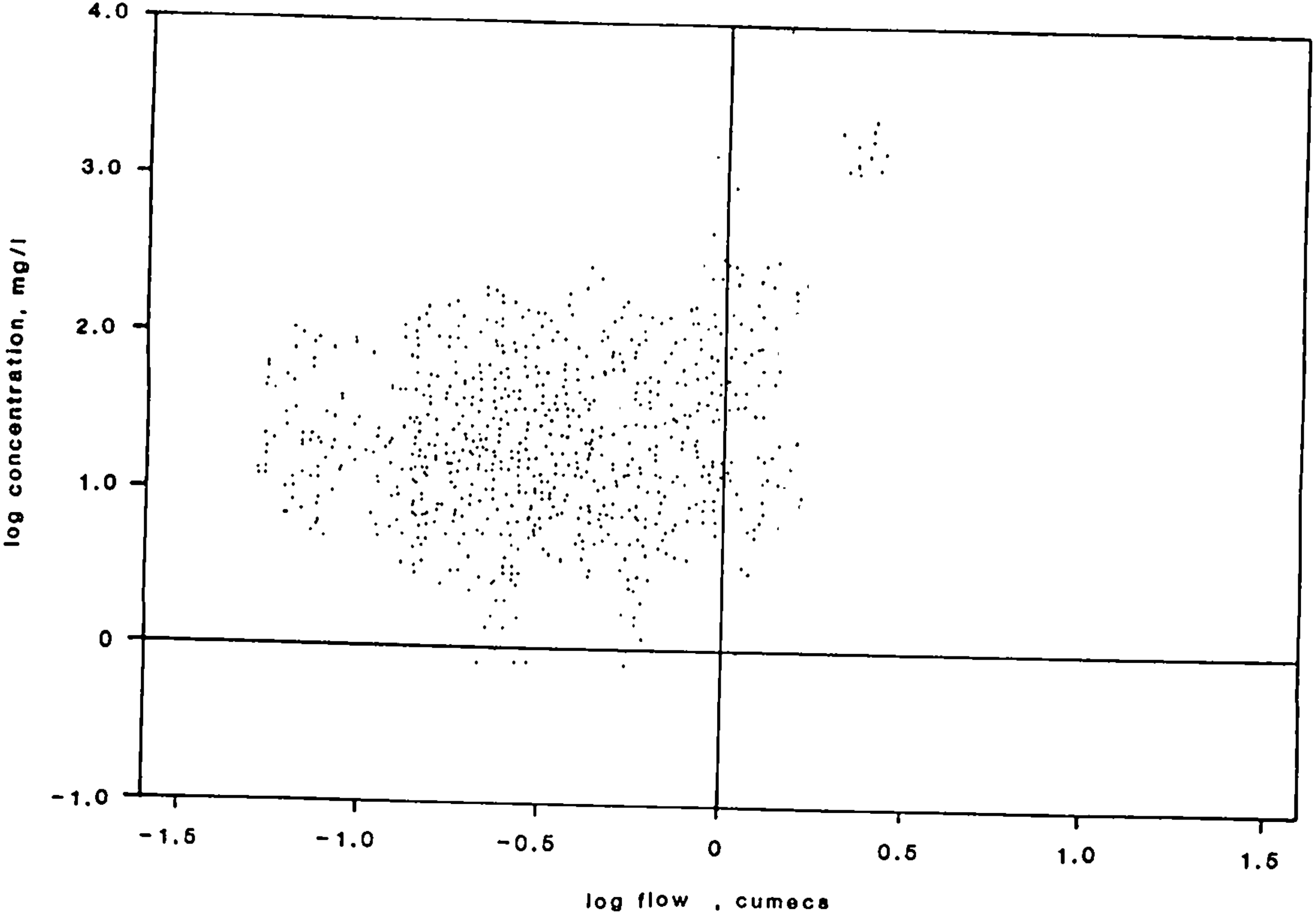

Figure 7.2.1 Kirkton suspended sediments 1988

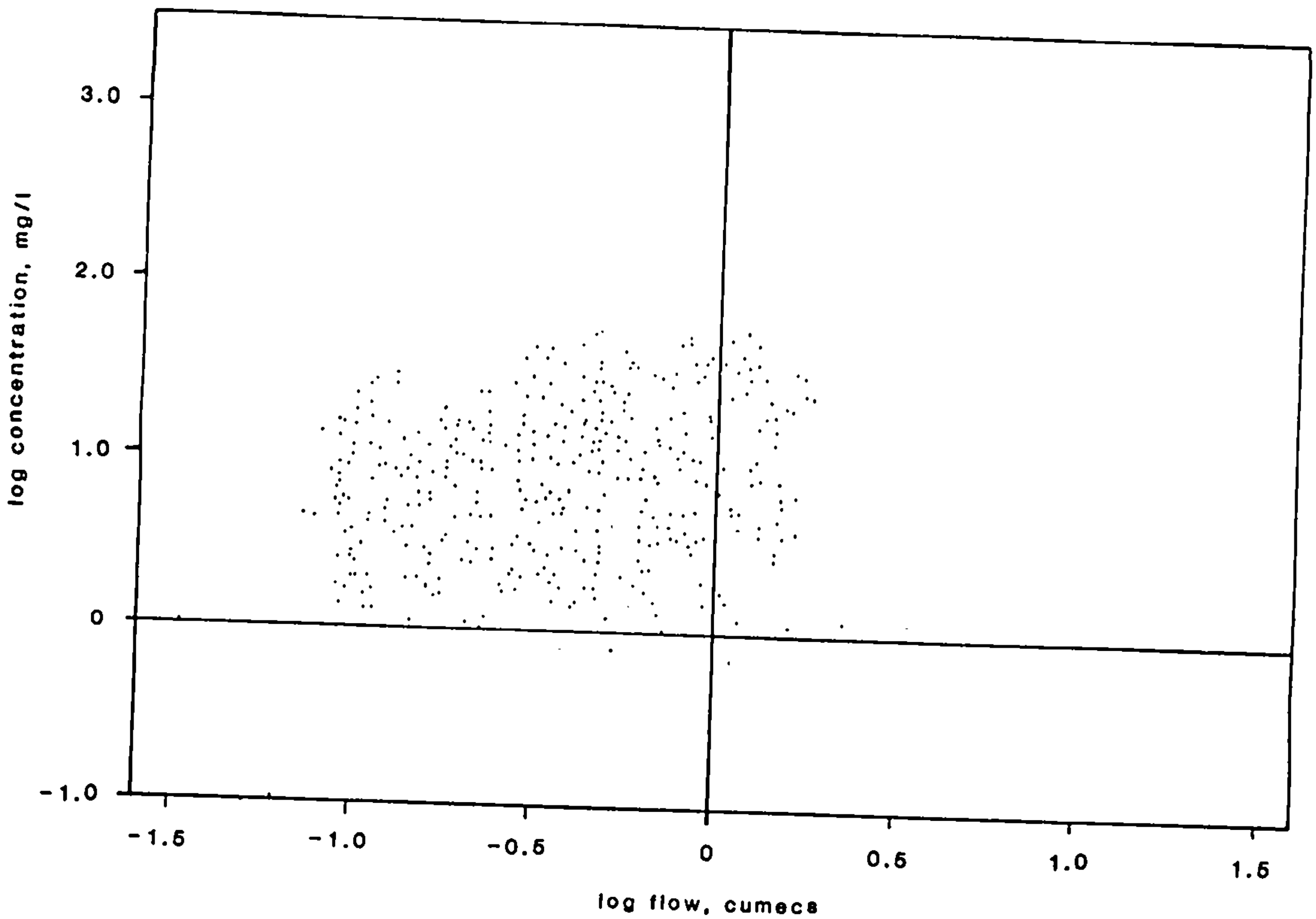

Figure 7.2.2 Monachyle suspended sediments 1988

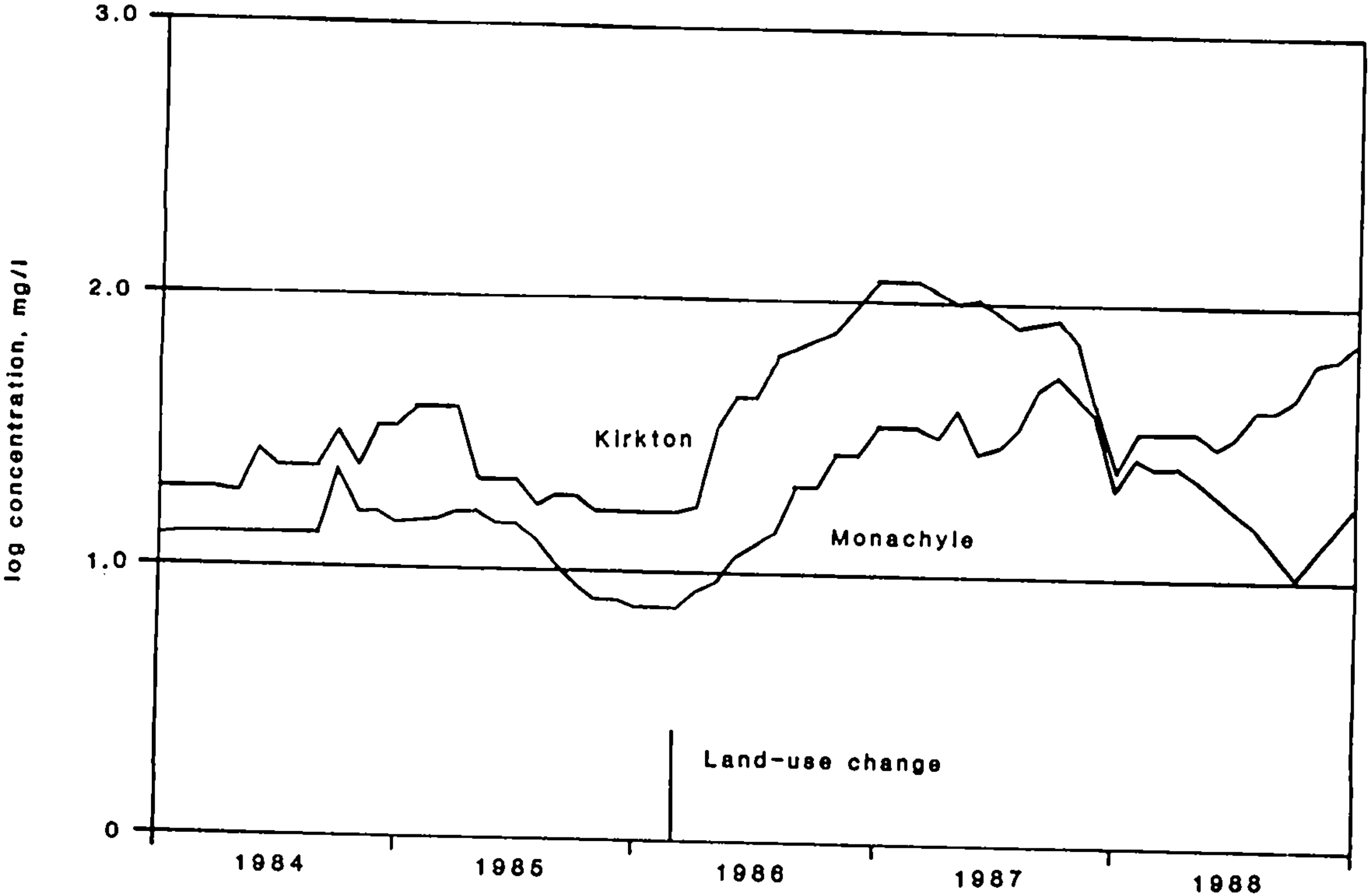

Figure 7.2.3 Monthly mean sediment concentration

Bedload amounts are easier to quantify because of the sampling methods used. Applying a conversion factor related to the proportion of the active stream bed sampled the 1988 March-December loads are:

Kirkton 1.3 tonnes

Monachyle 1.6 tonnes

i.e. similar to the pre-disturbance loads.

From work being done on the rate of movement of pebbles in tributaries the effects of the land disturbances on bedload will probably not be seen at the catchment outfalls for some considerable time.

Figure 7.2.4 shows the cumulative bedloads in both catchments were dominated by 6 events during 1988. The amounts moved in these storms were 90% of the total Kirkton load and 98% of the Monachyle load.

7.3 DISCUSSION

From the above results the annual loads are still in excess of the pre-disturbance amounts, although there is an indication that the Monachyle load is falling.

There is no evidence to suggest that the main 1983-85 sediment source, the tributary banks, have changed significantly. However, large amounts of erosion have been taking place from the roads in the Kirkton and plough lines in the Monachyle since 1986.

From Kirkton road surface surveys up to 10 cm of surface mateiral was lost between May and December 1988. By classifying roads and sampling surface material for density and size distribution analysis it has been estimated that some 1000 tonnes of material was lost from the roads during this period. Therefore the forest roads appear to have become the major sediment source in the Kirkton.

By summer 1988 the Monachyle plough lines, which took over the role of the major sediment source, had largely become revegetated so these sediment sources can be expected to become less active. There is an indication in Fig. 7.2.3 that there was a delay of some 18 months between the time of land disturbance and the maximum output of suspended sediment. However, the picture is complex as the 1987 rainfall distribution also appears to have a large influence on the trends in both catchments.

Because of the large scatter the analytical methods used on the 1983-85 data are clearly inadequate for the later years. Therefore, several long periods of intense sampling have been carried out to determine what is causing the apparently variable responses. It is too early to draw any conclusions but interesting results are being obtained from relating concentration not only to flow but also to rainfall intensity and ~~also~~ to flow and rain antecedent characteristics.

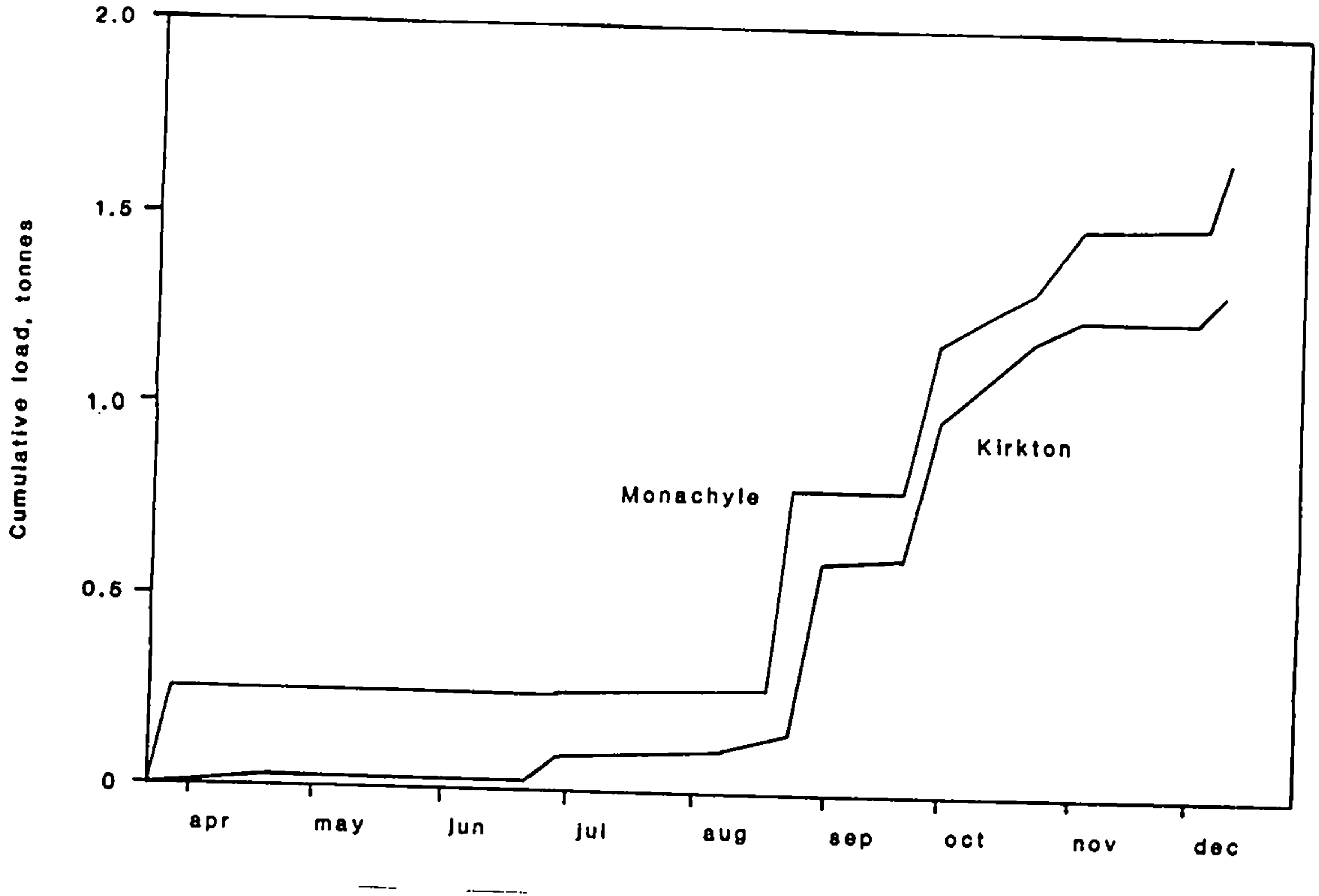

Figure 7.2.4 Bedload 1988

8. High Altitude Grassland Studies

8.1 BACKGROUND

It is standard practice to assume that the evaporation rates from all grassland are correctly estimated by the Penman potential evaporation rate. However, the results of recent catchment studies have cast doubt upon the validity of this assumption, and particulartly for high altitude grassland in the UK.

The results from the first phase of the Balquhidder catchment study gave an unexpectedly low mean annual water use of the partly forested Kirkton catchment, (see 1987-88 Report to Scottish Consortium). Even after allowing for experimental errors the result implied that grass on the Kirkton catchment uses considerably less water than predicted by the Penman potential evaporation.

It is likely that transpiration loss from high altitude grassland will be lower than that from the lowlands given a similar demand. The low temperatures lead to slow growth and, particularly in the spring and winter, only a small proportion of the grass is alive. Additionally, low temperatures may suppress the transpiration from even green vegetation. However transpiration is not the only loss. In areas of high rainfall, such as Balquhidder, the evaporation from rain wetted vegetation may be important. It is apparent that our understanding of the evaporation from high altitude grassland is far from complete and for this reason the high altitude grassland study was set up.

8.2 EXPERIMENTAL DETAILS

The principal objective of the high altitude grassland study is to make long term measurements of total evaporation from the upland grass and compare the rates of evaporation with those predicted by the Penman equation. A further objective is to separate the processes of transpiration and the evaporation of intercepted rainfall with a view to understanding the controlling mechanisms and improving predictive water use models.

As has been described more fully in a previous report, a process studies site has been installed on a grass terrace close to, and representative of, the high altitude areas of the Kirkton catchment (Gleann Crotha, Grid ref: NN507255). Total evaporation is measured using two weighing lysimeters each containing a soil monolith with a grass area of 0.5 m^2 and deep enough to include the complete root zone. Changes in lysimeter weight (single load-cell), rainfall input and pumped drainage output are monitored continuously and meteorological variables are recorded using an automatic weather station.

Measurements of soil moisture using a neutron probe were made for the first two years of the experiment but have failed to give a satisfactory estimate of the transpiration and have been discontinued. This is thought to be due to the inability of the neutron probe technique to take account of the changes in volume of the peat as it loses water.

Biomass sampling is continuing throughout the year to determine changes in the proportion of vegetation that is photosynthetically active.

8.3 RESULTS

The lysimeters are operated during the snow free season, approximately March to September. Data recovery for 1988 has been good with only a few breaks in the readings, during these breaks the lysimeters act as drainage lysimeters so the overall water balance is not lost.

Figure 8.3.1 shows the cumulative measurements of evaporation from the two monolith lysimeters from 24 March 1988 to 28 September 1988. Total evaporation for the period (188 days) is measured as 330 mm and 308 mm for lysimeters A and B respectively compared to 397 mm estimated using the Penman equation for the same period.

Figure 8.3.2 shows the seasonal change in measured evaporation (mean of two lysimeters) expressed as a ratio of the Penman estimate of evaporation for the individual periods. Although more detailed data are available from the load-cells, these measurements represent the most accurately monitored water balance using volumetric measurements with an adjustment for changes in water storage.

Changes in biomass composition (live grass/total biomass) for 1987 and 1988 are shown in Figure 8.3.3. The error bars are an indication of the possible divergence of the population mean from the sample estimate of live weight ratio.

8.4 DISCUSSION

Notwithstanding the periods of interpolation in Figure 8.3.1 necessitated by instrument failures, the performance of the two lysimeters are mutually consistent and noticeably different to the cumulative Penman estimate of evaporation for the same period. These data show for the first time that the high altitude grass prevalent on the Balquhidder uplands loses less water by evaporation than would be estimated by the Penman equation.

When viewed in more detail (Figure 8.3.2), these data suggest that period evaporation was mostly below the Penman rate (mean ratio of 0.7) at least until the end of June. After this date the losses are close to the Penman potential rate.

The primary influences to the overall shape of Figure 8.3.2 have not yet been isolated. Both live weight ratio (Figure 8.3.3) and daily mean temperature (Figure 8.3.4) follow a similar trend and can each suppress water loss. The changes in live weight ratio show that a reduced fraction of the biomass is photosynthetically active during the early months of the year and this should reduce the transpiration However, the stomata of the grass may also close at low temperature (below 6°C), reducing the transpiration from live grass. There is a very poor correlation between the detailed variations in evaporation ratio and the mean daily temperature (Figures 8.3.2 and 8.4.1), as might be expected if there were a physiological cut-off at temperatures below 6°C.

There does appear to be a coincidence between the low values of evaporation ratio and low rainfall in mid June and early September (Figure 8.4.2). This implies the transpiration from dry grass is less than Penman whereas the evaporation from wet vegetation is close to Penman, demonstrating the necessity to separate interception from transpiration losses, at least when modelling the process.

8.5 CONCLUSIONS

The lysimeters installed at the high altitude grassland site have returned valuable data over the past year. Analysis has indicated that for at least the early months of 1988 the total evaporation rate from the grass was significantly less than the Penman potential rate and 81% of Penman overall. Also that there is optimism for a simple model describing the deviations of actual evaporation from the Penman estimate, using meteorological or physiological input parameters.

Objectives for following year can be summarised as follows:

- Collect a further season of data to reinforce the current conclusions.
- Extend the measurement season at both ends to improve the understanding of seasonal patterns of evaporation.
- Investigate the drying and aerodynamic properties of the biomass to enable the construction of a predictive model of evaporation.
- Investigate the possibility of, or even the necessity to, separate the interception and transpiration components of the total evaporation loss.

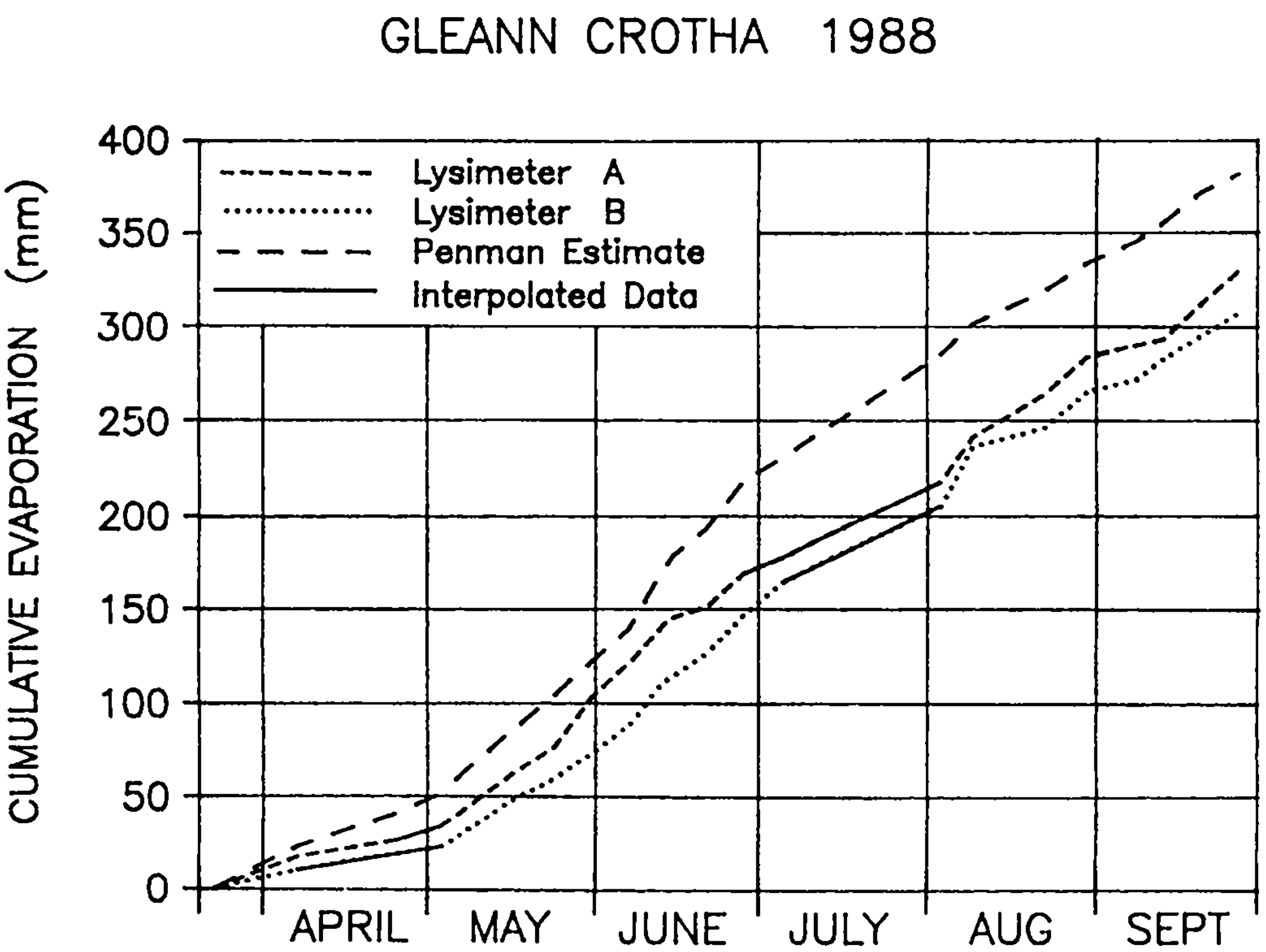

Figure 8.3.1 Gleann Crotha 1988

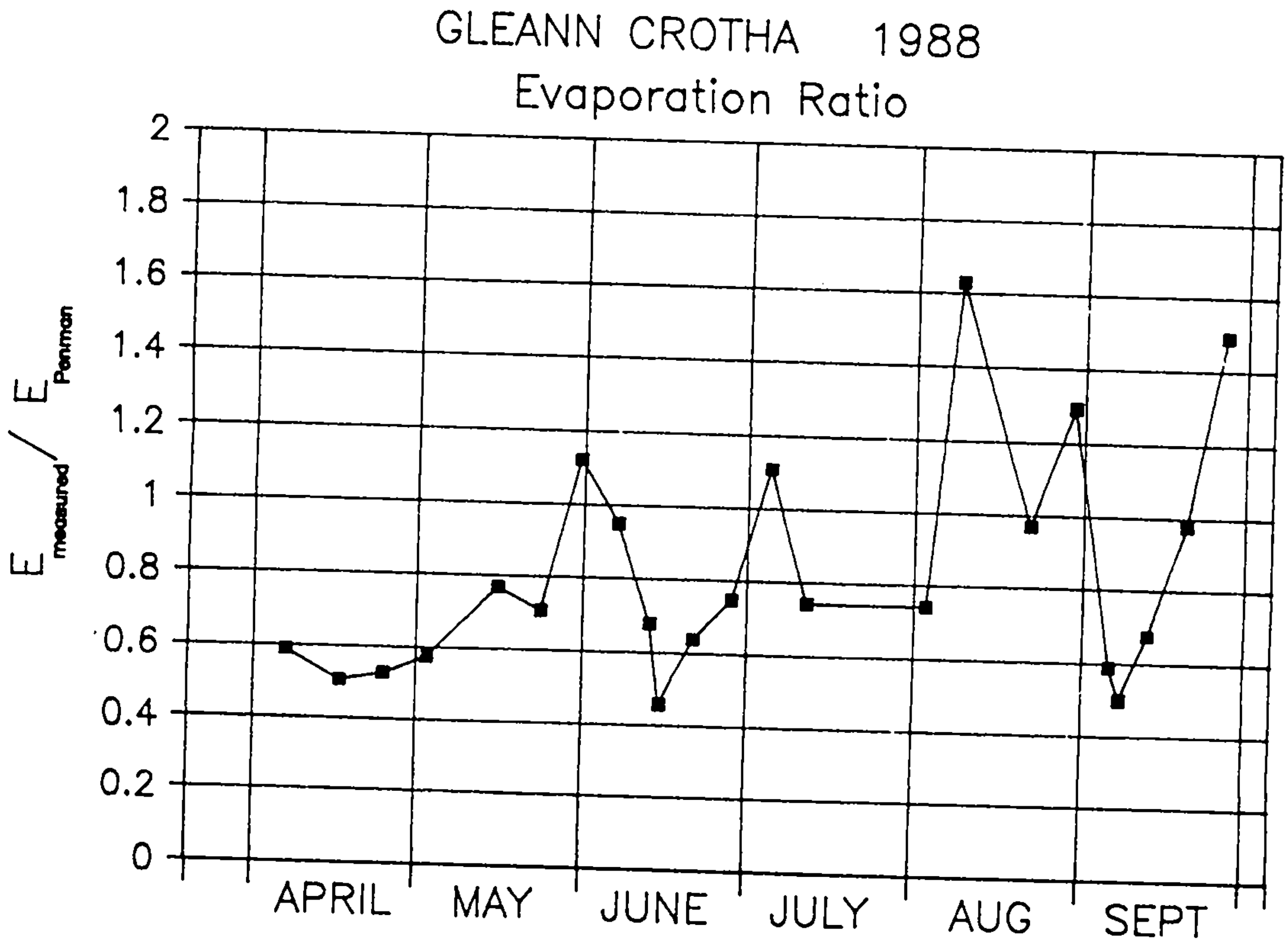

Figure 8.3.2 Gleann Crotha 1988, evaporation ratio

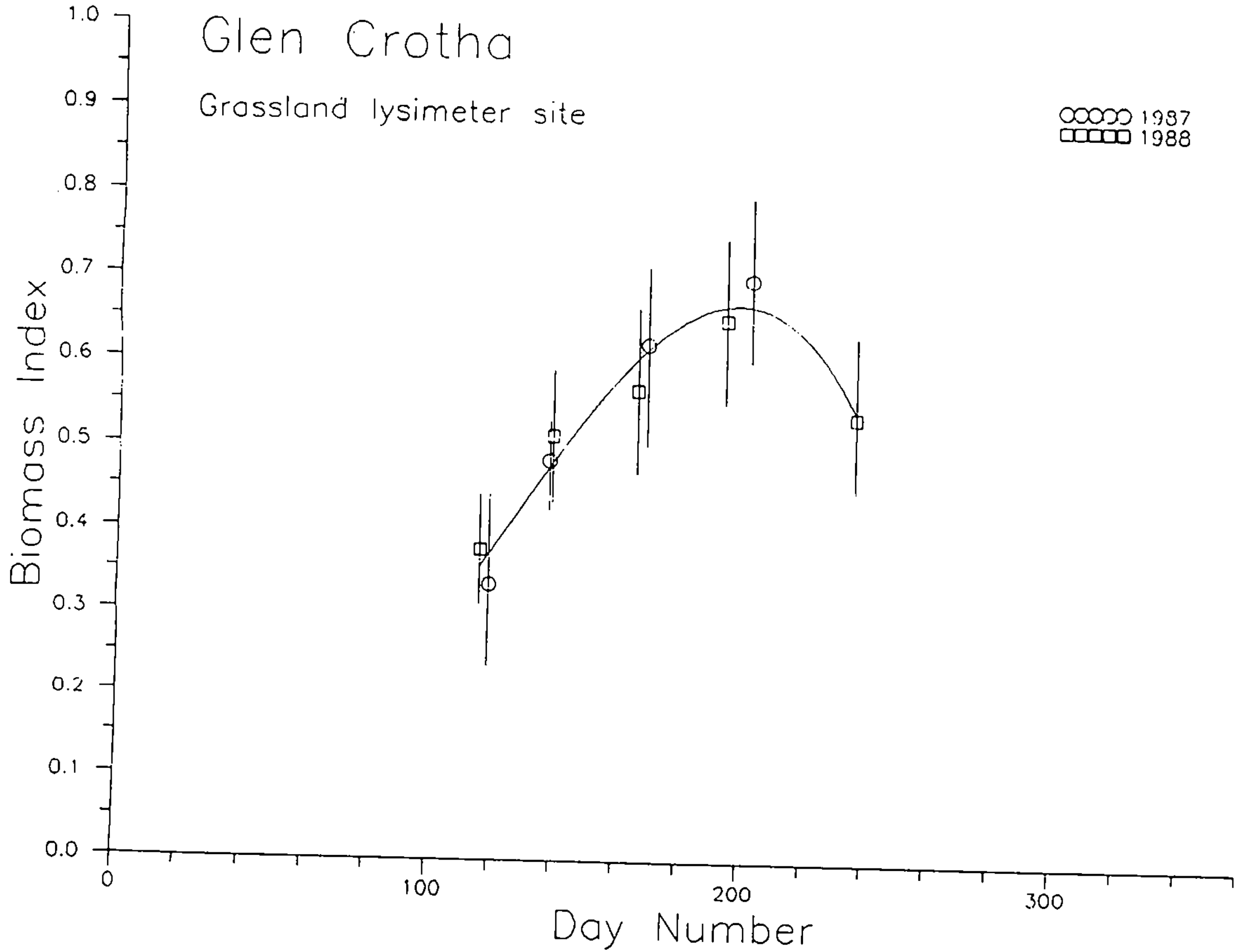

Figure 8.3.3 Gleann Crotha, grassland lysimeter site

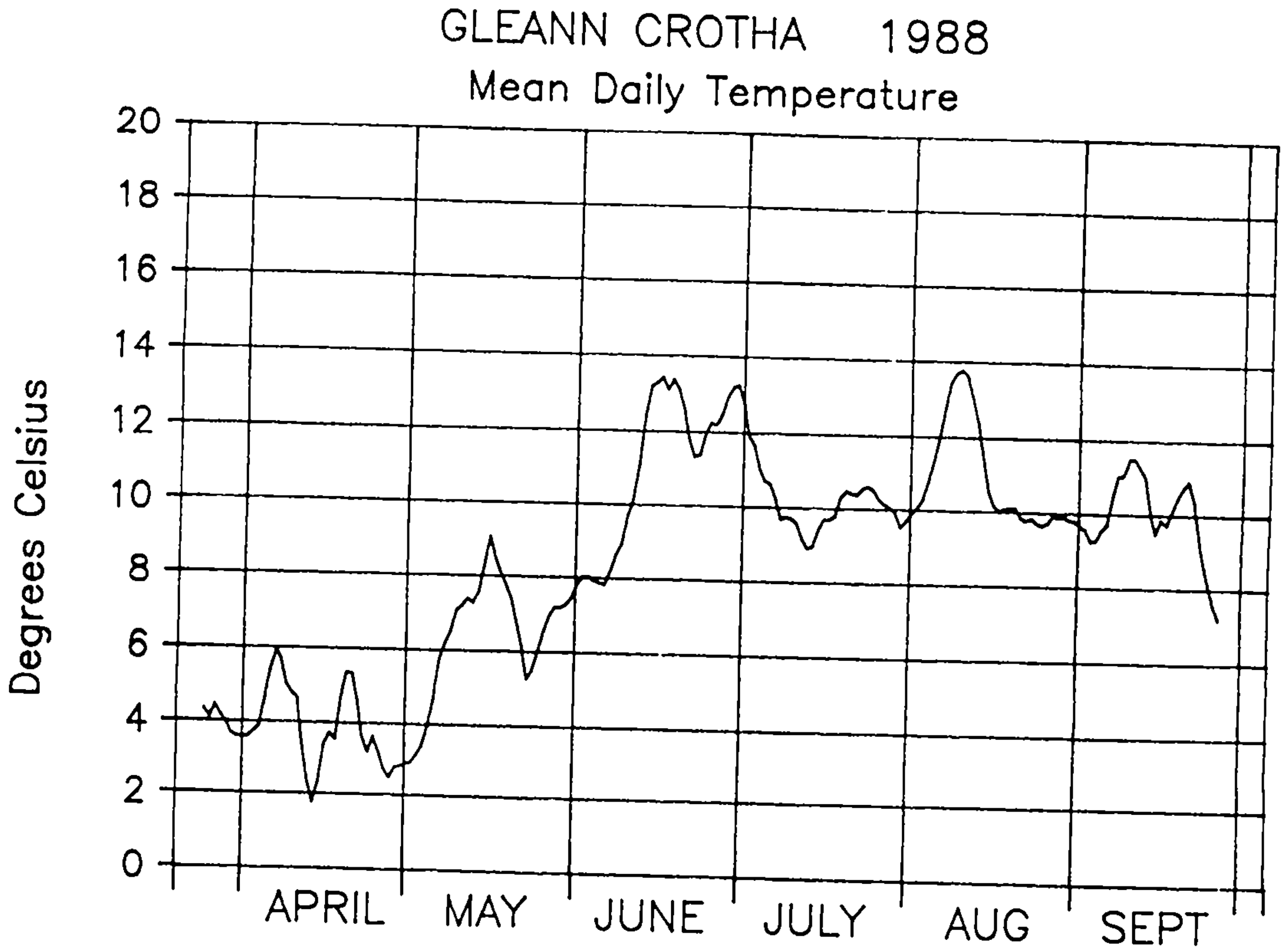

Figure8.4.1 Gleann Crotha 1988, mean daily temperature

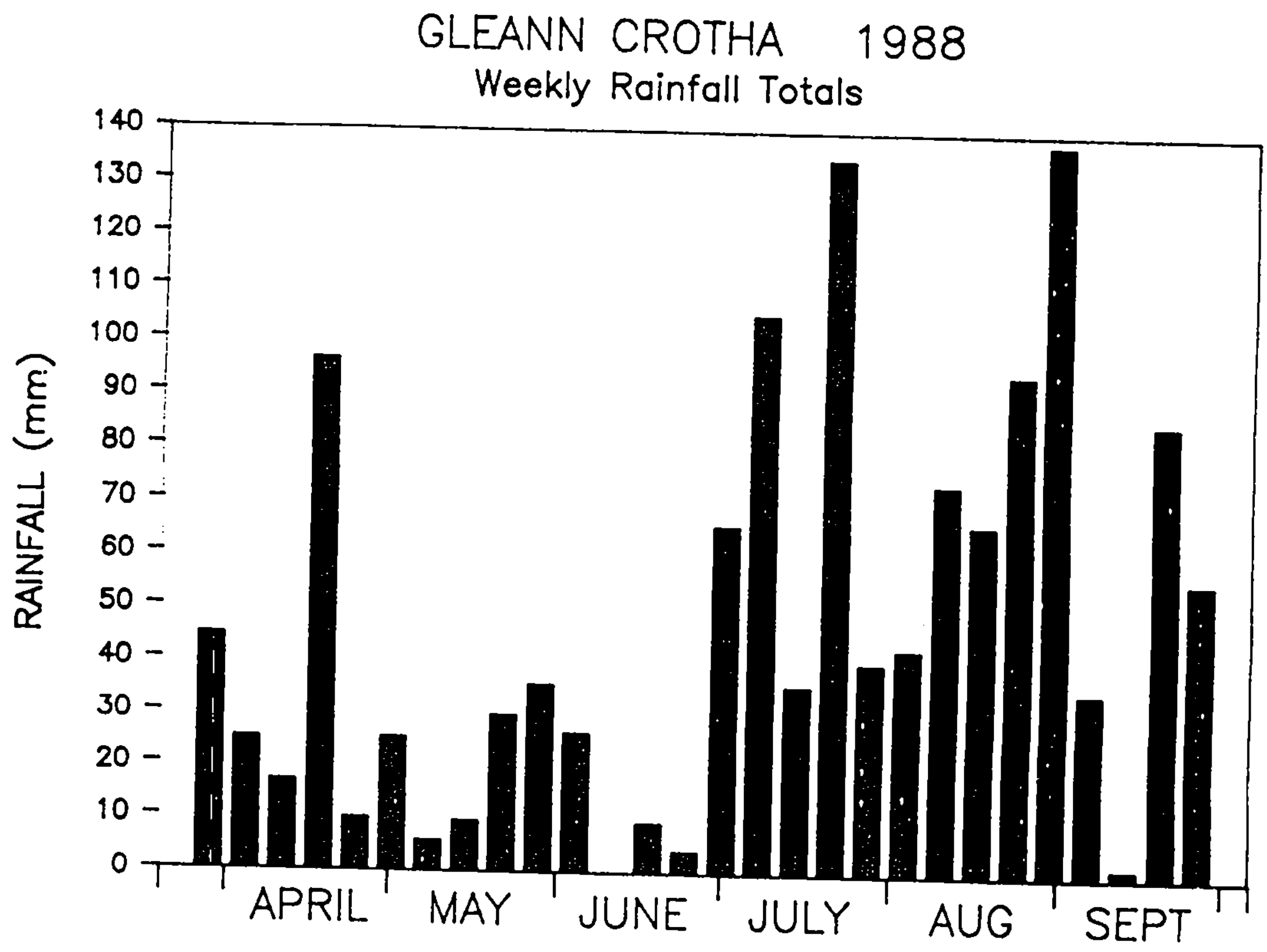

Figure 8.4.2 *Gleann Crotha 1988, weekly rainfall totals*

9. Discussion of results

This report covers the 1988 year of research in the Balquhidder experimental catchment. Work is continuing to improve the input, storage and output terms in the water balance equation and studies within the catchments are showing the processes taking place. The amount of data now collected is very large, and the following two years will concentrate on the analysis and new areas of research now being discussed.

Precipitation amounts are still not easy to quantify, mainly because of the winter snowfall. The existing networks of gauges have been shown to be giving representative samples of the available inputs and, when infilling is necessary, the secondary networks have correction factors which maintain accuracy.

The storage terms, mainly soil moisture deficit and snow, are now being studied. Soil moisture is measured at four sites which is not ideal for catchment use but the sites were selected to give readings under different types of vegetation and so should represent large areas of the lower subcatchments, where the soil depths are greater.

Snow storage is very difficult to estimate because of the variable depths over the rugged topography and because there has been only one person available to do the field work. The last two winters have been relatively snow-free, which has reduced the winter input errors due to snow. Unfortunately, this has also delayed further development of the snow survey technique.

Streamflow measurements in 1988 have been almost free of problems, again largely due to the mild winters. Sediment accumulation in both Crump weirs is increasing, so plans are being made for further current metering checks.

The comparison of the catchment water uses with the estimated ET values from the network of AWS sites continues to show the relationships as reported in previous years. The Monachyle P-Q value generally remains closer to the ET value than the Kirkton P-Q value for the quoted stations. There are still no apparent changes in the water use of the Kirkton even with over 40% of the forest clear-felled. There are no conclusive reasons for this but presumably the rough catchment surface, which is left after clear-felling, also has a large interception loss.

Within the catchments the 1988 summer was intensively monitored at the high altitude grassland site. The aim of this study was to see if the unexpectedly low Kirkton water use was due to the low evaporation losses from high altitude grasses. Two lysimeters measured interception and transpiration losses which were compared with ET estimates at the site. Results show that over the whole measurement period the total evaporation was significantly less (81%) than the Penman potential rate. For the early part of the summer period, until the end of June, the mean ratio was even less, 70%. These results from the site go a long way to confirming the water balance figures from the Kirkton catchments.

The final results from the Kirkton forest interception site have been submitted for publication in the Journal of Hydrology. Mean interception rates of 28% were found which compare well with results from other UK upland forests. In the context of the Kirkton catchment water balance figures this also indicates that the water use in the non-forested part of the catchment is less than the forested part.

Water quality data continues to be collected, including sediment release and discharge measurements. Results from the 1988 sediment work show that annual catchment discharges remain higher than the pre land-use change figures, 4.5 and 1.5 times higher in the Kirkton and Monachyle respectively.

10. Future work in the Balquhidder catchments 1989-1991

The Balquhidder catchments have been operating since 1981, and the quality of the data is now regarded as equal to that of the Plynlimon data in Wales. Recent indications from Plynlimon have shown that trends in catchment data can only be identified with long-term monitoring. Therefore the Institute of Hydrology hopes to continue operating the catchments at Balquhidder into the future, with the support of the consortium members.

Facilities have improved recently at the Balquhidder site, especially with the addition of a second member of staff. This will enable the data collection to continue and the production of more papers/reports. Because of this it has been necessary to increase the computer facilities with the purchase of an IBM PS2.

At Wallingford a post in the catchment data section which has been vacant since February 1989 will be filled in October 1989. This will speed up the quality control and analysis of the data and enable more rapid progress to be made on the catchment modelling

Over the final two years of the present contracts the networks of instruments will be maintained in the catchments. Monitoring of the water balances will therefore be done as the Kirkton Forest continues to be felled with the decay of the tree remains and the regrowth of grasses and in the Monachyle the growth of the newly planted forest.

Work is being done on precipitation gauge networks to estimate the accuracy of the catchments input figures. The calibration of the Crump weirs will be checked again because of the changing approach mentioned earlier in this report. New current meters have been purchased which have a better performance in low flow conditions.

The storage terms in the water balance equations are being looked at with the view of carrying out seasonal water balance analysis. Winter snow storage is very difficult to quantify because of its very variable depths. Changes in summer soil moisture storage are probably easier to estimate because four sites are regularly monitored. Assumptions will have to be made about both, so error estimates will be an important consideration.

The meteorological variables will continue to be monitored at the AWS sites. One change will be required in the Kirkton where the tower AWS will be dismantled, because of the approaching felling, and a new site established in the clear-felled area. The new logging system, introduced in 1988, has improved the data capture dramatically so analysis will be much easier in the future. During 1989 the water level recorders will also be converted to the Campbell logging system.

It was intended to operate the IH HYDRA at Balquhidder in 1989. Although some initial wind studies were done on the east Kirkton slopes in 1988, the full monitoring programme had to be postponed because of overseas commitments on the existing instrumentation. At the moment it is not clear whether the HYDRA will be available before 1991.

During 1988 some colour infrared stereo photographs ~~imagery~~ of the catchments were obtained from overflights by the NERC aircraft. These are being analysed, together with SPOT satellite data, during 1989. It is hoped that the analysis will yield more detailed information on the vegetation distribution and a useful check on parts of the catchment boundaries. Further overflights by the NERC aircraft have been requested.

Water quality monitoring will continue by the Freshwater Fisheries, Forth River Purification Board, Macaulay Institute, Strathclyde Regional Council and the Warren Spring Laboratories. It is planned to continue this along with the catchment water quality networks to monitor the effects of the land-use changes and to continue as long-term monitoring studies.

Similarly, the sediment studies in both catchments will continue to be monitored and more work will be done on identifying the new sources since the land-uses changed.

Following a successful IH project in Greenland in 1988, it is hoped to install instrumentation at the upper Monachyle AWS site to monitor snow melt. Details of the snow pack, including depth, density and water content, will be measured manually and linked to automatically monitored energy fluxes into and out of the pack. Comparisons will be made with other results from Greenland and Norway.

A link has been developed between IH and the Bristol University Remote Sensing Unit, who are looking into the remote sensing of snow. The proposal is still being discussed but the imagery could be used in the assessments of winter snow input and storage in the two Balquhidder catchments.

The High Altitude Grassland Study has provided two very contrasting summer seasons of observations of water use. It is proposed that the main lysimeters be converted to simpler drainage lysimeters after the 1989 season to provide long-term measurements of water loss. There will be a limited field work season in summer 1990 to provide measurements of the interception of rainfall by grassland. The primary work during 1990 will be the complete analysis of the lysimeter results and the incorporation of these into a simple water use model.

Conceptual models already operating at IH will be modified to incorporate the simple process-based model of water use by forest, grassland and heather. This will then be tested on the Balquhidder catchment data. This should provide information on the effect of land-use change on seasonal flow patterns. Previous experience (Blackie and Eeles, 198-) has shown that the fitting of such models also provides a further quality control check on the catchment data.

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APPENDIX

Sediment Budgets (Proceedings of the Porto Alegre Symposium, December 1988). IAHS Publ. no. 174, 1988.

Changes in the sediment output of two upland drainage basins during forestry land use changes

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Abstract As part of an experiment to investigate the environmental impact of forestry at Balquhidder in upland Scotland, sediment discharges have been monitored during the felling of a coniferous forest in one basin and ploughing/planting in another. Sediment sampling techniques are described including the determination of an optimal sampling point. The influence of different sediment generating processes on the supply of mobile material is assessed by determining seasonal influences. Average annual yields prior to the land use changes were 56 t km^{-2} from the forested basin and 37 t km^{-2} from the moorland basin. For the period after the land-use changes loads are shown to have increased by 5 and 3 times respectively. Sources are now dominated by forestry roads and plough furrows.

Modifications dans la production de sédiments de deux bassins versants des hautes terres à la suite de modifications dans l'utilisation des sols (déforestation ou création de forêt)

Résumé Constituant une des parties d'un ensemble expérimental en vue de la recherche de l'impact de la constitution d'une couverture forestière à Balquhidder, sur les hautes terres d'Ecosse, la surveillance des transports de sédiments a été organisée pendant l'abattage d'une forêt de conifères sur un bassin et le labour et la plantation sur un autre. On décrit la technique d'échantillonnage de sédiment y compris la détermination du point optimum de prélèvement. L'influence des différents processus libérant les sédiments sur la fourniture de matériaux mobiles est établie en déterminant les influences saisonnières. Le taux annuel moyen d'érosion avant modification de l'utilisation des sols était de 56 t km^{-2} pour le bassin sous forêt et de 37 t km^{-2} pour le bassin couvert de landes. Pour la période après modification de l'utilisation des sols, les charges solides ont été multipliées respectivement par 5 et 3. Les origines des sédiments sont maintenant principalement les routes forestières et les rigoles de labour.

INTRODUCTION

Forestry has developed into a major land-use in Great Britain over the past 40 years. The area of productive woodland reached two million hectares by 1987 (Forestry Commission, 1987), with most of this being in upland areas. The industry recently reached a significant stage in its development by starting the clearfelling of the first forest cycle coincident with changes in recommended forestry practices which show greater concern for the environment. Due to the harsh climate, rugged terrain and thin soil cover, the region in the UK potentially most easily disrupted by forestry is Scotland where recently the industry has been expanding at a greater rate than in England or Wales. The Institute of Hydrology established two research drainage basins at Balquhidder in 1981 to assess the effect of forestry in the highlands of Scotland. Water quantity and quality data have been collected through several phases of the forestry cycle.

The greatest impact forestry has on water quality is the increased sediment loads in the rivers. This is well documented in other UK work e.g. Robinson & Blyth (1982), where loads were shown to have increased by four times after pre-planting drainage. The only other work currently being done in the UK on changes in sediment discharge rates due to clearfelling is a study in Wales where loads increased by two times (Leeks & Roberts, 1987). Balquhidder represents the first long term study in Scotland on the effects of both clearfelling and cultivation using the current recommended forest practices.

THE BALQUHIDDER DRAINAGE BASINS

The two drainage basins (Fig. 1), Kirkton (6.85 km^2) and Monachyle (7.70 km^2), have a relief of over 600 m with an average lateral slope angle of 20°. Drainage consists of many small first-order lateral streams with one second-order main stream in each basin; drainage density is around 4 km km^{-2}. The underlying geology is mica-schist mantled by glacial deposits in lower areas. Soils of peats and peaty-gleys are thin, supporting a vegetation of heather, bilberry and coarse grasses. At the start of the project the lower Kirkton basin (2.88 km^2) also contained a mature (40-50 year old) coniferous forest. A network of old forestry roads existed in the Kirkton plantation, whereas there were no roads in the Monachyle basin.

Land use changed at the end of 1985 when road upgrading and felling started in the Kirkton basin, with some 40% of the forest having been felled by the end of 1987. Timber extraction to the roads was by cable-crane on steep slopes and tracked vehicles driven on brash mats on gentle slopes. Removal of the forest was by logging lorry operating on a frequency of about four loads each day. Road repairs were carried out by bulldozer and grader. In the Monachyle basin, preparation of the land for planting was started in spring 1986. Only 6% of the catchment could be ploughed because of the very steep, wet slopes. Plough lines were perpendicular to the slope terminating some 20 m before the main water course. Cut-off drains with

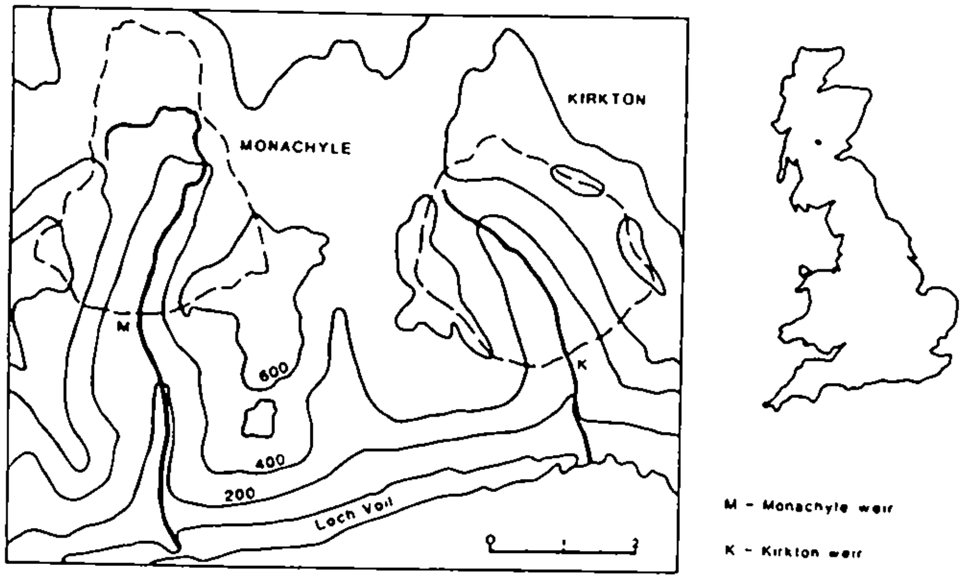

Fig. 1 Location diagram of the Balquhidder basins.

slopes of <3° were dug across the ends of the furrows and again terminated well before natural drainage lines.

Annual precipitation totals in the basins average 2400 m with a mean intensity of 1.2 mm h^{-1}. Winter precipitation contains significant amounts of snow, and there are, on average, 185 days each year when some snow is lying on the hills. At a low altitude weather station the average numbers of days of ground frosts is 141.

The flow duration curves for the basins during 1983–1985 showed that the Monachyle basin was more "flashy" with lower base flows. Maximum peak flows were 11.33 m^3 s^{-1} at Kirkton and 15.73 m^3 s^{-1} at Monachyle. Times to peak were similar but recession times were longer in the Kirkton basin.

Sediment sources in the basins have been identified (Stott, 1987) as being primarily the tributaries and, to a lesser degree, mainstream banks. There is a large storage of sediment on the stream beds, probably in a state of dynamic equilibrium. After the land use changes, the new dominant sources were the roads in the Kirkton basin, and the plough furrows in the Monachyle basin.

SEDIMENT MEASUREMENT TECHNIQUES

Suspended sediment concentration is sampled using single point automatic vacuum samplers and depth integrating manual samplers. To ensure that the samples taken automatically were representative of the whole cross section of flow, manual point samples were taken at 0.5 m width intervals across the streams and 0.1 m height intervals from the bed in different flow conditions.

Concentrations were found to be less in the flow above a well armoured bed than a sandy bed, with those samples 0.1 m above the armoured bed being closest in value to the mean of all samples. This therefore became the optimum position when a single point sample was taken.

Bed load is sampled using Helley-Smith bed load samplers (Helley & Smith, 1971) placed in the flow for 10 min durations. Again the optimum sampling positions were determined, using pairs of samplers.

SEDIMENT OUTPUT BEFORE THE LAND-USE CHANGES (1983–1985)

Suspended sediment and bed load were sampled mainly during flood events. This has the advantage of sampling when the flow is most likely to contain the highest sediment loads, but it does introduce a bias towards high flows which are only a small part of the annual flow regime. Rating curves were computed relating suspended sediment concentration and bed load to flow. The magnitude of errors involved in using rating curves can be large, sometimes estimated to be over 50% depending on the catchment and sampling interval (Walling, 1977). In all cases logarithmic relationships have been used with a correction (Ferguson, 1986) applied which, with the scatter and sample size taken into account, reduces the errors to give 100% of the annual load with a standard deviation of 20% (Ferguson, 1987, Tables 1 and 2). Samples have been subdivided according to discharge tendency (increasing or decreasing discharge >0.1 $m^3\ s^{-1}$ over 15 min) and "seasonal" classes (quarters of the calendar year) for further rating curve analysis. The bed load samples were sieved and the total basin load estimated from the size fractions greater than 1 mm to avoid overlap with the suspended sediment samples.

Table 1 1983–1986 ratings ($\log_{10}C = a + b\log_{10}Q$) where C = concentration (mg l^{-1}); Q = water discharge ($m^3\ s^{-1}$); r = correlation coefficient; s = standard error of estimate

	a	*b*	*r*	*s*
Kirkton				
1983	*0.958*	*1.30*	*0.56*	*0.58*
1984	*1.06*	*1.19*	*0.62*	*0.40*
1985	*0.784*	*1.73*	*0.57*	*0.45*
1986	*1.72*	*0.888*	*0.26*	*0.56*
1983–85 bed load	*– 1.11*	*3.00*	*0.74*	*0.60*
Monachyle				
1983	*0.794*	*0.660*	*0.19*	*0.54*
1984	*0.910*	*0.444*	*0.11*	*0.49*
1985	*0.769*	*0.272*	*0.13*	*0.53*
1986	*1.44*	*0.188*	*0.04*	*0.54*
1983–85 bed load	*– 2.27*	*2.48*	*0.76*	*0.54*

Table 2 Annual sediment loads (t)

	Suspended: Kirkton	*Monachyle*	*Bedload: Kirkton*	*Monachyle*
1983	*483*	*337*	*6*	*<1*
1984	*292*	*296*	*5*	*<1*
1985	*386*	*228*	*6*	*<1*
*1986**	*1965*	*1027*	*not available*	
*1987**	*986*	*860*	*not available*	

**Provisional figures.*

Figure 2 A and B show the envelopes containing the 1983–1985 data with details of the rating curves given in Table 1. A distinctive feature of the envelopes is the large amount of scatter in the Monachyle and lower flow range of the Kirkton. In the Monachyle this could be attributed to a limitation of supply through the year. However, the seasonal plots show that in the winter there is much less scatter. This is probably a result of the source areas being unprotected by vegetation and subjected to frequent freeze/thaw events, making sediment readily available. Scatter in the summer could be due to infrequent drying and loosening of sediment sources, or the generation of sediment by higher intensity summer rainfall, both limiting supply to irregular events. The Kirkton basin shows a large amount of scatter in the spring with the least in the autumn. Due to the shelter of the trees the effects of freeze/thaw, drying and intense rain are all probably reduced in duration and intensity, and the spring scatter is probably due to release of sediment by only occasional freeze/thaw events. The close relationship of flow to concentration in autumn is probably due to source areas being wet prior to a storm and responding rapidly to storm events.

Surprisingly, unlike in other work in Britain (e.g. Walling & Webb, 1981), there appears to be no difference in the rating equation and scatter between rising and falling stages, indicating that the sources have larger quantities of sediment available than in other experimental basins.

Bed load samples shows a good correlation with flow. They do not include samples in very high flows as the sampler cannot be operated under these conditions. Extrapolation of the rating curve into high flows could be adequate as during one period of almost a year a weir approach filled up with 17 t of sediment and in the same period the rating equation for unsieved samples estimated the load to be 19 t.

Table 2 shows all loads obtained by applying the individual years' ratings to the relevant 15 min flow data. Kirkton annual suspended loads (mean 387 t, 56 t km^{-2}) are greater than those for the Monachyle basin (287 t, 37 t km^{-2}) in two of the three years sampled. Bed load >1 mm is a very small proportion of the total load (<2%). The greater loads from the Kirkton basin indicate that it is still in a recovery period from the initial land disturbance, even though the trees now provide shelter to some source areas.

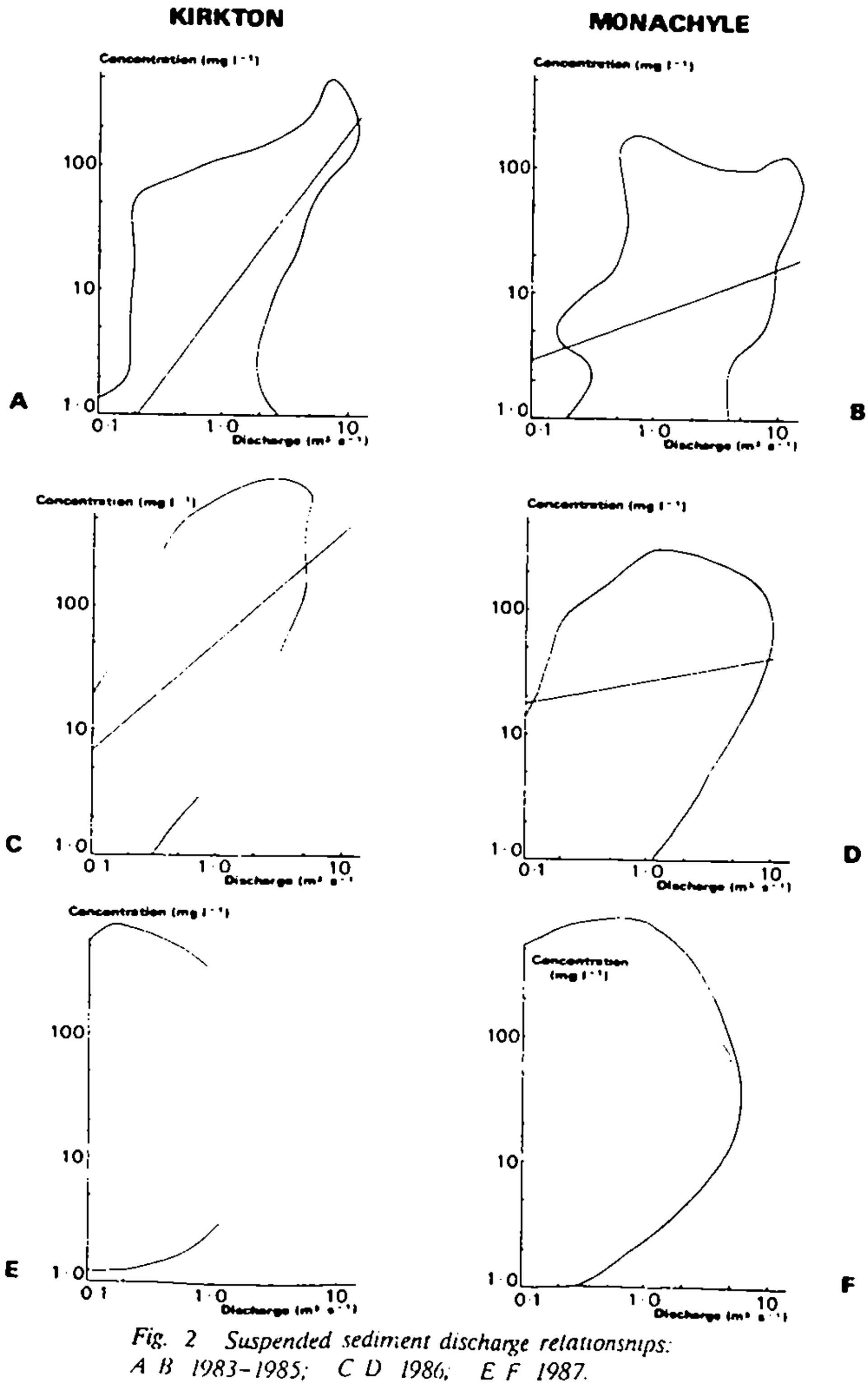

Fig. 2 Suspended sediment discharge relationships:
A B 1983–1985; C D 1986; E F 1987.

SEDIMENT OUTPUT AFTER THE LAND-USE CHANGES (1986–1987)

During 1986, suspended sediment sampling was intensified, again concentrating on flood events. Results (Fig. 2 C and D and Table 1) show that the rating curves changed significantly, increasing by an order of magnitude during the lower flow ranges. The scatter of points at low flows had increased, particularly in the Monachyle basin. It is difficult to find any differences between seasons or discharge tendencies in either basin.

Annual loads (Table 2) increased dramatically; in the Kirkton basin by a factor of 5.1 and in the Monachyle basin by 3.6. The primary reason appears to be the large increases in concentrations at flows below about 0.5 m^3 s^{-1} Sediment was much more available at the start of each storm, increasing concentrations even before the flow rose but this increased availability was not so marked at higher flows, as shown by the less steep rating curves. The lack of seasonal differences implies that in each basin there was a new dominant sediment source which was active all year.

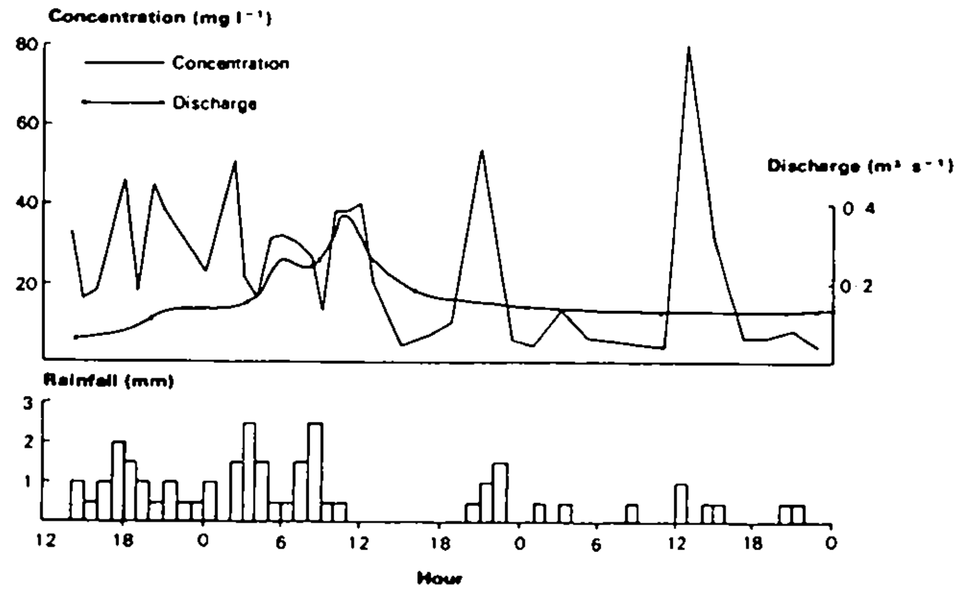

Fig. 3 Kirkton suspended sediment concentration, discharge and rainfall 29–31 May 1987.

The apparently increasing importance of the lower flows prompted a change in the suspended sediment sampling methods in 1987 with automatic samplers being used continuously at 8-h intervals. Figure 2E and F shows a broad envelope of sample points in both basins with no apparent relationship between concentration and flow. Some very high concentrations were sampled; in the Kirkton basin the maximum was 1818 mg l^{-1} and in the Monachyle basin the maximum was 1173 mg l^{-1}, compared to the 1983–1985 maxima of

487 and 188 mg l^{-1} respectively.

From observations of flow in plough-lines and road ditches, it became evident that sediment concentration in these locations was closely related to rainfall and this suspended load was often transmitted into the main streams. Figure 3 gives an example for the Kirkton basin during May 1987 when the sampling interval was reduced. The response to flood events is still evident, but the general pattern is linked more to rainfall with an intensity greater than 1 mm h^{-1}. The likely reason is that the sediment became more available for transport and whereas previously it took prolonged intense rainfall to release and transport sediment to the streams, sediment is now also transported during lower intensity rainfall. These are often conditions which do not significantly increase wi streams' flow, hence the poor correlation of concentration with discharge.

The calculation of an annual load for 1987 by a single flow related rating curve will contain unacceptably large errors, but combined flow and rainfall relationships are being developed. First estimates of annual loads indicate an apparent recovery of sediment discharge, compared to 1986, but the decrease is also due to rainfall in 1987 being 20% down on the 1983–1986 average.

CONCLUSIONS

Before the land use changes the annual sediment output from the Kirkton basin was greater than from the Monachyle basin, due to this basin still being in a recovery period from the initial land disturbance. During the year following the land use changes, the sediment output from the Kirkton basin increased by a factor of 5.1 and that of the Monachyle basin by 3.6 due to the Kirkton roads and Monachyle drainage lines becoming the major sediment sources.

Sediment sources are influenced greatly by the vegetation cover, with a close forest canopy providing shelter against frosts, intense rain and surface drying. These are illustrated by the seasonal differences between the basins. Frosts have more influence in the Monachyle, so that the availability of sediment is increased in winter and spring. Surface drying is more frequent in the Monachyle so that summer availability becomes irregular depending on these drying periods followed by intense summer rainfall. These results show how sensitive the Scottish uplands are to a major land use change such as forestry.

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BQ Report. (Errata)

p. 1. 2.1 para 1. line 8
'octatent' gauges"
(not 'catchment'),

p. 3. Table 2.1.1.

Line 1.	305.3	not 3.05.3
Line 3	−3.8	not −0.38
Line 8	247.6	not 347.6

p. 15 & 16.
Fig's 4.6.1 and 4.6.2.
Captions are OK but the Figures
are the wrong way round!
ie text references to 4.6.1 and 4.6.2
do not fit.
Easiest way to correct is to alter text
refs.
ie. p. 14 4.6. line 3 "Figures 4.6.2 and
line 4 " 4.6.1.
line 6. "Figure 4.6.2.
line 12 Figure 4.6.1"

p. 21. 5.3. last two lines
. . . indicating a slight - - -
. . . . from - - - -

p. 29 Figure 6.1.5 should be Figure 6.2

p. 36 last line. "but also to rainfall intensity
and to flow and more antecedent characteristics"

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p 39 ~~[illegible]~~ Four lines from bottom
"(Figure 8.4-1)

p 39 onwards Last 10 lines of 8.4
and all of 8.5 is missing !!
(i.e. 1 page)

Also page numbering is adrift.
Sect 9 should be p 45 not 43
(This is without allowing a page for the
missing bits noted above.

p 45 para 4, last. remove imagery !!

p 46 Para 2, line 5,
"(Blackie and Eeles, 1985)"

This reference is missing from the Reference
list on the same page.

i.e.:-

BLACKIE, J.R and EELES, C.W.O., 1985, Lumped
Catchment models in Hydrological
Forecasting (eds. M.G. Anderson and T.P. Burt).
Wiley pp. 311-347.

The demand for long-term scientific capabilities concerning the resources of the land and its freshwaters is rising sharply as the power of man to change his environment is growing, and with it the scale of his impact. Comprehensive research facilities (laboratories, field studies, computer modelling, instrumentation, remote sensing) are needed to provide solutions to the challenging problems of the modern world in its concern for appropriate and sympathetic management of the fragile systems of the land's surface.

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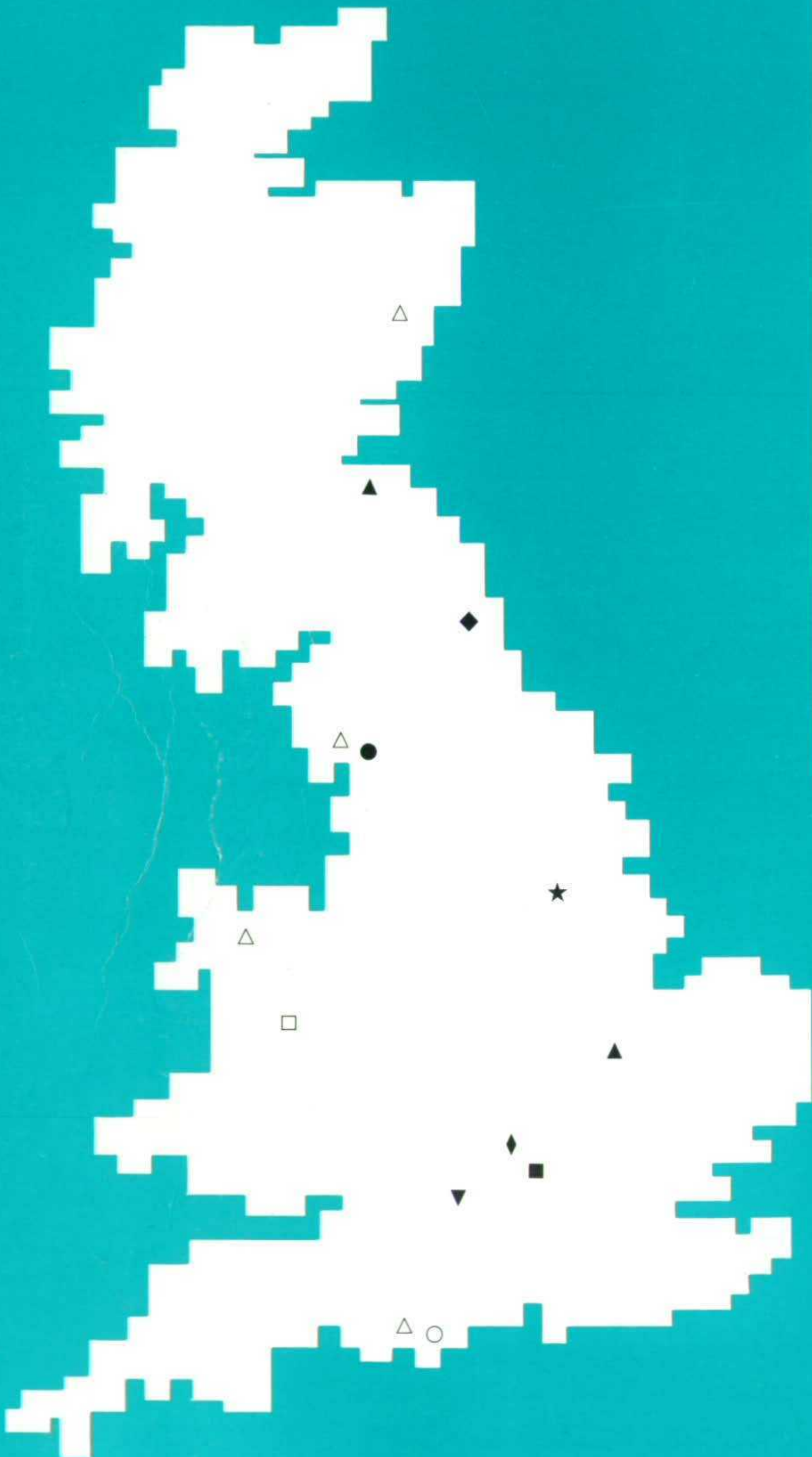

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