UPLAND AFFORESTATION AND
WATER RESOURCES

Preliminary Analysis of Phase 1

of

The Balquidder Catchment Studies

THE BALQUHIDDER CATCHMENT STUDIES

A Preliminary Analysis of the
Data collected during Phase I

by

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INTRODUCTION

When it was decided to initiate these experimental studies at Balquhidder in 1981 the immediate objective was to determine the differences in water use and sediment yield between the Kirkton catchment, 40% of which was under mature plantation forest, and the Monachyle catchment under a mixed heather/grass/bracken cover. This first phase of the study was scheduled to run until early 1986. The second phase of the study would then begin, in which the effects of progressive clear felling of the mature forest in the Kirkton and of initial planting in the Monachyle would be monitored. To provide reference data during phase 2 it was agreed that a sub-catchment in the Monachyle, above the area to be planted, should also be instrumented.

Design, construction, installation and testing of instrument networks and structures capable of operating accurately and reliably in this difficult terrain took some time and it was November 1982 before the two main catchments began to yield complete sets of precipitation, streamflow and meteorological data of acceptable accuracy. Difficulty of access to the upper Monachyle sub-catchment required the design and construction of a light alloy structure which could be transported to the site by helicopter. This became operational in July 1983.

Following a description of the catchments and the methods used to determine precipitation, streamflow and the meteorological variables the results of an initial analysis of the data accumulated during phase 1 of the study are presented. A great deal of detailed analysis has still to be carried out on these data, particularly in hydrograph analyses and the application of catchment response models. This must await the completion of a more refined time distribution of the precipitation data, to give hourly values rather than the monthly totals used in this analysis. The results emerging at this stage and their implications for the future of the study are considered to be of sufficient importance to merit presentation for immediate consideration.

THE CATCHMENTS

The location and relative positions of the Kirkton and Monachyle catchments are shown in fig. 1. Both are steep-sided glaciated valleys aligned approximately N-S with shallow peats, peaty gleys and upland brown earths overlying mica schists. Some areas of deeper peat are present in the more gently sloping upper part of the Monachyle and a few lochans provide localised storage above the steep valley sides in the Kirkton. The areas commanded by the streamflow structures are 6.85 km^2, 7.70 km^2 and 2.24 km^2 for the Kirkton, the Monachyle and the upper Monachyle respectively. The Forestry Commission boundary fence encloses 44% of the area of the Kirkton. With allowance for unplanted areas, clearings, roads, etc. the actual forest cover is estimated to be 35%. The boundary fence within the Monachyle indicating the target area to be planted in 1987/88, encloses 31% of the catchment which represents 43% of the lower part of the catchment.

In the Kirkton the area outside the forest is under a mixed heather/grass cover with grasses dominant on the main valley slopes and heather dominant on the relatively flat ridge tops. Rock exposure is limited to a few small areas on the ridge tops, most notably above the saddle on the north-west boundary.

In the Monachyle heather dominates the vegetation on the ridges and in the upper basin. Grasses predominate within the lower basin particularly in the area enclosed by the Forestry Commission fence though there is significant bracken coverage in the north-west part of this enclosed area and some patches of scrub forest below the crags on the western side. There are considerable areas of exposed rock on the western ridge above the forestry fence.

Forest roads midway between the main stream and the forest boundary and along each side of the stream permit limited vehicle access to the Kirkton. The sole road into the Monachyle terminates some 200 m beyond the main streamflow structure. This limitation has placed considerable constraints on the type and frequency of observations that can be made in the catchments. A light cross-country vehicle is used to transport equipment to the upper Monachyle structure and weather station site but the raingauges in this catchment and those above the forest in the Kirkton can only be visited on foot.

PRECIPITATION

Network Design

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

The approach adopted to the estimation of precipitation inputs to the Balquhidder catchments has been described in detail in previous progress reports. The basis is a network of 11 ground level storage raingauges in each catchment located as shown in figs. 2 and 3. The networks were designed to ensure that each significant altitude, aspect and slope domain in each catchment was sampled. Where a gauge is sited on a slope the orifice and anti-splash grid are mounted parallel to the slope and a cosine correction is applied to the readings to give the equivalent catch on a horizontal surface. These basic networks are read at approximately monthly intervals and the period totals distributed in time as described below. Whilst ground level gauges are known to give more accurate measurements of rainfall in these conditions they are not accurate in snow accumulation periods when the presence of the pit and anti-splash grid disturbs rather than maintains the aerodynamic continuity of the surface.

To provide estimates of precipitation inputs during snow accumulation periods a second, smaller network is used. This comprises standard Meteorological Office gauges and adjacent 1 m high snow gauges mounted in five existing clearings within the forested area of the Kirkton catchment. These clearings also contain five of the gauges in the ground level network (fig. 3). The standard gauges are used preferentially. The snow gauges provide a "last resort" estimate when the depth of fall exceeds the standard gauge funnel capacity or when they become buried. Depth/density sampling within each clearing is carried out to check the validity of the snow gauge readings during major accumulation periods.

Readings from the five snow sites are not used directly to estimate catchment inputs. During many periods only the higher gauges in the ground level networks are affected by snow. The relationships between each site in the networks and the catchment mean and also the mean of the five clearing gauges, established during rainfall only periods, are used to estimate a period total for that site when necessary. These relationships and their validity are discussed in a later section. Other methods of estimating inputs during snow periods have been explored but no practical alternatives to the above have been found. Outside the shelter of the forest, drifting is a major problem resulting in highly variable readings from either standard or snow gauges. The difficult terrain and the presence of only one observer limit what can be done in the way of depth/density surveys. In any case altitudinally differing melt rates mean that these result in a biassed estimate of input in all but the most severe temperature conditions.

Time Distribution

With one observer on the ground it is not possible to read all the gauges at the same time or even on the same day. It was necessary therefore to design into the system a means of distributing the period gauge data onto a common time base. Two methods were adopted, one relying solely on the standard daily read gauge at Tulloch Farm meteorological site and the other using the recording gauges attached to each of the four automatic weather stations (AWS) in the catchments (see fig.1).

In the latter method the period total is compared with that in the "nearest" recording gauge and time distributed proportionally. "Nearest" in this context refers to domain similarity rather than to map distance. A data set of hourly values for each site in the networks is being constructed using this method. At this stage in the analysis this data set is incomplete because of difficulties in dealing with frequent gaps and inconsistencies in the recording gauge data caused by freezing of the tipping buckets and other malfunctions.

The first method time distributes all gauge totals proportionally to the daily (0900-0900) readings at Tulloch Farm. Daily values obtained in this way are less accurate because of differences in the reading times of the period and the standard gauge and because of the real time differences in rainfall between the sites. When the values are accumulated into longer interval totals the proportional errors decrease however. A data set of calendar monthly totals calculated using this method has been assembled and is the basis of the preliminary analysis presented in this report.

Comparison of networks

The five clearing sites within the main Kirkton network each contain ground level (GL), standard (T) and snow (S) gauges. A complete set of T gauges was not established in these clearings until summer 1984. Comparison of the standard with the ground level (angle corrected) gauges, during snow free months when complete records from both were available, revealed good agreement (Fig.4), with the standard gauges consistently undercatching by between 2% and 5%. Use of the standard gauges, with appropriate adjustment, to infill for the adjacent GL gauges where necessary was therefore considered to be justified.

Comparison of the snow gauges with the ground level gauges revealed much poorer agreement (Fig.4). The snow gauges were found to undercatch by up to 40% relative to the ground levels during light, intermittent rainfall periods and to overcatch by up to 10% during prolonged, heavy rainfall. Evaporation losses from the deep funnels of these gauges are considered to be the reason for the undercatch but the high rainfall overcatch has yet to be explained satisfactorily. Despite this, the snow gauges have been used to infill data during the major snow accumulation periods in January and February 1984 and January and February 1985 when no other readings were available. Some justification for this was provided by the good agreement between snow gauge catch and depth/density sampling during these periods.

Spatial Variability

Using months when all the network gauges were operational and precipitation occurred only as rainfall the distribution patterns within each catchment were examined. The results are presented in Tables 1 and 2 for the Monachyle and the Kirkton and graphically as departures from the catchment mean in Figs.5 and 6.

From these it can be seen that there are reasonably well defined distribution patterns in each catchment which persist from year to year. The persistence of these patterns provides some justification for the method of estimating 'missing' data for individual gauge sites described below. Whilst the presence of the distribution patterns can be demonstrated, it has not yet been possible to relate them satisfactorily to physical characteristics. Figs.5 and 6 each demonstrate a weak trend with altitude. Comparison of the means for each period between Figs.5 and 6 demonstrate the pronounced downward gradient from West to East. This is also demonstrated within the Monachyle by the relative catches of C2W and C2Z, both at comparable altitudes but on the Western and Eastern ridges respectively (see Fig. 2). Relationships with aspect and slope are less well defined however and the large, persistent departures from the mean of gauge C3Y in the Kirkton and B1Y and B2Z in the Monachyle have yet to be explained.

Estimation of missing data

To complete the monthly arrays of data from the networks from which the catchment means were estimated, it was necessary to estimate values for those gauges for which readings had not been obtained. The following methods were used.

In a month when only a few ground level gauge readings were missing, either through gauge malfunction or snow cover at the higher levels, the method adopted was to estimate the catchment mean from

$$\hat{P} = \frac{\Sigma P_i}{\Sigma a_i}$$

where P_i are the observed values and a_i are the ratios of readings at these sites to the catchment mean, as listed in Tables 1 and 2. The missing values were then estimated from

$$P_j = a_j \hat{P}$$

and inserted in the array.

In a month when all readings from the catchment ground level gauges were missing because of snow cover the values were estimated from

$$P_i = b_i . \overline{PT}$$

where $\overline{PT}$ is the mean of the five Kirkton clearing sites, estimated from the standard gauges, and b_i is the ratio of readings at site i to this mean, as listed in Tables 1 and 2, or from

$$P_i = b_i \cdot \overline{PS}$$

where $\overline{PS}$ is the 'clearing' mean estimated from the snow gauges.

The second of these options had to be applied only in January and February 1984 and January and February 1985.

Catchment Estimates

Various methods of estimating catchment mean precipitation from the arrays of values for the individual gauges in the networks have been examined. For the purposes of this report two only were considered for use with the monthly time distributed data sets. These were the arithmetic mean of the networks and the weighted mean obtained by weighting each gauge by the domain area it represents.

Application of these two methods to the periods with complete sets of rainfall readings, as used in Tables 1 and 2, produced the results summarised in Table 3. As can be seen the differences in the estimates by the two methods were insignificant. Consequently the arithmetic mean approach was adopted to produce catchment estimates for each of the 35 months used in the present analysis. The values obtained are presented in columns 1 and 2 of Table 6.

The sequence of calculations leading to these estimates of catchment monthly precipitation can be summarised as follows:

(a) For each catchment, an array of monthly values for each of the 11 gauges was set up. Where readings existed for each gauge these were time distributed as described above using the Tulloch Farm daily gauge.

(b) In months where readings were missing from a few gauges in the networks, because of snow cover on the high level gauges or gauge malfunction, an estimate of the catchment mean was obtained from the remaining gauges using the within catchment relationships. Estimates for the missing gauges were then calculated from this mean, also using those relationships, and the values entered in the array.

(c) In months where all or nearly all gauge values were missing because of snow cover, estimates for each gauge site were calculated from the established relationship between that site and the mean of the five 'snow' sites in Kirkton. The latter mean was derived from the standard gauges in periods where these had not been overtopped by snow and from the snow gauges when major accumulation occurred. This latter situation arose in four months only, in January and February 1984 and January and February 1985.

(d) From each catchment array, completed as above, the arithmetic mean was then calculated for each month.

Whilst considerable errors may be present in each monthly estimate as a result of the time distribution method used this will not have affected the cumulative totals. Errors arising from the methods of estimating missing data are difficult to assess. For each site, consideration of the data summarised in Tables 1 and 2 suggests that any error will be random and unlikely to exceed 2% of the monthly mean in 'rainfall' months. For months where data are missing because of snow cover, no basis for error estimation is available.

Two other sources of error must also be considered. One, relating specifically to the Monachyle, concerns the network design. The altitude domain above 700 mm which comprises an area of 10% of the catchment at the South and of the Western ridge has not been sampled. This omission was due to sound practical reasons but the altitude and W→E gradients identified suggest that precipitation in this area could be some 20% above the existing network mean. Thus the catchment total could be systematically underestimated by up to 2%.

The second source of error concerns the Kirkton. Gauge C3Y which consistently reads some 20% below the network mean has been included in calculating the catchment estimate. If this is found not to be representative of its domain, consideration of the catchment relationships indicated in Figure 6 would suggest that the Kirkton total could be underestimated by some 2%. It is proposed to install a second gauge in this domain in the near future.

STREAMFLOW

Gauging Structures

The design chosen for the main gauging structure on each catchment was the Crump weir. The considerations leading to this choice have been discussed at length in previous reports. The most important factors involved were the ability to provide accurate estimates of flow over a very wide flow range, minimal problems from sediment, ease of construction at difficult sites and cost.

This choice was acknowledged to be a compromise however with certain potential disadvantages. In these steep streams the approach conditions were close to the upper acceptable limits, particularly in the Kirkton, making it necessary to check in situ the validity of the theoretical ratings. To achieve structures capable of containing the estimated 50 year flow (26 m^3/s on the Monachyle and 30 m^3/s in the Kirkton) required crest widths of 5 m and 7 m respectively. This meant that the dry season base flows would inevitably drop below the 0.3 m minimum stage recommended in British Standard 3680, resulting in poor sensitivity in this range. To provide this sensitivity, separate low flow structures were installed in series with the Crumps. These were short trapezoidal flumes prefabricated in fibre glass, supplied by Forth River Purification Board. Each was designed to overlap the lower part of the acceptable flow range of the Crump it complemented.

The decision to install a further structure in the Upper Monachyle presented even greater constraints on design because of the inaccessibility of the site. Scottish Development Department designed a flat vee structure for this site which was fabricated entirely in light alloy by IH workshops. Sections were transported by helicopter from the road head and keyed into the rock bar chosen as the site with minimal use of concrete.

Water Level Recording

All five structures were equipped initially with the standard potentiometric water level recorders used by IH. These have a potential accuracy of ± 1 mm throughout the flow range. Readings at 5 minute intervals are logged on Microdata cassette recorders. Starting levels for each tape are determined using a 'dipflash' device in which contact with the water surface in the stilling well closes a circuit. This is also potentially capable of an accuracy of ± 1 mm. Paper chart recorders installed and operated by Forth River Purification Board are used as back-up on the main Monachyle and Kirkton structures.

Rating Checks

As already indicated both main structures were considered to be close to the limits within which the theoretical ratings of crump structures can be considered reliable. It was necessary therefore to check the ratings of these structures.

At low flows on the main structures the good agreement between the Crumps and the low flow flumes in the overlap range provided some indication of reliability of the ratings in this range. Spot checks using dilution gauging techniques confirmed this at low flows both on the main structures and on the Upper Monachyle flat vee.

Dilution gauging at a high flow in the Kirkton revealed however that the theoretical rating was underestimating the flow by a significant amount. The development of a revised rating based on detailed current metering over a wide range of flows is described below. The few dilution gauging points obtained at medium flows on the Monachyle and upper Monachyle structures give no positive indication that the theoretical ratings of these structures are in error. This, together with the much better approach conditions particularly on the upper Monachyle, suggests that these ratings are unlikely to be in error to the same extent as that of the Kirkton. Nevertheless a similar current metering exercise to that on the Kirkton will be carried out in spring 1986. Further dilution gauging on the upper Monachyle, where current metering is not feasible except at very high flows, will also be carried out in 1986.

Re-rating of the Kirkton Structure

The current metering exercise on the Kirkton structure was initiated with the installation of a rigid bridge across the structure. Movable mounting cradles for the current metering rod were attached to the upstream face of the bridge in line with the tapping point to the recording well. An array of up to six current meters was mounted on this rod which was used to measure velocities on 15 verticals across the 6.9725 m width of the weir. At each profile the surface water level was obtained using a rod mounted dipflash and the sediment surface level in the approach channel using the current meter rod which had a flat base plate. Simultaneous measurements of water level in the stilling well were taken at each profile.

The data derived from each gauging were analysed by micro-computer to give estimates of

(i) Mean head, h, over the gauging period

(ii) Mean, V_a, and maximum, V_m, approach velocities

(iii) Discharge, Q_c, from the integration of velocity and cross-section area.

Instead of fitting an empirical curve to these points the above data were used within the basic British Standard expression

$$Q = C_D . \sqrt{g} . b . H^{3/2}$$

to derive a new relationship between discharge, Q, and measured head, h, in the approach section.

The relationship between total head, H, in the above expression and h is given by

$$H = h + \alpha V_a^2 / 2g$$

where

$$\alpha = 1 + 3e^2 - 2e^3$$

and

$$e = {}^{V_{max}}/_{V_a} - 1.$$

Total head could therefore be calculated for each gauging, using the estimates of V_a and V_{max} obtained.

Under ideal conditions the discharge coefficient, C_D, is quoted by Ackers et al (1978) as remaining constant at a value of 0.633. With the data available, it was possible to calculate a value of C_D for each gauging from

$$C_D = {}^{Q_c}/(\sqrt{g} \, . \, b. \, H^{3/2})$$

Values of C_D, α, and V_a obtained from the gaugings were then related to h. A linear relationship gave the best fit between α and h but polynomial functions gave the best fit between C_D and h and V_a and h (see Figs.7 and 8).

The expressions obtained,

$$\alpha = 1.52 + 0.65 \, h$$

$$C_D = 0.44238 \, h^2 - 0.41476h + 0.67959$$

$$V_a = 1.15889 \, h^2 + 1.43023h - 0.02357$$

were then used together with the standard expression

$$Q = C_D . \sqrt{g} \, . \, b. \, (h + \alpha \frac{V_a^{\,2}}{2g})^{3/2}$$

to compute the revised rating.

This is compared in Fig. 9 with the original rating and with the estimates of flow, Q_c, obtained from each current meter gauging.

Observation of 'equilibrium' sediment level in the approach section indicated that the effective crest height of the weir is in the region of 0.4 m during medium to high flows as compared to the true height of 0.7 m. This is one factor contributing to the departure from the theoretical rating. A second is the high and variable value of α, compared to the

British Standard estimated maximum of 1.25. This is considered to be due in part to a rock intrusion from the right bank immediately upstream of the approach section which induces progressively greater asymmetry in the velocity distribution with increasing flow. These two factors together with the upstream channel slope all act in the sense of increasing the velocity head and hence the volume flow for a given stage.

Processing and quality control

Processing of the cassette tapes to produce flow data using the ratings described above is carried out on the computer at Wallingford. The 5 minute water level data are converted to 15 minute estimates of flow, expressed as mm depth over the catchments. The programme suite contains basic quality control routines which identify sudden discontinuities and check initial and final water levels and times against those observed. Further quality control is carried out manually by comparing the output hydrographs with precipitation data and between catchments. Any gaps or doubtful data are investigated further by comparison with the FRPB paper charts or with meteorological data. The latter is frequently necessary in winter when freezing of the stilling wells can give spurious water levels. In general, however, flows are on the lower reach of the recession curves when such cold conditions occur. Corrections can be interpolated between spot readings of water level obtained by the observer breaking the ice. Where gaps occur in the records these are infilled using recession curve approximations or data abstracted from the chart records. Another source of error encountered has arisen from partial blockages of the structures by ice. These blockages are usually short lived however and the records can be interpolated through the false 'spikes' on the hydrographs. Periods when flow is below the minimum 'British Standard' level in the main structures are identified and records obtained from the low flow flumes for these periods.

Complete arrays of quarter hourly flows from the two main catchments have been obtained using these techniques for the period December 1982 to October 1985 inclusive.

Prolonged freezing of both the stilling well and the approach section of the upper Monachyle structure has resulted in large gaps in this array for both the 83/84 and 84/85 winters. For part of each winter the stream has been completely frozen at this site. For much of the time however some flow was observed under the sheath of ice. During autumn 1985 pressure transducers were installed in the stilling well and in the float well. Analysis of the data obtained is not yet complete but the indications are that they will provide a more complete record of flow for winter 1985/86 than has previously been achieved.

Catchment response characteristics

Detailed analysis of the hydrographs has yet to be carried out. Superficial examination reveals however that the response characteristics of the two catchments are very different. The extreme flows recorded during the 35 month period were:

	Monachyle	Kirkton
Max 15 minute flow	1.76 mm (15.04 m^3/s)	1.15 mm (8.79 m^3/s)
Max daily flow	81.6 mm	51.1 mm
Min daily flow	0.08 mm	0.27mm

Flow duration curves, using daily flows, for the two catchments presented in Fig.10 emphasise further the marked difference in response. In Fig.11 hydrographs from all three structures for a typical wet period are compared. From this it can also be seen that the response of the upper Monachyle is very similar to that recorded at the main catchment structure.

The much flashier response of the Monachyle is surprising. Because of the presence of the relatively flat upper basin its mean slope is considerably less than that of the Kirkton and the more extensive areas of deep peat and of glacial till would suggest greater moisture storage. There are however very shallow soils interspersed with extensive rock exposure on the western ridge, the wettest part of the catchment.

Flow estimates

Monthly totals for the Monachyle and the Kirkton for the period 12/82 to 10/85 inclusive are listed in Table 6 and displayed graphically in Fig.15. Totals for those months for which complete records were obtained from the upper Monachyle are compared with the main Monachyle values in Table 4.

The effect of the flashier response in the Monachyle is evident in these monthly totals. In general the Monachyle totals are greater in wet months and lower during dry periods.

The accuracy of these monthly totals is difficult to determine. The revised rating of the Kirkton structure is probably within 2% over the flow range covered by the current metering. Until a similar current metering exercise is completed on the Monachyle no firm estimate of the accuracy of the theoretical rating can be made. Consideration of the approach conditions relative to those specified in British Standards would suggest that it is unlikely to be out by more than 5% however. Some indirect evidence of the accuracy of both the Monachyle structures is provided by the close agreement of the monthly flows in Table 4.

The two main sources of random error in the flow estimates are the effects of icing and the accuracy with which each tape is initiated using the dipflash readings. As indicated earlier icing can result in large proportional errors but flows in these conditions are generally low and the effect on the cumulative flow total small. The periods of greatest uncertainty are on the rising limbs of 'melt' events when the ice in the stilling wells may not melt till after the rise has started. Random errors in setting the tapes can arise from reading errors or from a lag (5 min. max) between dipflash reading and first recording in a situation where stage is changing rapidly. The checks and quality control described above minimise these errors but it is possible that random errors of up to ± 3 mm can be present. On the Kirkton, for example, this would represent an error in flow varying from ± 15% at minimum acceptable flow in the crump to ± 1% at the highest observed stage.

PENMAN POTENTIAL TRANSPIRATION, ET

One of the primary purposes of the Balquhidder studies is to determine the water use of each of the vegetation covers. Whilst this is of interest in the immediate Balquhidder context, it is necessary to relate water use to some more readily measurable variable if the results are to be used to predict land use effects elsewhere. Relating water use to precipitation is of some limited value but its relationship to the meteorological variables which "drive" the evaporation processes is much more relevant.

Consequently a network of three Automatic Weather Stations (AWS) were installed in 1982 to record these variables at a range of altitudes. A fourth AWS was installed close to the upper Monachyle structure site late in 1983. For comparison purposes a manually read meteorological site was installed at Tulloch Farm (Fig.1) alongside the lowest of the AWS.

Each AWS records values of temperature, humidity, solar and net radiation, windspeed and wind direction onto cassette tape at 5 minute intervals. As already indicated, a tipping bucket raingauge mounted at ground level is also included at each site. Overall data capture from these stations has been good, generally exceeding 90%. This figure includes periods, however, when individual sensors were producing suspect data. The windspeed sensor on the Kirkton station has been a particular problem.

Detailed analysis of these data to determine the variability of climate in the catchments is a continuing part of the studies. One paper (Johnson, 1985) dealing with the contrasts between the Tulloch Farm and Kirkton sites is attached as an appendix.

In this section a preliminary analysis of the potential transpiration estimates (ET) calculated from the AWS data is presented. Each station is sited so that the vegetation "seen" by the net radiation sensor is primarily grass. Consequently the ET values calculated and compared relate to grass rather than to heather or forest.

The starting point for this analysis was to determine monthly mean daily values for each site for all months for which a minimum of 22 days complete data were available. These monthly means were then used to establish relationships between the sites. The results are listed in Table 5 and the comparison between the most distant sites, the upper Monachyle and Tulloch Farm, is illustrated in Figure 12.

These relationships were then used to estimate values for the incomplete months at each site, using data from the other sites in the order of preference dictated by the precision of the relationships. For example, an estimate for a missing month at Kirkton was made from the Tulloch Farm, the upper Monachyle, or the Monachyle Glen values in that order of preference.

The results of accumulating the monthly estimates so derived into successive 12 monthly totals for the periods October-September are presented in Figure 13 where they are plotted against altitude. The totals for the higher altitude sites are consistently higher. This results primarily from the higher windspeeds and better radiation horizons at these sites as compared with the valley bottom ones.

An indication of the seasonal pattern of ET is given in Figure 14 where the monthly estimates for each site for 1984 are plotted. The prolonged dry spell from April through August 1984 resulted in ET values considerably higher than in the other years. Complete snow cover at all sites for prolonged periods in January and February gave less scatter than normal between sites in these months.

Before these data can be used for modelling purposes it will be necessary to carry out this exercise more rigorously using daily values rather than monthly means. Nevertheless the above estimates do give a reasonable indication of the magnitude of potential transpiration and its variability in time and location. The latter raises the question of how best to estimate a mean value for each catchment. In this context a notable omission from the network is any sampling point within the lower confines of the Kirkton. The practical difficulties of installing an AWS over forest precluded such a site initially, but serious consideration is now being given to rectifying this omission.

For comparison, the estimates of monthly totals for the Kirkton site are included with the water balance figures in Table 6.

MONACHYLE AND KIRKTON WATER BALANCES

Monthly and cumulative values

Monthly catchment values of precipitation, P, and streamflow, Q, for the period December 1982 to October 1985 computed by the methods described above are presented, together with values of P-Q, in Table 6 and graphically in Figure 15.

From the cumulative totals it can be seen that precipitation in the Monachyle exceeds that in the Kirkton by some 18% or 400 mm in the average 12 month period when the Monachyle receives 2636 mm. Streamflow from the Monachyle also exceeds that from the Kirkton but by only 15.5% or 278 mm in the average 12 month period. These differences result in a value of the cumulative total of P-Q for the Monachyle that is 28% or 122 mm per 12 months higher than that from the Kirkton. The cumulative value of P-Q from the Monachyle is very similar to that for ET as estimated from Kirkton AWS whereas the Kirkton P-Q value is some 20% lower.

12 month moving totals

To examine the differences in more detail moving 12 monthly totals of P, Q and P-Q are plotted in Figure 16. From this it can be seen that the between-catchment differences remain reasonably constant throughout the period and particularly so from 4/83 onwards. Thus if there are significant errors in the data they are systematic, applying throughout the period, rather than large random errors present in a few months only.

P-Q as an estimate of water use

It must be emphasised that P-Q provides a measure of actual evapotranspiration, AE, plus the net increase in storage, ΔS, in a watertight catchment. Over long periods the cumulative total of evapotranspiration becomes large relative to the possible range of storage change and hence P-Q becomes a progressively better estimate of AE. For periods as short as 1 month, however, ΔS can greatly exceed AE. Consequently the monthly values of P-Q in Table 6 are, individually, very poor estimates of AE. Negative values result when streamflow release exceeds precipitation input. This can happen when, for example, snow accumulation in one month is released in a melt period in the following month. April 1984 in Table 6 is such a case.

In these catchments, where the range of total storage could be 200 mm or more, even the 12 month totals of P-Q present a first approximation only to AE. The relatively constant relationship between 12 month P-Q values from the two catchments in Figure 16 results from the general similarity in the time distribution of inputs and outputs. The high values of P-Q in the 12 month periods ending in Jan-Mar 1984 and the low values in the periods ending 12 months later reflect the large accumulations of snow that occurred in both catchments in early 1984.

Discussion

Despite these points the cumulative figures suggest that total water use in the part forested Kirkton is considerably lower than that in the heather/grass/bracken covered Monachyle. Monachyle figures are broadly in line with the results of process studies of the interception and transpiration characteristics of heather (Hall 1985, Wallace et al, 1982) when compared with the ET estimate.

The Kirkton figures do not accord with estimates based on forest canopy process studies elsewhere or with the Plynlimon catchment results. The upland grassland control catchment at Plynlimon gave a mean AE figure representing some 0.85 ET. A crude estimate suggests that cover in the Kirkton could be classified as 35% forest, 55% grass and 10% heather. Applying the Plynlimon figure would give water use by the grass area equivalent to 255 mm depth over the whole catchment, leaving some 182 mm to be accounted for by interception loss and transpiration from the forest and heather.

Assuming that the water use of the heather dominant area is comparable to that of the Monachyle accounts for a further 56 mm equivalent depth, leaving 126 mm. This is equivalent to 360 mm depth over the forest area, in contrast to the 700 mm that the Plynlimon results would suggest. Alternatively, the Calder and Newson (1979) model provides an estimate of the Kirkton catchment water use as 720 mm per 12 months as compared to the mean figure of 437 mm estimated from Table 6.

Possible sources of error

Clearly some explanation of these apparently anomalous results from the Kirkton is required. The most obvious source would be some systematic error in the data. The discussions of the precipitation and streamflow data in earlier sections suggest that systematic errors in excess of 2% of the precipitation or 5% in the flow are considered unlikely. In the worst case, combination of these could result in an error of 30% or 130 mm per 12 months in the estimate of AE. This extreme case could therefore give AE figures for the Kirkton comparable to those from the Monachyle, but still considerably lower than either the Plynlimon or process-based estimates.

Other possible sources of error concern the catchment area, the possibility that Kirkton flows are augmented by sub-surface inflow or that the value obtained from Kirkton AWS grossly overestimates potential ET in the lower forested part of the glen. Independent estimates of the catchment boundary, which is reasonably well defined, show a spread only marginally in excess of 1% in the calculation of the catchment area, ruling this out as a significant source. The possibility of aquifer discharge into the catchment appears unlikely from a consideration of the topography but a more detailed study of the geology and of the tributaries which maintain the relatively high dry season flow will be undertaken. As indicated in the section on ET, a further AWS will be mounted in the lower part of the Kirkton during 1986, to investigate possible differences.

Process implications

Assuming that none of these investigations produce positive results, then consideration must be given to the possibility that the interception or transpiration processes within the Kirkton do not conform to those on which current prediction models are based. The preliminary results of the interception study in the lower Kirkton are discussed in the following section. Though observed interception has varied widely with different events, the mean values are only marginally lower than those predicted. The other possibility deserving further consideration and possible investigation is that water use by the grass areas is considerably lower than either the ET estimate or the Plynlimon figures would suggest.

INTERCEPTION STUDIES

A level site in the lower part of the Kirkton adjacent to 'clearing' site AIW (Fig. 3) supporting a uniform stand of spruce averaging 18 m in height was instrumented to sample throughfall and stemflow. A random network of 60 calibrated buckets provides an estimate of drip plus throughfall for each event sampled whilst 9 trees are equipped with stemflow measuring devices. The figures are converted into mean depth over the area sampled and this is compared, for each event, with the precipitation measured at site AIW.

Preliminary analysis of the 1984 data presented in the 1984/85 Progress Report suggested a surprisingly low mean interception loss of 12.4% of precipitation. More detailed examination of the data has shown this figure to be in error. A rigorous analysis of all data obtained during phase 1 will be presented in due course. Present indications are that the interception loss at this site is very variable but the overall mean is in the range 25%-28% of the precipitation. This is comparable to that observed in similar stands in other upland regions (Calder and Newson, 1979).

SEDIMENT STUDIES

From the inception of the Balquhidder catchment study the Institute has made measurements of both suspended and bed loads of sediment moving from the outlets of the Monachyle and Kirkton basins. In the last year these efforts have been expanded by the additional effort of a NERC CASE Award student working from the University of Stirling. He has made rapid progress in calibrating the sediment yield of small source areas under moorland and forest. The study is now at the point where a joint paper is being prepared indicating the approximate sediment balance; this will be presented at an IASH Symposium at Alberquerque, New Mexico in August 1986. The major points to be included in the paper are summarised below.

Sediment Sources

The basins have high drainage densities by UK standards with many steep first or second order tributaries. In the upper reaches these often flow over exposed bed-rock but lower on the valley sides they are usually incised into glacial till. Timber check dams, lined with nylon netting, were installed on several tributaries and are emptied regularly for mass and size analysis.

Pebble tracing was carried out on 2 similar tributaries, one in each catchment. 130 pebbles were used in each stream, systematically selected from 6 size groups. Bank erosion pins were placed along both main channels and sediment bars, often related to bank erosion sites, were regularly surveyed.

Suspended sediment concentrations were determined using automatic vacuum samplers triggered by float switches so that most significant flows could be sampled.

Sediment Outputs

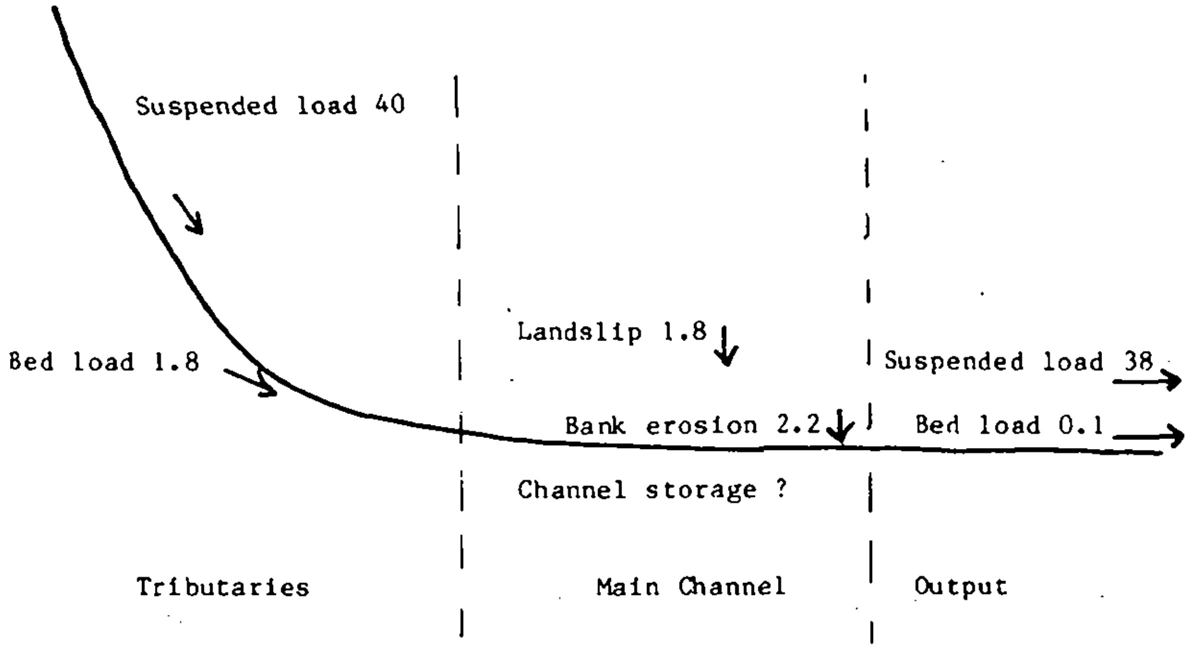
Outputs from both catchments have been measured by taking spot samples of coarse and fine sediment then converting these to a total sediment discharge using the stage measurements made at the Crump weirs.

Coarse sediment (bedload) is sampled using a modified Helley-Smith sampler. This is held down on the river bed for a known time allowing water to pass through a 6" orifice and be filtered by a fine nylon bag. The sediment collected is dried and analysed for weight and size distribution. Fine sediment (suspended load) is spot sampled using either a USDH sampler or automatic vacuum sampler. Samples are filtered and the weight of sediment determined.

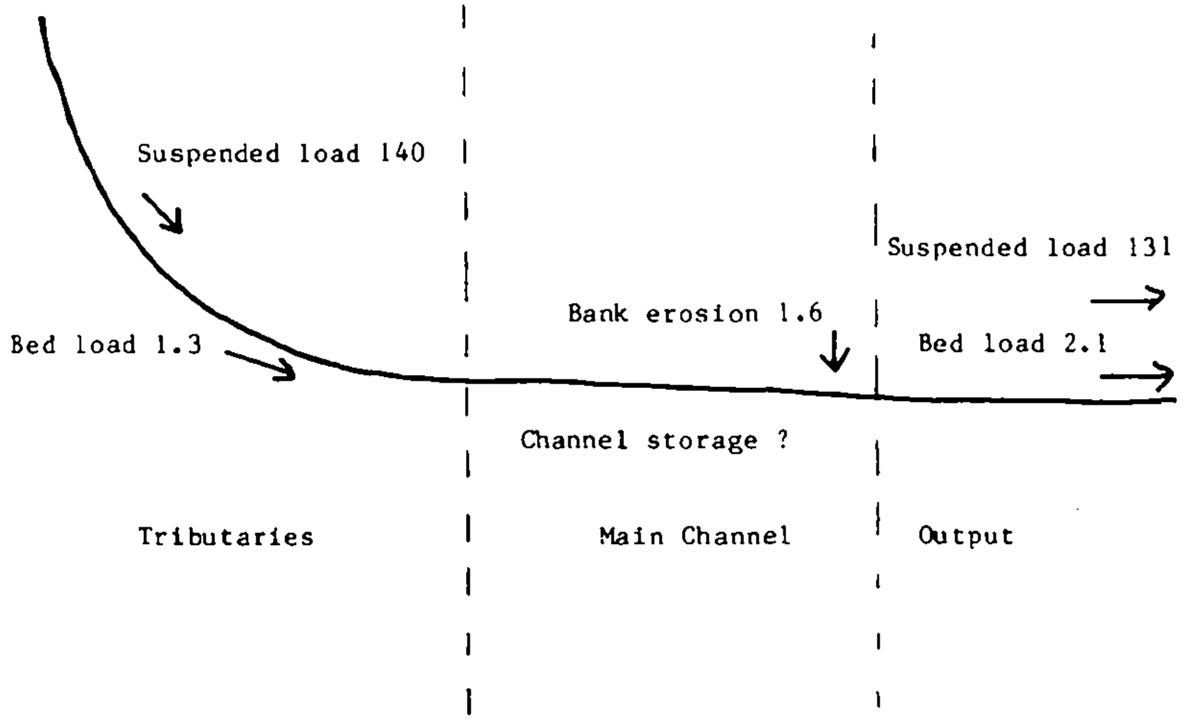
Results

The following schematic sediment budget based on 1985 source data and 1982-85 output data summarises the results obtained. Figures are yields in tonnes km^{-2} yr^{-1}.

Monachyle



Kirkton



From the diagrams it can be seen that the delivery ratios between source areas and basin outputs are close to 1.0, except for the Monachyle bedload, implying that most of this is still in channel storage.

Catchment mean annual outputs (tonnes) are:-

	Suspended	Bed load	Total
Monachyle	293	0.8	294
Kirkton	891	14	905

While there are unavoidable errors apparent in the sampling techniques there is a clear difference between the "natural" catchment and the forested catchment. In common with the Plynlimon study there is a greater availability of material in the forested catchment. Despite the lower streamflow rates this results in greater overall transport from the Kirkton. In contrast to Plynlimon however the greater part of the loads from both Balquhidder catchments comprise fine suspended material.

Future developments

The work will continue through phase 2 to find the effects of the felling operations in the Kirkton and the ploughing and planting in the Monachyle.

It is also hoped that another NERC application from Birkbeck College, London, will succeed and that Drs. Reid and Frostick will install recording bedload traps at Plynlimon and Balquhidder (Kirkton only); such traps allow a much more accurate picture of the sediment transport process.

FUTURE WORK

Phase 2 of these studies, in which the effects of progressive clear felling of the Kirkton and of initial planting in the lower part of the Monachyle are to be monitored, is already under way. Felling within the Kirkton boundary started early in 1986 and ploughing in the Monachyle commenced in April 1986, some six months ahead of schedule. Routine data collection and processing, together with the modifications necessary to the networks and sampling methods and frequencies will utilize a considerable part of the resources available for the study.

It is clear from the preceding sections however that much work remains to be done in analysing the data from phase 1. Recomputing the rainfall arrays on an hourly time scale, insofar as this is possible, will provide a basis for detailed analysis of the flood hydrographs. It will also provide the inputs for the application of more sophisticated modelling techniques with which to explore the water use characteristics of the catchments. A more rigorous analysis of the AWS data than that presented here may identify the reasons for the surprisingly high values of ET obtained from the high altitude sites.

In the catchments the current metering exercise now under way on the Monachyle structure will be continued until a wide enough range of flows has been sampled to check the present rating. A further AWS will be installed in the Kirkton to compare potential evaporation conditions in the valley bottom with those at the present ridge top site. An additional ground level raingauge will be installed to check on the extent to which gauge C3Y figures are representative of that domain. A study of the tributary streams which contribute most to the low flows in the Kirkton will be initiated to determine whether any groundwater movement into the catchment could be occurring.

Should none of these checks identify the reasons for the anomalously low water use figures for the Kirkton emerging from this preliminary analysis, serious consideration must then be given to intensifying studies of the evapotranspiration processes in the catchment.

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

Table 1. Precipitation distribution within the Monachyle during rainfall only periods.

	GROUND LEVEL GAUGES											CATCHMENT MEAN	KIRKTON CLEARING MEAN
	A1W	A2W	A3W	A3Y	B3W	B3Y	C1W	C3W	C3Y	D2Y	D3Y	(KM)	(CM)
TOTALS, 7.83 - 11.83	822	849	826	809	910	872	977	936	726	933	949	874	843
RATIOS, GAUGE/KM	0.94	0.97	0.95	0.93	1.04	1.00	1.12	1.07	0.83	1.07	1.09		0.965
RATIOS, GAUGE/CM	0.97	1.01	0.98	0.96	1.08	1.03	1.16	1.11	0.86	1.11	1.13	1.036	
TOTALS, 6.84 - 12.84	1363	1455	1373	1324	1439	1421	1553	1504	1082	1483	1497	1409	1391
RATIOS, GAUGE/KM	0.97	1.03	0.97	0.94	1.02	1.01	1.10	1.07	0.77	1.05	1.06		0.987
RATIOS, GAUGE/CM	0.98	1.05	0.99	0.95	1.03	1.02	1.12	1.08	0.78	1.07	1.08	1.013	
TOTALS, 4.85 - 10.85	1322	1477	1334	1319	1447	1477	1504	1531	1180	1567	1586	1431	1382
RATIOS, GAUGE/KM	0.92	1.03	0.93	0.92	1.01	1.03	1.05	1.07	0.82	1.09	1.11		0.965
RATIOS, GAUGE/CM	0.96	1.07	0.97	0.95	1.05	1.07	1.09	1.11	0.85	1.13	1.15	1.036	
TOTALS, ABOVE PERIODS	3507	3781	3533	3452	3797	3770	4034	3972	2988	3983	4032	3713	3616
RATIOS, GAUGE/KM	0.94	1.02	0.95	0.93	1.02	1.02	1.09	1.07	0.81	1.07	1.09		0.974
RATIOS, GAUGE/CM	0.97	1.05	0.98	0.95	1.05	1.04	1.12	1.10	0.83	1.10	1.12	1.027	

Table 2. Precipitation distribution within the Kirkton during rainfall only periods.

	MONACHYLE		KIRKTON	
PERIOD	AM (mm)	DM	AM (mm)	DM
7.83 - 11.83	1026	1021	874	866
6.84 - 12.84	1708	1703	1409	1386
4.85 - 10.85	1617	1615	1431	1428
TOTALS	4351	4339	3714	3680

Table 3. Precipitation totals for rainfall only periods estimated by the arithmetic mean (AM) and domain weighted mean (DM) methods.

DATE	PRECIPITATION M (mm)	PRECIPITATION UM (mm)	STREAMFLOW M (mm)	STREAMFLOW UM (mm)
1983				
AUG	46.3	42.8	4.1	4.6
SEP	327.0	315.3	183.5	167.9
OCT	515.9	503.0	457.5	457.4
NOV	105.5	101.4	91.9	96.4
1984				
MAY	26.2	28.6	17.1	10.3
JUN	89.3	89.4	18.3	18.4
JUL	64.3	64.4	13.6	16.4
AUG	74.3	75.4	7.8	5.4.
SEP	254.0	248.2	158.8	?
OCT	378.9	360.5	348.3	325.2
1985				
APR	184.6	183.4	144.6	153.1
MAY	120.1	127.1	88.0	89.1
JUN	85.6	80.7	28.8	25.6
JUL	267.7	262.0	193.0	198.1
AUG	441.9	427.8	365.3	351.0
SEP	298.1	294.0	246.9	229.4
OCT	219.4	217.8	245.1	235.4
TOTALS (excl 9.84)	3245.1	3173.6	2453.8	2383.7

Table 4. Monthly totals of precipitation and streamflow in the Monachyle (M) and upper Monachyle (UM catchments

Kirkton (KH) and Tulloch Farm (TF)

$KH = 1.179\ TF + 0.047$ $TF = 0.831\ KH - 0.015$

$n = 21$, $r^2 = 0.9799$

Monachyle (MG) and Tulloch Farm

$MG = 1.086\ TF + 0.035$ $TF = 0.897\ MG - 0.006$

$n = 28$, $r^2 = 0.9740$

Upper Monachyle (UM) and Tulloch Farm

$UM = 1.326\ TF - 0.067$ $TF = 0.736\ UM + 0.069$

$n = 15$, $r^2 = 0.9768$

Upper Monachyle and Monachyle

$UM = 1.186\ MG - 0.058$ $MG = 0.833\ UM + 0.064$

$n = 15$, $r^2 = 0.9877$

Upper Monachyle and Kirkton

$UM = 1.004\ KH + 0.001$ $KH = 0.953\ UM + 0.055$

$n = 10$, $r^2 = 0.9567$

Kirkton and Monachyle

$KH = 1.056\ MG - 0.100$ $MG = 0.726\ KH + 0.398$

$n = 24$, $r^2 = 0.7669$

Table 5. Summary of regression relationships between the AWS sites in the Balquhidder catchments.

DATE	PRECIP (P)		STREAMFLOW (Q)		P-Q		PENMAN ET
	MONACHYLE	KIRKTON	MONACHYLE	KIRKTON	MONACHYLE	KIRKTON	KIRKTON HIGH
1982							
DEC	352	317	288	242	64	75	6
1983							
JAN	548	441	465	338	83	103	19
FEB	131	85	41	63	90	22	3
MAR	286	247	268	191	18	56	23
APR	75	89	64	72	11	17	41
MAY	170	135	121	97	49	38	45
JUN	94	83	60	60	34	23	80
JUL	31	40	7	19	24	21	101
AUG	46	45	4	12	42	33	86
SEP	327	287	183	144	144	143	46
OCT	516	409	457	354	59	55	28
NOV	105	94	92	84	13	10	10
DEC	483	381	385	292	98	89	14
1984							
JAN	396	338	204	191	192	147	14
FEB	184	157	226	161	-42	-4	19
MAR	180	153	128	149	52	4	33
APR	96	78	167	172	-71	-94	65
MAY	26	24	17	35	9	-11	104
JUN	89	76	18	25	71	51	102
JUL	64	57	14	19	50	38	113
AUG	74	63	8	15	66	48	84
SEP	254	218	159	100	95	118	52
OCT	379	322	348	271	31	51	31
NOV	500	411	428	379	72	32	13
DEC	247	262	309	264	38	-2	10
1985							
JAN	98	84	79	70	19	14	3
FEB	94	80	118	118	-24	-38	12
MAR	125	114	88	84	37	30	24
APR	185	165	145	154	40	11	52
MAY	120	107	88	85	32	22	81
JUN	86	85	29	49	57	36	82
JUL	268	257	193	176	75	81	65
AUG	442	368	365	300	77	68	55
SEP	298	268	247	211	51	57	36
OCT	219	180	245	250	-26	-70	34
TOTALS	7688	6520	6058	5246	1630	1274	1586
MEAN 12 MONTHS VALUES	2636	2236	2077	1798	558	437	543

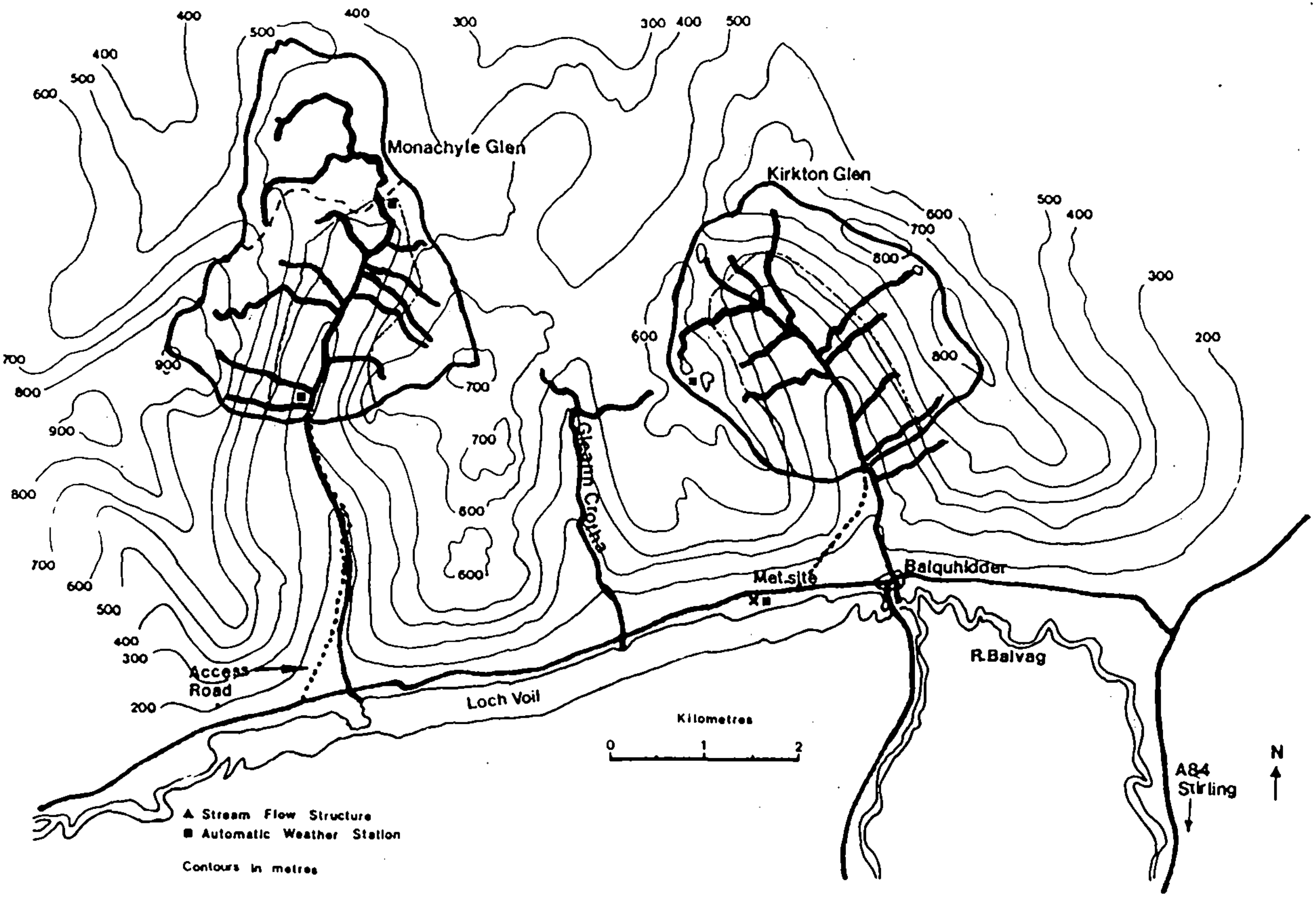

Figure 1. The Balquhidder catchments

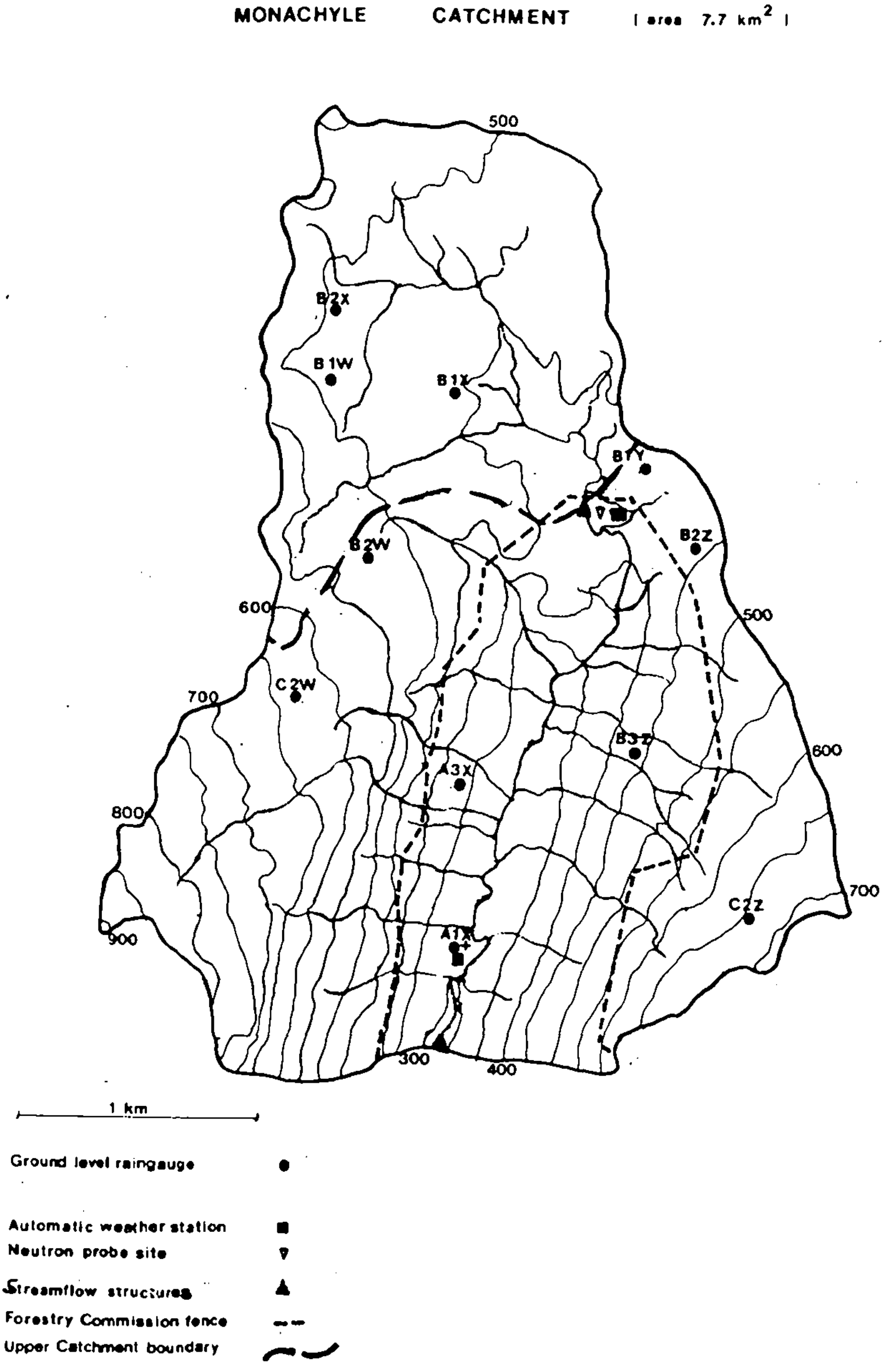

Figure 2. Monachyle instrument networks

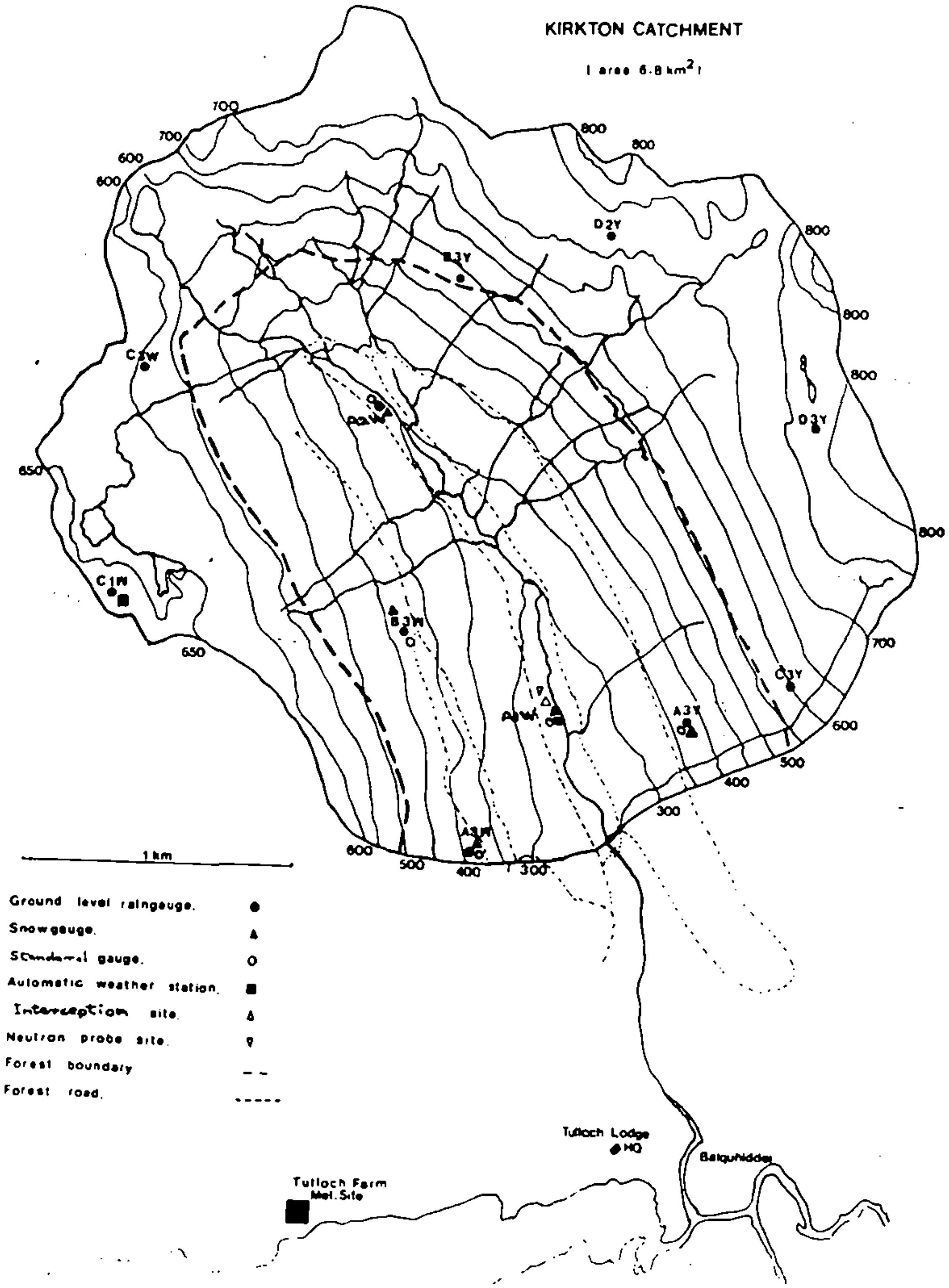

Figure 3. Kirkton instrument networks.

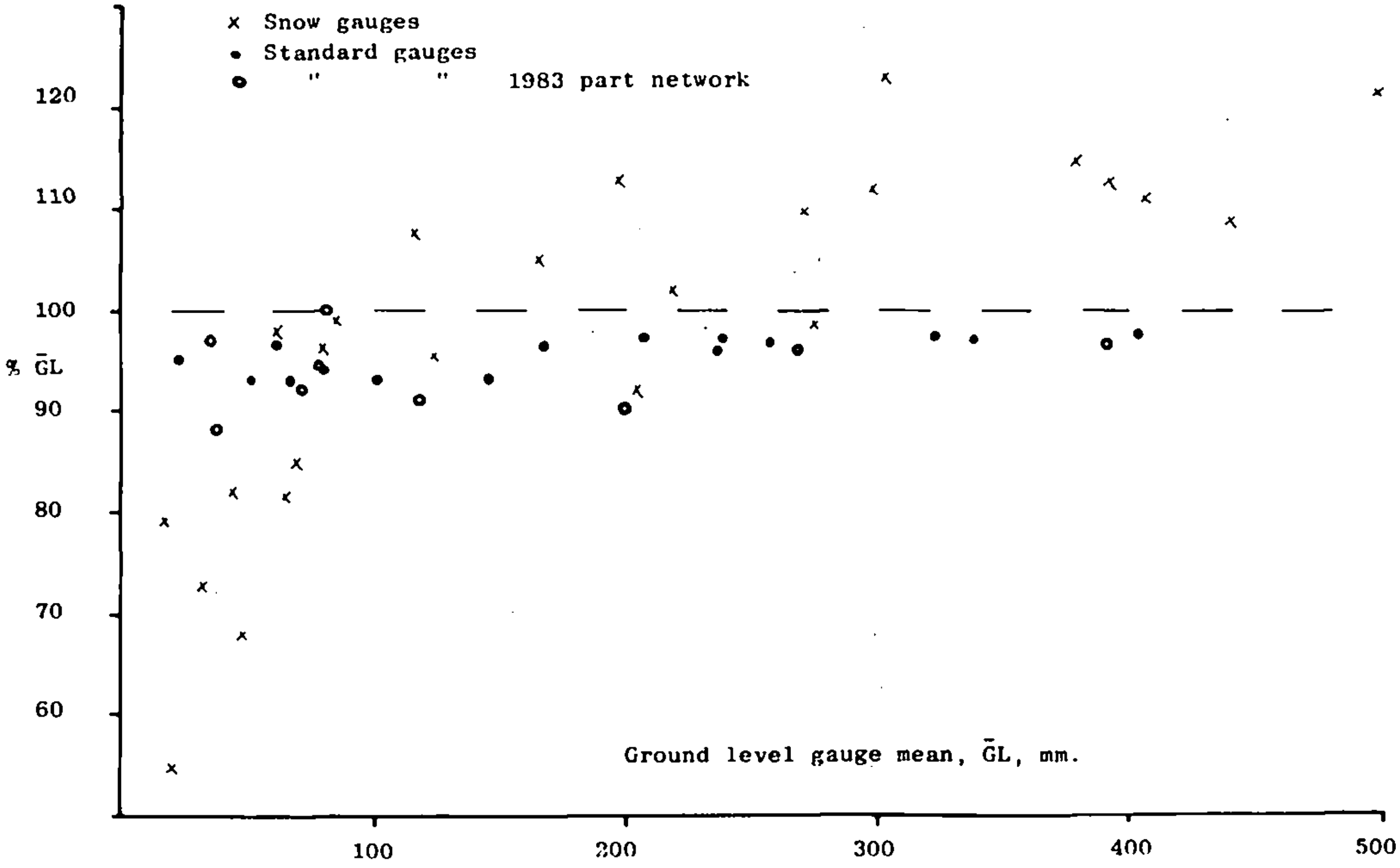

Figure 4. Comparison of standard and snow gauge network means with the clearing site ground level gauges means for "rainfall only" periods.

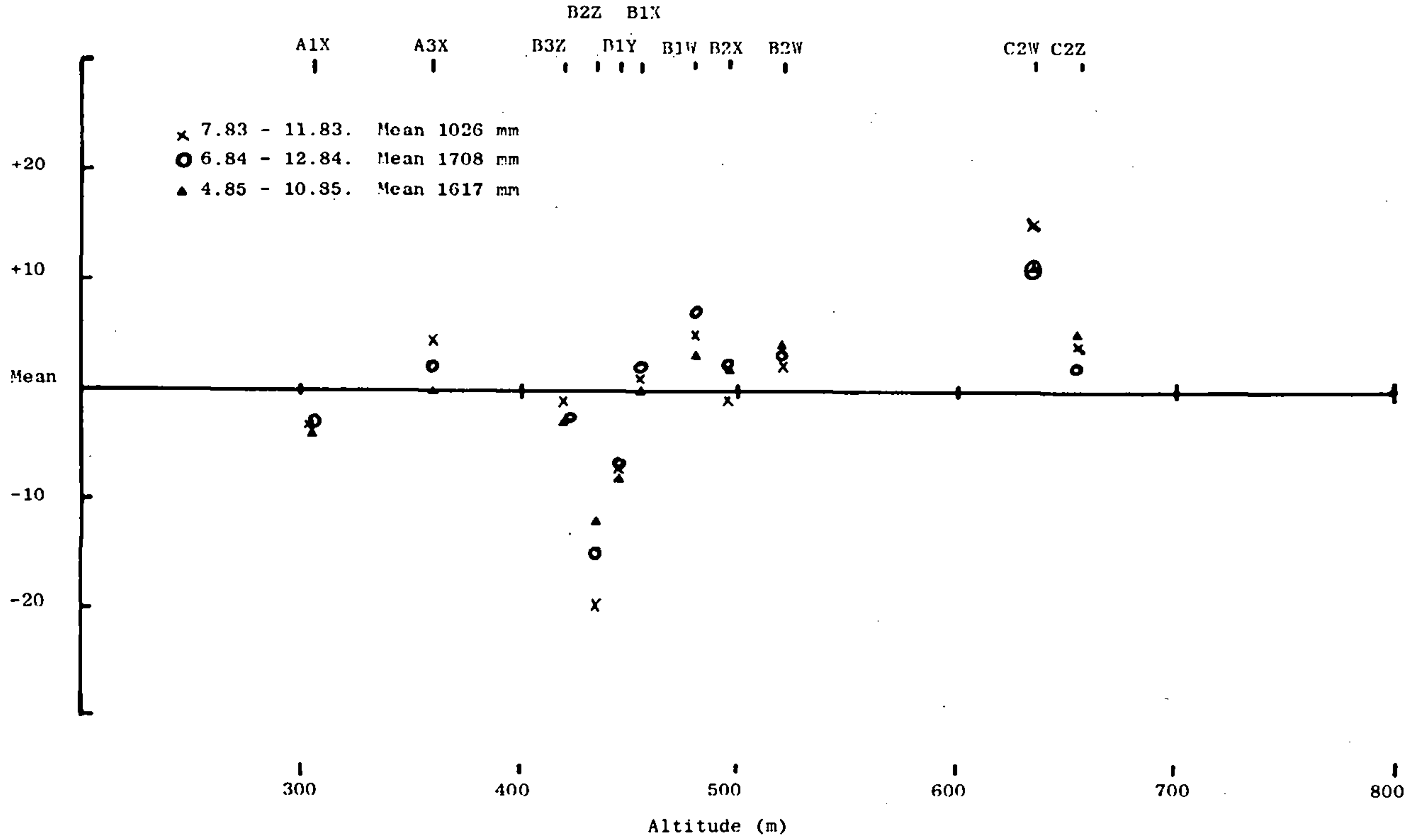

Figure 5. Monachyle ground level gauge totals in "rainfall only" periods expressed as % departure from the period means.

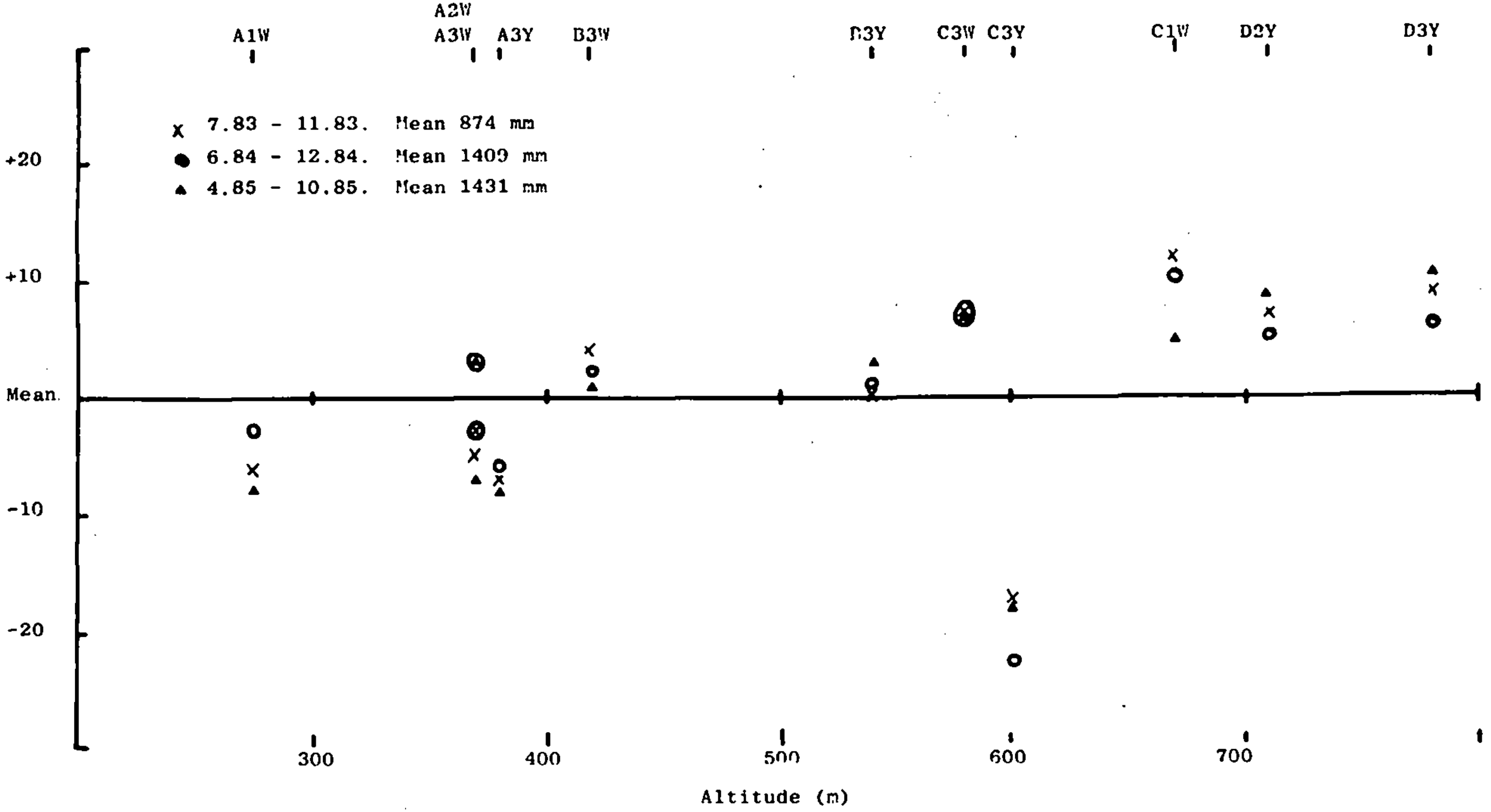

Figure 6. Kirkton ground levels gauge totals in "rainfall only" periods expressed as % departures from the period means.

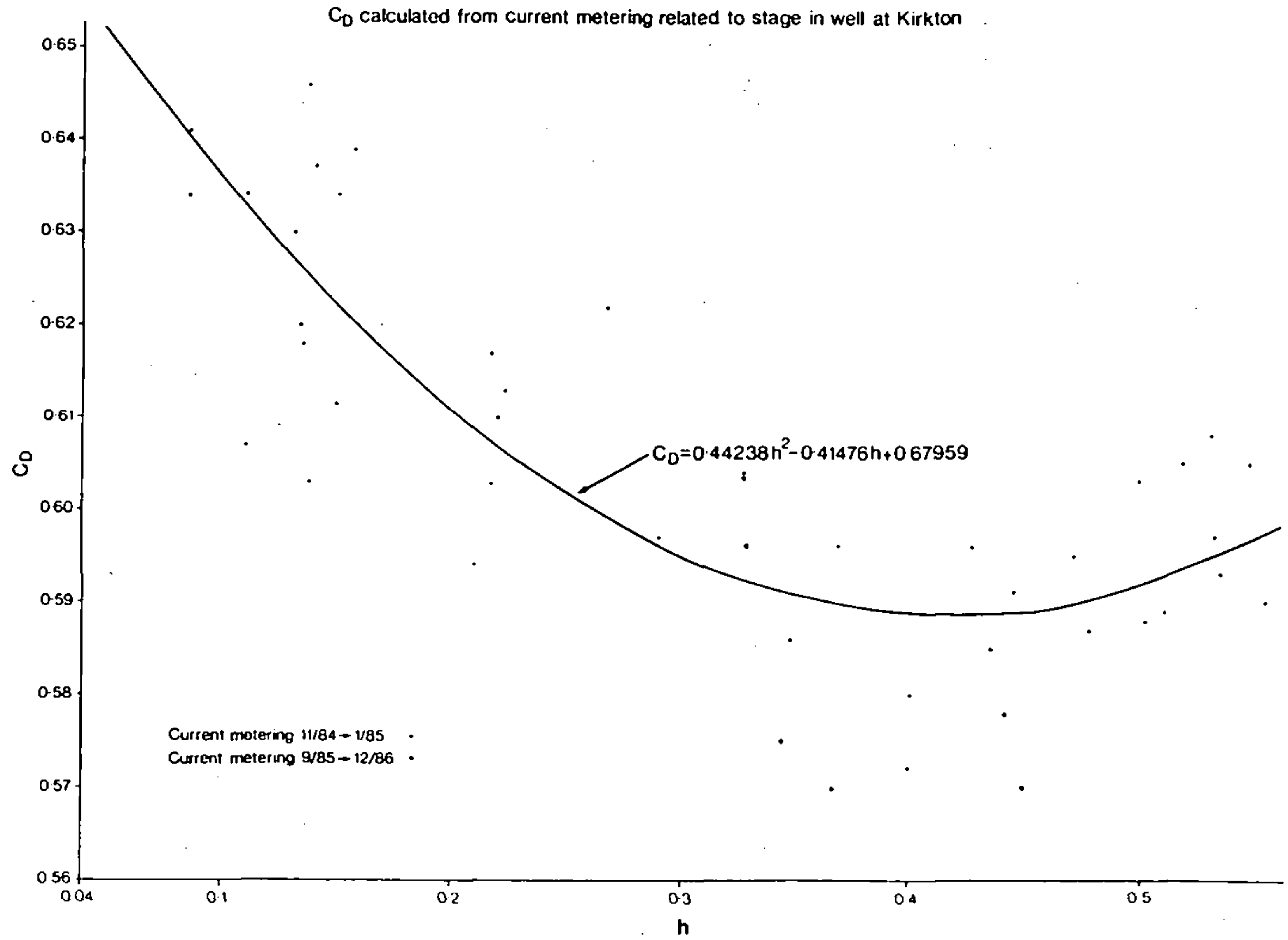
C_D calculated from current metering related to stage in well at Kirkton
$C_D=0{\cdot}44238h^2-0{\cdot}41476h+0{\cdot}67959$
C_D
0·65
0·64
0·63
0·62
0·61
0·60
0·59
0·58
0·57
0·56
0·04
0·1
0·2
0·3
0·4
0·5
h
Current metering 11/84 → 1/85 ·
Current metering 9/85 → 12/86 •

Figure 7.

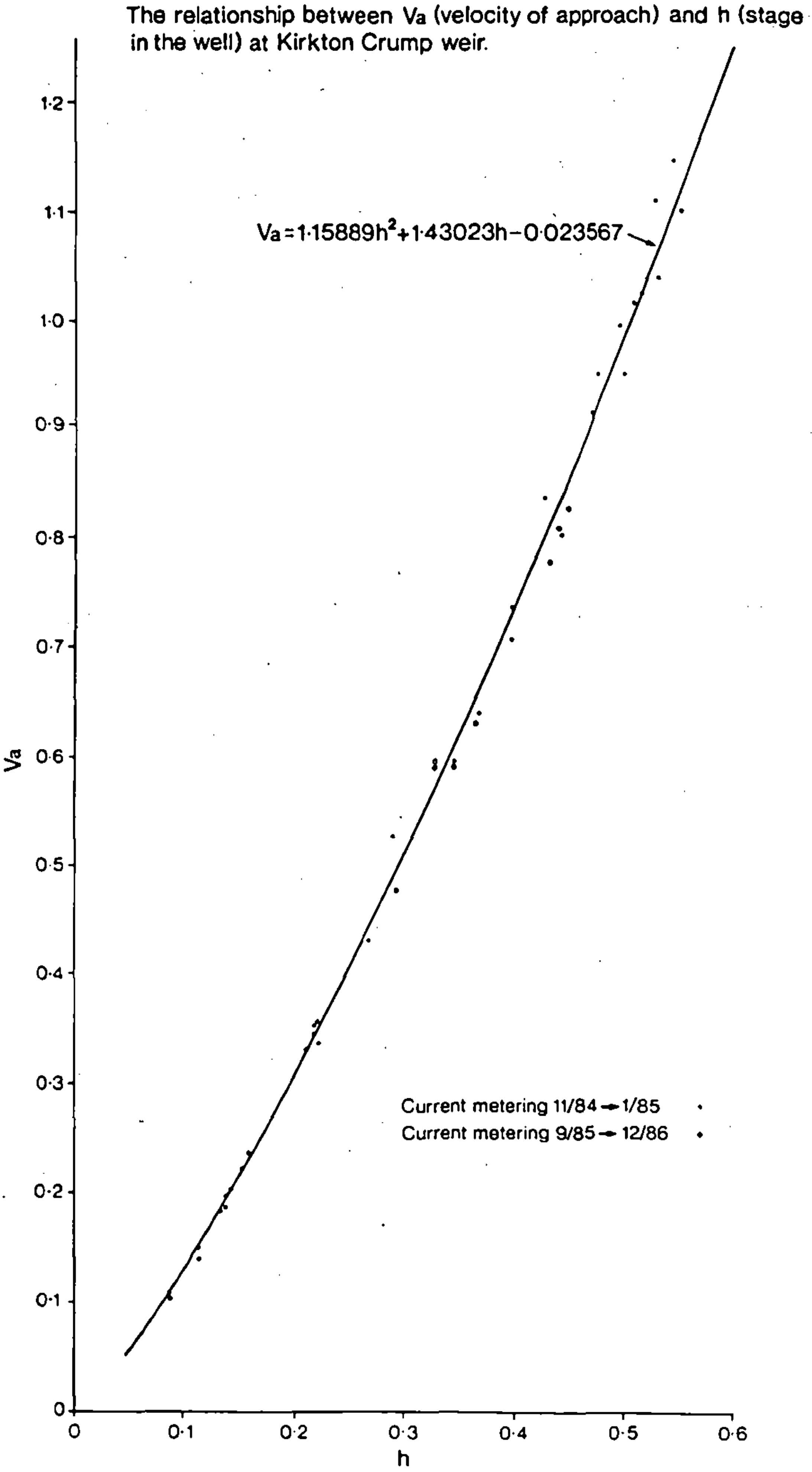
The relationship between Va (velocity of approach) and h (stage in the well) at Kirkton Crump weir.
Va=1·15889h²+1·43023h−0·023567
Current metering 11/84 → 1/85 ·
Current metering 9/85 → 12/86 •
Va
h
0
0·1
0·2
0·3
0·4
0·5
0·6
0·7
0·8
0·9
1·0
1·1
1·2
0
0·1
0·2
0·3
0·4
0·5
0·6

Figure 8.

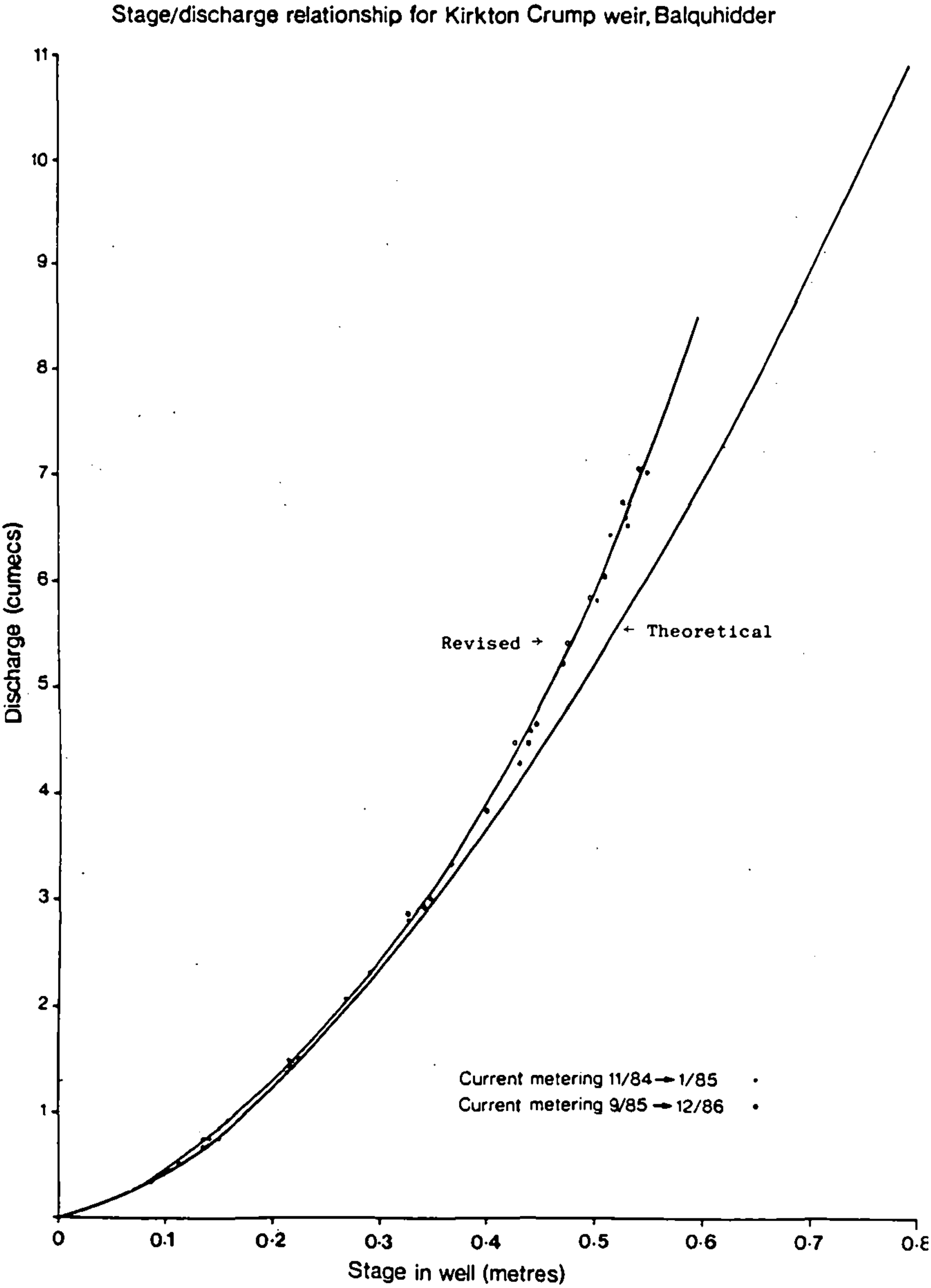
Stage/discharge relationship for Kirkton Crump weir, Balquhidder
Discharge (cumecs)
11
10
9
8
7
6
5
4
3
2
1
0
0·1
0·2
0·3
0·4
0·5
0·6
0·7
0·8
Stage in well (metres)
Revised →
← Theoretical
Current metering 11/84 → 1/85 •
Current metering 9/85 → 12/86 •

Figure 9.

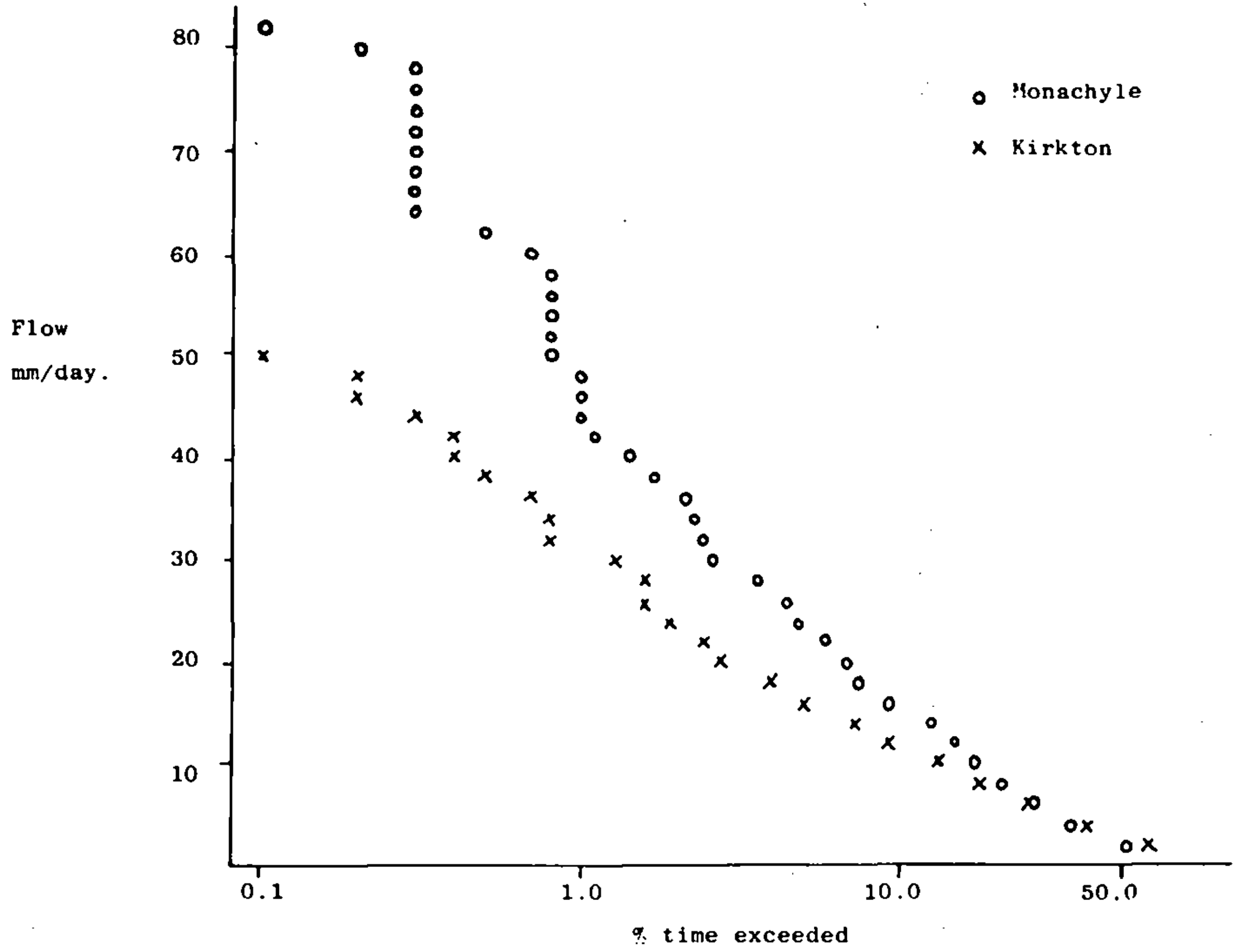

Figure 10. Flow duration curves for the Monachyle and Kirkton.

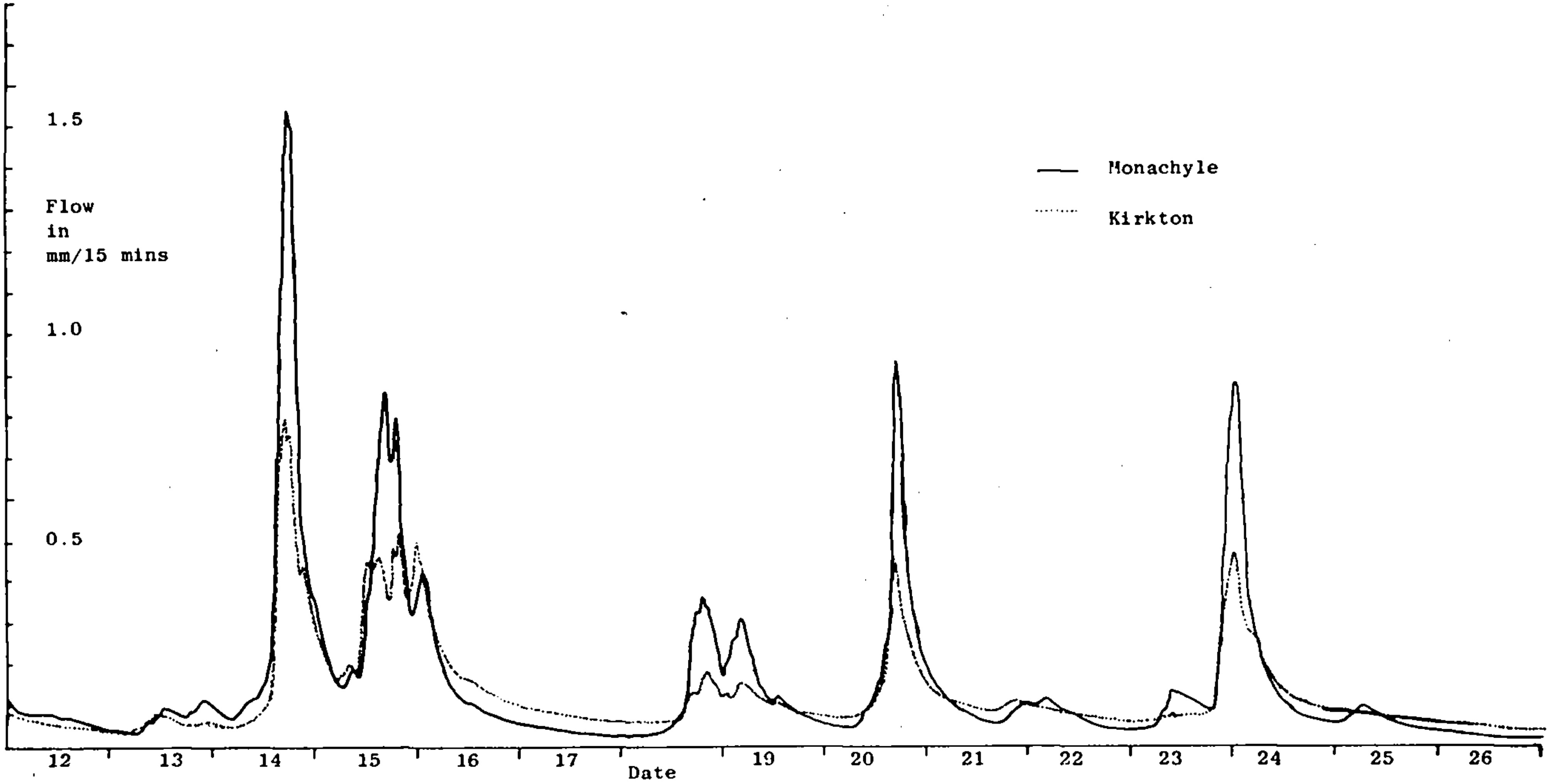

Figure 11. Comparison of Monachyle and Kirkton hydrographs over a wet period in August 1985.

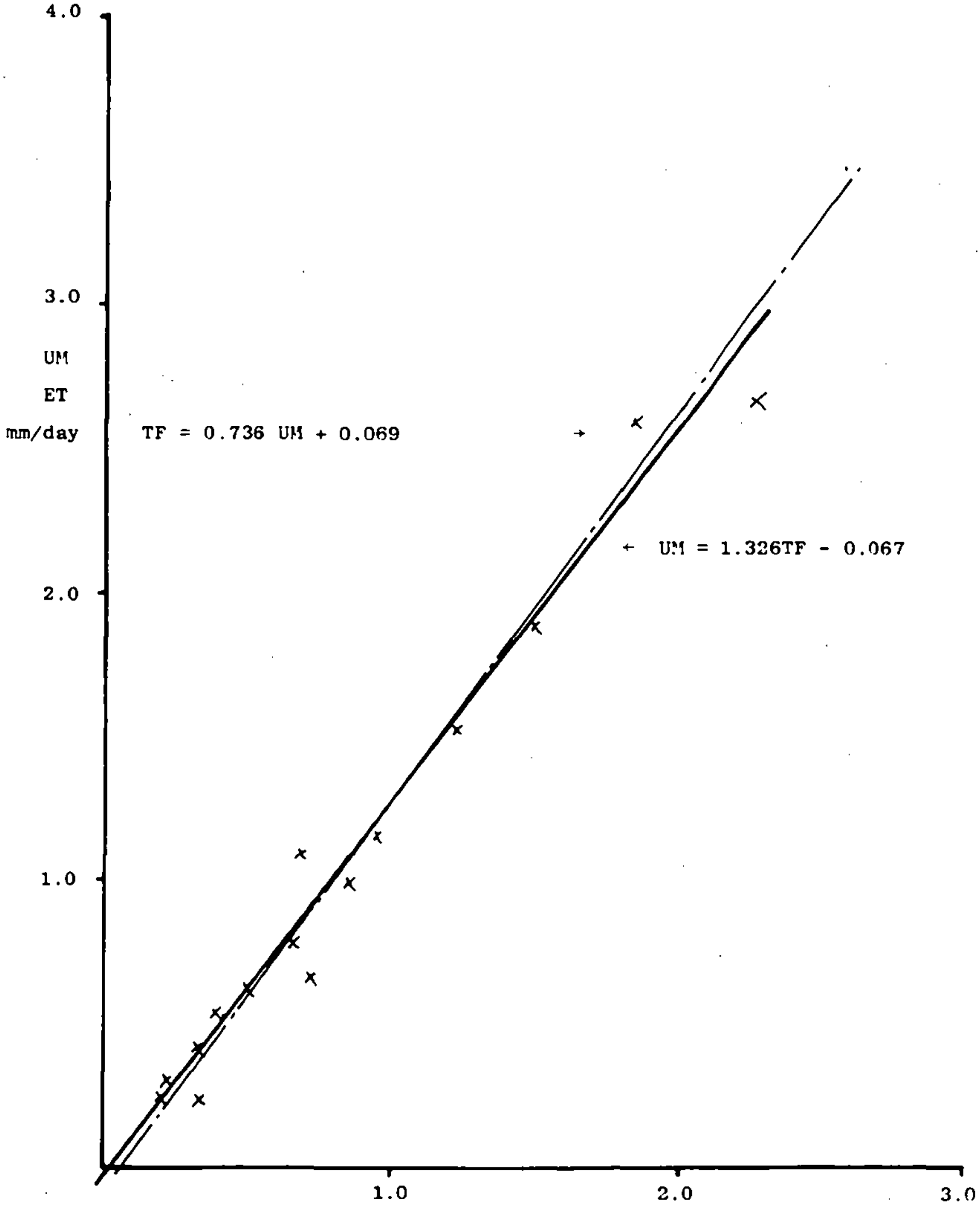

Figure 12. Upper Monachyle (UM) versus Tulloch Farm (TF) monthly mean daily estimates of ET (see Table 5).

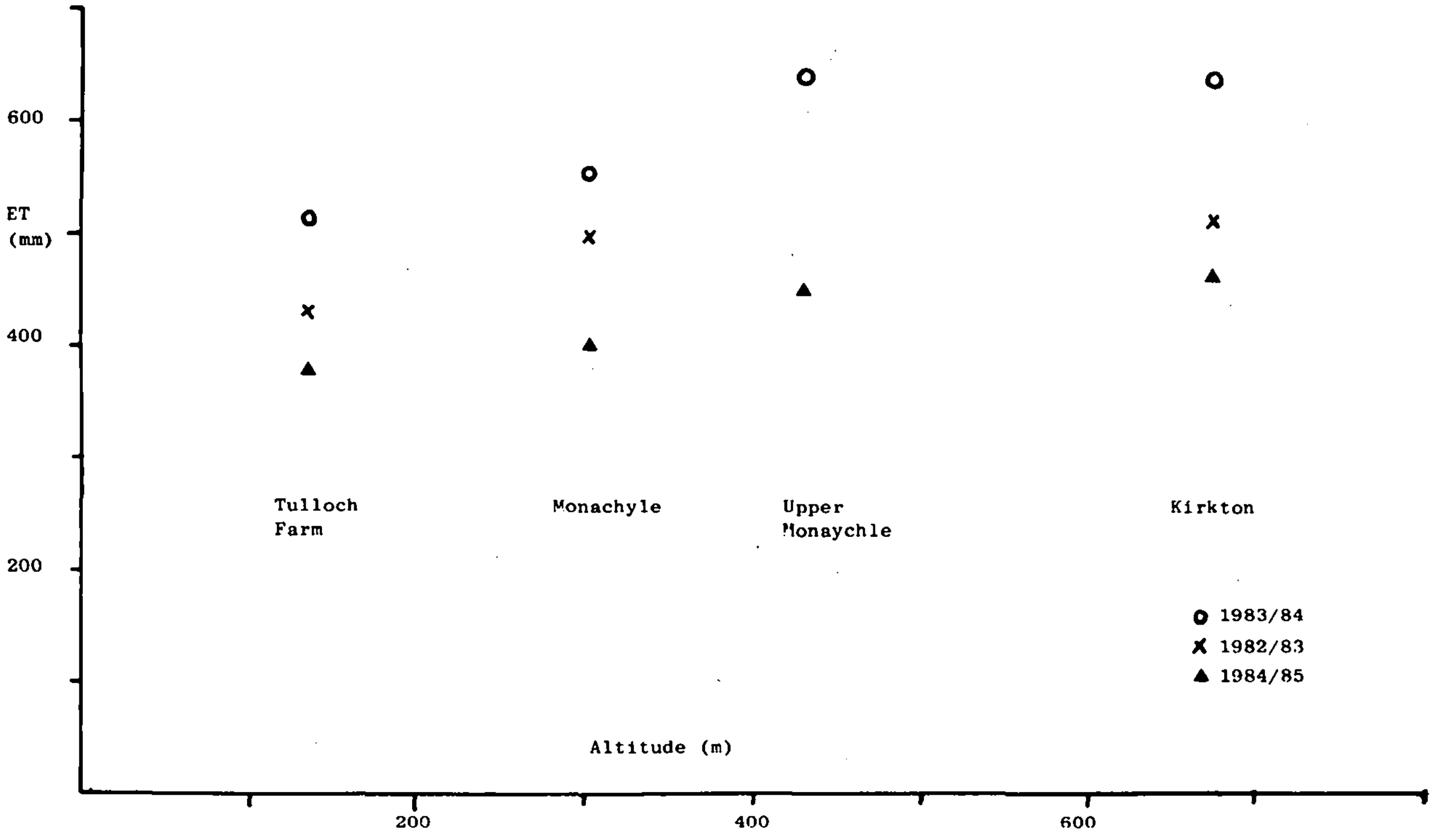

Figure 13. Oct - Sept totals of Penman ET from each AWS.

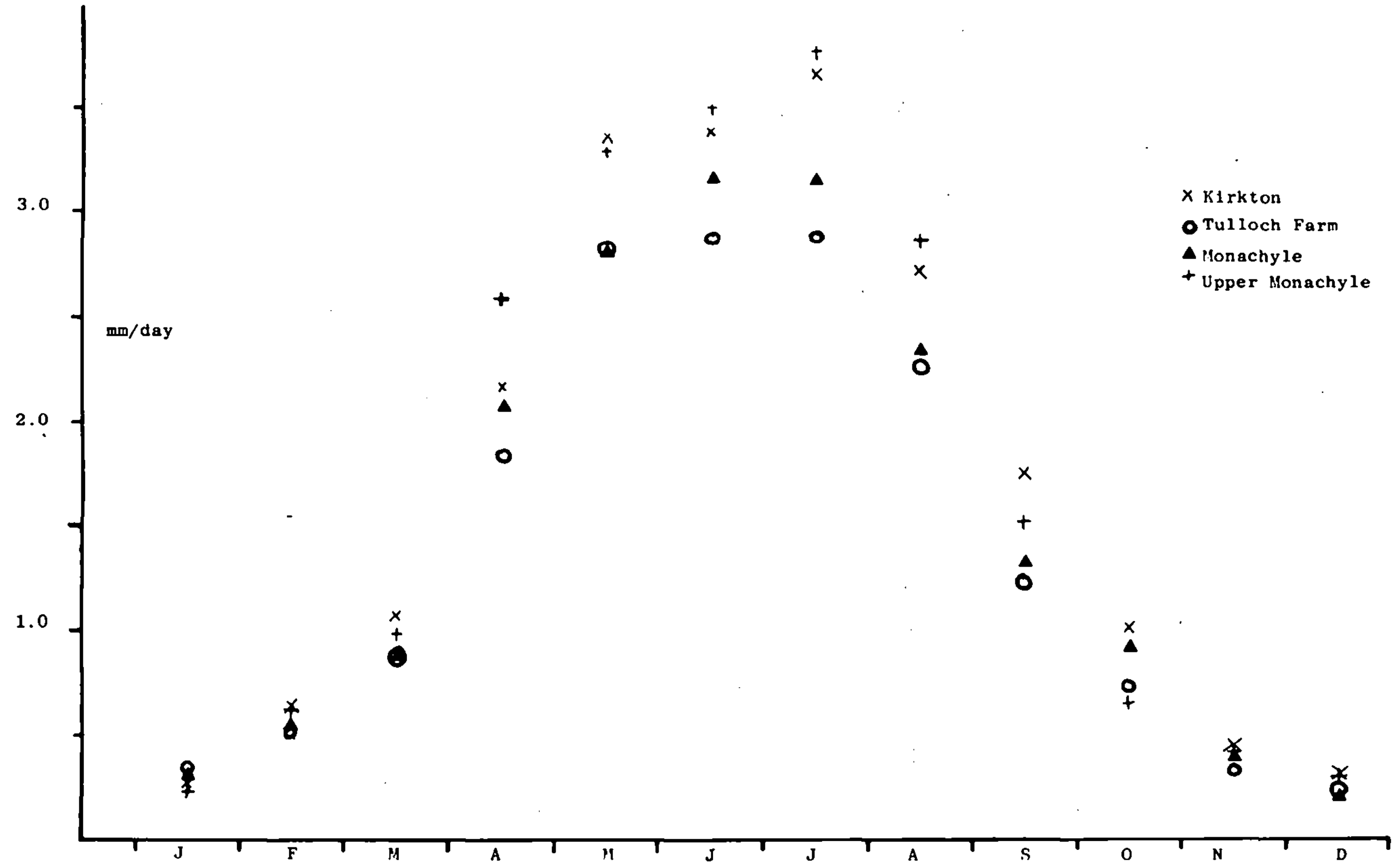

Figure 14. Monthly mean daily estimates of Penman ET from each Automatic Weather Station.

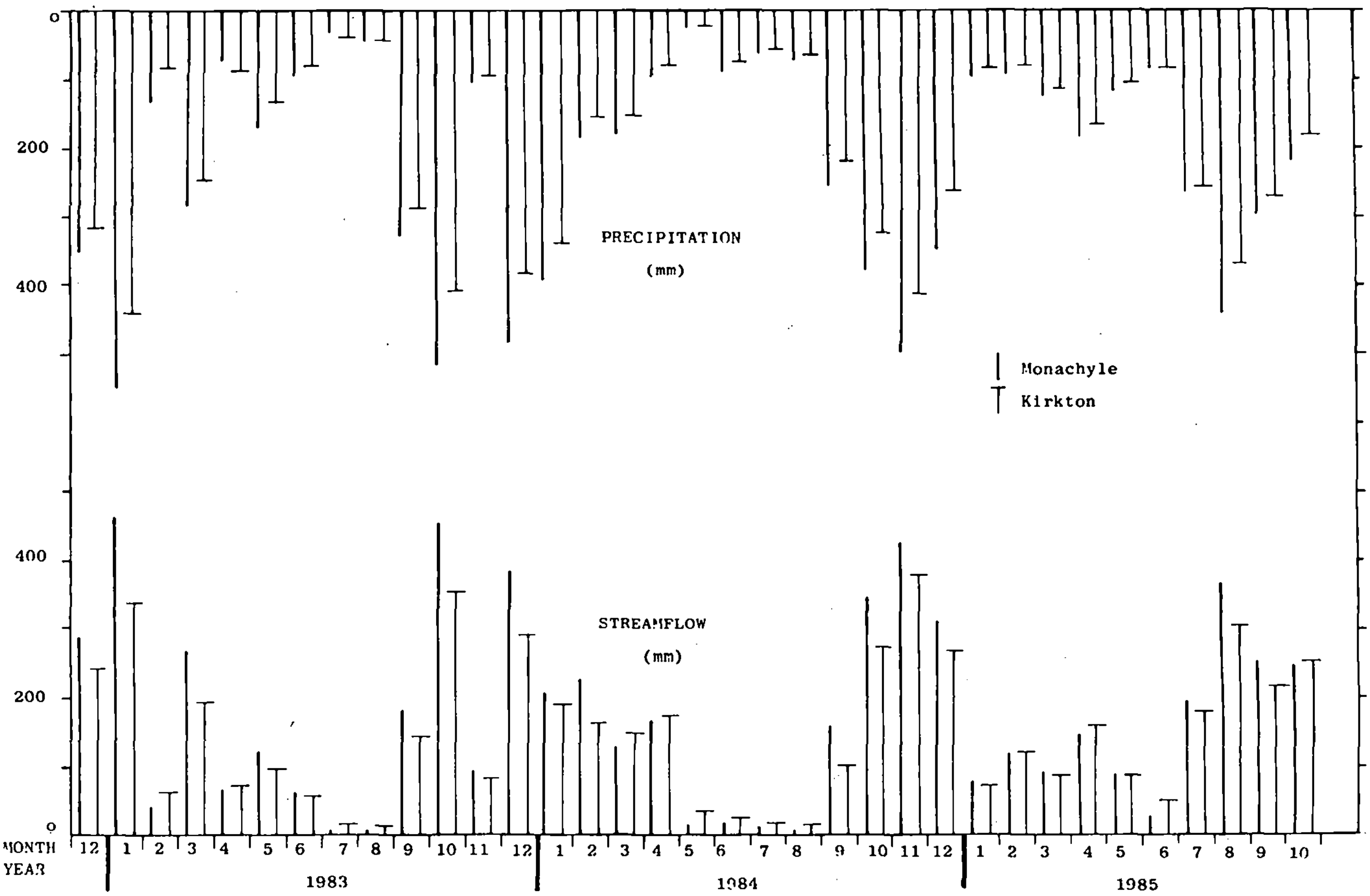

Figure 15. Monthly precipitation and streamflow for the Monachyle and Kirkton catchment.

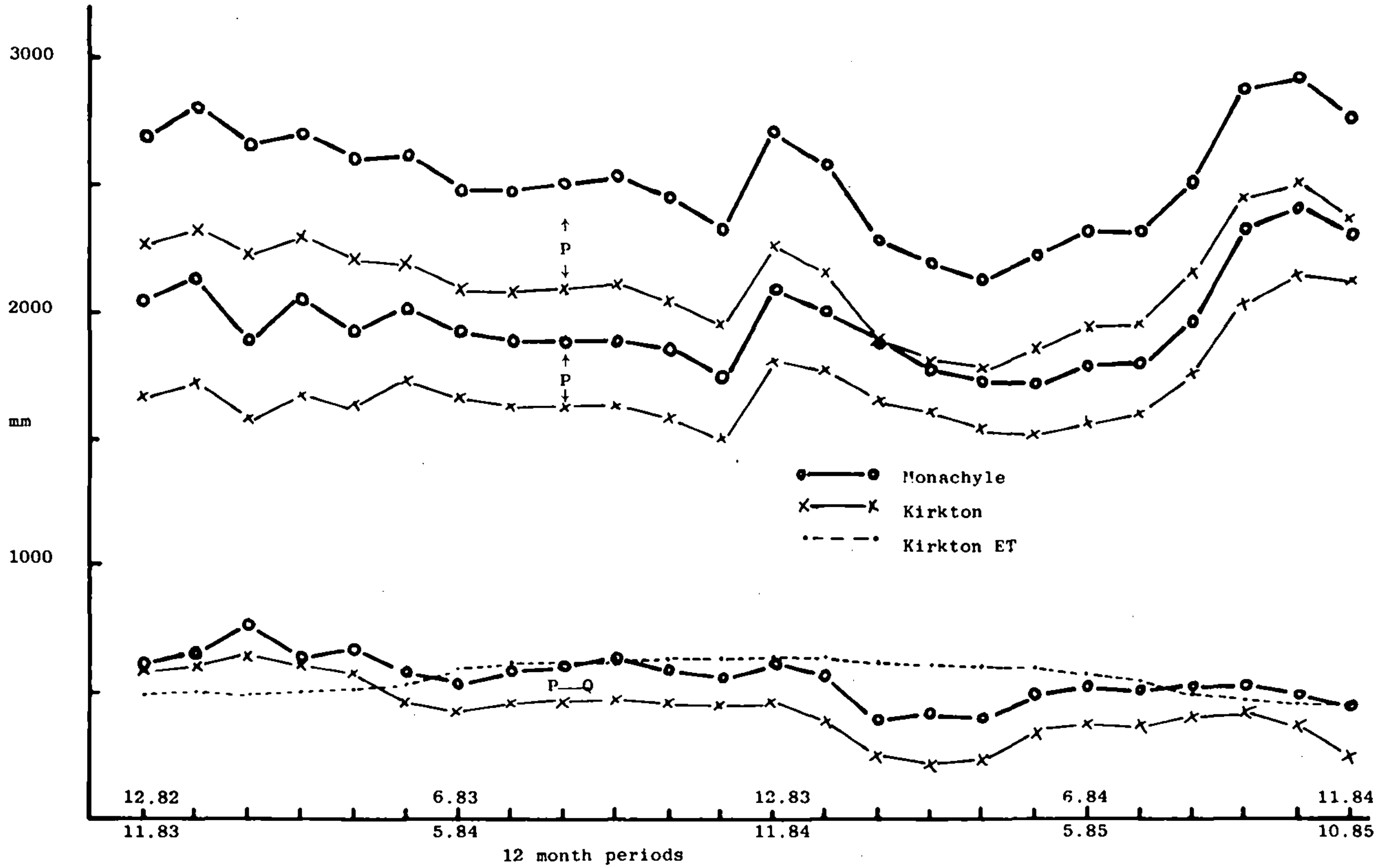

Figure 16. Moving 12 months totals of precipitation, P, streamflow, Q, and P-Q.

Appendix

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MOUNTAIN AND GLEN CLIMATIC CONTRASTS AT BALQUHIDDER

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

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

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

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

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

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

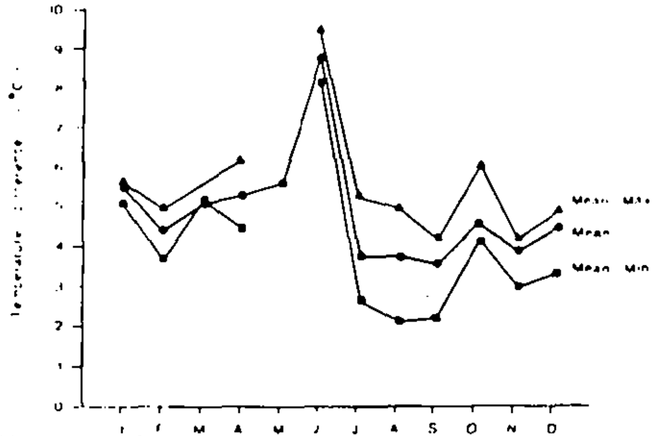

Fig.1: Monthly variation of temperature differences between Kirkton and Tulloch Farm, 1983.

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

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

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

TABLE 1.

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

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

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

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

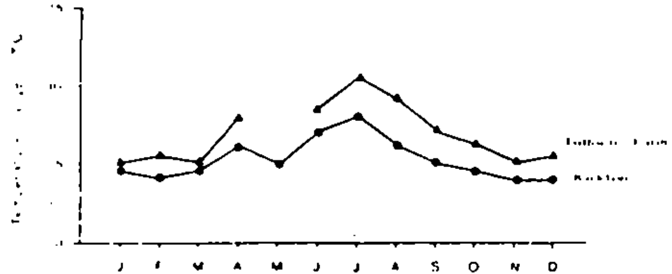

Fig.2. The mean monthly range of temperature at the two sites.

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

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

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

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

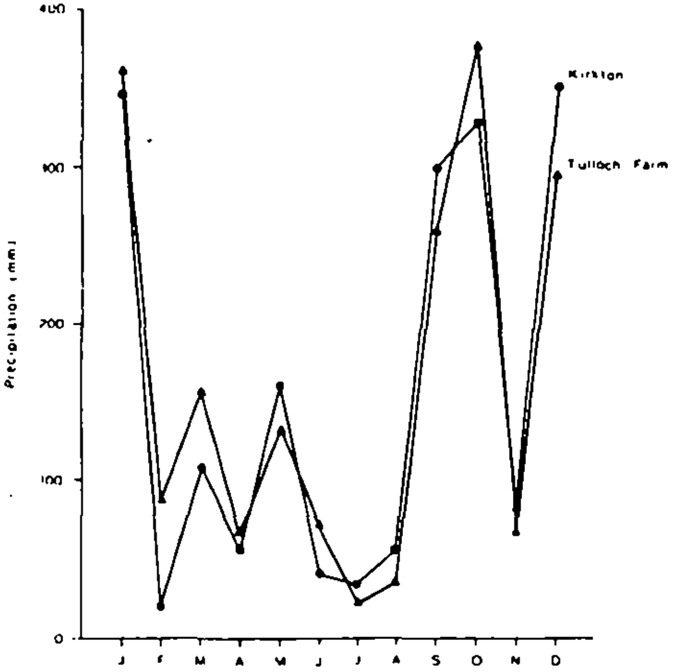

Fig.3: Monthly precipitation values for the two sites, 1983.

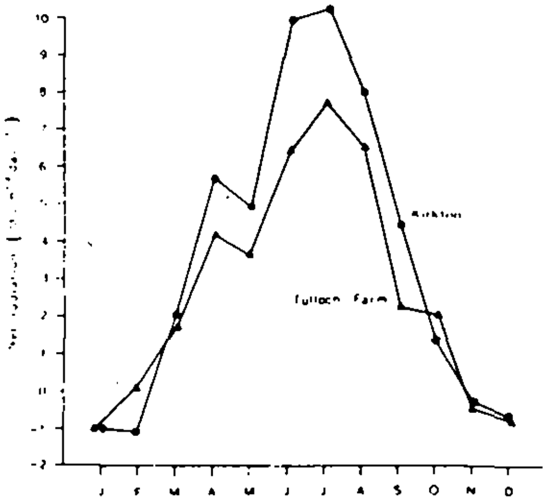

Fig.4· Monthly net radiation totals for the two sites, 1983.

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

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

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

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