**Institute of Hydrology**

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Natural Environment Research Council

# UPLAND AFFORESTATION AND WATER RESOURCES

Progress Report 1983/84
on
The Balquhidder Catchment Studies
and
The Physical Process Studies

# Progress Report on the Balquhidder Catchment Studies

1983/84

by

J.R. Blackie, J.A. Hudson and R.C. Johnson

# INTRODUCTION

During the year under review considerable progress has been made in all aspects of this study of the hydrology of the two catchments at Balquhidder. Installation of the streamflow structures in the Monachyle catchment was completed. The use of a helicopter in this operation was exploited to obtain a collection of aerial photographs which has been used to complete the accurate mapping of all instrument locations in both catchments. Some modifications and additions have been implemented on the precipitation gauge networks and an additional weather station (AWS), together with other instrumentation, has been installed adjacent to the upper Monachyle streamflow structure to obtain more detailed information on snow accumulation and melt (Fig. 1).

Data collection routines have become firmly established with a very high capture rate. Dilution gauging studies to check the ratings of the streamflow structures were initiated during the year and will continue through 1984. Additional instrumentation for sediment sample analysis was installed and some initial indications of the form of the sediment rating curves for both catchments have been obtained.

Whilst the routine initial processing of the accumulating mass of data has proceeded reasonably quickly during the year, the subsequent analysis has not yet reached a stage where detailed conclusions can be presented on the relative effects on the streamflow and water loss of the heather/bracken/grass cover in the Monachyle and of the 40% mature forest in the Kirkton.

In the following sections more detailed descriptions of progress in instrumentation and data collection are given followed by a discussion of the problems encountered and the methods being adopted in the analysis of these data.

Completion of the float well and recorder housing on the low flow flume in the Monachyle was subject to several delays but the structure became operational in August. Data capture from this and the two main Crump structures has been in excess of 95% during the year. With the back-up provided by the FRPB chart recorders on the latter no significant data loss has occurred. Sediment accumulation in the long inlet pipe to the float well on the Kirkton low flow flume has caused some data loss during the year. Considerable bed-load movement occurs in both catchments during storm events. Whilst deposition in the approach to the Monachyle Crump is negligible, it is necessary to clear the Kirkton Crump approach at regular intervals.

Theoretical ratings derived from structure geometry and approach conditions are currently in use to translate the water levels logged at 5 minute intervals to volume flows. Inevitably these incorporate some assumptions. To provide an independent check on these a programme of dilution gauging using sodium iodide was initiated during 1983. Only small parts of the flow ranges have been covered so far and the programme will continue in 1984.

## Precipitation

The only significant change in the rainfall networks during the year was the installation of additional ground level (GL) gauges alongside the existing combined snow/rainfall gauges in 3 of the forest clearing sites in Kirkton. As was shown in the last progress report these latter gauges were found to undercatch significantly during the warm summer months but were comparable to the GL gauges in late spring and autumn. All five clearing sites now have both types of gauge. In addition, a standard 5" gauge has been installed at one site for comparative purposes. Whilst accurate estimation of rainfall input to these catchments present considerable problems, the major challenge in estimating total precipitation is the assessment of that proportion falling as snow. Evidence from two years experience suggests that this proportion varies from some 15% at the lower altitudes to over 40% at the higher levels. As has been repositioned on this site, and an additional Automatic Weather Station was installed. The wind generator, together with a large capacity 12V battery, was also moved onto the site. This now provides power for the mag. tape water level and AWS recorders, for the solid state rainfall and snowmelt recorders and for the heaters on the tipping buckets in both the latter.

## Weather Stations

The three Automatic Weather Stations installed during 1981/82 have continued in operation throughout the year. The loggers have given minimal trouble with less than 2% data loss on any of the sites. Individual sensors have failed for longer periods, most notably the windrun sensor on the high level station in Kirkton which developed a series of faults from October 1983 onwards. A sensor fault common to all three stations is intermittent freezing up of the Rimco recording raingauge. This is a design fault in all tipping bucket type raingauges. It can be overcome by providing sufficient internal heat to prevent the water in the lower inlet pipe and the buckets from freezing, as is done in the recording melt gauges in the catchments, but this requires power on site.

As already described, a fourth AWS was added to the network in December 1983.

Daily readings on the Met. Office manual station at Tulloch Farm were maintained throughout 1983.

## Sediment Movement

The programme of suspended and bed load sediment sampling was extended during the year to cover the upper Monachyle site as well as the main Monachyle and Kirkton outfalls. Bedload samples are taken manually whilst suspended sediment is sampled automatically at both Monachyle sites and by a combination of manual sampling and fixed rising limb samplers at Kirkton. Bedload accumulation in the approach to the Kirkton structure is surveyed monthly.

## DATA PROCESSING AND ANALYSIS

Precipitation data have now been accumulating since July 1981. Whilst the nominal duration of the meteorological records is similar, teething troubles resulted in very patchy records till early in 1982. The streamflow record from the Kirkton started in July 1982, the Monachyle in December 1982 and the Upper Monachyle in July 1983. Whilst there have been problems in establishing the data collection systems these have been largely overcome and the emphasis is shifting to the problems of processing and analysis. There is always a temptation to rush through this stage of a study so that 'results' and their interpretation can be presented quickly. This temptation is being resisted in the present case, except insofar as it is necessary to set up some working hypotheses to provide initial order-of-magnitude checks on the data and indications of any additional data requirements. Consequently no firm 'results' are being presented at this stage, nor will they be presented until a fully quality controlled data base has been achieved.

### Precipitation

In the previous progress report details were given of the location, altitude, aspect and slope of the ground level raingauge network. Field surveys and extensive use of aerial photographs taken from the helicopter used in the installation of the Upper Monachyle structure have resulted in some minor corrections to that data. The installation of ground level gauges alongside all snow gauges in the Kirkton clearings has made it possible to begin the task of determining the relationships between this network and the other gauges in both catchments. These relationships will form the basis of the eventual retrospective estimation of snow inputs over the catchments. A problem arising in this context is the need to reduce all the storage gauge data to a common time base before quality control and the determination of between gauge and between network relationships can be carried out accurately. In the previous report illustrations were given of some initial attempts to do this on seasonal and monthly bases. After due consideration it was decided to attempt to distribute

A useful cross-check is provided by the fact that the separate low flow structures overlap the lower ends of the main structure flow ranges; a discrepancy of some 10% has been identified between low flow and main structures in the Kirkton. In table 1 the Monachyle main and low flow structures are shown to agree within 2% in their overlapping range. To resolve these differences and to provide some independent checks over the rest of the flow range, a programme of dilution gauging checks has been initiated. Insufficient points have been obtained so far to make definite judgements but they suggest that, over the low to medium flow range, errors in the Monachyle main, low flow and upper structure ratings are less than 10%. The Kirkton rating may well be underestimating at high flows but this has still to be confirmed.

Some further indirect evidence of the validity of the Monachyle ratings is illustrated in Figure 2 where hourly flows from the main and upper structures are shown to be closely comparable over a range of flows.

## Meteorological data

Comparisons of the individual variables sampled by the AWS have been continued during the year. In general the between-stations relationships found in 1982 have been confirmed. A departure from the established relationship for windspeeds was the first indication of problems arising with the wind sensor in the Kirkton station. Considerable scatter was present in the winter data, particularly in net radiation. This was largely due to differences in the duration of snow cover.

These relationships are valuable for infilling gaps in the records from any station and give some insight into local climatic variations. The main purpose of the AWS however is to provide estimates of potential evaporation for comparisons with catchment water use and ultimately for inclusion in mathematical models of the catchment response. From the individual station estimates catchment mean values must be derived. Bulked monthly totals of Penman ET for 1983 from the three stations are compared in Figure 3(a). This indicates that the Monachyle (300 m alt.) and Kirkton (670 m alt.) stations give values exceeding those from Tulloch Farm (135 m alt.) in summer; the reverse obtains in winter. A major factor, of course, is the greater frequency of snow cover in winter and hence much lower net radiation at the higher stations. In Figure 3(b) cumulative totals of ET are compared with the Met. Office MORECS area estimate.

A summary of data from the Tulloch Farm manual meteorological site is presented in Table 2.

## Forest interception

Data from the relatively few events studied in detail so far on the interception site are still being analysed. The approach adopted initially is to compare the observed totals of stemflow and throughfall with the precipitation total observed in the adjacent clearings during the event. Each 'event' used runs from a situation where the canopy is clear and dry until that state has been reached again after the precipitation input. The difference between stemflow plus throughfall and the total in the clearing provides an estimate of the loss from the canopy by evaporation. Initial figures suggest that stemflow accounts for some 2 - 4% of the input during rain and mixed precipitation events but less than 1% during snow only events. Throughfall in rainfall events is very variable resulting in 'loss' ratios ranging from 2% to 46% of the total input. Work is now in hand to establish the extent to which this variability can be correlated with the meteorological variables, particularly windspeed and direction. During the major snow events in January and February 1984 loss ratios in excess of 80% were recorded. These data are still being analysed but visual observation indicated that a large proportion of this 'loss' was due to snow being blown from the canopy in the very high winds experienced in this period.

## Sediment movement

A considerable body of sediment data has now been obtained from both main catchment outfalls, much more on suspended than on bed load as a result of the installation of the automatic samplers. Whilst full interpretation of this data must await accurate flow data,some initial indication of the catchment characteristics can be obtained from plots against instantaneous discharge as presently computed. In Figures 4 and 5 the current best regression lines, using (a) all data and (b) data from flows above 1 $m^3/s$, for suspended sediment from the Monachyle and Kirkton catchments are illustrated. The much steeper slope and smaller scatter in the Kirkton suggests that supply of sediment is much less limiting on transport from the forested catchment than from the heather/grassland Monachyle. This is in line with similar comparisons at Plynlimon and elsewhere.

The next phase of analysis will involve computation of ratings for each season and for rising stage and falling stage situations.

Insufficient data are available so far to identify between-catchment bedload differences, but the figures seem to warrant more detailed study. A proposal is being prepared by the IH Unit of Fluvial Geomorphology to construct bedload traps in both catchments and possibly also to insert pressure-weighing devices in the streambeds. Working in conjunction with the Unit, the Dept. of Environmental Services, University of Stirling, has applied for a CASE Award to study the spatial variability of sediment production and transport within the catchments.

At an appropriate time, small traps will also be inserted by IH to study the effects of the felling and initial afforestation on sediment production and transport.

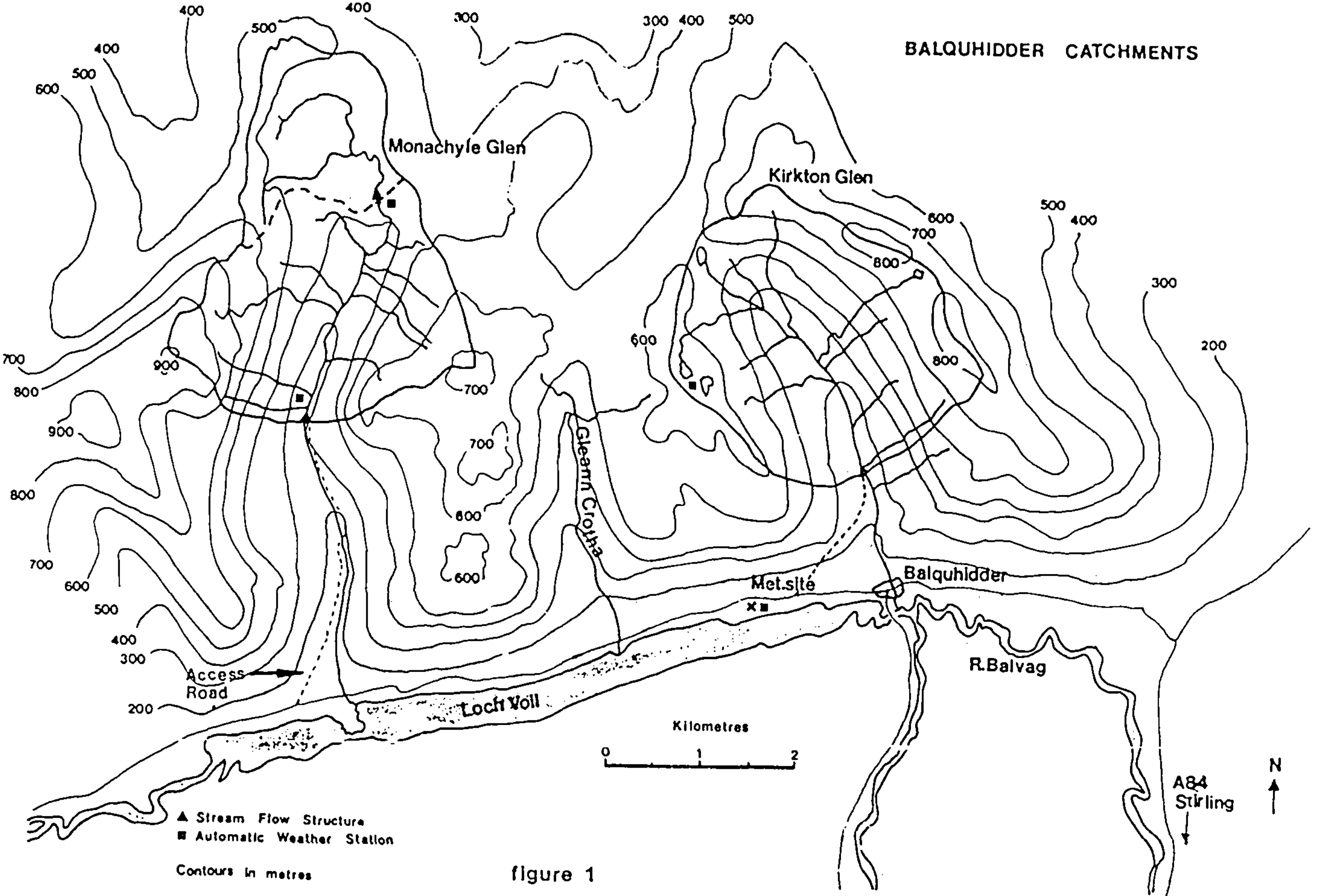
### Stream characteristics

Some initial results of the regular sampling of temperature, pH and conductivity are illustrated in figure 6. The general trend of the temperature differences, from lower values in the forested Kirkton in summer to higher values in winter, is similar to that observed in the forest-grassland study at Plynlimon. Further interpretation of the pH and conductivity data in consultation with the water quality scientists is clearly required. The contrast in pH between the two catchments is very marked and is thought to stem from the presence of a limestone intrusion in the Kirkton catchment.

## CONCLUSIONS

In the three years since the formal initiation of this project the Balquhidder catchment study has made much progress. With the completion of the Upper Monachyle streamflow structure in June 1983 the basic hydrological networks were designed and installed in two years. Given the difficulties of access and climate in this location this represents a considerable achievement which would not have been possible without the support and practical assistance of Consortium members. The contributions of SDD, Forth River Board and Forestry Commission in particular were invaluable.

The problems of data collection from the dense networks with only one


BALQUHIDDER CATCHMENTS
Monachyle Glen
Kirkton Glen
Gleann Crotha
Met.site
Balquhidder
R.Balvag
Loch Voil
Access Road
A84 Stirling
N
Kilometres
0
1
2
400
500
400
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▲ Stream Flow Structure
■ Automatic Weather Station
Contours in metres

figure 1

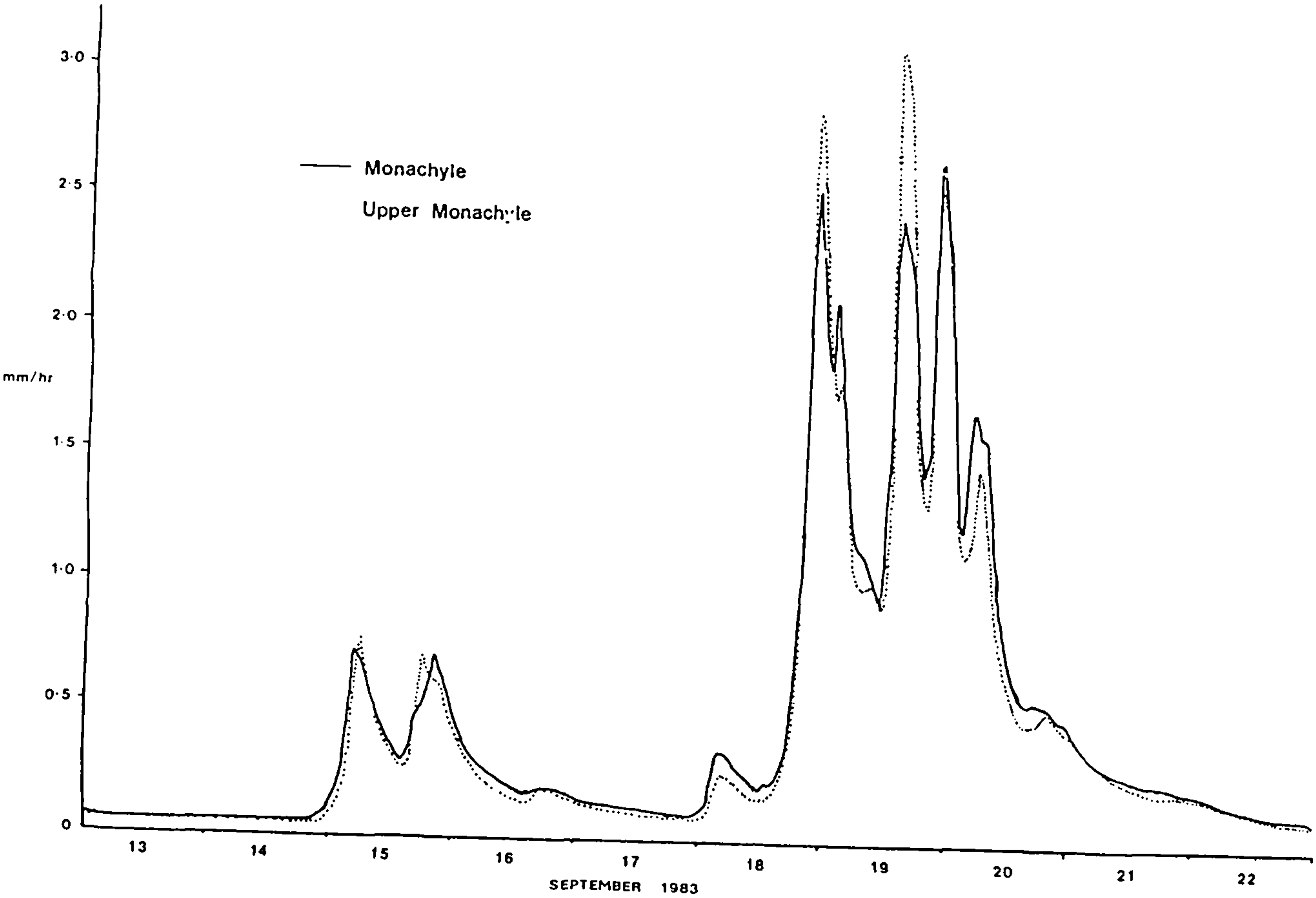


Figure 2. Comparison of hourly flows recorded at the main and upper Monachyle structures.

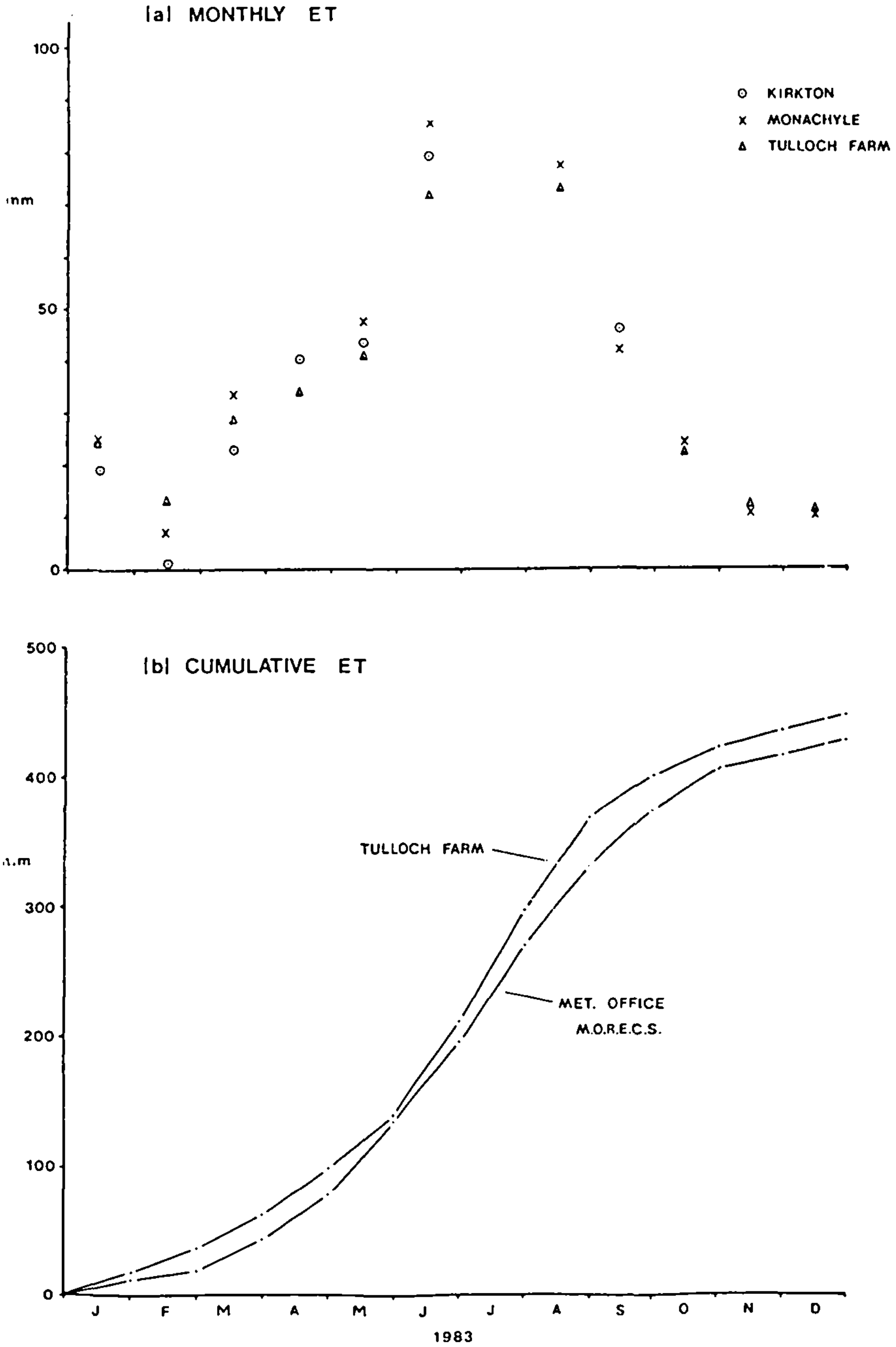
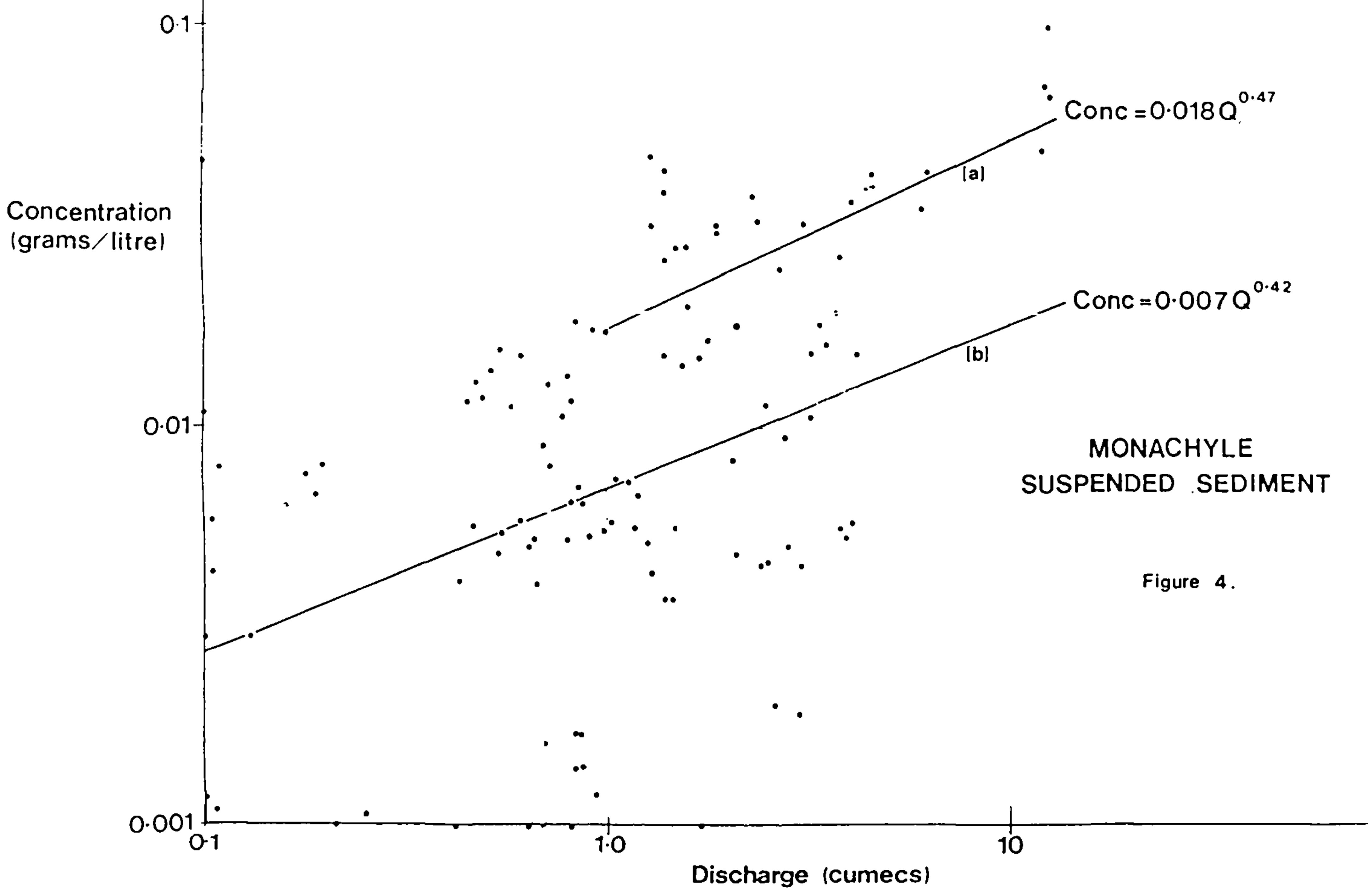
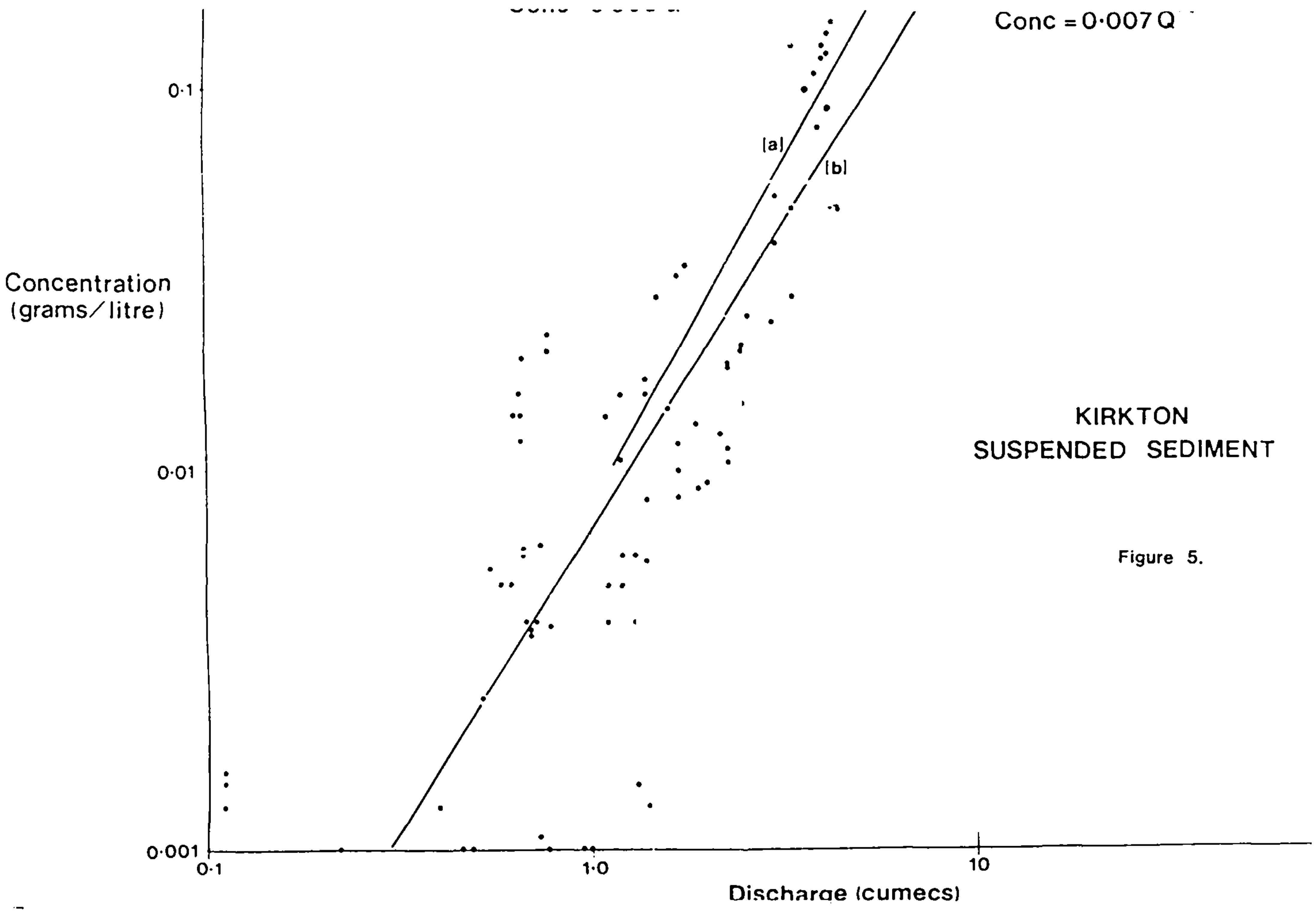


Figure 3. Comparisons of monthly totals of Penman ET computed from AWS data.



MONACHYLE
SUSPENDED SEDIMENT

Figure 4.



KIRKTON
SUSPENDED SEDIMENT

Figure 5.

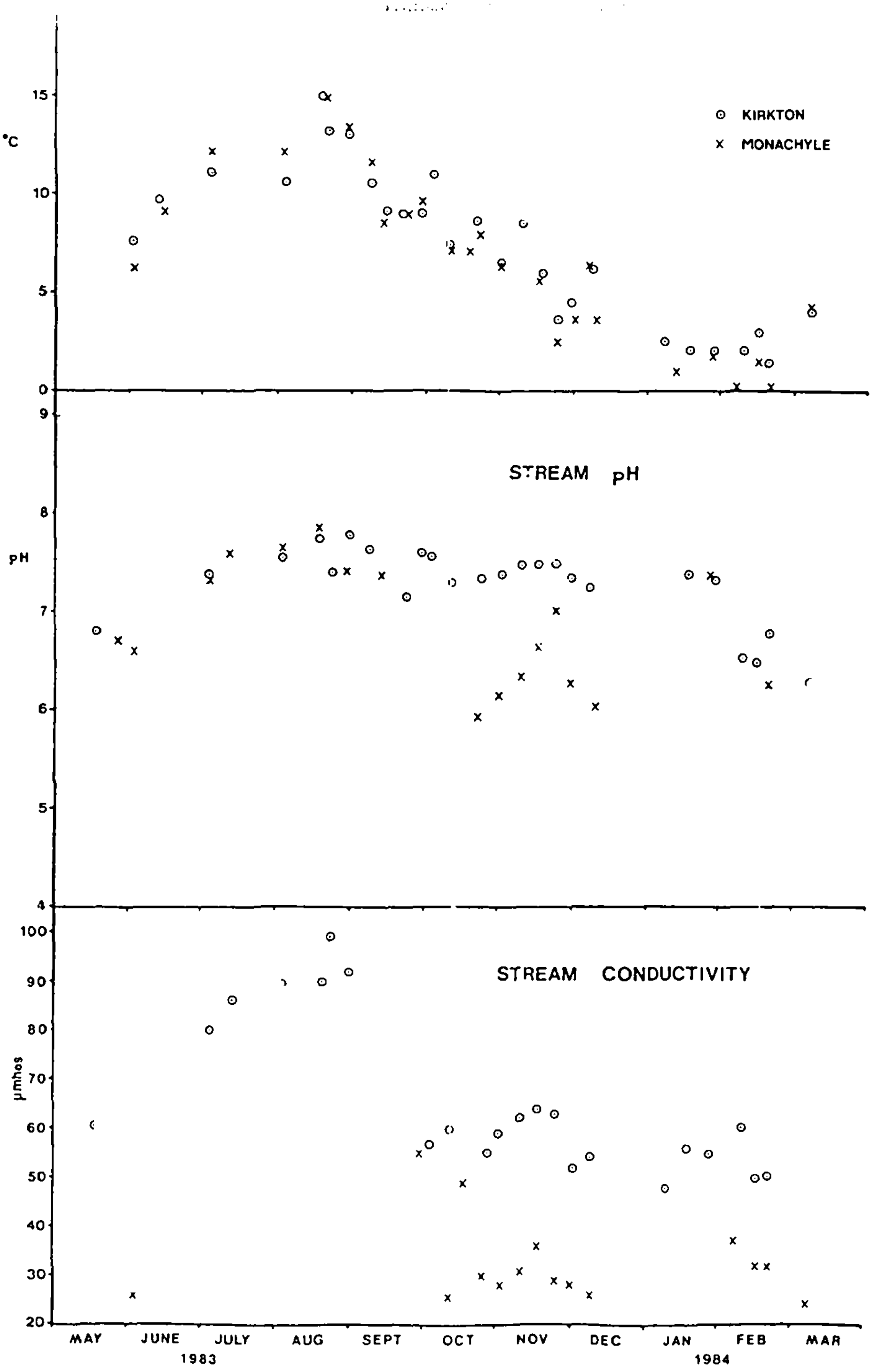


Fig ure 6. Weekly spot samples of stream characteristics.

# UPLAND AFFORESTATION PROGRESS REPORT. PROCESS STUDIES 1983-1984

by

I.R. Calder, R.L. Hall, R.J. Harding, P.T.W. Rosier and I.R. Wright

## INTRODUCTION

Over the past year the effort on the physical processes component of the upland afforestation project has been almost equally divided between operation of field experimental studies and the analysis and interpretation of data from these experiments.

Particular effort has been directed towards the commissioning of the gamma-ray attenuation rig for snow interception studies. Delays with this project had been caused by instrumental problems.

By the middle of 1983 the development of the forest gamma-ray attenuation rig had been completed and successfully tested under field conditions at Plynlimon. During this testing period seven rainstorms were recorded and the data from these events are now being prepared for publication. In October 1983 the rig was moved to the Queen's Forest site at Aviemore and a number of rainstorm and snow events were recorded subsequently.

Good quality snow interception data have also been obtained from the heated plastic-sheet net-rainfall gauges at both the Aviemore and Plynlimon sites and from the "weighing tree" experiment at the Aviemore site.

Soil moisture measurements were obtained from sites at Balquhidder and Crinan under three different vegetation covers: forest, heather and myrtle. These data will eventually be used in evaporation modelling studies.

Analysis still continues on the results from the wet-surface weighing lysimeter system. A lecture describing this work was given by Dr Hall to the Hydrological Group of the Scottish section of the Institute of Civil Engineers and a paper (see Appendix 1), describing the work has been accepted for publication by the Journal of

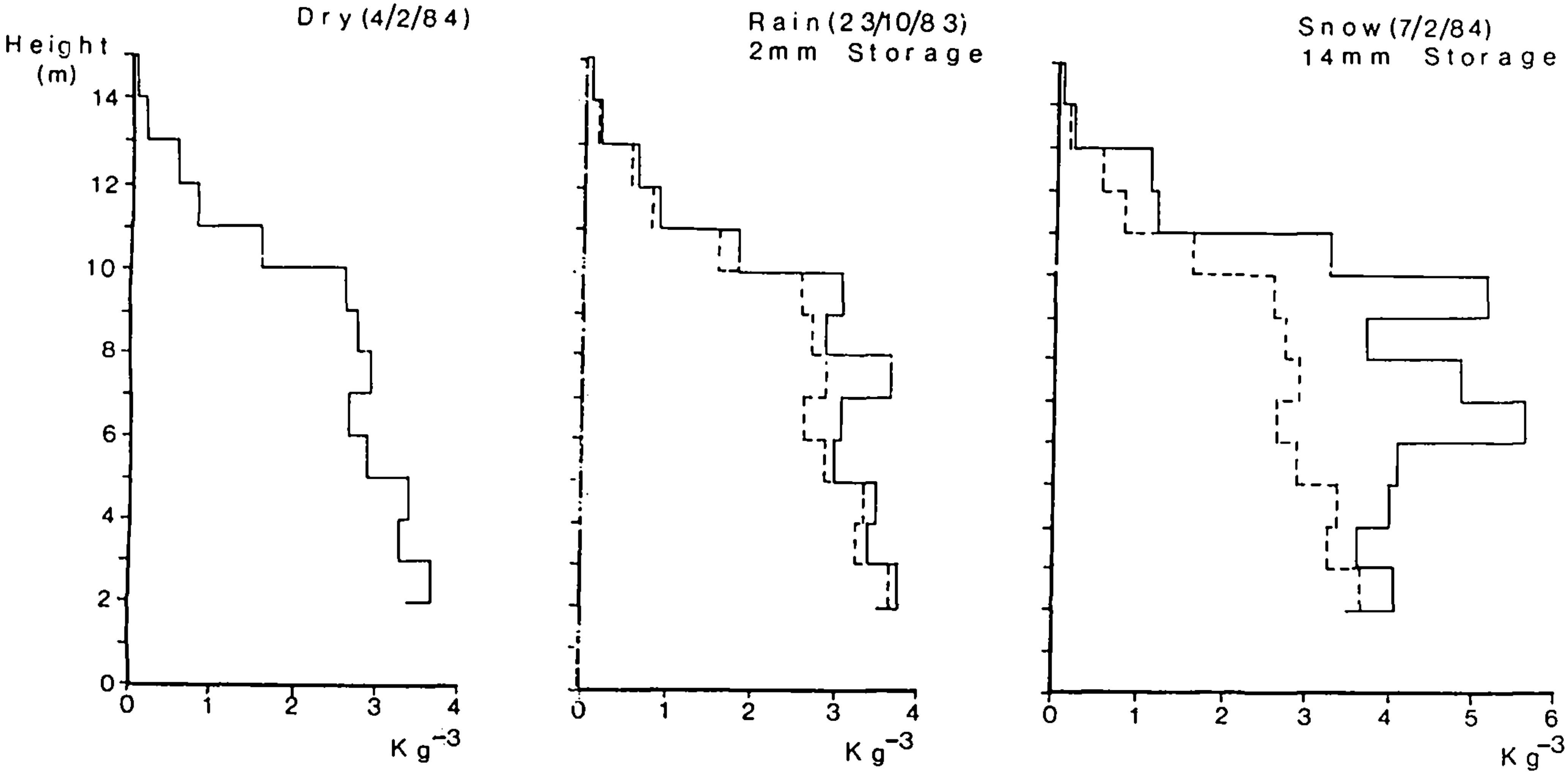


Figure 1: Canopy densities versus height for dry conditions, with intercepted rain and with intercepted snow

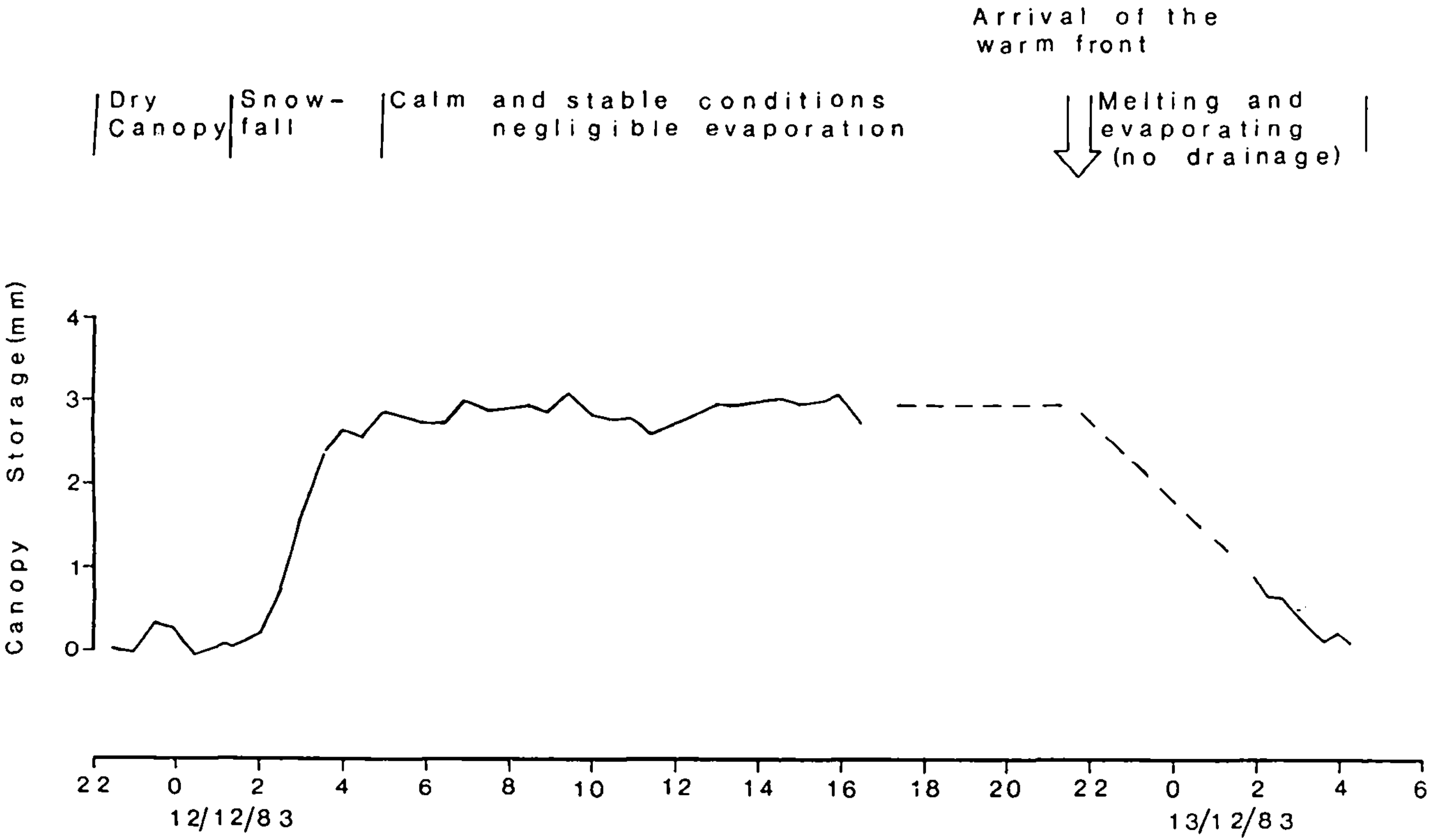


Figure 2 Gamma Ray attenuation measurements of the depth of snow on forest canopy (mm water equivalent)

high canopy capacity, indicate a potential for significant snow interception losses. The longer term significance of this phenomenon is discussed below.

## TREE WEIGHING MEASUREMENTS OF SNOW INTERCEPTION

Several large falls of snow were recorded at the Aviemore site during the winter of 1983/84. Snow remained on the forest canopy for all but 11 days of the 44 day period between 1 January and 13 February and for half of this time more than 10 mm water equivalent was recorded on the forest canopy.

Figure 3 shows the depth of snow (in units of mm water equivalent) measured by the weighing tree experiment for a period at the beginning of January, together with manual meteorological observations from the Aviemore Meteorological Station and estimates of evaporation calculated using the Penman-Monteith equation (using weather station observations taken above the canopy). Events 1 to 3 were primarily rain events, events 4 to 6 were snow. The increased storage on the canopy of the snow compared with rain and its consequent increased persistence is immediately apparent.

One distinctive feature of the three snow events presented in Figure 3 was the very rapid loss from the canopy at the end of each event. These periods of rapid loss generally coincided with the arrival of warm sector air flow within a frontal system. Rain, above zero temperatures and relatively high humidity deficits were generally associated with these warm fronts, see Table 1. Although a large proportion of these losses was melt and washout by rain, significant evaporation must have taken place; evaporative demand (calcuated by the Penman-Monteith method for a wet surface) was typically between 0.3 and 0.5 mm $hr^{-1}$ giving total losses for each of these periods of 2 - 3 mm.

In addition to the losses observed during melt conditions the tree weight measurements show that substantial evaporation takes place

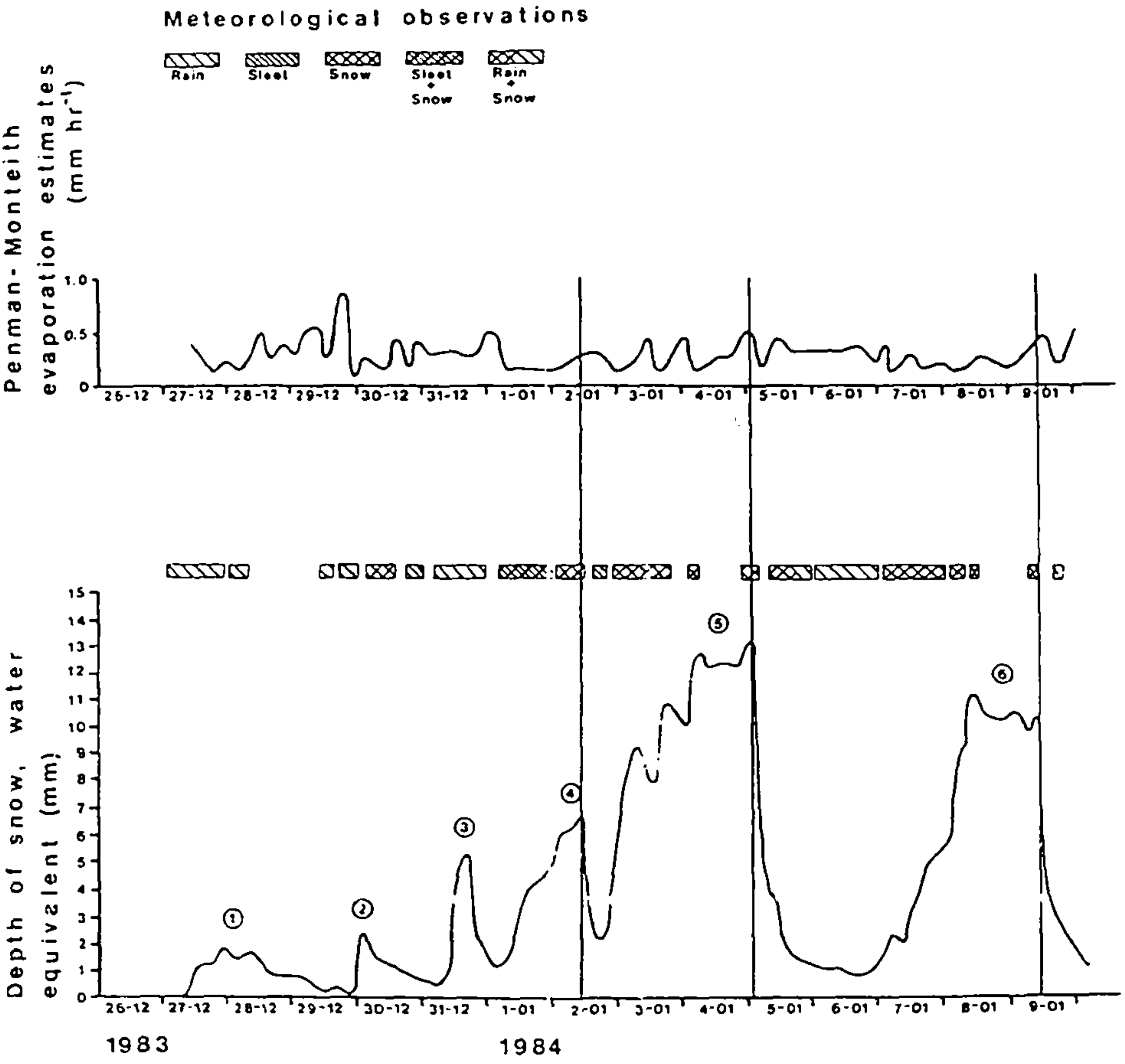


FIGURE 3. The depth of snow on the forest canopy in units of mm water equivalent; measured with the "weighing tree" together with Penman-Monteith estimates of evaporation and Meteorological Office observations of precipitation at Aviemore.

during freezing conditions (sublimation); in mid afternoon of 3 January and in the early morning of 4 January 1.3 mm and 0.8 mm respectively were lost from the canopy by this process. Further work is required to determine the full significance of snow interception losses from forests but it appears that in the maritime climate of the U.K. a substantial proportion of snowfall may be lost through this mechanism.

## A STUDY OF THE SOIL MOISTURE OBSERVATIONS OF UPLAND VEGETATION TYPES

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

Table 2 gives the details of the six soil moisture sites (two at Balquhidder and four at the Knapdale Forest, near Crinan on the Kintyre Peninsula). The myrtle/spruce site at Crinan was ploughed and planted with Sitka Spruce in 1977. In 1979 the vegetation was dominated by myrtle shrubs, approximately 0.5 m high; by spring 1983 the spruce were 3 m high and the canopy was beginning to close. At the lower heather site (NR 817885) the surrounding area was ploughed and planted in 1980. An area approximately 20 m x 20 m surrounding the soil moisture tubes was left untouched and there is no evidence yet that the disturbance has changed the soil moisture regime within the experimental plot.

An analysis scheme based on a daily accounting SMD model, similar to that used by Calder et al (1983a), was employed which can be described by the following equations:

$$SMD(i+1) = SMD(i) \quad R(i) + E(i) \qquad \text{when } SMD(i) > 0$$

$$SMD(i+1) = E(i) - R(i) \qquad \text{when } SMD(i) < 0$$

TABEL 2. Details of soil moisture sites

| SITE | TUBE NO. | GRID REF. | VEGETATION | SOIL TYPE | TUBE DEPTHS | PERIOD |
|---|---|---|---|---|---|---|
| <u>Crinan</u> | | | | | | |
| Myrtle/ Spruce | 01 - 03 | NR 801878 | Myrtle/Spruce | Peat | 2.5m | 2.8.79 to present |
| Crinan Forest | 04 - 07 | NR 796879 | Sitka/Spruce | Brown Earth | 1.0m - 1.20m | ———— " ———— |
| Crinan Lower Heather | 26 - 31 | NR 817885 | Heather | Peat | 1.0m - 1.20m | ———— " ———— |
| Crinan Peninsula Heather | 32 - 37 | NR 810860 | Heather | Peat | 1.0m - 1.20m | ———— " ———— |
| Balquhidder Kirkton | 01 - 07 | NN 529226 | Sitka/Spruce | Brown Earth | 1.2m | 17.2.83 to present |
| Balquhidder Monachyle | 01 - 06 | NN 482852 | Heather | Peat/Brown Earth | 1.0m | ———— " ———— |

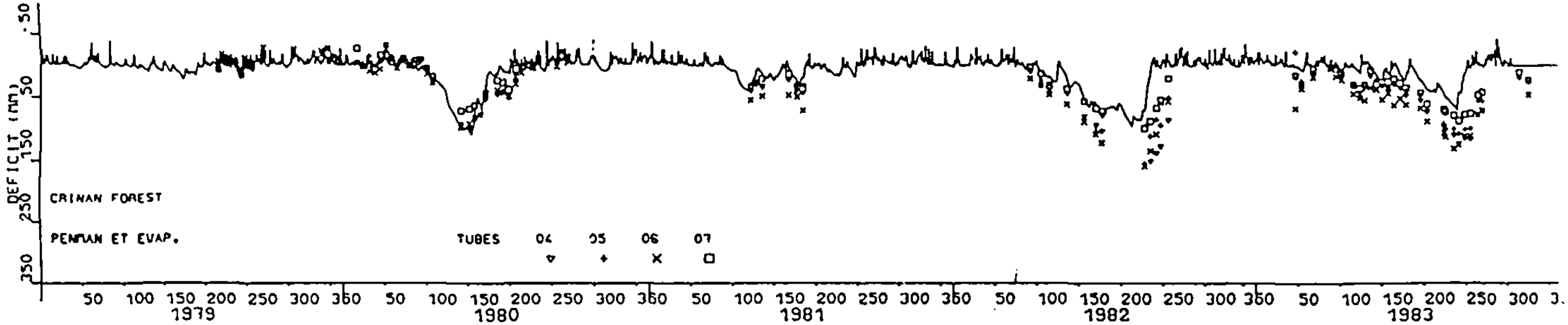

-50
50
150
250
350
DEFICIT (mm)
CRINAN FOREST
PENMAN ET EVAP.
TUBES 04 ▽ 05 + 06 × 07 □
50 100 150 200 250 300 350
1979
1980
1981
1982
1983

Figure 4a

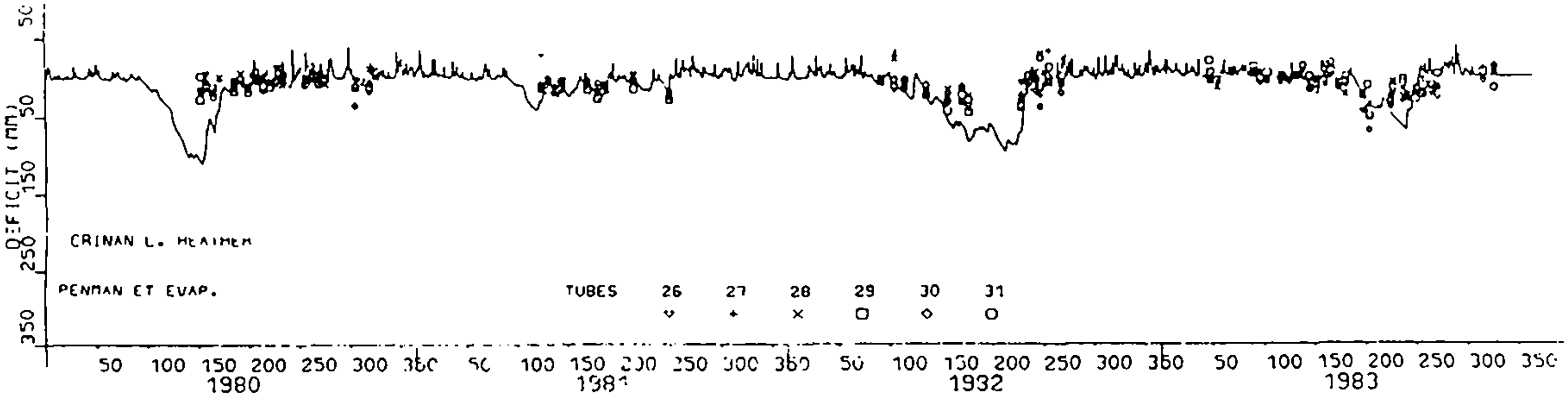

50
50
150
250
350
DEFICIT (mm)
CRINAN L. HEATHER
PENMAN ET EVAP.
TUBES
26 ∇
27 +
28 ×
29 □
30 ◇
31 ○
50 100 150 200 250 300 350
1980
50 100 150 200 250 300 350
1981
50 100 150 200 250 300 350
1982
50 100 150 200 250 300 350
1983

Figure 4b

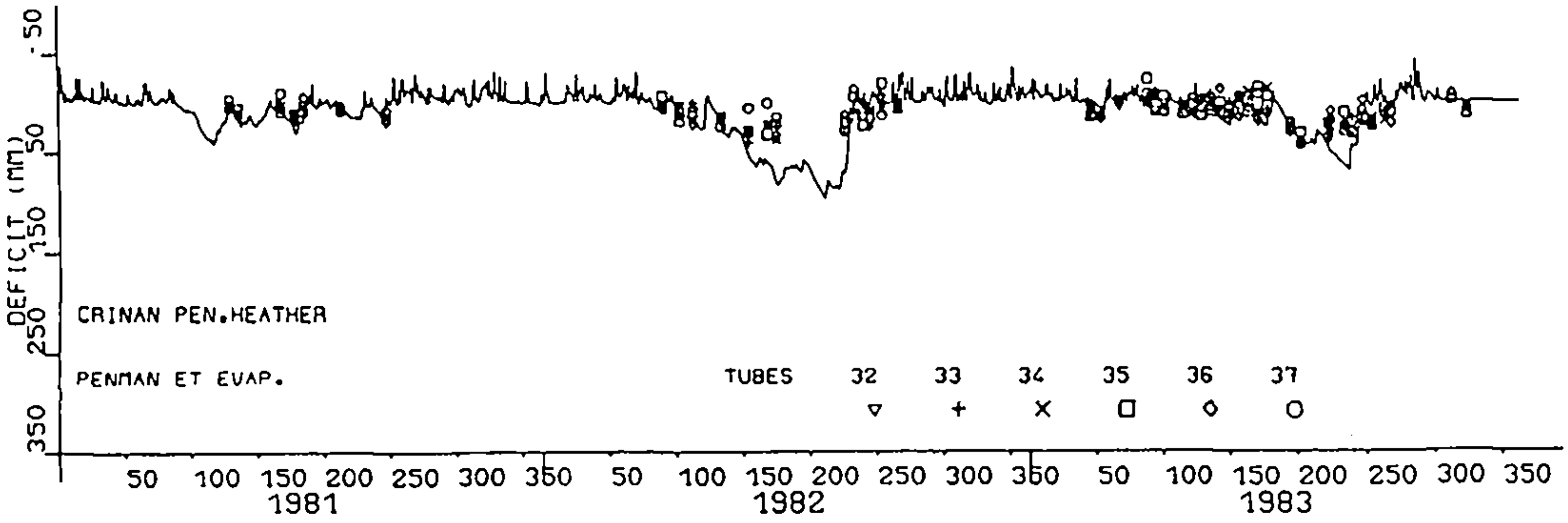
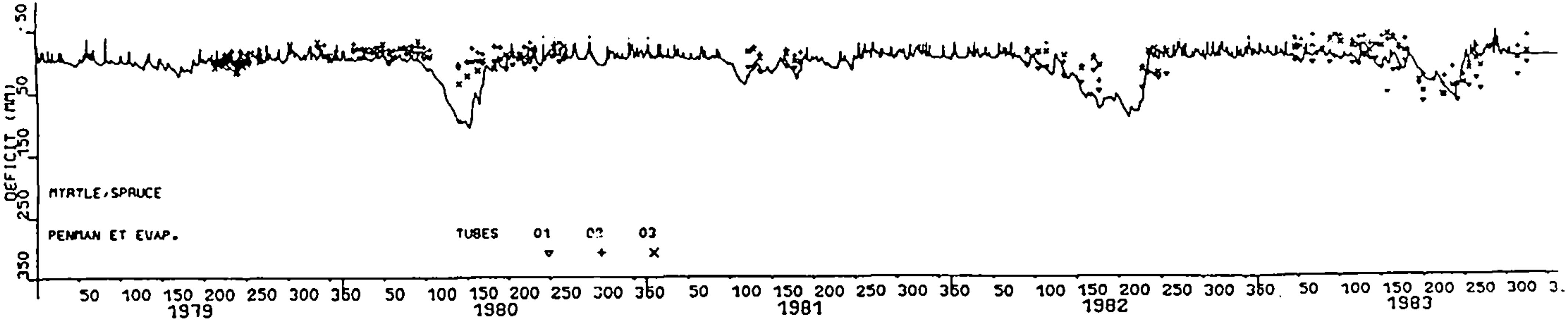

-50
50
150
250
350
DEFICIT (MM)
CRINAN PEN.HEATHER
PENMAN ET EVAP.
TUBES
32 ▽
33 +
34 ×
35 □
36 ◇
37 ○
50 100 150 200 250 300 350
1981
50 100 150 200 250 300 350
1982
50 100 150 200 250 300 350
1983

Figure 4c


DEFICIT (MM)
.50
50
150
250
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MYRTLE/SPRUCE
PENMAN ET EVAP.
TUBES 01 02 03
50 100 150 200 250 300 350
1979
1980
1981
1982
1983

Figure 4d

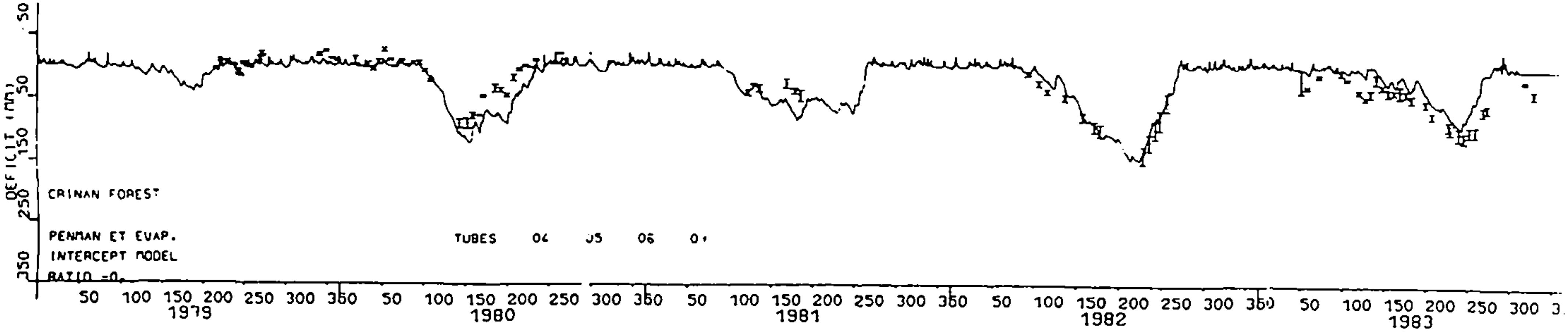
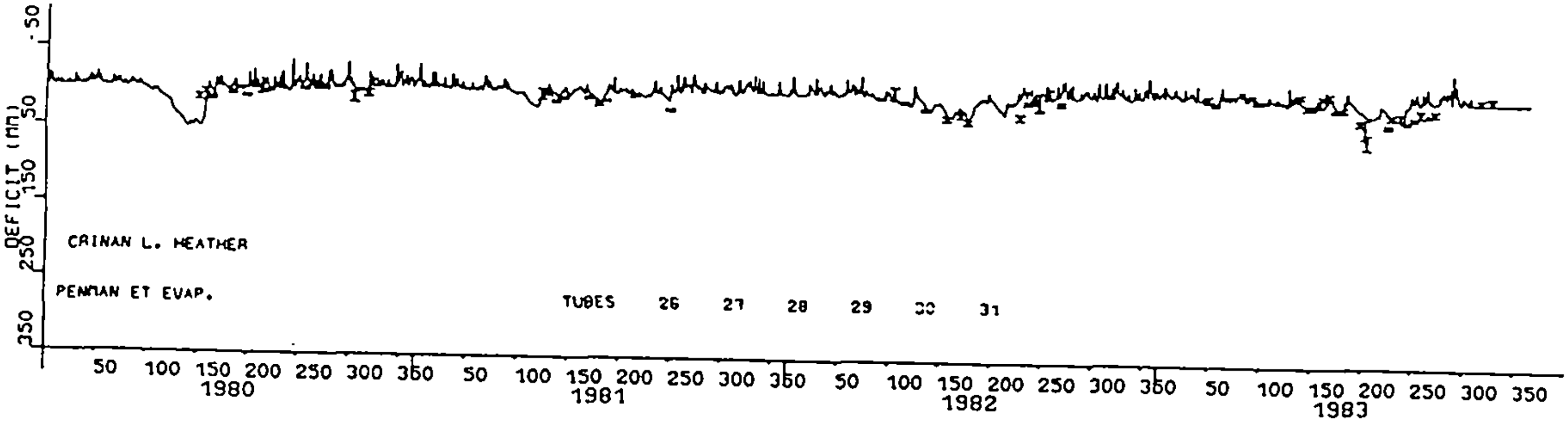

-50
50
150
250
350
DEFICIT (mm)
CRINAN FOREST
PENMAN ET EVAP.
INTERCEPT MODEL
RATIO =0.
TUBES 04 05 06 07
50 100 150 200 250 300 350 50 100 150 200 250 300 350 50 100 150 200 250 300 350 50 100 150 200 250 300 350 50 100 150 200 250 300 3
1979
1980
1981
1982
1983

Figure 5a



-50
50
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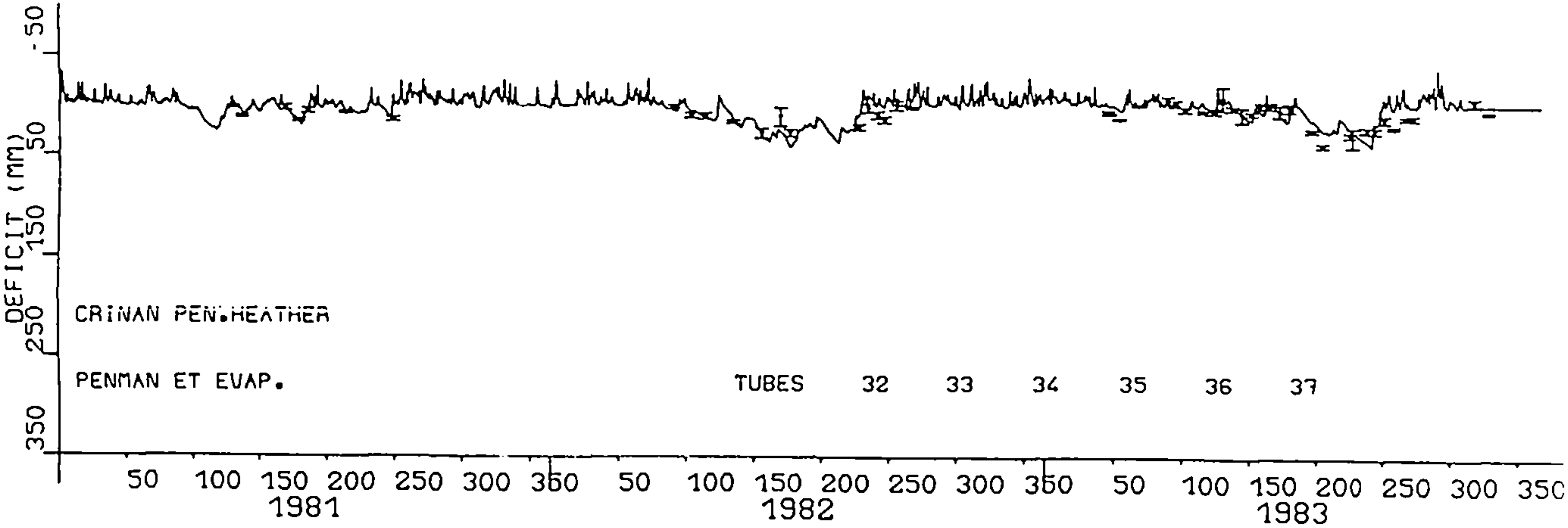
DEFICIT (mm)
CRINAN L. HEATHER
PENMAN ET EVAP.
TUBES 26 27 28 29 30 31
50 100 150 200 250 300 350 50 100 150 200 250 300 350 50 100 150 200 250 300 350 50 100 150 200 250 300 350
1980
1981
1982
1983

Figure 5b


-50
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DEFICIT (MM)
CRINAN PEN.HEATHER
PENMAN ET EVAP.
TUBES
32
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35
36
37
50
100
150
200
250
300
350
1981
1982
1983

Figure 5c

Figure 5c shows that in some years (notably 1980 and 1983) the model fit is displaced from the observations by a constant factor. This may be due to errors in the estimate of rainfall; in a topographically uneven area such as the Knapdale Forest it is possible that there is a large spatial variability in the precipitation from individual storms. (The spatial variability of rainfall at this site will be the subject of further analysis).

## HEATHER INTERCEPTION STUDIES

### *Measurements of the aerodynamic resistance of heather*

Analysis of the results from the fieldwork at Killin and Berner's Heath has continued.

The data from Berner's Heath have yielded a relationship for the windspeed (u) dependence of the aerodynamic resistance $r_a$ viz.

$$r_a = 60u^{-1.1}$$

derived using the rearranged Penman-Monteith equation. An analysis of variance on these data has corroborated the findings of the Killin work that differences between resistances calculated from rain events and artificial spray runs are not significant. The wet-surface weighing lysimeter has now produced the relationships shown in Table 4 for the different sites at which it has been used. (The relationships were determined using the method of unweighted linear regression of ln $(r_a)$ on ln (u)).

It is believed that these relationships reflect the different turbulence regimes at the different sites; the resistances at Killin are lower than at the other two sites for a given windspeed (except at very high windspeeds when the resistances are all about the same) due to the increased turbulence from an uneven mountainous terrain.

A retrospective site survey made in September 1983 has made it possible to analyse the Killin data with respect to the two sites used there. Although there was a considerable difference between the morphology of the heather at the two sites the aerodynamic resistance values were shown by an analysis of variance to be not by rainfall and emptied only by evaporation; overflow from the reservoir represents drainage from the heather.

Table 5 shows the monthly interception ratios estimated by the above model, and the totals of rainfall and drainage for the months March to September 1981. The overall interception ratio for the period was 22.3%.

Unfortunately, because of the limited meteorological data available from this site it was only possible to obtain an interception ratio for the period March to September. However, a seasonal variation is expected and forest interception studies show that the interception ratio during the summer months is greater than during the winter; the annual interception ratio for heather for a complete year is therefore likely to be less than 22.3%.

TABLE 5. Interception ratio estimates for the months March to September 1981.

| Month | Rainfall mm | Drainage mm | Interception Ratio % | Number of raindays |
|---|---|---|---|---|
| March | 98.2 | 87.0 | 11.5 | 7 |
| April | 8.5 | 3.4 | 59.7 | 3 |
| May | 48.1 | 37.3 | 22.3 | 7 |
| June | 14.2 | 10.7 | 24.9 | 4 |
| July | 160.8 | 122.4 | 23.9 | 19 |
| August | 72.4 | 51.1 | 29.4 | 11 |
| September | 89.8 | 70.2 | 21.9 | 6 |
| Overall values | 492.0 | 382.1 | 22.3 | 57 |

## SUMMARY OF FUTURE WORK

The process study components of the upland afforestation project has already provided new information on the evaporative characteristics of heather and of forests in snow conditions and these results are currently being incorporated into models of evaporation.

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# APPENDIX 1

# THE USE OF A "WET-SURFACE" WEIGHING LYSIMETER SYSTEM IN RAINFALL INTERCEPTION STUDIES OF HEATHER (CALLUNA VULGARIS)

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# Abstract

A portable, wet-surface lysimeter system, for measuring the in-situ interception characteristics of short to medium height vegetation is described. The system, comprising an electronic balance and meteorological sensors linked to a microcomputer, has been used successfully at a number of U.K. sites of widely varying topography. In this paper results are presented from two heather sites near Killin in Scotland. The aerodynamic resistance ($r_v$) to the transport of water vapour from a canopy of wet heather was found, from solution of the Penman-Monteith equation, to be $r_v = (20.0 \pm 2.0)\, \bar{u}^{-(0.60 \pm 0.06)}$ (where $\bar{u}$ is the mean windspeed) and the canopy capacity of intercepted water was found to be $(1.4 \pm 0.2)$ mm. A review of methods of determining aerodynamic resistance is also given.

## Introduction

In high rainfall upland areas of Britain evaporation losses from forest are greater than those from rough pasture (Law 1956, Clarke and McCulloch 1975, Calder 1979). The main reason for this is the much higher interception loss rate from trees compared with grass. In Scottish catchments, however, afforestation often occurs at the expense of heather (Calluna vulgaris). The prediction, via a mathematical model, of the effects of afforestation on run-off requires information on the interception characteristics of heather.

The Penman-Monteith equation (Monteith 1965) provides a method for estimating both the transpiration and interception components of the evaporation from vegetation. In conventional notation (see Appendix) the one-dimensional flux density of latent heat from a homogeneous single layer source is

$$\lambda E = \frac{\Delta' H + \rho c_p (q_s - q)/r_{vh}}{\Delta' + c_p (1 + r_s/r_{vh})/\lambda} \qquad \mathrm{W\ m^{-2}}. \qquad (1)$$

The aerodynamic resistance, $r_{vh} = r_v$, to the transport of water vapour from a source to some reference position is given by the "definition" equation:

$$r_v = \frac{\rho (q'_s - q)}{E} \qquad \mathrm{s\ m^{-1}}. \qquad (2)$$

Determination of the evaporation rate from (1) thus requires the measurement of certain meteorological variables and the estimation of the two parameters $r_v$ and $r_s$. When the canopy is dry $r_s$ can be equated to the bulk stomatal resistance, a complex function of past and present environmental and physiological factors. For a partially wet canopy, beans (Impens 1966a), sugar beet (Biscoe 1972) and bracken (Roberts et al. 1980).

Thom (1968) used an artificial bean leaf of thin aluminium covered with filter paper in wind tunnel experiments to measure the transfer coefficients for mass, heat and momentum as functions of leaf angle and windspeed. From these he found $r^{\ell}_{v,b}$ to be independent of leaf angle and given by the empirical relationship

$$r^{\ell}_{v,b} = 1.84 \left(\frac{b}{u}\right)^{\frac{1}{2}} \left(\frac{D}{\nu}\right)^{-2/3}$$

based upon the theory of forced-convection, laminar flow over a thin flat plate. Wind tunnel and assimilation chamber experiments were performed by Landsberg and Ludlow (1970) using real shoots of Sitka spruce and heather coated in a thin layer of gypsum which when wetted acted like the classic blotting paper. They made the measurements necessary to solve (2) and found an $r^{\ell}_{v,b}$ dependence on windspeed for both the spruce and heather.

More recently Grace et al. (1980) developed a "cooling curve" technique using brass replica leaves in a wind tunnel to determine the conductance (inverse of resistance) to heat transport across the leaf boundary layer.

Hunt and Impens (1968) used a technique devised by Impens (1966b) which involved altering the energy balance, by reducing transpiration, of one leaf of an identical pair and then solving the simultaneous energy balance equations for $r^{\ell}_{vh,b}$. A method using the *dynamic* energy balance under unsteady state conditions was described by Linacre (1964, 1967, 1972) which gave an expression relating $r^{\ell}_{vh,b}$ to the rate of change of temperature of leaves abruptly shaded. This method was also used on sunflower leaves in the field by Hunt et al. (1968): $r^{\ell}_{vh,b}$ was also estimated using the canopy to the atmosphere above the canopy, usually to the height z at which meteorological variables are measured. Thus

$$r_v = r'_v + \bar{r}_{v,t} \tag{5}$$

$$= \frac{\bar{r}^{\ell}_v}{n} + \bar{r}_{v,t} \, , \tag{6}$$

since $r'_v$ is the resistance due to n foliage elements, each of effective mean resistance $\bar{r}^{\ell}_v$, connected in parallel. It is therefore possible to form an estimate of $r'_v$ by summing in parallel the measured aerodynamic resistances of individual elements. This, however, only gives an approximate value since it neglects the effects of aerodynamic sheltering. Micrometeorological measurements within a maize canopy have been used in a multilayer, energy-balance model to derive the individual layer $r'_v$ values (see Cowan and Milthorpe 1968, p.185).

Very few direct measurements of $r_v$ for whole vegetation canopies have been made. Recently Johns et al (1981) applied Linacre's method to a canopy of grass turf in an environmental simulation chamber to determine $r_h$. They compared this with values of $r_v$ obtained from (2) and (4) for a wetted canopy ($r_s = 0$) and with $r_v$ calculated from the difference between the total resistance and the surface resistance: small but significant differences were found between $r_h$ and $r_v$ and between values of $r_v$ obtained using the different methods.

The aerodynamic resistance of forests has engaged the attention of several workers. Rutter (1967) measured the evaporation rate of intercepted water by monitoring the weight loss from wet shoots of Scots pine while measuring ambient air temperature and humidity and the difference between air and leaf temperature and was thus able to solve (2). He found a transfer are augmented for momentum transfer by form drag (Chamberlain 1966). Stewart and Thom (1973) used an "excess resistance" term to allow for this and the related difference in source/sink distribution within the canopy. Under certain circumstances the stability factor and excess resistance term may be compensating (Rutter et al 1975) and Eq. (7) could then be used to give $r_v$. However, the method still has the constraint that wind profile measurements from an area of flat, uniform terrain and vegetation are required.

This review, summarised in Table 1, indicates that most work in determining $r_v$ has involved either experiments with artificial leaves in artificial environments, assumptions about the equality of the resistance to transfer of mass, heat and momentum or has stringent constraints in terms of horizontal fetch.

The method presented here allows direct measurement of $r_v$ from (2) and (3) using vegetation samples in situ, and in using (2) makes no assumption about the equality of the resistances to latent and sensible heat transfer. The resistance measured is the mean aerodynamic resistance experienced by water vapour evaporated from the entire wetted surface, diffusing by molecular and eddy diffusion processes to z, the height (1.2m) of the meteorological sensors.

## The wet-surface weighing lysimeter system

### a. Lysimeter design

All lysimeters must be fully representative of the area under study while causing the minimum of disturbance to the environment (Tanner 1967).

|  |  |  |  |
|---|---|---|---|
| $r'_v$ | Multilayer energy balance model | Maize | Cowan and Milthorpe (1968 |
| $r_{vm}$ | Wind profile<br>$r_v = r_m = \frac{1}{uk^2} \ln (\frac{z-d}{z_o})^2$ | Alfalfa | Monteith and Szeicz (1962)<br>van Bavel (1967) |
| $r_v$ | $r_v = \frac{\phi_v}{\phi_m} r_m + r_B$ | Scot's pine Forest | Stewart and Thom (1973) |
| $r_h$ ; $r_v$ | Solved equations (2) and (3) and used Linacre's method. | Turf grass | Johns et al (1981) |
| $r_v$ | Solved equation (2) | Scot's pine Forest | Rutter (1967) |
| $r_v$ | Solved equation (2): obtained E from water balance of canopy | Sitka and Corsican spruce forest | Robins (1974) |
| r | Used optimisation techniques on interception models. | Sitka spruce forest | Calder (1977) |

vegetation sample on top of the balance. A block of expanded polystyrene in the base affords high thermal insulation to eliminate spurious evaporation caused by heat, generated by the balance (about 10 W), being conducted into the sample. The walls of the tray were designed with a tapering cross section, thin at the top, to provide the necessary structural support to the specimen whilst minimising the gap between the specimen and the surroundings.

The meteorological variables monitored are air temperature and wet bulb depression, at 1.2 m above the top of the heather canopy, net-radiation using two Funk radiometers and the wind speed at 2 m above the top of the heather canopy. The canopy surface temperature is also measured using five insulated bead thermistors. These thermistors, approximately the same size (one millimetre diameter) and colour as the heather leaves, were considered to provide a good measurement of the surface temperature. Two soil heat flux plates of the Australian CSIRO pattern placed 1 cm beneath the soil surface are also monitored. A list of all the sensors used is given in Table 2.

### b. Experimental errors

Of the meteorological variables measured, the net-radiation, which was taken as the mean of the readings from the two Funk radiometers, was considered to be accurate to about 5%. Repeated calibrations of the thermometers and thermistors against a standard mercury and glass thermometer indicated an accuracy of 0.1 K.

Problems were experienced with the soil heat flux plates in that there appeared to be some drifting of the zero points. However, soil heat flux beneath heather is only a very small proportion of the total energy exchange at the surface; Oliver (1982) found it to be always less than 5%.

The mean windspeed was measured using a metal-cupped anemometer, with a stalling speed of about 0.25 m $s^{-1}$ and a precision of 0.2 m $s^{-1}$.

As there is no reason to expect correlation of instrumental errors the standard error of $r_v$ was calculated from the standard equation

$$S_{r_v}^2 = \sum_{1}^{x} s_w^2 \left(\frac{\partial r_v}{\partial w}\right)^2 \tag{9}$$

where $S_{r_v}$ is the total standard error, $s_w$ the standard error of the variable w and x is the total number of variables.

### c. Lysimeter operation

The lysimeter was installed in a pit and the levelling frame used to adjust the level and height of the sample so that when in place it was flush with the surrounding vegetation (see Fig. 3). Figure 4 shows a cross-sectional diagram of the lysimeter in situ.

When there had been no rain, or not enough to wet the canopy thoroughly, sprayers were used, both petrol driven and manual pump types, to saturate the vegetation and thermistors on and around the sample and the vegetation beneath the radiometers. If there had been rain then the radiometer domes were carefully wiped dry. Care was taken when setting up the lysimeter and throughout the experiment to ensure that surrounding vegetation was disturbed as little as possible.

The Pet microcomputer interrogated the meteorological sensors at minute intervals and the balance at approximately one second intervals; the mass readings were averaged over the period between sensor scans. The average mass and all the environmental data were then stored for later analysis. The duration of the runs varied but most lasted about two hours with regular inspections of the canopy to observe the degree of wetness.

resistance operating for the first 22 minutes after the canopy has been fully wetted; an interval during which, for all the windspeeds observed, the canopy remained wet.

## Sites and samples.

The results considered in this paper were obtained at two sites near Killin, Scotland (O.S.ref.NN 617314) over the period 31 August 1981 to 17 September 1981. The sites (100m apart) were at an altitude of 450 m on a small peat covered plateau (approximately 100 m x 200 m) on a north facing hillside two kilometres south of Loch Tay. The vegetation on the plateau and surrounding area was predominantly heather (approximately 60% - 70%) but with patches of grass and other short upland species: the two sites selected (now designated A and B) were within stands of almost pure heather.

Representative samples of heather together with the top 10 cm of peat were cut from the two sites. Few roots were observed below 10 cm and cutting at this depth resulted in no observable deleterious effects upon the samples; neither did the cutting appear to affect the long term survival of the heather which was observed to be in a healthy condition two years later. The results of a survey of the sites are shown in Table 3.

At each site the height of the heather was found by making 60 measurements at half-metre intervals along two transects at right angles. Six representative 0.25 $m^2$ samples of heather were cut at ground level during a rainstorm and weighed while wet and again when dry; a canopy capacity was calculated from these weights. (While some water must have dripped off during cutting there was no time for drainage and the canopy capacity calculated is likely to be an upper value). Sub-samples were taken and from these the average length and areal density of the stems were calculated. The Leaf Area Index (LAI), on a projected area basis, was also measured using a leaf area meter (Model LI-3100, LR-COR Ltd., Lincoln, Nebraska, USA), and the stem surface area calculated from measurements of the mean dimensions of the stems and branches.

The results in Table 3 support visual observation that the heather at site A was older, in the mature phase, and more variable than at site B where the heather was considered to be in the late building phase (see Gimingham 1972 for details of classification).

## Results and discussion

### a. Windspeed dependence

Table 4 is a summary of 35 runs in order of increasing windspeed. Resistances ($r_v$) were calculated using data averaged only over the period when the heather was wet. (As the canopy dries out so $r_s$ will become significant and the resistance measured by the wet-surface weighing lysimeter will be some complicated function of $r_v$ and $r_s$). Values of $r_v$ calculated using (2) and (3) are plotted against mean windspeed in Fig. 5 and Fig. 6 respectively.

A weighted linear regression analysis of $\ell n(r_v)$ versus $\ell n(\bar{u})$ (see Fig. 7) was performed and the results are given in Table 5. Unfortunately it was not possible to obtain a well defined relationship between resistances calculated from (3) and windspeed using only values derived from rain events

## Table 4

Mean values of $r_v$, calculated from (2) and (3) over a range of mean windspeeds from data collected near Killin, Scotland for the period 31 Aug to 17 Sept 1981.

| Type of run * | Site | $r_v$ and standard error calculated from (3) | | $r_v$ and standard error calculated from (2) | | Mean windspeed $\bar{u}$ at two metres. Standard error is 0.1 m $s^{-1}$. |
|---|---|---|---|---|---|---|
| | | $(r_v \pm S_{r_v})$ s $m^{-1}$ | | $(r_v \pm S_{r_v})$ s $m^{-1}$ | | $\bar{u}$ m $s^{-1}$ |
| R | B | 5.9 | 8.4 | 56.8 | 9.3 | 0.7 |
| S | B | 20.3 | 2.0 | 43.8 | 2.5 | 0.9 |
| S | B | 17.0 | 0.9 | 26.0 | 1.5 | 1.1 |
| S | B | 12.7 | 0.7 | 25.6 | 2.0 | 1.2 |
| S | B | 16.8 | 0.7 | 26.3 | 1.7 | 1.2 |
| S | A | 15.0 | 1.0 | 17.6 | 1.6 | 1.7 |
| S | A | 18.2 | 1.3 | 19.0 | 1.5 | 2.1 |
| S | A | 21.0 | 3.5 | 20.7 | 1.6 | 2.1 |
| S | B | 17.4 | 1.2 | 18.5 | 1.8 | 2.2 |
| S | B | 12.5 | 0.7 | 13.2 | 1.3 | 2.4 |
| S | B | 13.1 | 0.7 | 16.8 | 1.4 | 2.7 |
| S | B | 7.7 | 1.3 | 4.4 | 2.3 | 3.2 |
| R | B | 5.0 | 0.4 | 9.3 | 1.1 | 3.5 |
| R | A | 9.4 | 4.9 | 11.4 | 4.0 | 3.5 |
| R | B | 13.5 | 1.2 | 16.5 | 1.5 | 3.6 |
| S | B | 10.5 | 0.5 | 10.1 | 1.3 | 4.0 |
| S | B | 7.2 | 0.3 | 12.7 | 1.6 | 4.2 |
| R | A | 12.3 | 2.3 | 8.1 | 1.4 | 4.6 |
| S | B | 6.0 | 0.6 | 8.7 | 0.9 | 4.7 |
| R | B | 11.1 | 0.6 | 14.4 | 1.6 | 4.8 |
| R | A | 9.1 | 1.9 | 11.9 | 1.9 | 5.1 |
| S | B | 5.1 | 0.3 | 6.3 | 0.5 | 5.1 |

systematic difference is a systematic error in surface temperature which is only used in (2). This error could arise because of either spatial variation in canopy temperature or bias in the sensors themselves due to differences between the surface characteristics of the vegetation and the sensors. Accurate measurement of the surface temperature is crucial to the calculation of resistances using (2); sensitivity analysis shows that under virtually all meteorological conditions the equation is most sensitive to this variable and that this variable contributes the major part of the error in the calculated resistance.

Sensitivity analysis also shows that when the atmosphere approaches saturation, large errors will be introduced into the calculation of $r_v$ from (3). The denominator of (3), being a difference term, gives rise, when the atmosphere approaches saturation, to very large errors in $r_v$, see for example the first value in the third column of Table 4. The method then becomes grossly inaccurate.

### c. Comparison or $r_v$ calculated from data collected after spraying and after rainfall.

To obtain data without having to rely upon rainfall events much use was made of the sprayers. However, it cannot immediately be assumed that the resistances derived from these data will be the same as the values which would be obtained following natural rainfall for the same windspeed. The creation of a small area of artificially wet vegetation in the midst of an expanse of dry or less wet vegetation gives rise to three-dimensional vapour fluxes whereas $r_v$ calculated using (2) and (3) is the aerodynamic resistance to vapour transport in the vertical direction only. In an attempt to produce only one-dimensional fluxes from the sample the heather around the lysimeter was sprayed as well as the sample itself.

The results of the weighted linear regression analysis (see Table 5) show no difference between the $r_v$s calculated from data collected after spray and rain events. However, the errors associated with the regression parameters for resistances calculated from (3) are very large and the results of this regression cannot be used to resolve if there is a systematic difference between the two data sets. A further investigation was undertaken using analysis of variance to remove this uncertainty.

To implement the standard analysis of variance technique it was necessary to reject the one point, discussed in section 5b, which had an anomalously large error. The results of the analysis then revealed that there was a difference, but of only small significance, between the two subsets of resistances calculated from (3) (the significance level calculated for an $F_{2,30}$ distribution was 3.7 per cent). For the subsets of resistances calculated from (2) there was no significant difference (the significance level for an $F_{2,31}$ distribution was 18.9 per cent). There is, therefore, little evidence to suggest that the spray technique produces significantly different results to those produced under natural rain conditions; preliminary analysis of measurements from two other sites also support this view.

### d. Comparison of $r_v$ calculated from data collected at the different sites.

The results in Table 3 demonstrate that there are some differences in the characteristics of the heather growing at the two sites. These differences, however, are not reflected in the resistances: an analysis of variance of the resistances pertaining to the two sites indicated that there was no significant difference between them, for either of the subsets calculated using equations (2) and (3).

### e. Comparison with other work

The values of $r_v$ presented here are believed to be the first published for the aerodynamic resistance to water vapour transfer from a natural heather canopy. Values of $r^{\ell}_{v,b}$ for heather shoots in an assimilation chamber have been published (Landsberg and Ludlow 1970) but a direct comparison with

## Conclusions

The wet-surface weighing lysimeter system has proved to be a reliable and practical method of estimating the aerodynamic resistance from a wet canopy in the field.

No major differences were found between the $r_v$s calculated from artificial spray and rain event runs, hence the use of sprayers when there is insufficient rain to saturate the canopy appears to be justified.

A correlation between $r_v$ and windspeed has been found which took the form $r_v = Mu^x$ where $M = 20.0 \pm 2.0$ and $x = 0.60 \pm 0.06$ for values calculated from the rearranged Penman-Monteith equation (3), and $M = 32.6 \pm 2$ and $x = -0.77 \pm 0.05$ for values calculated from the definition equation (2).

An upper value for the storage capacity of heather was determined as (1.4 ± 0.2) mm.

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| | | |
|---|---|---|
| $r_B$ | Excess resistance | $s\ m^{-1}$ |
| $r_s$ | Surface resistance of vegetation to water vapour transport | $s\ m^{-1}$ |
| $r'_v$ | Bulk effective resistance to water vapour between the foliage and the air within a canopy of vegetation | $s\ m^{-1}$ |
| $\bar{r}_{v,t}$ | Mean resistance to water vapour between air within a canopy of vegetation and the atmosphere above the canopy | $s\ m^{-1}$ |
| $R_n$ | Net-radiation flux density | $W\ m^{-2}$ |
| $T$ | Air temperature | K |
| $T_s$ | Surface temperature of vegetation | K |
| $\bar{u}$ | Mean windspeed | $m\ s^{-1}$ |
| $u_*$ | Friction velocity | $m\ s^{-1}$ |
| $z$ | Vertical distance: height at which meteorological variables are measured | m |
| $z_o$ | Roughness length | m |
| $\Delta'$ | Gradient of the saturated specific humidity versus temperature curve | $kg\ kg^{-1}K^{-1}$ |
| | Latent heat of vaporisation of water | $J\ kg^{-1}$ |
| | Molecular diffusivity of momentum in air | $m^2s^{-1}$ |
| [illegible] | Density of moist air | $kg\ m^{-3}$ |
| $\phi_m$ | Stability function for momentum exchange | |
| $\phi_v$ | Stability function for vapour exchange | |

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linear regression analysis, to the values of $r_v$ calculated from (2).

Fig. 6 Bulk aerodynamic resistance ($r_v$) to water vapour transport from a canopy of wet heather to a height of 1.2m above the top of the canopy, calculated from (3), plotted against the mean windspeed ($\bar{u}$) measured at 2m above the top of the canopy. The symbols used are as in Fig. 5. The shaded area represents the range of the function, $r_v = (20.0 \pm 2.0)\bar{u}^{-(0.60 \pm 0.06)}$ fitted, using a weighted linear regression analysis, to the values of $r_v$ calculated from (3).

Fig. 7. The natural logarithm of the aerodynamic resistance, $r_v$, calculated from (2) and (3) plotted against the natural logarithm of the mean windspeed.

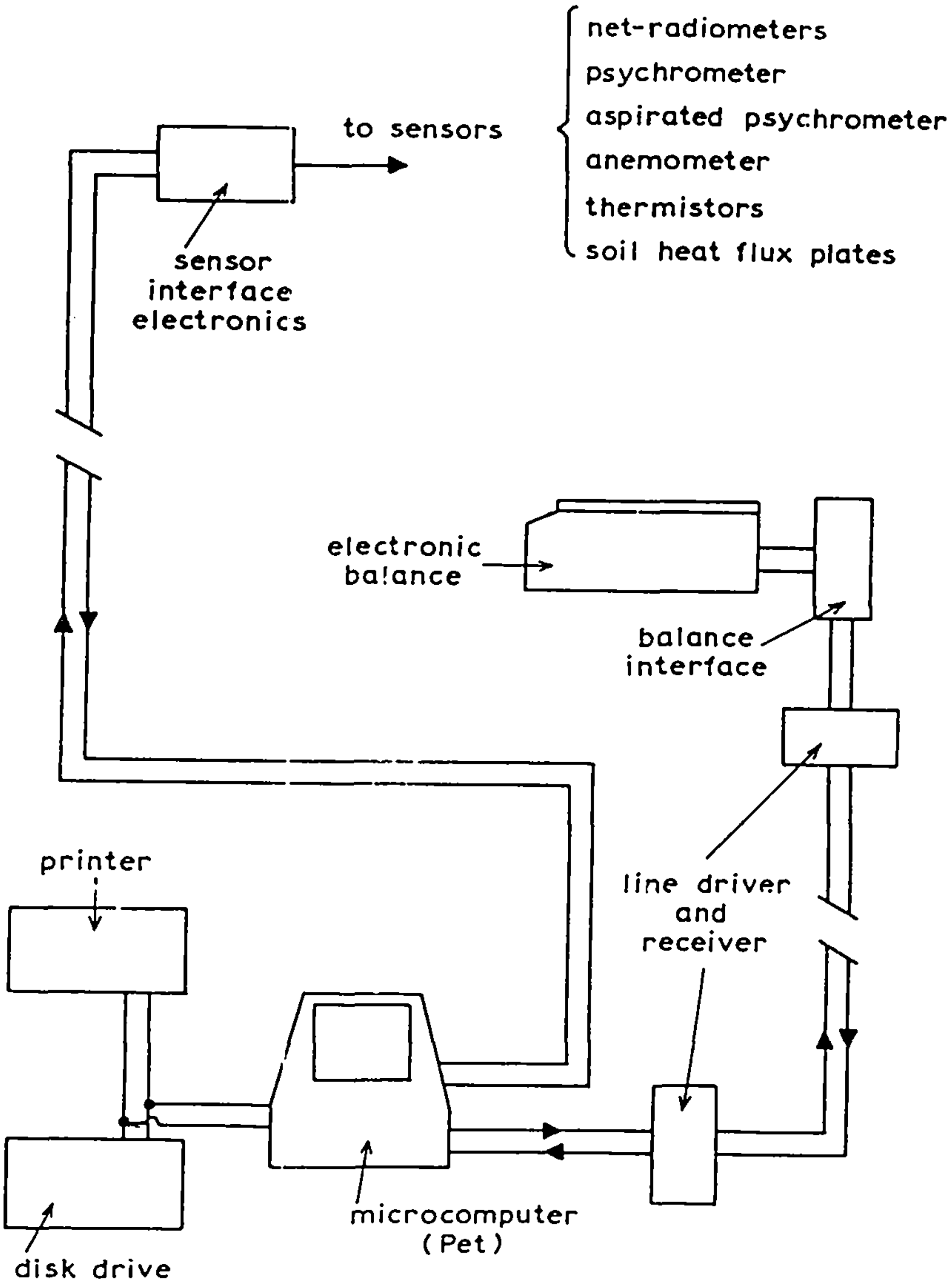
+ $r_v$ calculated from (2) using data collected after spraying the sample.

x $r_v$ calculated from (2) using data collected after rainfall.

○ $r_v$ calculated from (3) using data collected after rainfall.

● $r_v$ calculated from (3) using data collected after spraying the sample.

Fig. 1.



net-radiometers
psychrometer
aspirated psychrometer
anemometer
thermistors
soil heat flux plates
to sensors
sensor interface electronics
electronic balance
balance interface
line driver and receiver
printer
disk drive
microcomputer (Pet)

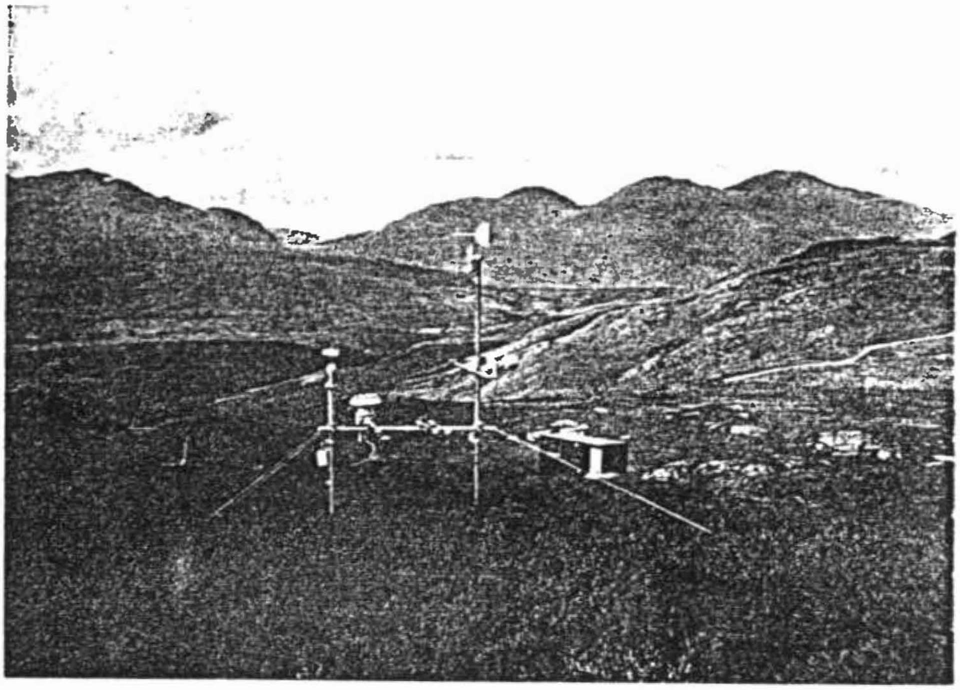


Fig. 2.

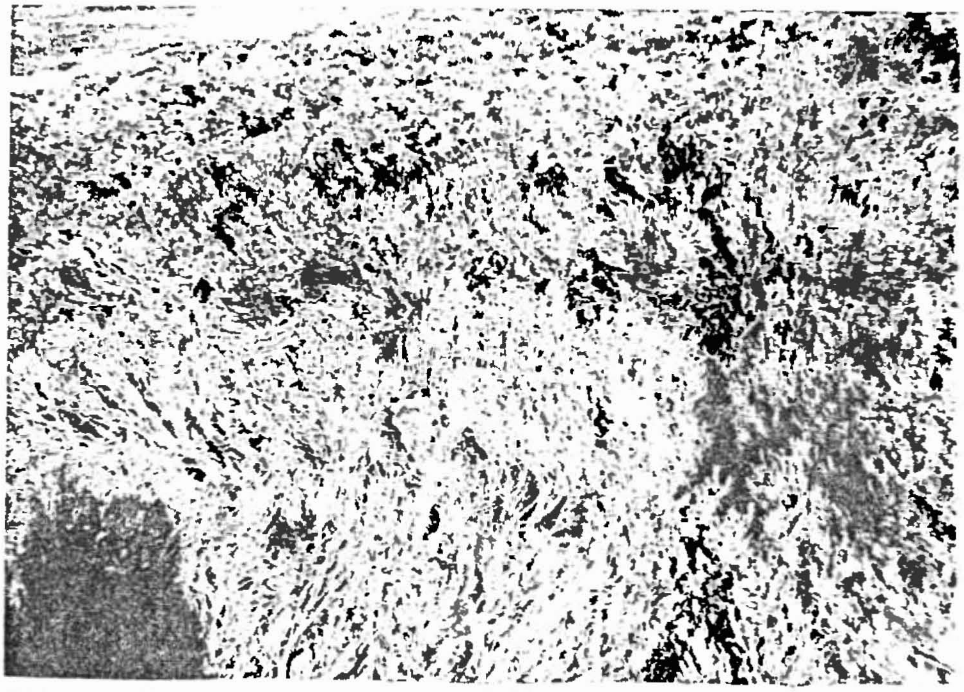


Fig. 3.

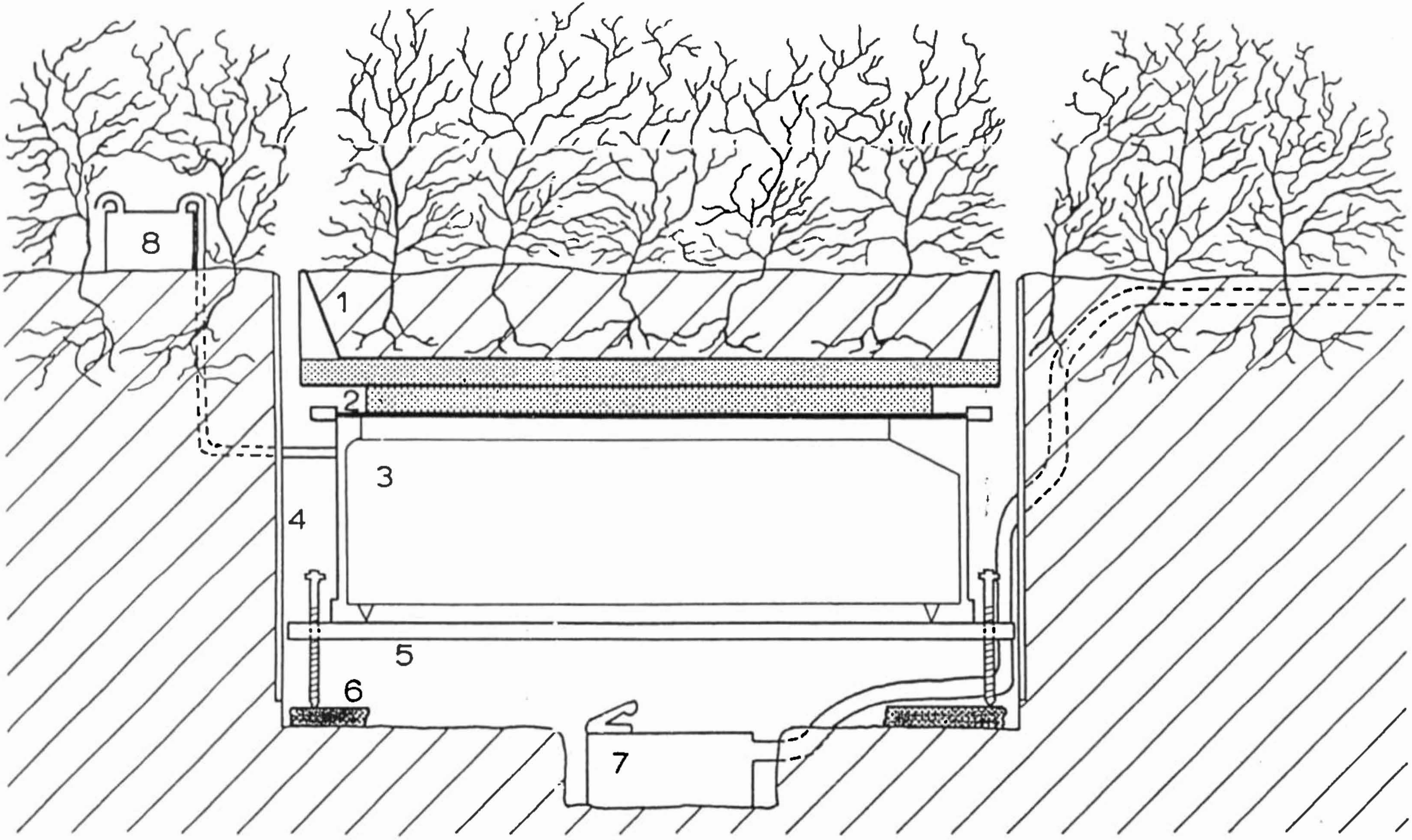


Fig. 4.

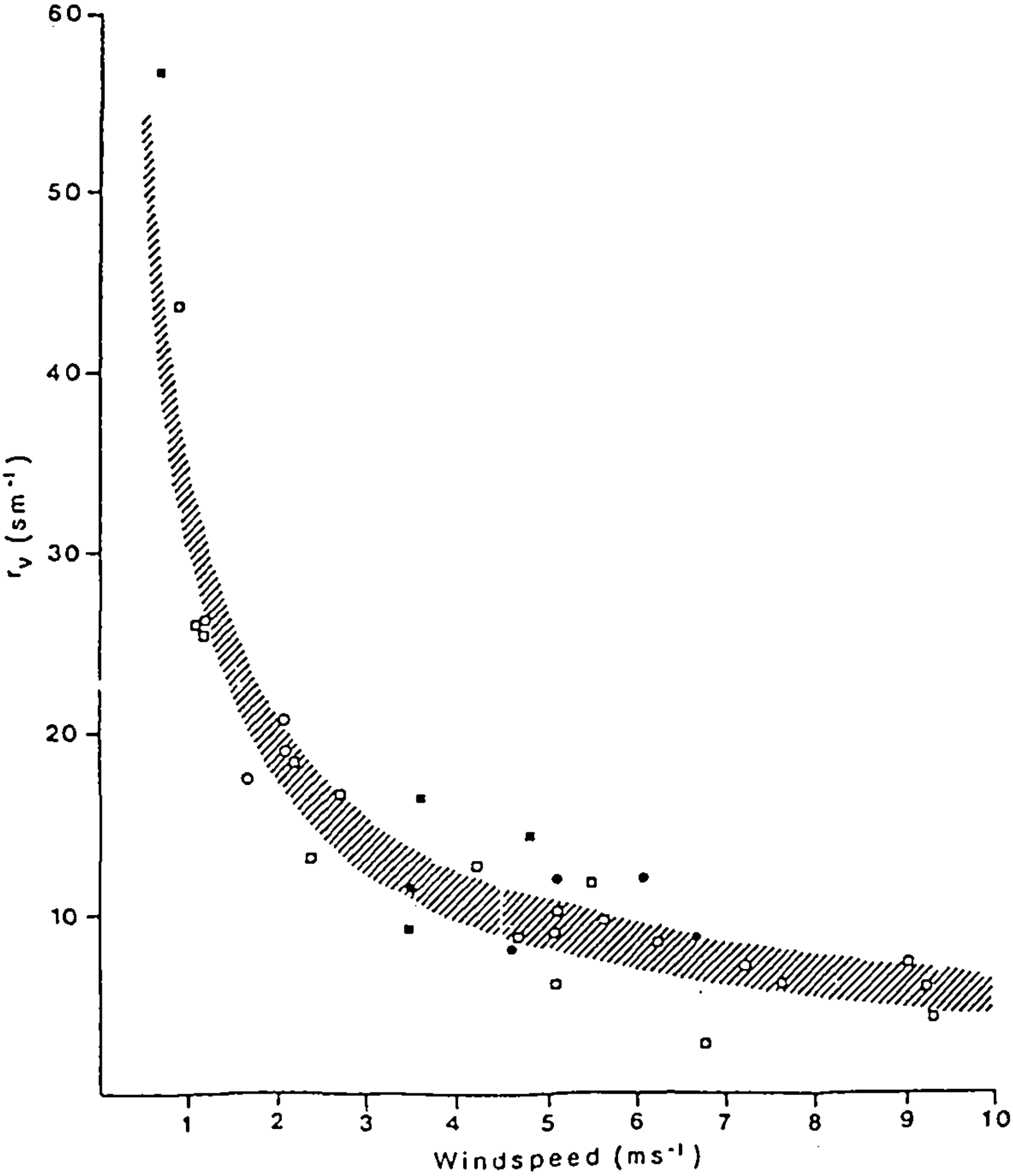


Fig. 5

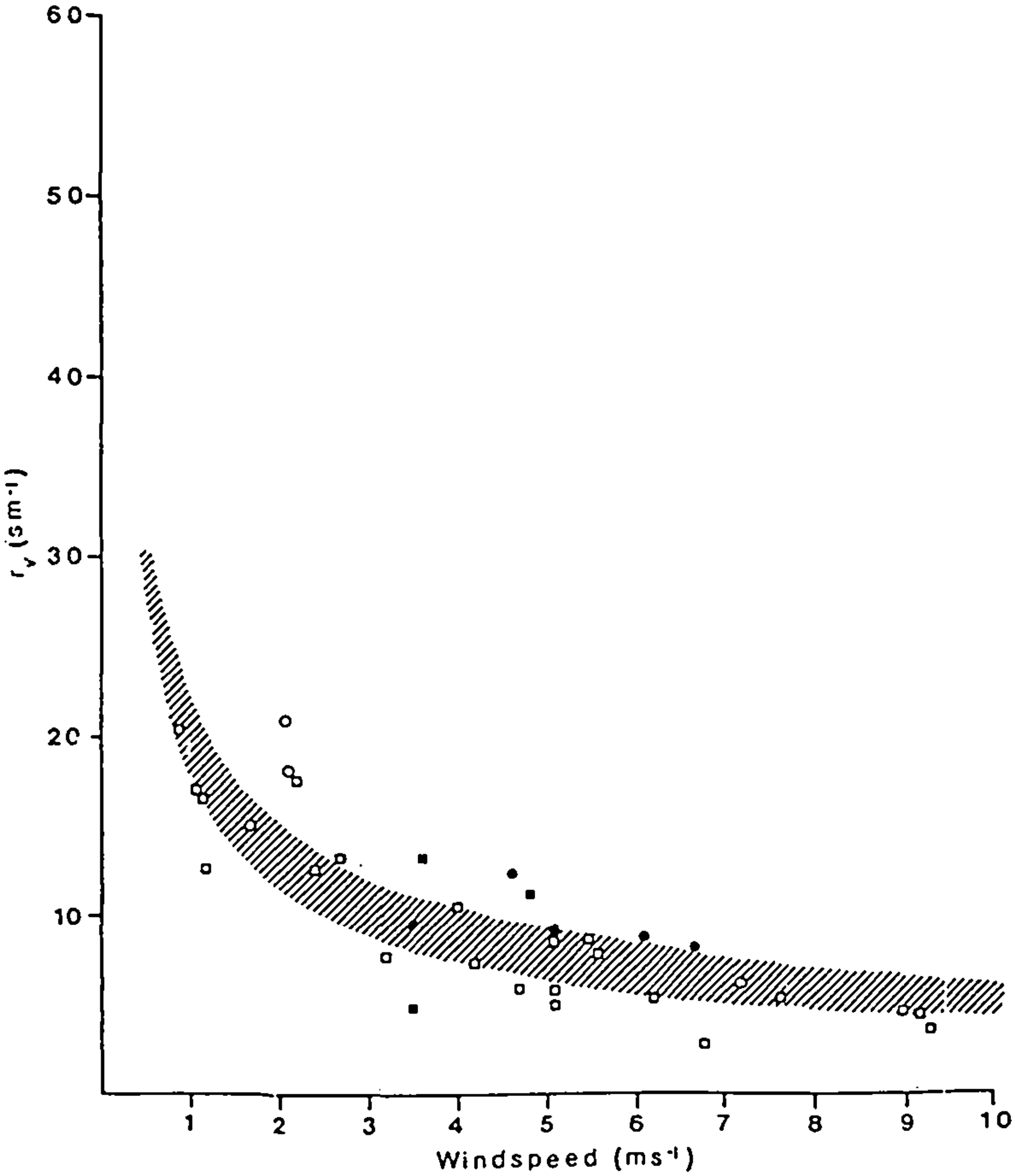


Fig.6

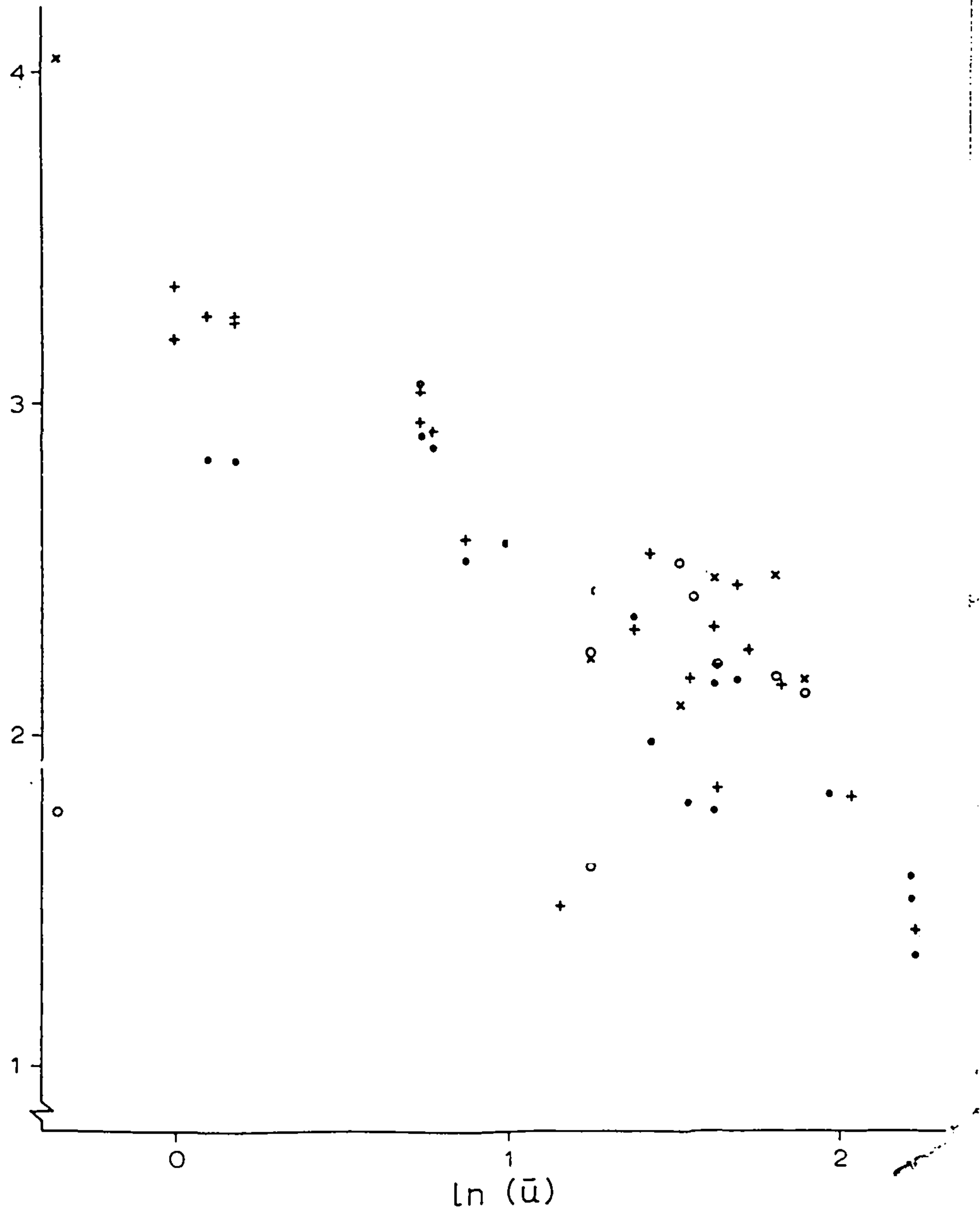


Fig.7