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BALQUHIDDER CATCHMENT STUDIES
PROGRESS REPORT 84/85

UPLAND AFFORESTATION AND
WATER RESOURCES

BY:

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**UPLAND AFFORESTATION AND WATER
RESOURCES**

Progress Report 1984/85

on

The Balquhidder Catchment Studies

and

The Physical Process Studies

Progress Report on the Balquhidder Catchment Studies

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INTRODUCTION

The Plynlimon study has shown how afforestation of grassland catchments on the upland western margin results in higher evapotranspiration losses and reduced streamflow. These results are not directly transferrable to areas where the vegetation being replaced is heather and bracken or where colder winters mean significant snow accumulation. Such conditions prevail in parts of Highland Scotland where afforestation is in progress or is being considered. The Balquhidder catchments have been instrumented as a means of quantifying differences in hydrological response between forested and non-forested areas in such conditions. These catchments also provide an opportunity to study the effects of the clear-felling and initial planting phases of forestry within a reasonable time span.

Starting in 1981 instrument networks to yield estimates of areal rainfall and snowfall, of streamflow and sediment loads and of the meteorological variables were designed and installed. The rugged terrain and difficult climatic conditions caused a few problems and delays at both the design and installation stages but the bulk of the instrumentation was operational by mid 1982 and the final streamflow structure was completed in June 1983.

With the networks and the data collection methods firmly established and producing a steady flow of data, the emphasis has moved towards detailed examination and assessment. To achieve accurate quantification of the differences in water use between the Kirkton catchment, 40% of which is under mature forest, and the heather/bracken/grass covered Monacyhle catchment (fig. 1) with its separately gauged upper catchment each term in the water balance must be determined to a much higher accuracy than would be acceptable in normal operational work. As an indication of the orders of magnitude, annual precipitation in the area is some 2000 mm and streamflow is expected to be in the range 1500-1700 mm. To identify water use differences of say, 25% will require an accuracy of better than 5% in both precipitation and streamflow.

Consequently much of the effort during the year under review has been devoted to assessment of instrument performance. Much effort has also gone into devising optimum methods of combining data from the storage precipitation gauges, read of necessity at differing times, with that from the recording gauges to achieve accurate estimates of the spatial and temporal distribution within the catchments. Details of progress achieved in these and other aspects of the study are given in the following sections.

PRECIPITATION

The types of gauge used for precipitation measurement and the network designs for each catchment have been described in detail in previous reports. Briefly, the network on Monachyle comprises 11 ground level storage gauges with recording gauges, also at ground level, attached to each of the two Automatic Weather Stations (AWS) and one additional recording gauge. That on the Kirkton comprises 11 sites of which 6 are above the tree line and 5 are in clearings in the forest. All sites have ground level storage gauges and the 5 in the forest also have tall (1 m) snow gauges. These sites now have standard 5 inch gauges as well. One recording gauge is attached to the AWS in the catchment and a second to the AWS at the Tulloch Farm meteorological site (fig. 1), where examples of each type of gauge are installed. Sparse networks of snow poles and of snow melt gauges are also deployed, one of the latter in each catchment being of the recording type.

2.1 Gauge Performance

The ground level gauges have operated successfully during rainfall periods but, as was expected, not so well during periods of mixed precipitation. These gauges are mounted with their rims parallel to the ground and the readings corrected to give the equivalent input on a horizontal surface. Their readings are disregarded during periods of significant snow accumulation.

The tall snow gauges were designed to provide measurements of precipitation input in such periods and sited in the forest clearings where adverse aerodynamic effects and lateral movement of snow would be minimal. During the snow period in January and February 1984 snow cores were taken at the snow gauge sites after each fresh accumulation. The results showed that the water equivalents of the snow cores were within 10% of the snow gauge catch, confirming that the gauges were operating successfully in these conditions.

	A1W	A2W	A3W	A3Y	B3W
Jan	113.9	106.2	117.6	82.9	113.8
Feb			76.7	88.2	103.3
March	95.1	84.1	76.7	88.3	82.8
April	87.5	81.4	79.0	76.1	72.8
May	85.8	88.4	98.4	84.9	83.8
June	80.7	76.8	65.1	79.6	82.8
July	79.3	52.0	62.7	69.9	77.4
Aug	79.4	34.9	59.1	62.8	65.3
Sept	63.7	85.5	96.4	89.2	98.1
Oct		113.5	101.3	93.3	92.3
Nov	111.1	107.4	121.4	106.0	108.3
Dec	125.2	117.1	124.5	90.1	111.8
Total	100.6	97.7	100.6	89.7	99.7

Table 1. Mean values of snow gauge catch as a percentage of ground level gauge catch at the Kirkton forest clearing sites. Snow accumulation periods are excluded.

The snow gauges in the Kirkton forest clearings are read throughout the year. This is done to assess their performance in all conditions. The results of this ongoing comparison with the ground level gauges are summarised in table 1. For each site mean percentage catch of the snow gauge relative to the ground level has been calculated. Periods with mixed precipitation are included but snow accumulation periods have been omitted.

The reduced summer catch of the snow gauge, commented on in the 1982/83 report, is due to evaporation from the inside of the collecting tube and can be reduced by the addition of a funnel at the top end. The apparent overcatch in winter at most sites is less easy to explain.

To investigate this discrepancy each forest site has been equipped with a standard 5 inch raingauge. The results of the comparison between them and the ground level gauges in rain and mixed precipitation periods are summarised in table 2 and Figure 2.

Site	$\frac{\text{Standard}}{\text{ground level}} \times 100$
Tulloch Farm	98.1
A1W	98.3
A2W	96.8
A3W	94.8
A3Y	94.4
B3W	94.0

Table 2. Mean values of standard gauge catch as a percentage of ground level gauge catch for the Kirkton forest clearing sites, exlcuding snow accumulation periods.

Figures for the Tulloch Farm site are also included. The agreement is generally good although the relative catch of the standard gauge decreases with increasing exposure and altitude of the sites. This undercatch of the standard gauges which is a wind related phenomenon is not extreme compared to other sites. Undercatches of 16% have been recorded on exposed Welsh hillsides (Harrison and Newson, 1978). Thus it would appear that the forest sites experience reasonably sheltered conditions.

This comparison suggests therefore that the winter discrepancy between the ground level and snow gauges is a factor relating to the latter. Pending further investigation however, the preferred estimates from these sites will be:

(a) those from the ground level gauges during rainfall periods,
(b) those from the standard gauges during mixed precipitation periods,
(c) those from the snow gauges during snow accumulation periods.

2.2 The Networks

The main object of the networks is to determine the spatial variation of precipitation within the catchments. Their design ensured that each major domain of altitude, location, aspect and slope was sampled. With the volume of data now available it becomes possible to start constructing models of spatial variation which can be used to estimate catchment areal means.

2.2.1 Time Distribution

Before any such analysis can be undertaken the first step is to reduce the data from all gauges to a common time base. Because the networks are operated by one man it has been necessary to devise a system which will accept readings taken at any time on any day during the month. A computer programme has been written that distributes each gauge total into hourly values by multiplying proportionally the hourly values from the nearest recording gauge. The results are then summed to give the total in any required interval.

A hierarchal definition of "nearest" has been incorporated in which map distance is taken as the main criterion. However if the distances to two recording gauges are within 20% the one nearest in altitude is preferred. The system allows for progressive ranking of all five recording gauges within the networks so that the "best" operational recorder will be used.

In this difficult environment quality control of both manual and automatically recorded readings is essential. Because of their key role in the time distribution programme the recording gauge data are checked manually against their accompanying storage gauges for volume and against the AWS weather data for timing before being used in the programme. Some indication of the validity of the storage gauge readings is obtained from the snow diary but final quality control on these has to be performed after time distribution.

The programme described is able to cope with time distribution during rainfall periods when at least some of the recording gauges were operational. For periods when this was not the case a second programme has been written which uses the daily observations at Tulloch Farm meteorological site as the means of time distribution. Obviously this precludes flood hydrograph studies for such periods but makes the data available for any analyses requiring daily or longer time intervals. This programme can be used also to time distribute snow inputs during the periods when only the snow or standard gauge readings from the forest sites in Kirkton are valid. These two programmes will yield data, time distributed on either an hourly or a daily basis, for all sites during rainfall periods and for the forest sites during snow periods from April 1982 onwards. To cover gaps in the recording gauge data from summer 1981 until the Tulloch Farm site became operational in April 1982 daily time distribution will be computed from the nearest available site conforming to Met. Office standards.

Outputs from the first run of the "hourly" programme, accumulated into monthly totals, are shown in in table 3. Gaps appear against

MONTH	YEAR	MONACHYLE GROUND LEVELS										
		A1X	A3X	B1W	B1X	B1Y	B2W	B2X	B2Z	B3Z	C2W	C2Z
JUN	1981											
JUL												
AUG												
SEP												
OCT												
NOV		384.7	402.0	391.4		357.9	401.4	436.5	285.2	371.6	520.8	366.7
DEC												
JAN	1982											
FEB												
MAR		362.9	438.4	513.6		368.9	346.9	455.8	294.6	365.3		373.9
APR		•	•	•	•	•	•	•	•	•		•
MAY		•	•	•	•	•	•	•	•	•	144.4•	•
JUN		95.4	103.6	95.7	103.0	102.1	119.3	95.9	97.6	99.6	114.7	107.7
JUL		50.1	51.0	52.0	53.8	50.2	60.6	51.5	51.2	53.7	55.2	57.0
AUG		215.9	274.1	290.3	280.6	239.4	292.3	270.3	209.5	251.7	316.1	253.5
SEP		•	•	455.1	447.2	•	•	486.7	•	•	•	•
OCT		•	•	328.6		•	•	344.2	•	•		
NOV		392.5	402.3			391.4			232.3	397.5		
DEC		373.5	410.2			351.8			301.8	353.6		
JAN	1983		639.1			554.8			421.3	524.2		
FEB			68.0			78.7			91.9	76.5		
MAR		268.1	268.4	305.9	399.3	225.3•	504.4	318.2	197.3	248.5		309.4
APR		74.2	76.4	74.2	75.6	72.2	76.3	86.4	76.5	72.2		73.9
MAY		179.4	188.7	173.0	176.7	177.9	180.5	189.0	192.4	•		179.5
JUN		86.1	88.6	83.1	83.8	74.6	86.9	80.9	74.1	•		86.5
JUL		19.8	23.1	22.9	22.6	17.7	24.3	20.9	17.1	•	30.2	20.8
AUG		51.9	57.2	44.4	44.5	43.1	44.2	42.8	41.3	48.2	60.8	62.4
SEP		362.3	380.2	365.0	351.3	343.1	364.1	354.3	309.1	368.6	403.8	393.5
OCT		452.7	484.6	522.2	495.1	350.9	493.0	487.5	356.4•	468.3	541.6	466.4
NOV												
DEC												

Table 3a. *Provisional monthly rainfall totals (mm) for the Monachyle storage gauges.*

MONTH	YEAR	KIRKTON GROUND LEVELS											
		A1W	A1W	A3W	A3Y	B3W	B3Y	C1W	C3W	C3Y	D2Y	D2Y	TF
JUN	1981												
JUL													
AUG													
SEP													
OCT													
NOV													
DEC					376.0	401.7							
JAN	1982												
FEB					261.5	262.4		274.2	274.8				
MAR				446.1		381.2	371.7	386.2	279.0		300.0		
APR				•	•	•	•	•	•		•		
MAY				•	•	•	•	•	•	•	•	•	
JUN				•	•	•	•	•	107.1	•	•	•	
JUL				51.3	53.5	51.3	32.2	50.0	48.1	38.7	37.3	42.9	
AUG				198.1	194.9	209.7	195.4	216.7	203.9	179.1	210.2	224.0	
SEP				19.6	21.2	20.3	237.4	136.8	142.1	173.4	210.0	235.8	
OCT					225.1	250.8	111.6	165.5	199.9	61.2	88.1	94.3	
NOV				352.1	311.4	355.0	93.2	361.1	477.5	52.6			
DEC				300.0	274.6	276.1	281.9	427.2	570.9	314.2			
JAN	1983			441.7	468.0	526.3	463.0	558.0	627.7	419.3			
FEB				97.0	30.4•	51.1	58.9	55.5	65.0	39.0			
MAR				214.5			260.4	318.0	275.1	166.3	275.2	238.5	
APR		80.6	87.8	75.7	82.3	91.6	101.7	90.3	98.9	88.7	122.2	183.6•	
MAY		148.9	172.1	181.2	171.8	189.0	158.5	172.5	177.6	156.6	161.1	158.7	
JUN		71.1	58.2	28.0•	40.9•	30.9•	66.5	63.4	71.0	64.5	87.4	86.5	
JUL		21.0	26.0	41.3	24.5	36.8	36.0	20.2	20.2	33.9	26.0	38.4	
AUG		42.0	50.3	35.7	41.5	43.0	49.2	53.4	51.2	41.3	50.4	50.6	
SEP		288.8	311.3	291.6	281.3	323.5	296.0	321.4	322.0	271.3	316.9	232.6	258.5
OCT		374.8	308.8	377.3	367.9	418.1	383.2	460.0	427.5	288.5	407.8	404.1	
NOV													
DEC													

Table 3b. Provisional monthly rainfall totals (mm) for the Kirkton storage gauges

months where good quality recording gauge data were not available and against individual gauges where snow accumulation occurred or where errors have already been identified. Comparison of this output with a less rigorous manual attempt at time distribution (1982/83 Report, table 1) is generally encouraging though it has identified some errors in data compilation. After data correction the programme will be rerun and the results, accumulated on a daily basis, compared with a complete run of the "daily" distribution programme for further quality control. The final product of these two programmes will be:

(1) An array of hourly rainfall data, where available, for all sites.

(2) An array of daily rainfall data derived from (1), with gaps infilled from the "daily" programme, for all sites.

(3) An array of daily snowfall data for the Kirkton forest sites only.

2.2.2 Spatial Distribution

Once the data can be compared on a common time base work can begin on quantifying spatial variability in the precipitation. A preliminary indication of the range of this variability for seasonal rainfall totals was given in the 1982/83 Report. Work is now in hand on deriving relationships between monthly totals and the controlling factors of location, altitude and aspect. Comparison of the results from each month with those derived from seasonal and annual totals will determine the form of the model ultimately used to compute catchment areal means.

As an example, the September 1983 data from table 3a and 3b are presented in table 4 as departures from the mean for comparison with the seasonal distributions derived for 1981 and 1982. The

MONACHYLE

PERIOD	GROUND LEVEL GAUGES											
	A1X	A3X	B1W	B1X	B1Y	B2W	B2X	B2Z	B3Z	C2W	C2Z	MEAN (mm)
8/81-10/81	+ 0.5	+ 5.7	+ 2.9		- 7.2	+ 4.1	- 0.8	-14.4	- 1.2	+ 7.0	+ 3.5	860
5/82-8/82	- 1.8	+ 1.3	+ 4.0	+ 3.8	- 8.2	+12.6	- 1.3	-15.9	+ 4.2	+13.5	+ 0.4	477
SEPT 83	- 0.3	+ 4.7	+ 0.5	+ 3.3	- 5.5	+ 0.2	- 2.4	-14.9	+ 1.5	+11.1	+ 8.3	363

KIRKTON

PERIOD	GROUND LEVEL GAUGES											
	A1W	A2W	A3W	A3Y	B3W	B3Y	C1W	C3W	C3Y	D2Y	D3Y	MEAN (mm)
8/81-10/81				-11.5	+ 4.2	-3.6	+11.3	+ 8.1	-11.3	+ 6.0	+ 5.2	780
5/82-9/82			- 8.3	-10.8	- 2.4	- 2.9	+ 6.9	+ 6.4	-13.0	+ 7.2	+ 8.6	863
SEPT 83	- 5.1	+ 2.3	- 4.2	- 7.6	+ 6.3	- 2.7	+ 5.6	+ 5.8	-10.9	+ 4.4	+ 6.3	304

Table 4. Comparison of % gauge catches relative to the mean in Monachyle and Kirkton between periods in 1981 and 1982 and the month of Setpember 1983.

general pattern is seen to be similar with only one site departing significantly in Kirkton and three in Monachyle. Whilst this type of qualitative comparison is reassuring in that it indicates a reasonable degree of stability in the inter-site relationships, a more quantitative approach is necessary to define the model from which catchment areal means can be derived.

The results of regression analyses of the September 1983 figures are shown in table 5 and illustrated in figures 3 and 4. Whilst the linear regressions with longitude (fig. 3) indicate that a decreasing west to east trend is present, it is clear that other factors play a significant part in determining rainfall variability. Altitude contributes also (fig. 4), particularly in Monachyle, but even when these two are combined with aspect in multiple regressions (table 5), the unexplained variance remains unacceptably high. Work is continuing on this type of analysis.

STREAMFLOW

Accurate assessment of streamflow in steep, flashy catchments is always a difficult proposition. The structures installed on the Kirkton and Monachyle catchments were considered to be the best compromise achievable within the site and cost constraints prevailing. Nevertheless it was recognised that the main Crump structures in particular would be operating very close to their design limits in terms of approach conditions and rigorous checking of their performance would be necessary before data from them could be used with confidence.

3.1 Structure Performance

The 5 gauging structures have given a few problems through the year. The table below shows the percentage possible data that were collected.

The rating for the Kirkton Crump weir was found to be in error for high flows and a series of dilution gaugings and current meterings

Monachyle

RAIN 954.0 - 0.138 (LONG) + 0.136 (ALT). $r^2 = 0.376$

RAIN 240.0 + 0.0209 (LONG) + 0.0978 (ALT) - 0.156 (ASPECT)
$r^2 = 0.474$.

Kirkton

RAIN = 949.0 - 0.127 (LONG) + 0.0522 (ALT). $r^2 = 0.397$

RAIN = 406.0 - 0.0225 (LONG) + 0.0735 (ALT) - 0.135 (ASPECT)
$r^2 = 0.470$.

Table 5. Statistical analysis of rainfall patterns for September 1983 using Monachyle and Kirkton ground level raingauges.

Structure	% Data Collection
Kirkton	100
Kirkton low flow	(see text)
Monachyle	93.4
Monachyle low flow	81.6
Upper Monachyle	57.3

Table 6.

are being carried out in order to produce a new rating (see section 3.2.3). To do the current metering a bridge was constructed between the wing walls, supporting cradles on which the current meters are located. The bridge is able to be moved to the upstream ends of the wing walls to carry out sediment clearance from the stilling pool.

During the 1983 summer in low flow conditions it was discovered that the recorder on the Kirkton low flow structure was not responding to stages of less than 159 mm. This was due to sediment accumulation in the bottom of the well, a float with too large a displacement being used, and the tapping pipe sloping upwards towards the well. Measurements in the well indicated that the problem with the tapping pipe resulted in a minimum recordable stage of 97 mm. The left hand bank stilling well was therefore abandoned in July 1984 and a new well installed on the right hand bank. One of the parallel pair of fibreglass flumes was blocked off thus increasing the sensitivity of the structure in low flow conditions and eliminating the right hand flume which was found to be deforming along its floor. An overlap with the Crump weir has been maintained, though over a smaller range than previously.

The Upper Monachyle structure was closed down for the 1983-4 winter because of a distortion in 2 of the base plates. This part of the structure was strengthened in April 1984 and there has been no structural problem since then.

Ice in all of the structures has been a problem during the 1984-5 winter. Ice build up in the structures is inevitable during intense cold spells but, since these are normally dry periods, missing data can be replaced by interpolation of the recession curves. A more serious problem arises when the stilling wells freeze and do not thaw quickly enough to respond to subsequent flow events.

The Upper Monachyle weir was closed down from December to March because both the well and the burn froze. Similarly both low flow structures were inoperative for several weeks but the Crump weirs were freed of ice when possible. In the wells of the Crump weirs ice was regularly forming, reaching thicknesses of 5-10 cm. Polystyrene balls, put on the water surface to provide some insulation, have proved to be of little use. It was found that the ice could occasionally lift the floats by up to 184 mm overnight and maintain this false reading for a considerable period. As a means of minimising the well freezing problem it is proposed to install pressure transducers housed in separate oil filled pipes before the 1985/6 winter to supplement the float recorders through cold spells.

3.2 Calibration Checks

Initially water level data from all the structures have been processed to give flow values in mm depth over the catchments using theoretical stage-discharge ratings. Two approaches have been adopted to check the validity of these ratings. The first is the dilution gauging technique. This can produce very accurate estimates of flow in the right conditions but it is not possible to keep the equipment and the operator continuously on site to cover all flow ranges. Where spot readings by this method have revealed problems then the more conventional current metering method has been adopted to obtain coverage of the flow range as quickly as possible.

3.2.1 Upper Monachyle Flat-Vee Structure

Six dilution gaugings of the upper Monachyle between October 1983 and November 1984 showed good agreement with the theoretical rating over the low flow range but some deviation at higher flows. Subsequent reassessment of the high flow checks revealed some uncertainties in the measurements. These will be repeated as soon as flow conditions permit.

3.2.2 Monachyle Crump and Low Flow Flume

So far only low flows have been checked by the dilution method on the Crump weir. No significant departure from the theoretical rating was detected in this range. As indicated in the 1983/84 report, analysis of simultaneous stage readings in the overlap range between the Crump and the Flume using the theoretical ratings revealed agreement within 2%. Subject to the results of higher flow dilution gaugings, no immediate problem is apparent at this site.

3.2.3 Kirkton Crump Weir

The steepness of the Kirkton burn with its alternating waterfalls and pools and relatively high sediment loads posed problems at the site selection and structure design stages. The site chosen was considered to be the best available but not ideal. Theoretically a Plynlimon type of steep stream critical depth flume would have been the logical choice of structure but had to be ruled out on grounds of cost and the technical difficulties involved. Similar considerations also ruled out a trapezoidal flume. This left the 7 m Crump as the best compromise choice, with additional low flow sensitivity being provided by a parallel pair of small flumes downstream of the main structure.

Reservations about the effects of the approach conditions and the sediment loads lead to early dilution gauging checks on the theoretical rating. Whilst the low flow range appeared reasonable (figure 5), the observations were found to depart significantly at medium to high flows (figure 6). Some marginal uncertainty surrounded these observations but the departure was serious enough to warrant detailed investigation.

To this end a lightweight bridge was built across the structure (section 3.1) and a programme of current metering initiated in November 1984. The 25 meterings performed so far cover the stage range 86-554 mm but do not yet overlap the higher dilution gauging points. Nevertheless they are in close agreement with the dilution gauging values in the low flow range (figure 5) and show a similar departure trend from the theoretical at the higher stages (figure 6). The "total head" values shown in the figures are computed using the current metering data to determine velocity head, combining this with the observed static head and entering the resulting total head in the theoretical discharge expression.

It is clear that a problem exists with this structure at high flows. The departure between "total head" and theoretical indicates that the approach velocities are too high. Continuation of the current metering programme to higher flows will reveal whether a stable rating with useable stage sensitivity can be derived from it. Concurrently, the extent to which sediment build up in the approach is contributing to the problem will be investigated. The possibility of building a sediment trap upstream of the weir has already been mooted. Judicious design and siting of such a structure may provide part of the answer to reducing the approach velocities as well as better bedload estimates.

3.2.4 Kirkton Low Flow Flume

The 7 m width required to contain high flows over the Crump meant that its sensitivity at very low flows would be poor. To provide better estimates in this range a parallel pair of fibreglass trapezoidal flumes were installed downstream of the main structure. The modifications carried out on these during 1984 have been described in section 3.1. Dilution gauging checks on the revised configuration have yet to be done. Whilst the reduction to a single flume has reduced the overlaps with the Crump, a useful margin still exists to aid in cross-checking the ratings.

METEOROLOGICAL OBSERVATIONS

4.1 Automatic Weather Stations

1984 was another successful year for data retrieval from the 4 automatic weather stations (AWS). The table below shows the percentages of possible data there were collected.

AWS	% Data Collection
Kirkton High	95.1
Tulloch Farm	95.1
Lower Monachyle	99.2
Upper Monachyle	95.6

Table 7.

The Upper Monachyle AWS was installed in December 1983 near to the upper weir for use in assessing potential evapotranspiration in the Upper Monachyle catchment and for snow melt studies. The wind generator which supplies power for this site was replaced in 1984 by a more efficient one.

Comparisons between the weather stations are continuing and a paper has been accepted for the Journal of Meteorology. (Johnson, 1985).

4.2 Tulloch Farm Meteorological Site

3 years data have now been collected from the Tulloch Farm climatological station. Monthly values are summarised in Figure 7.

SEDIMENT YIELDS

The amount of sediment transported by the streams out of both catchments continues to be monitored as both suspended sediment and bedload. Although final analyses will not be done until the land uses in the catchments change and the flow data becomes available, some initial analyses have been carried out.

The suspended sediment analyses for both catchments are shown in table 8. Samples are classified by season and rising or falling stage to give logarithmic relationships of sediment load against stream discharge. As was indicated last year the Kirkton shows the steepest gradients indicating that the forested catchment is less sediment supply limited than the heather/grassland catchment. Analysis of individual flood events and more values in the least sampled seasons will clarify the distributions.

Bedload sampling has been concentrated on the Kirkton catchment because of the time limits before felling. 108 samples have been taken and again these are classified by season and rising or falling stage. All samples are being sieved to relate particle size distributions to discharge in different conditions.

A CASE student based at the University of Stirling has started work on sediment production and transport within the catchments. This will eventually link up with the work being done by IH at the catchment outfalls and is also of interest to the Freshwater Fisheries laboratories and FRPB for their aquatic biota studies.

Year	Season	Rise/Fall	Intercept Coefficient	Gradient	r^2	Number of values	Significance
<u>KIRKTON</u>							
1983	Autumn		5.3	2.4	0.65	24	***
	..		2.3	1.3	0.76	19	***
1984	Autumn		13.3	2.4	0.93	56	***
	..		2.2	3.5	0.52	28	***
Both	Winter		3.2	2.5	0.80	4	
	..		6.3	1.8	0.98	8	***
Both	Spring		19.4	6.5	0.46	14	**
			4.3	2.1	0.14	20	
Both	Summer		7.1	4.3	0.96	3	
..	..	F	9.7	3.3	0.99	3	
<u>MONACHYLE</u>							
1983	Autumn		4.3	1.9	0.75	51	***
	..		6.9	1.4	0.41	60	***
1984	Autumn		28.0	3.3	0.15	16	
..	..		11.6	0.78	0.27	31	**
Both	Winter		3.3	2.0	0.86	13	***
			5.4	1.8	0.72	21	**
Both	Spring		3.1	0.18	0.05	5	
			7.2	1.3	0.53	55	
Both	Summer		14.6	1.3	0.89	5	
		F	5.3	1.5	0.68	15	***

r^2 Correlation Coefficient

Significance - significance of correlation coefficient on variation and number of samples

*** - highly significant, 0.1% of samples occur by chance

** - 1% occur by chance

- 5% occur by chance

Table 8. Seasonal relationships between sediment loads (S) and stream discharge (Q) using: $\log S(\mathrm{gm/s}) = A + B \log Q\ (\mathrm{m^3/s})$

SITE STUDIES

In addition to the catchment scale data collection, a number of more detailed site studies are in progress within the catchments. The sediment production study has been mentioned in section 5 and the soil moisture studies under heather and spruce are described in the Process Studies Report. Also in hand are a plot scale study of interception in the Kirkton and work on direct measurement of snowmelt.

6.1 Forest Interception

The interception site in the Kirkton forest is situated under sitka spruce in the base of the catchment where site aspect has little influence on precipitation.

Precipitation, throughfall and stemflow are all measured and from these the percentage of the input evaporated is calculated. Table 9 summaries the data collected. For each set of readings the amount of loss from the canopy can be related to evaporative mechanisms occurring when the canopy is wet or holding snow. The basic categories of frontal or showery types of precipitation are shown in table 9 to illustrate that loss from frontal precipitation is much less than from showery precipitation. Readings were taken in 1984 on 98% of the total precipitation and these showed that there was a total evaporation loss of 265 mm, 12.4% of the input.

The variability of throughfall is monitored under a single tree on the site using systematically placed collectors set radially at 1 m intervals from the stem to the edge of the canopy. (Figure 7). The table includes these measurements for comparison with the randomly placed bucket method used over the whole plot. Amounts under the single tree are generally less but this is probably a result of the tree's structure rather than a comment on sampling techniques. Figure 7 shows the pattern of throughfall under the tree for the total of all readings.

6.2 Snow Melt Studies

An important part of the Balquhidder study is the effect of snow accumulation. The presence of snow will affect the evapotranspiration rates and hence the volume of flow. Its presence will also affect the time distribution of the flow. Snow melt rates for hydrograph modelling purposes are usually derived from observations of snow pack depletion or estimated from meteorological data using some variant of the "degree-day" method. Both approaches are possible in this case, with snow accumulation and meteorological data available from the networks.

In addition, however, attempts are being made to obtain point measurements of snow melt at selected points within the catchments using a simple design of recording gauge mounted under porous plastic grass. These instruments worked resonably well during trials at Plynlimon but have been beset with problems in the more extreme conditions at Balquhidder. Despite the use of a battery/wind generator system to power small heaters, the tipping bucket mechanisms freeze up repeatedly.

A modified design which dispenses with the tipping bucket system is now under development.

FUTURE WORK

From the preceding sections it can be seen that whilst the basic data collection is proceeding well, much testing and analysis remains to be done in the coming year before these data can be interpretated to give accurate water balances and streamflow response characteristics for the catchments.

Calibration work on the high flow range of the Kirkton Crump weir is a particular priority and current metering there will proceed as quickly as flow conditions permit. As this proceeds, the strength of the case for modifying the approach conditions by the installation of a sediment trap will be clarified.

Work will continue on the analysis of the precipitation data, building on the progress made in the past year in developing time distribution methods and identifying patterns of spatial variability, to produce better methods of estimating areal inputs.

When clear felling of the Kirkton forest starts in 1986 the 'shelter' provided to the forest clearing sites will progressively disappear. Work has been initiated on testing the existing snow gauges on more exposed sites to determine what modifications will be necessary to the snow network thereafter. This will continue in 1985.

The problem of ice formation in the structure stilling wells is now fully recognised. Suitably sited and protected pressure transducers will be installed during 1985 in a bid to minimise the winter data loss, at the Upper Monacyhle site in particular.

Studies of sediment loadings are producing sound comparative relationships between the catchments under their present covers. Continuation of the data collection through the planned felling and planting operations will identify any resulting changes.

These studies are producing valuable data which, when fully analysed and interpreted, will provide a basis for assessing the overall effects of afforestation on hydrology in the Scottish Highland environment.

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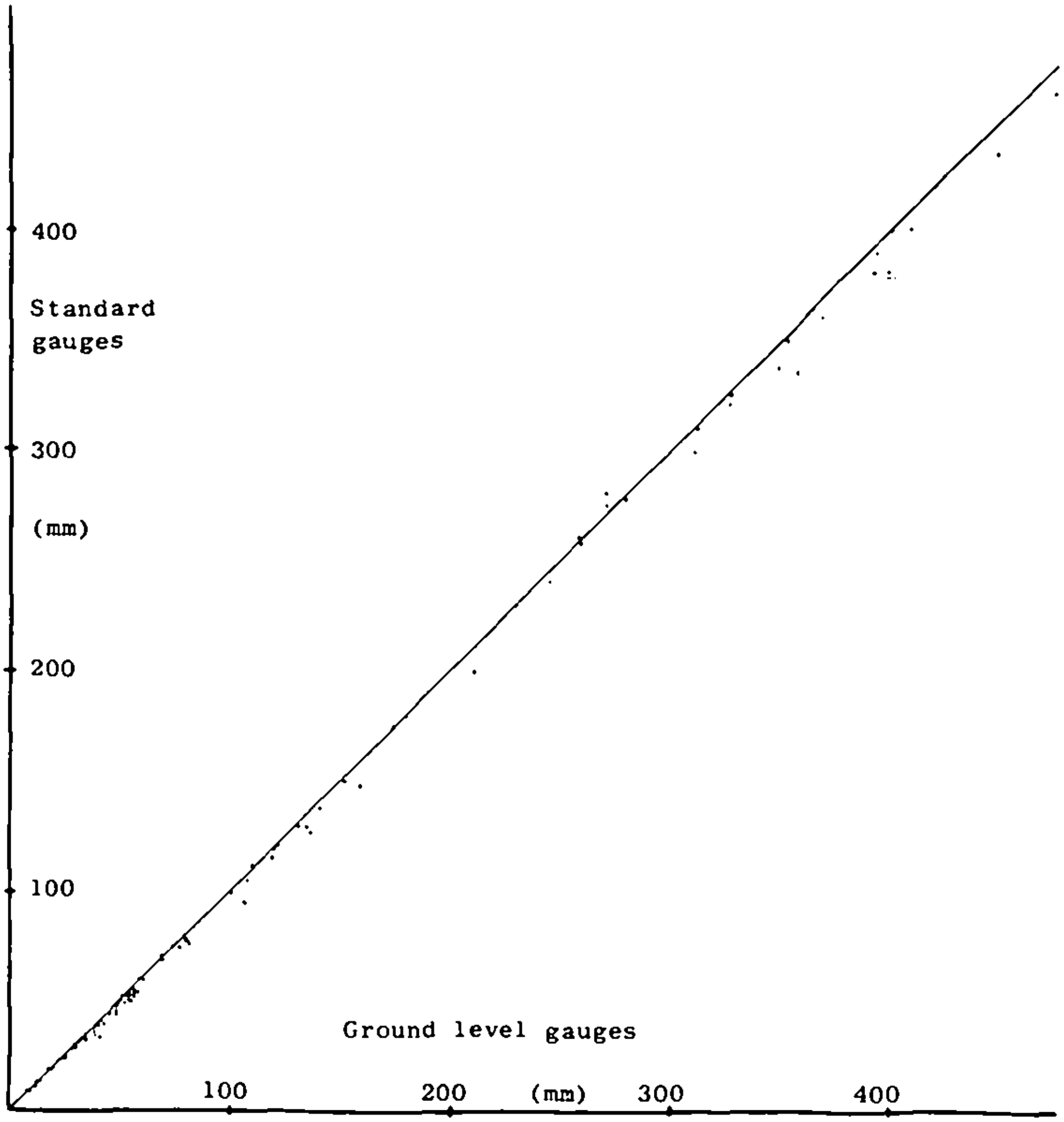

Figure 2. Comparison of standard and ground level gauges at the Kirkton forest clearing sites.

BALQUHIDDER CATCHMENTS

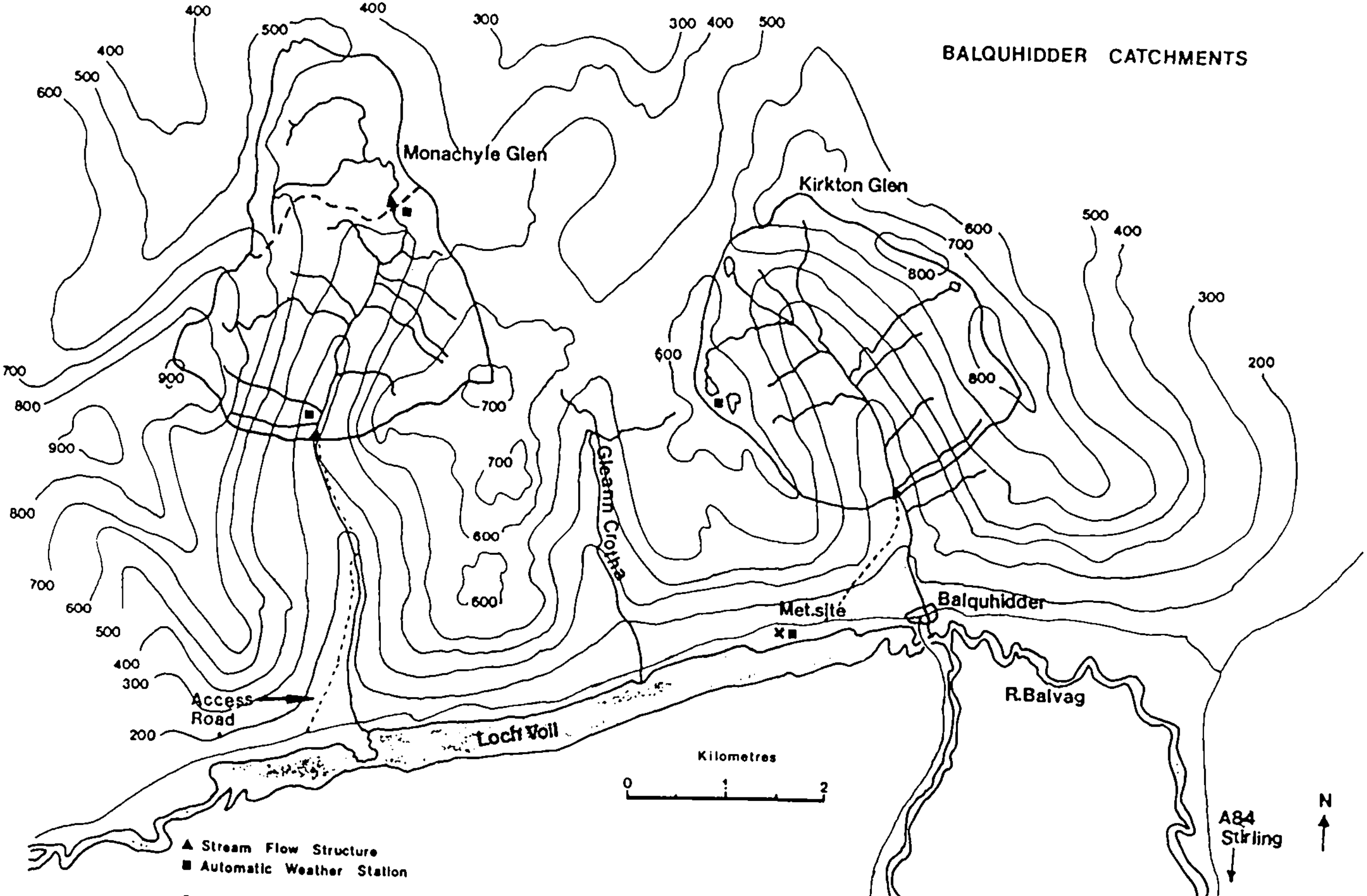

figure 1

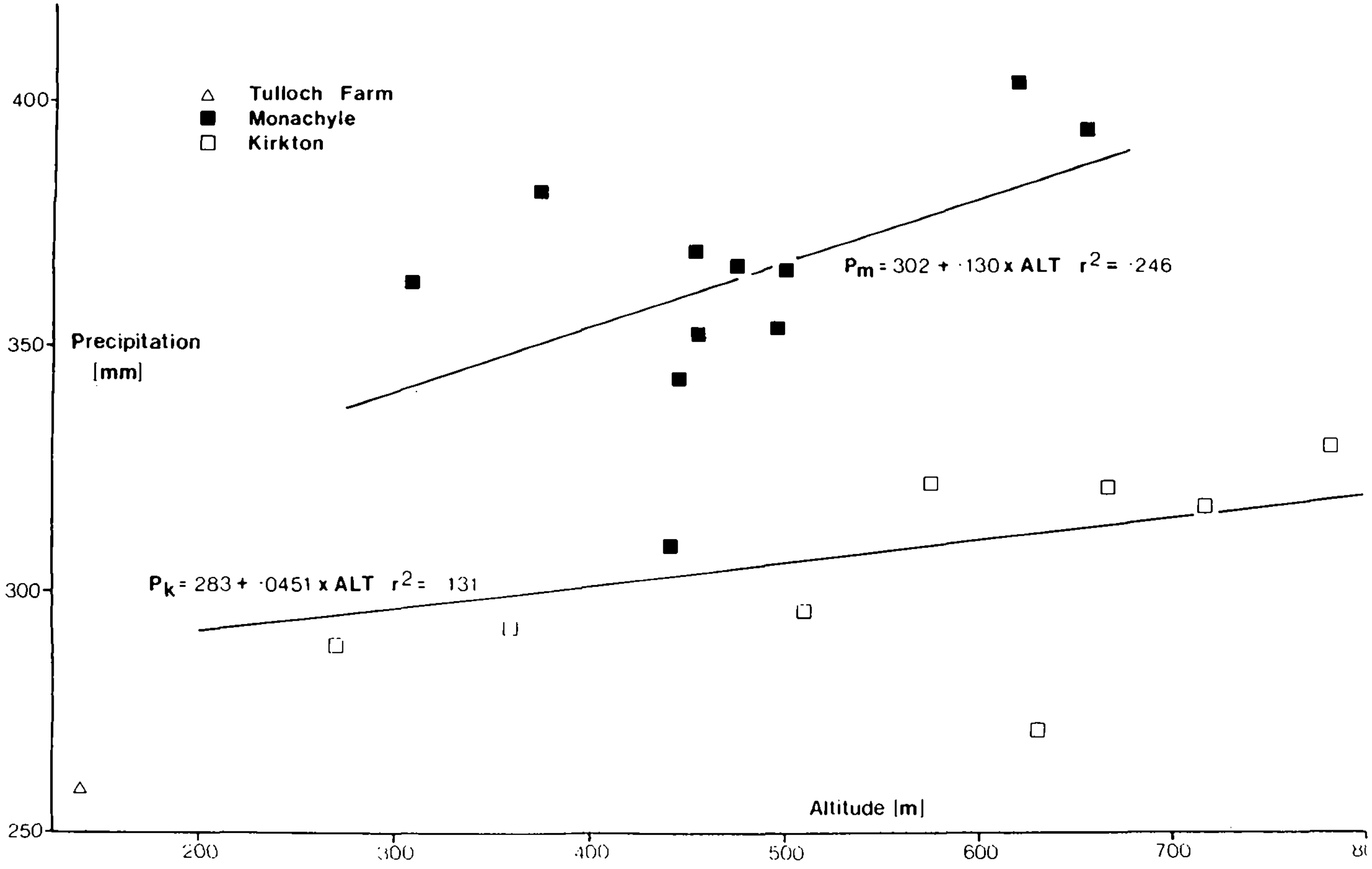

Figure 4. Regressions of September 1983 rainfall on altitude.

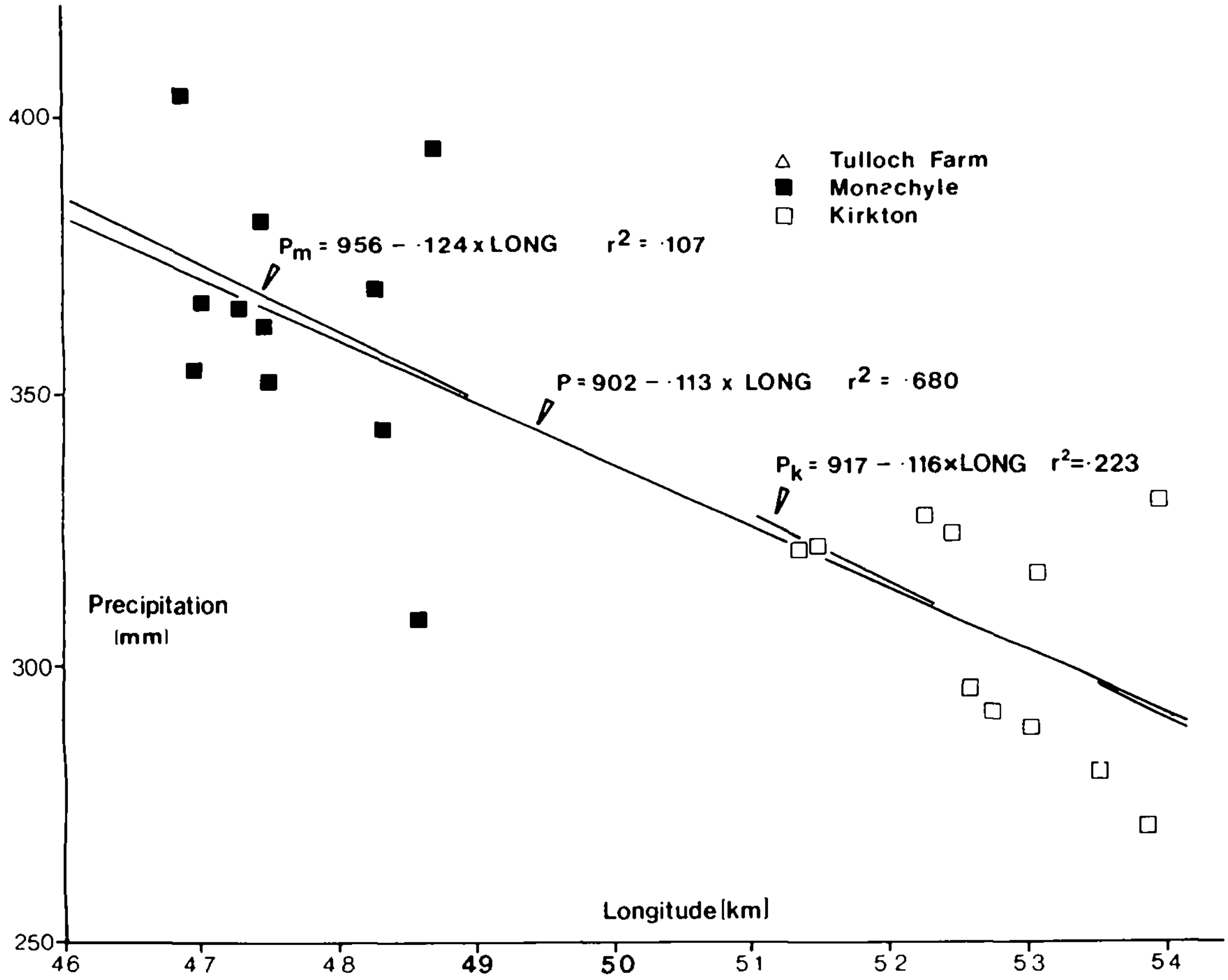

Figure 3. Regressions of September 1983 rainfall on longitude, expressed as distance East from an arbitrary point.

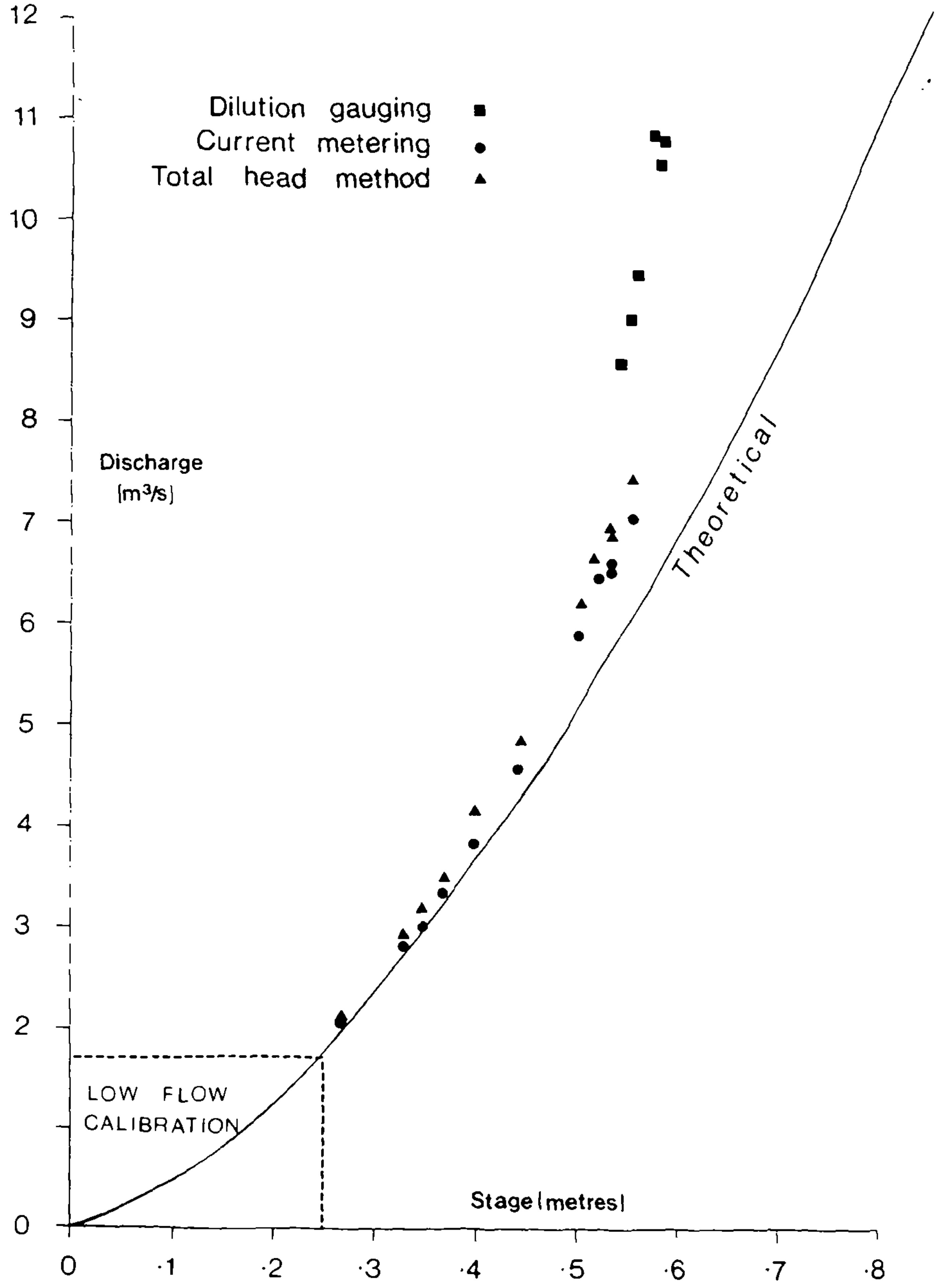

Figure 6. Kirkton Crump Weir calibration checks - medium to high flows.

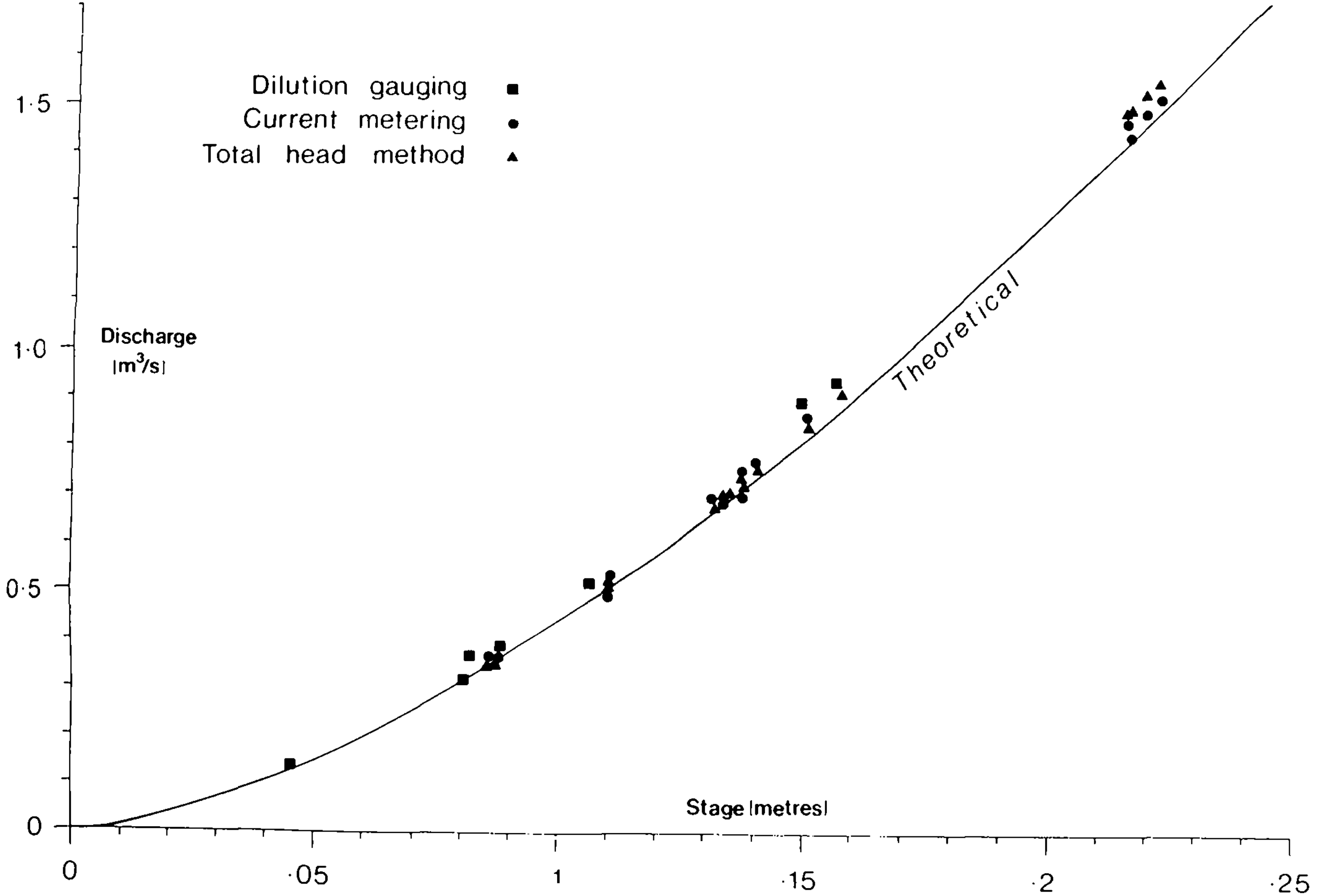

Figure 5. Kirkton Crump Weir calibration checks - low flows.

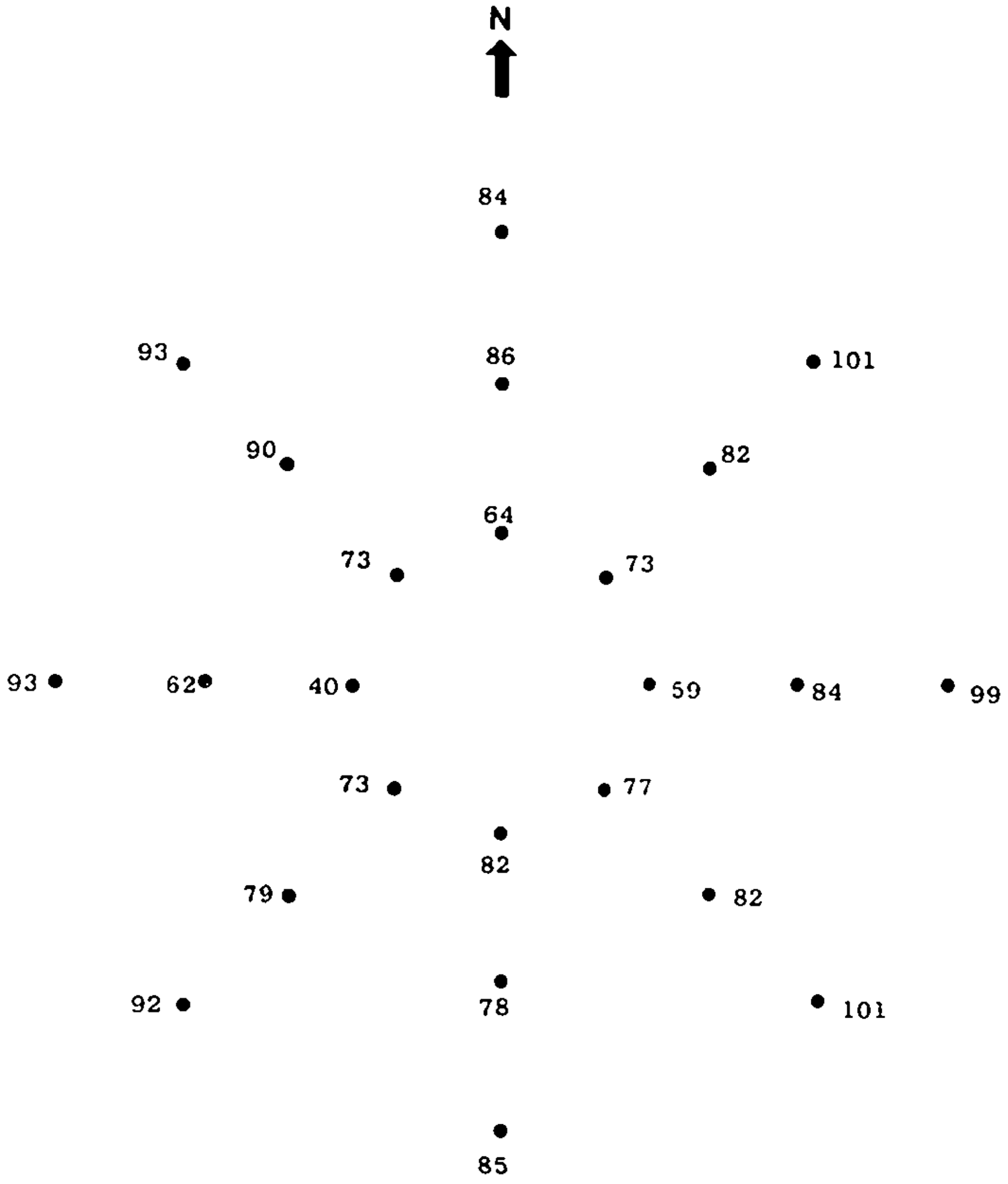

Figure 8. Radial pattern of gauges at 1 m spacing under a spruce canopy showing the throughfall catch as a percentage of the total precipitation in all sample periods.

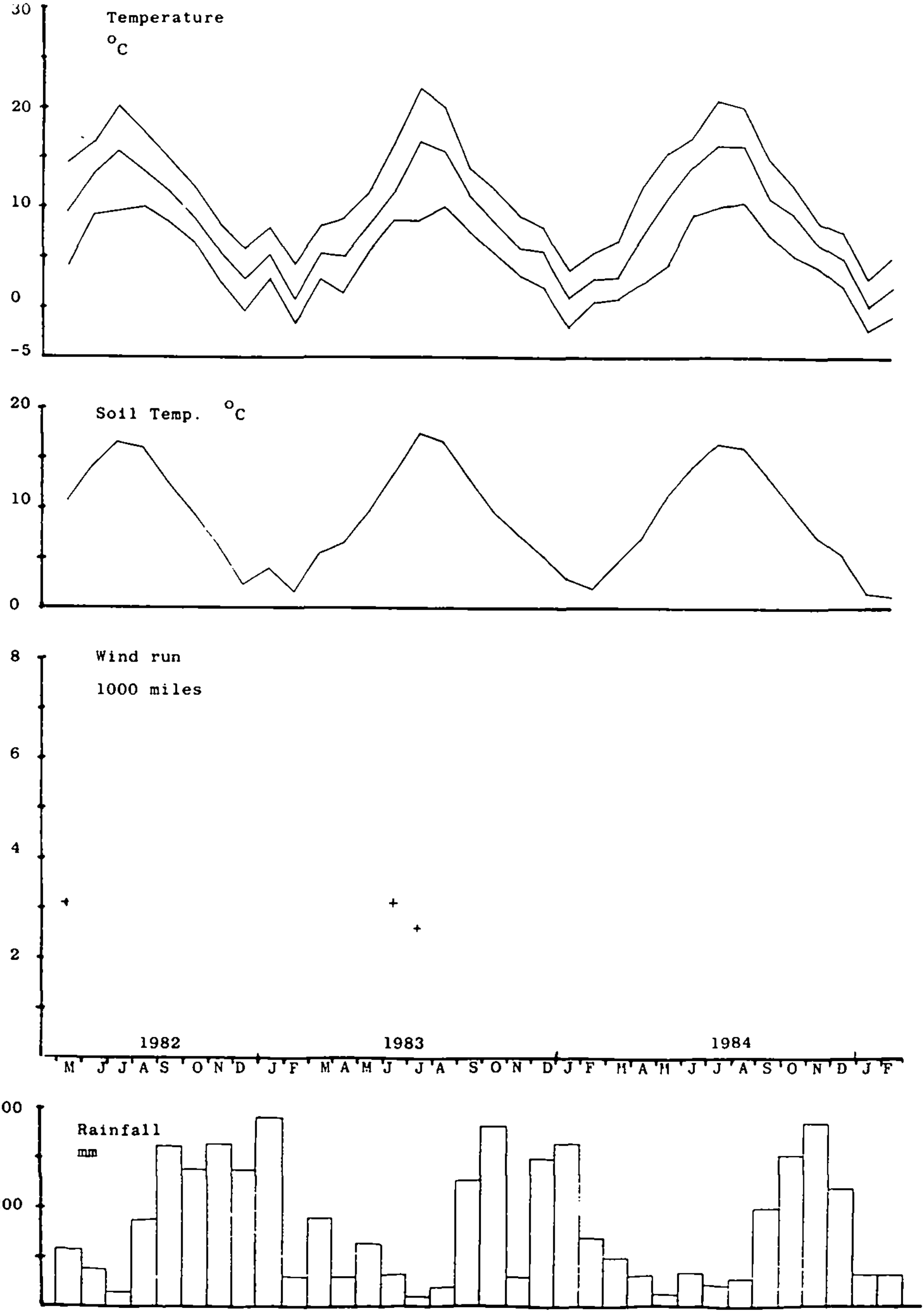

Figure 7. Tulloch Farm climatological data.

UPLAND AFFORESTATION. PROCESS STUDIES 1984-1985

by

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

INTRODUCTION

In the past year field studies of interception and transpiration losses from various upland vegetation types have continued. These studies have included: the interception of snow, the effects of forest thinning on interception, the evaporation of intercepted water from grass and the measurement of soil moisture beneath heather, grass and forest. A major effort has gone into the measurement of the interception of snow and the field programme of this project is nearing completion. In the coming year it will therefore be possible to place a greater emphasis on the assessment of the results of process studies in the wider water resource context.

New studies envisaged for the future are the measurement of the interception characteristics of Larch, using the gamma-ray attenuation technique, and a study of the effects of afforestation on low flow events using simple techniques similar to those pioneered for the study of soil moisture. This second area would be of particular interest to the water supply industry because it is in low flow periods that the effects of afforestation on water yield are likely to be most acute.

In the past year papers have been submitted for publication on the gamma-ray technique applied to rainfall interception (Appendix 1) and on the interception charateristics of heather (Appendix 2). In addition two papers have been presented in Edinburgh, one to The Institute of Biology the other to The British Hydrological Society. A further paper is to be given at this year´s Easter School at the University of Nottingham. The paper presented to The Institute of Biology gives a

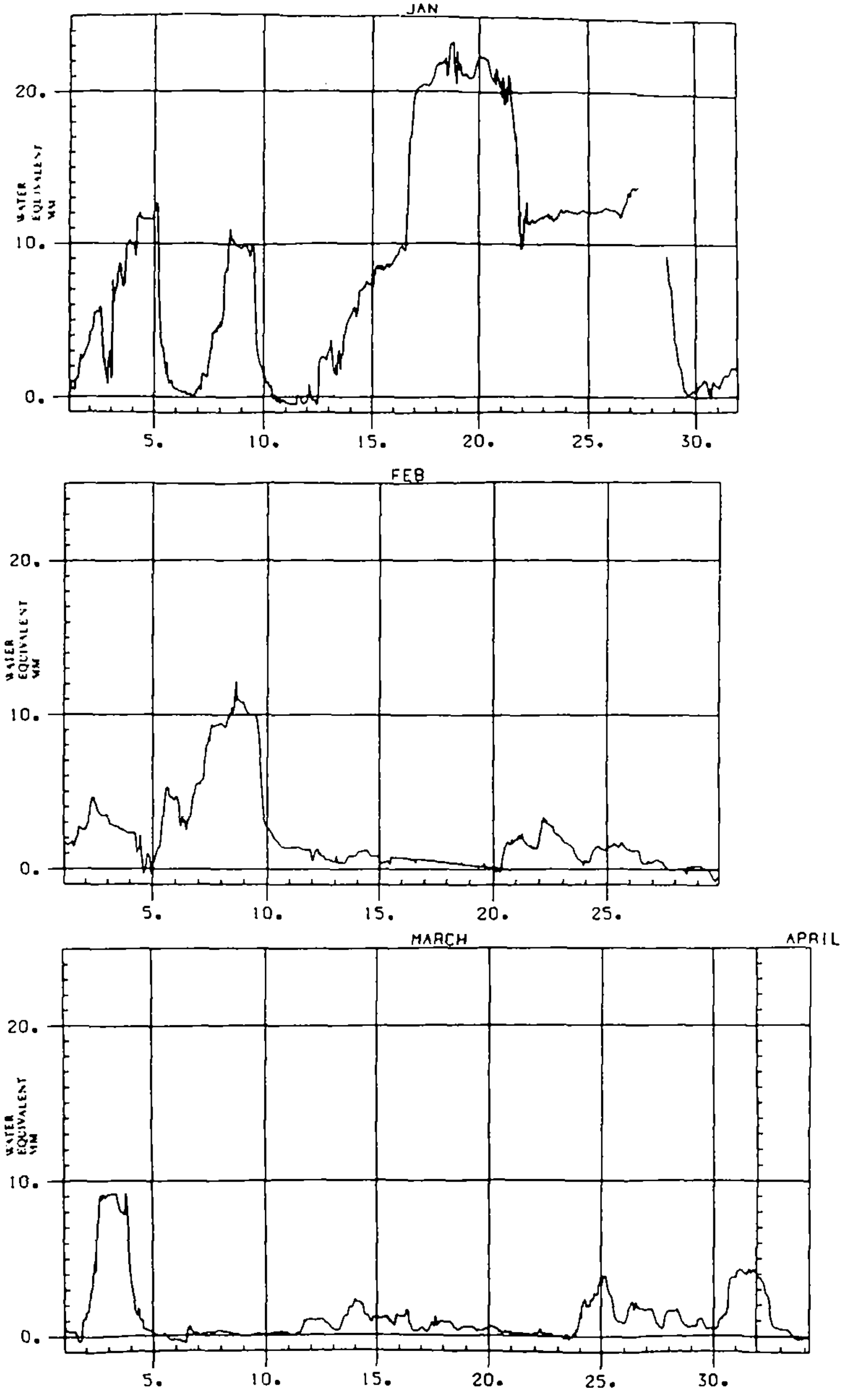

Figure 1
The water equivalent of snow and water in millimetres on the weighed tree for the months of a) January, b) February and c) March and the beginning of April, in 1984.

comprehensive review of forest evaporation studies and is reprinted in Appendix 3.

SNOW INTERCEPTION

The collection of data at the Queens Forest site has continued through the winter season 1984/85 with the operation of weighed tree, net rainfall gauges and gamma-ray equipment. The frequency of snow events this season has not been as great as 1983/84 but a number of storms has been recorded, notably between 21 January and 28 January 1985 during which a maximum of 28 mm water equivalent of snow was observed on the forest canopy.

During the summer and autumn of 1984 the gamma-ray equipment was updated with the result that the stability and accuracy have been improved significantly; the measurement errors are now approaching their theoretical limit of 0.1 mm of canopy storage. We now have a very powerful tool to investigate the interception processes occurring on a variety of forest canopies.

Figure 1 shows the water equivalent of snow (and rain) on the weighed tree for the main snow period in the 1983/84 winter: January, February, March and the first part of April. This figure shows a charcteristic pattern of accumulation and loss, viz:

1. a period during which a large accumulation of snow occurs on the forest canopy,
2. a period in which there are only small changes in the weight of snow on the canopy,
3. a period with rapid loss from the canopy due to melt, with

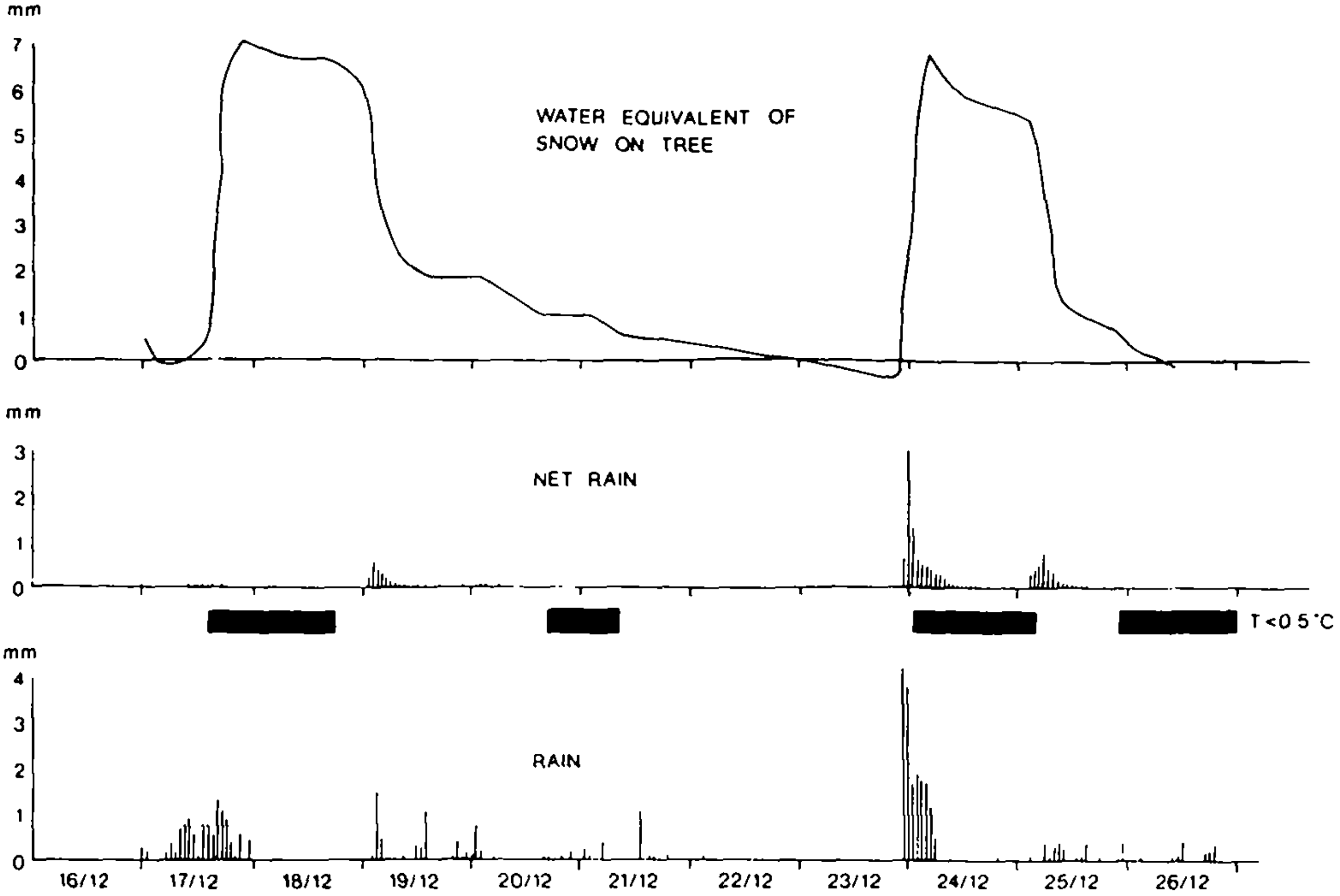

Figure 2
An example of the results from the weighed tree and the interception site for two storms in December 1984 showing: the weight of snow on the tree in millimetres (top), the hourly drainage through the canopy (middle) and the hourly precipitation (bottom). The thick, horizontal bars indicate periods when the air temperature was below 0.5 °C, and any precipitation would be expected to be snow.

subsequent drainage, and evaporation.
This pattern is the result of the passage of successive depressions in a westerly air stream with their associated fronts; viz, the arrival of snow on a cold front, sub-zero temperatures following the front and, finally, the arrival of warm air. Evaporation rates of between 0.2 and 0.5 mm hr^{-1} are observed in both the cold air following the initial storm and in the rapid loss period.

Figure 2 shows an example of two storms from December 1984 which illustrate further the characteristic pattern described above. The total evaporative losses from these storms were 9.3 mm (69% of precipitation) from storm 1 and 7.1 mm (40% of precipitation) from storm 2: had these storms been composed wholly of rain it is likely that the interception losses would have been smaller. (Assuming an interception ratio of 35% the evaporation would have been 4.7 mm and 6.2 mm respectively.)

The similarity of many of the snow events should make the modelling of the long-term water losses from a snow covered forest considerably easier. The first attempt at modelling using a modified Penman-Monteith formulation is giving encouraging results.

SOIL MOISTURE

The soil moisture observations have continued at the Crinan canal and Balquhidder sites; the data from 1984 will prove to be extremely valuable, with the dry period from April to September leading to the development of large deficits, particularly beneath the forest.

TABLE 1

SITE	TUBE NO.	GRID REF.	ALTITUDE (m)	VEGETATION	SOIL TYPE	TUBE DEPTHS (m)	OBSERVATION PERIOD
Kirkton	01-07	NN529226	290	Sitka spruce	Brown earth	0.55 - 1.55	17.2.83 to present
Kirkton	08-10	NN528226	305	Sitka spruce	Brown earth	1.25 - 1.75	8.5.84 to present
Monachyle	01-06	NN482252	430	Heather	Peat/brown earth	0.75 - 1.25	17.2.83 to present
Monachyle	07-12	NN474228	350	Grass	Brown earth	0.75 - 1.25	9.5.84 to present

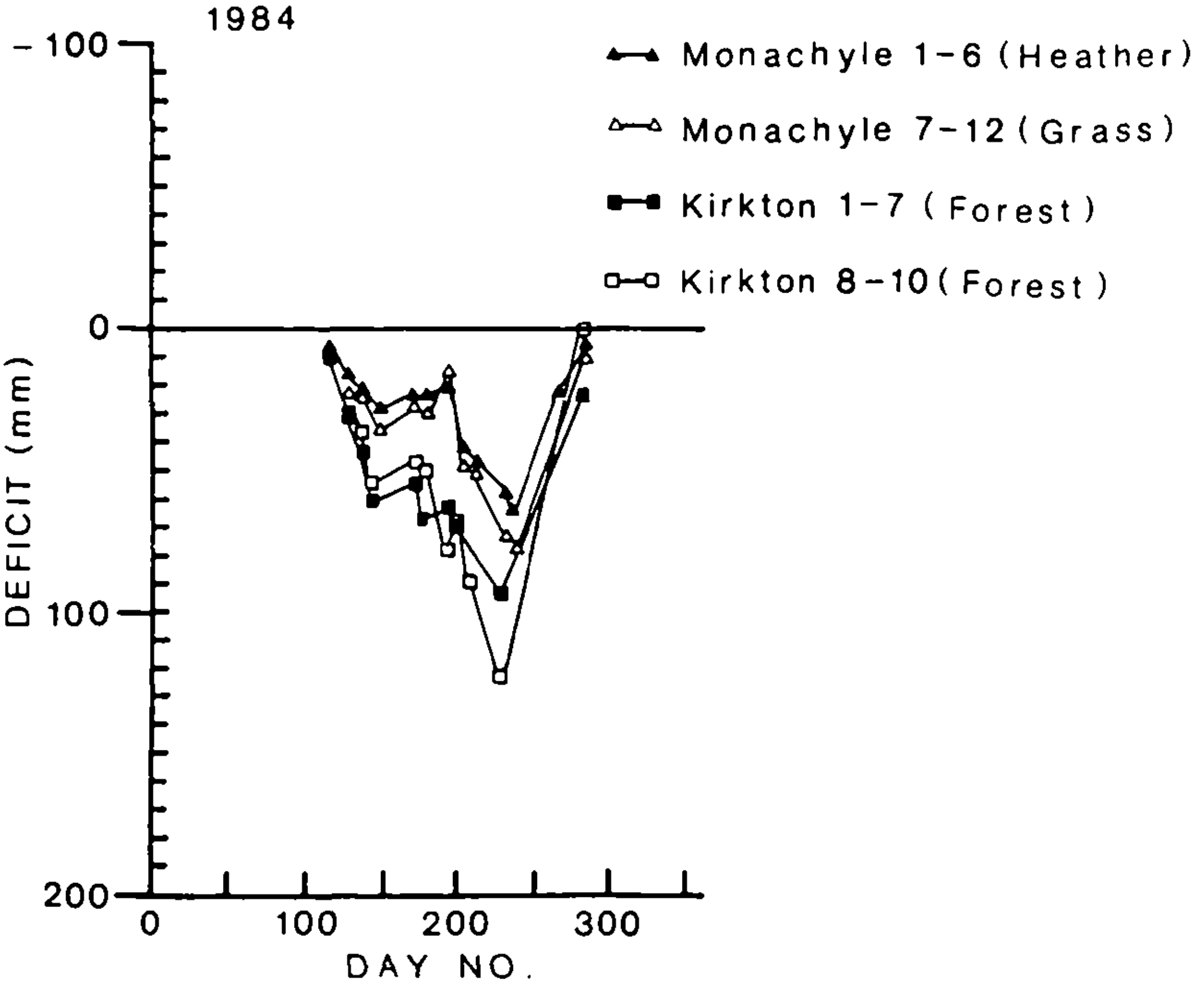

Figure 3.
Observed soil-moisture deficits, measured with a neutron probe, beneath grass, heather and forest at Balquhidder from April to September 1984.

TABLE 2

SITE AND TUBE NO.	MAXIMUM S.M.D. (MM) 1983	MAXIMUM S.M.D. (MM) 1984
Kirkton 01-07	75	95
Kirkton 08-10		125
Monachyle 01-06	72	65
Monachyle 07-12		78

MAXIMUM LENGTH OF SUMMER S.M.D. (>20mm) DAYS

	1983	1984
Kirkton 01-07	100	165
Kirkton 08-10		150
Monachyle 01-06	85	150
Monachyle 07-12		165

In last year's report (Calder et al 1984) an analysis of the Crinan canal soil moisture observations was presented which showed that a simple evaporation model fitted the observations very well. The best fits were obtained using interception ratios for forest and heather of 40% and 20% respectively and ratios of actual to potential evaporation of 90% and 50%. With the help of the British Waterways Board the observations at Crinan have continued with an emphasis on the study of the soil moisture regime beneath a plantation of young Sitka spruce. The network of access tubes at Crinan has been correspondingly modified with an expansion of the forest plantation site and the abandonment of one of the heather sites.

At Balquhidder the soil moisture study has been expanded with the addition of a second forest site and a site on rough grassland in the lower Monachyle (see Table 1 for site details). There are now two years of observations from the original group of Balquhidder access tubes and one year from those installed more recently. While the data sets are not yet long enough to allow comprehensive modelling, the results shown in Figure 3 indicate that deficits beneath the forest are greater than those beneath either grass or heather. This is emphasised in Table 2 which shows the maximium deficits and the lengths of the deficit periods under the various vegetation types.

THE EFFECT OF FOREST THINNING ON INTERCEPTION LOSS

An opportunity arose in spring 1984 to investigate the effect of routine forest thinning on interception loss at Plynlimon. The site was line thinned by one third in February and early March 1984 and subsequently the two plastic-sheet net-rainfall gauges have been replaced together with the forest tower and two weather stations. The details of this experiment and a preliminary analysis of the data are presented in Appendix 4 and a brief discussion of the conclusions is given below.

Forest thinning would be expected:

1. to increase the free throughfall component,
2. to increase the surface roughness and the penetration of the turbulence through the canopy.

The effects of 1 will be to decrease the total interception loss while 2 will cause it to increase. At Plynlimon the mean interception loss in the last year (post-thinning) has been 40%. This is within the year-to-year variability of the pre-thinned value and implies that the two effects are mutually compensating. Analysis of the daily interception values shows that for small storms the losses are decreased by 25% (as would be expected with an increase in the free throughfall component) but the average interception loss on days with high rainfall has increased from 6 mm to 7.5 mm. It is planned to monitor this site for a further two years until the canopy is closed.

INTERCEPTION FROM GRASSLAND

Preliminary fieldwork has commenced at Wallingford using the wet-surface weighing lysimeter system to compare evaporation rates from wet grass with the Penman potential evaporation rate. At present there are insufficient data to make possible a meaningful comparison.

SEASONAL MODELLING

To place the results of the process studies in their proper climatological and hydrological context it will be necessary to develop simple models which describe the evaporation from different vegetaion types accurately but which require a minimum of observations (probably only daily or monthly observations will be available with sufficient temporal and spatial coverage). As models are simplified their empirical content becomes greater and it becomes increasingly necessary to calibrate the models against observations or against the predictions of more complex models. The work of Calder and Newson (1979) was an early attempt at a simple model and although this model was successful it could make no estimate of either the seasonal distribution or year-to-year variability of the effects of afforestation on evaporation losses.

To include seasonal variability a daily interception model has been developed which assumes that:

1. in small storms of less than 2 mm the canopy is not completely saturated and the total evaporation from the storm equals the rainfall,
2. for large rain events the canopy is wet for the entire day and the total evaporation will approach a maximum value constrained by average atmospheric demand.

The equation,

$$I = K\left(1 - \exp\left\{ -K^{-1}(R-S)\right\}\right) + S$$

where R is the daily rainfall, S is the experimentally determined

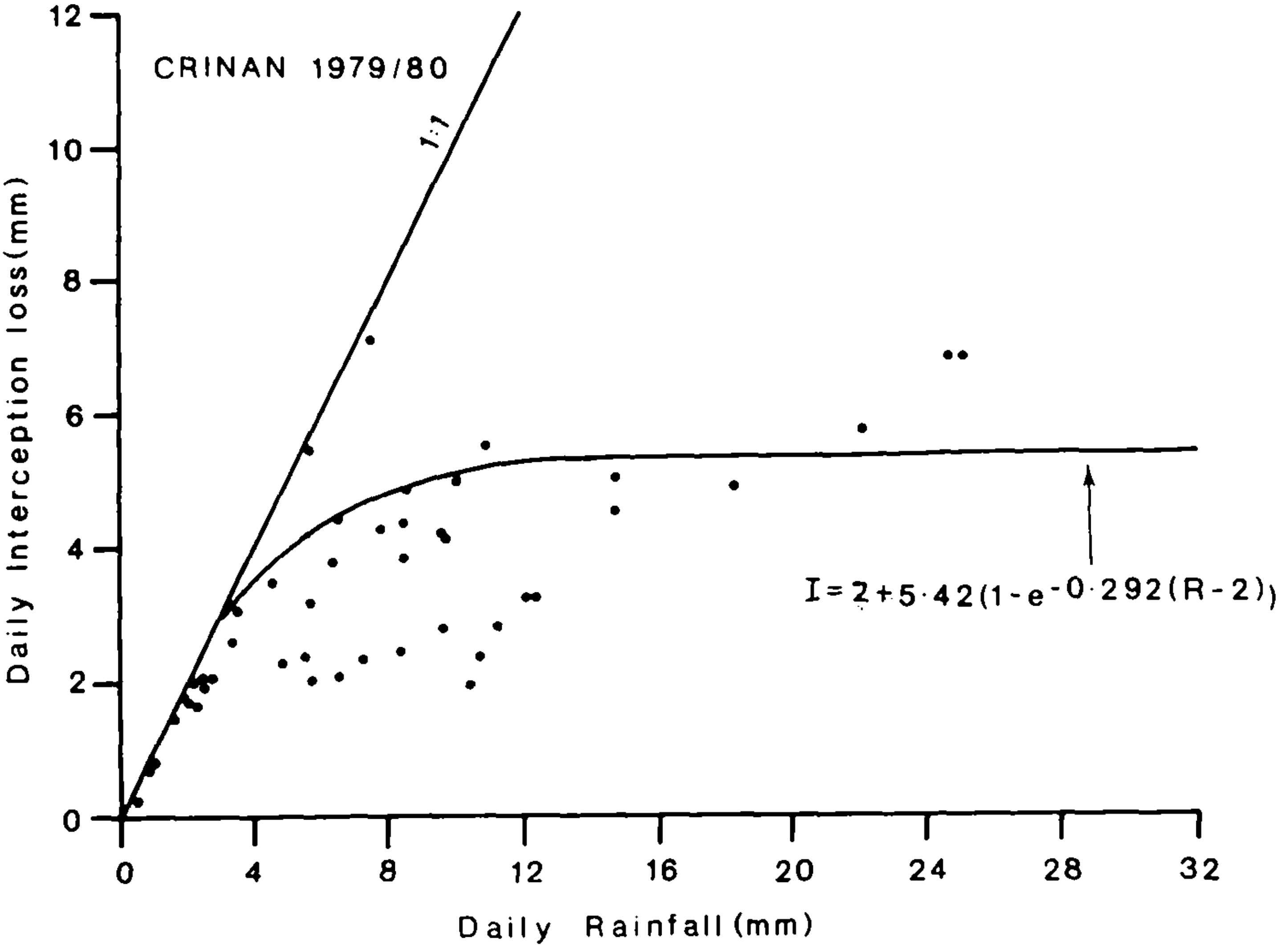

Figure 4.
Daily interception loss plotted against daily rainfall at Crinan for 1979/80. Also shown is the curve fitted to the data using a simple daily interception model.

storage capacity and K is an optimised parameter, embodies these two assumptions. A least squares technique was used to fit this equation to the daily values of rainfall and interception loss which are plotted in Figure 4 together with the fitted line. Although the scatter about the fitted line is large the model does represent the average interception observations very well. The model has been fitted to the Crinan and Plynlimon interception data and it is planned to apply the technique to heather and further forest interception data. The model has already shown itself useful in highlighting the differences between the thinned and unthinned forest and when tested in a soil moisture model against the forest soil moisture observations from Crinan it produced a 10% improvement in the model fit over the model with a constant interception ratio (17.7mm against 19.4mm, see Calder et al, 1983 for details of this error calculation).

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

To establish the form of relationship between low stream flows and SMD use has been made of records of daily rainfall and flows from the Wye (rough pasture) and Severn (62% afforested) catchments at Plynlimon for the years 1972 to 1979. The daily rainfall has been used in a daily accounting SMD model (see Calder et al 1983 and Calder et al 1984) which included evaporation models for grass, the simple layer model described in Calder et al (1983), and for forest, that described in Calder et al (1984). The SMD model generates a time series of daily predicted SMD values and these have been plotted for deficits greater than 10 mm against flow for each year for both catchments. An example of such a graph is given in Figure 5 which shows SMD versus flow for the Severn catchment in 1978.

Figure 6 shows a summary of the results for the readily available data (1972 1979) for the Severn catchment; the curves were obtained by joining points on graphs such as the example shown in Figure 5. Figure 7 is a summary graph of the Wye catchment results over the same period. A consistent form of relationship is seen for both catchments with the flow approaching a minimum value usually of about 0.5 mm day^{-1} at a predicted deficit which ranges from 22 mm to 55 mm for the Wye and from 22 mm to 70 mm for the Severn. The greater variability among the Severn results is mostly associated with the atypical drought years of 1975 and 1976. There are also more curves on Figure 6 than Figure 7 showing that for forest there were more occasions when the predicted deficit exceeded 10 mm than there were for grass. Apart from these differences the two sets of curves are very similar.

This preliminary study has shown that a consistent relationship does exist between low flow and SMD. It remains for future work to determine its functional form and, through examining data from other upland catchments, to establish its generality.

FUTURE WORK

1985/86

In summer 1985 it is planned to dismantle the snow interception site. The soil moisture and tree-thinning experiments are by their nature long term and will continue at a low level in the coming year. The work

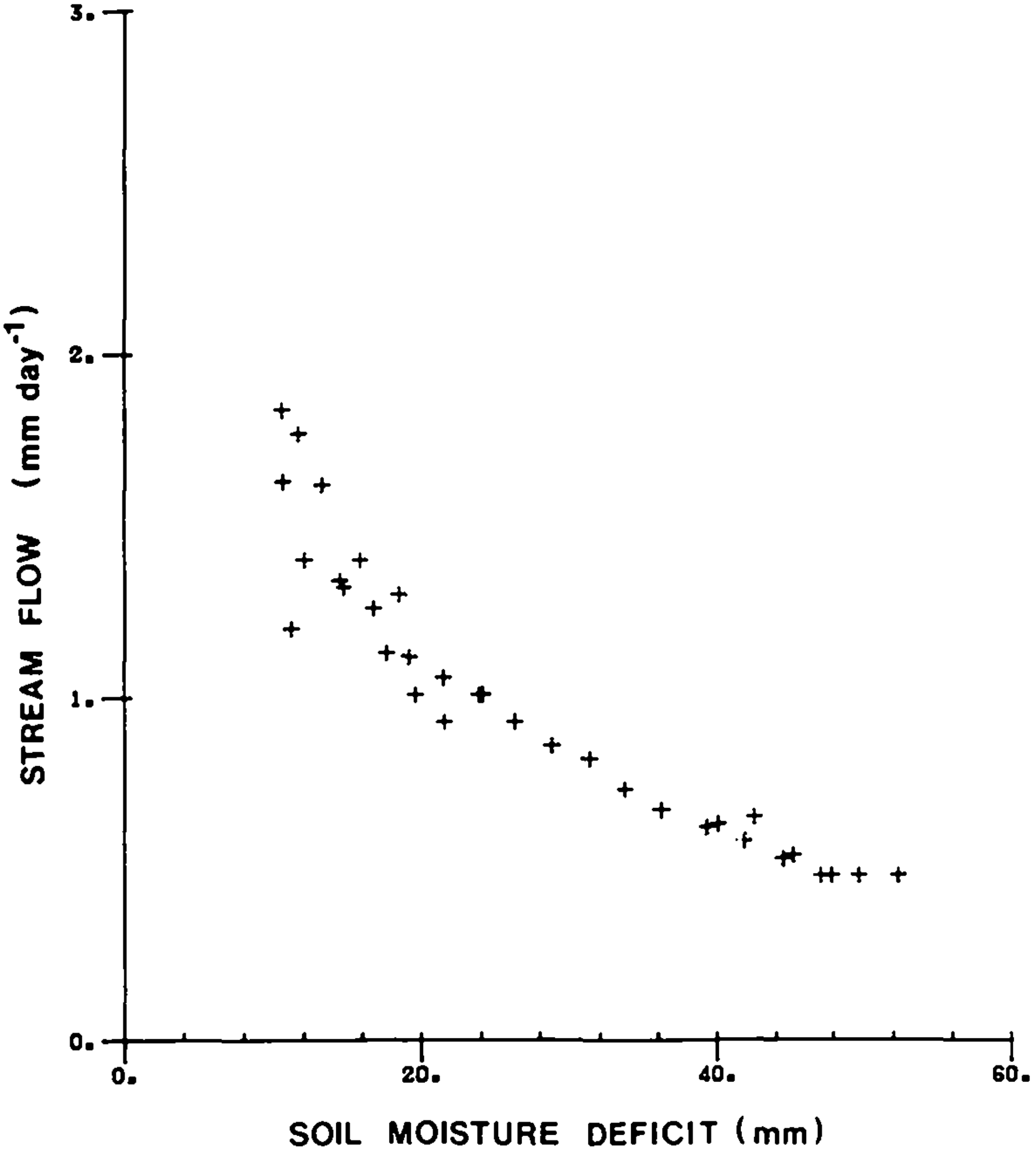

Figure 5.
Measured streamflow plotted against predicted SMD for deficits greater than 10 mm for the Severn catchment in 1978.

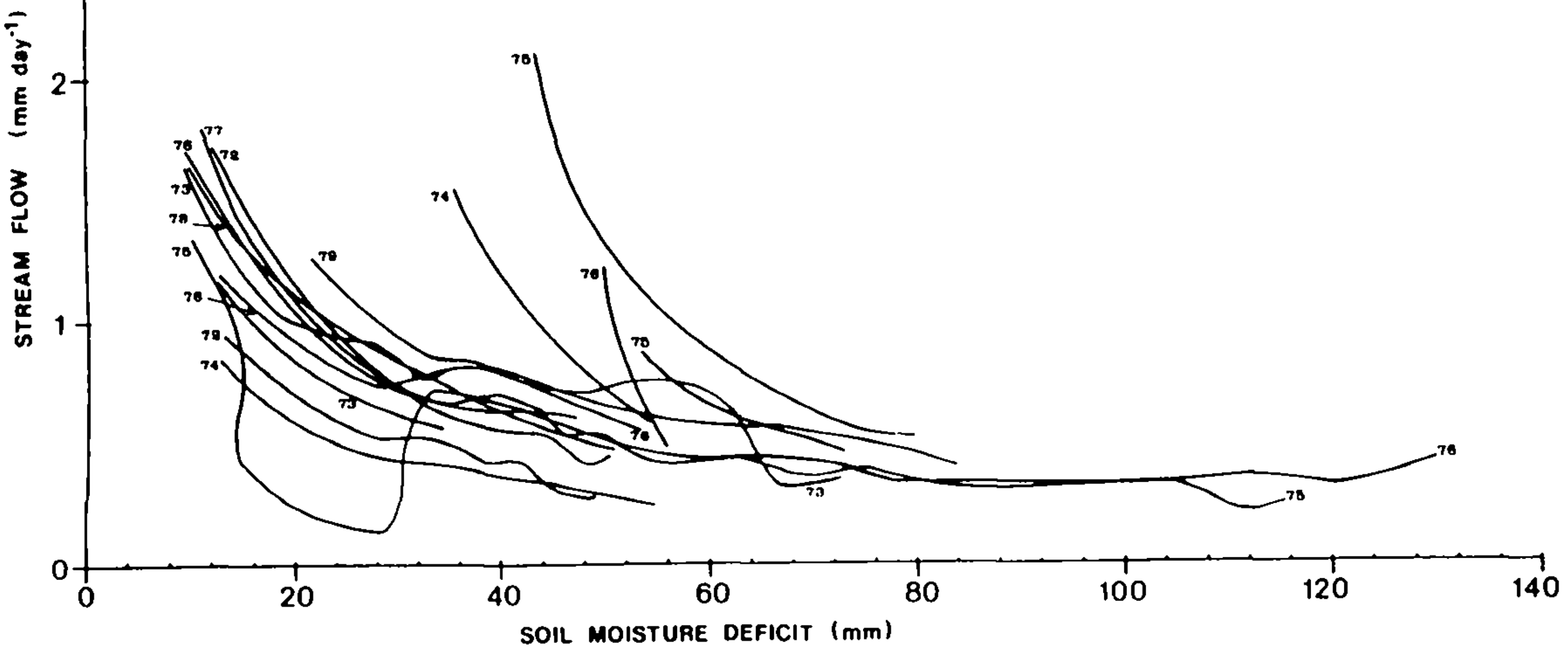

Figure 6.
The relationship between streamflow and predicted SMD for deficits greater than 10 mm for the Severn catchment (62% afforested) over the period 1972 to 1979.

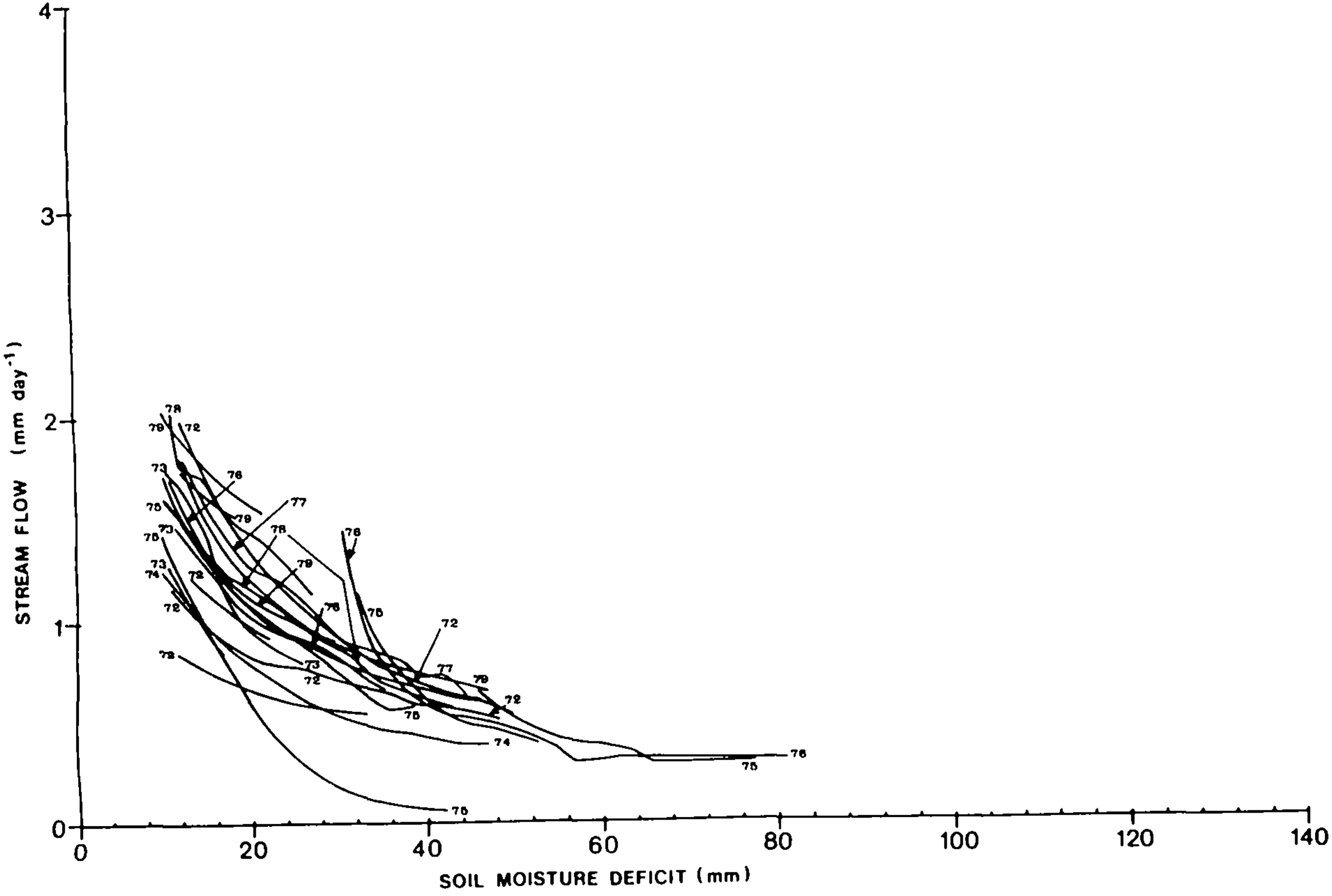

Figure 7.
The relationship between streamflow and predicted SMD for deficits greater than 10 mm for the Wye catchment (rough pasture) over the period 1972 to 1979.

on the interception of rough grassland will continue and probably be expanded with the movement of the equipment to an upland site.

There will be an increase in effort in the modelling of evaporation from upland vegetation in Scotland. The daily interception model will be developed and tested further and a model containing both interception and transpiration components will be applied to data sets from representative sites in Scotland and Wales to provide estimates of the average seasonal distribution of losses and their year-to-year variability.

1986/87

1. Larch

The completion of the snow interception measurements will release equipment and man-power to investigate the water balance, and in particular the interception losses, from Larch. It is proposed to use the gamma-ray equipment in conjunction with plastic-sheet net-rainfall gauges, automatic weather stations and possibly soil moisture observations.

The work could commence in spring 1986 and with the help of the Forestry Commission a start has been made to find a suitable site. One problem is that it has been forestry practice to plant Larch in small blocks within forests of other species. The edge effects associated with these blocks will affect both the humidity structure and the penetration of the turbulence through the open canopy of the Larch. It will be necessary to find an area of Larch plantation large enough for these effects to be considered negligible.

2. Low flows.

We are now in a position to calculate the seasonal evaporative losses from forest and heather. The differences in the losses will affect the flows in dry periods but in a way which is dependent upon catchment characteristics. Upland catchments, however, exhibit a degree of uniformity in soil type, which is often peat-based, and the underlying rock strata which are often impervious. It is therefore expected that it will be possible to identify the major effects of land-use change on low flows with a relatively simple analysis.

The preliminary study described above has shown the existence of a relationship between flow and SMD in dry periods and therefore it ought to be possible to relate the effects of afforestation to low flows through SMD´s which are relatively easily calculated. There are, however, at present a number of unexplained aspects which with further study are likely to provide insight into the mechanisms controlling low flows. It is therefore proposed to extend the study in two areas: first, a more detailed analysis of the relationship between low flow and SMD using existing catchment data and second, an investigation into which regions within a catchment supply the stream flow in dry periods. The use of naturally occurring chemical tracers and monitoring of the water pH are techniques which may be applicable in this second area of study. Funding in the first instance is sought for one year to complete the analysis of catchment data and to perform a feasibility study of the measuring techniques.

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APPENDIX 1

This appendix is the first draft of a paper which has been accepted for publication in Water Resources Research.

GAMMA-RAY ATTENUATION STUDIES OF THE RAINFALL INTERCEPTION CHARACTERISTICS OF SITKA SPRUCE

I.R. Calder and I.R. Wright

ABSTRACT

Various forest canopy characteristics of stands of Sitka spruce (Picea sitchensis (Bong.) Carr.), including canopy density, the aerodynamic resistance and the rates of change of drainage and evaporation with respect to canopy storage, were investigated using direct measurements of canopy mass and water storage. The measurements, made at sites located in Wales and Scotland, utilized the attenuation of a horizontal beam of gamma rays which was arranged to scan through the canopy at different levels. The drainage rate, D, of intercepted water was well fitted by the equation:

$$D = 0.013\ (e^{1.71\ C} - 1)\quad \mathrm{mm\ h^{-1}}$$

where C is the amount of water stored on the canopy (mm). The aerodynamic resistance to a reference level 5 metres above mean tree height was found to be consistent with a value of $3.5\ \mathrm{s\ m^{-1}}$. These results are shown to be generally in good agreement with those obtained from previous interception studies. The aerodynamic resistance value is however lower, and shows less wind speed dependence, than would be expected from conventional formulae which are based on eddy diffusion theory and tree height. The possibility of explaining these discrepances in terms of an additional transport mechanism involving large scale eddies is discussed.

INTRODUCTION

The importance of rainfall interception from forests as a significant component of the hydrological cycle, is now well accepted [Law 1956, Calder 1979, Binns 1980]. Many studies have been reported [e.g. Rutter 1963, Leyton et al. 1967, Stewart and Thom 1973, Rutter et al. 1975, Calder 1976, Singh and Szeicz 1979] and a number of models have been suggested which can perhaps be categorised in terms of either research [Rutter et al. 1971, Calder 1977, Massman 1983] or practical models [Calder and Newson 1979,1980, Gash 1979] for calculating interception losses. The present study is concerned with developing further the research models, particularly those of the Rutter type which use the Penman-Monteith equation for estimating the evaporation rate from the wet canopy. These models are described by the following equations (see Notation):

$$-\frac{dC}{dt} \qquad D - Q \qquad \text{mm h}^{-1} \tag{1}$$

$$\text{where} \quad D = K\,(e^{bC} - 1) \qquad \text{(the drainage function)} \tag{2}$$

$$\text{and} \quad Q = (1-p)R - E_W^{PM} \qquad \text{for } C > S \tag{3}$$

$$Q = (1-p)R - E_W^{PM} \cdot \frac{C}{S} \qquad \text{for } C < S \tag{4}$$

where C = canopy storage, mm

E_W^{PM} = Penman-Monteith estimate of the evaporation from a wet surface ($r_s = 0$), mm h^{-1}

S = canopy storage capacity, mm.

and R = rainfall rate, mm h^{-1}.

Unfortunately although these models can be quite successful in predicting interception losses under average meteorological conditions [see e.g. Calder 1977, Gash et al. 1980] doubts still remain concerning their operation under extremes. These doubts can be attributed to the following considerations.

1) The functional form of the model parameters is not very well known; in particular the relationships between the following are poorly understood:

(a) the canopy drainage rates and the amount of water stored on the canopy,

(b) the canopy drainage rates and windspeed,

(c) the aerodynamic resistance to the transport of water vapour from the vegetative surface to the atmosphere, r_a, and windspeed

and (d) the evaporation rate and canopy storage.

2) The exact values of the individual parameters, when derived using optimisation techniques which fit time sequences of predicted net rainfall intensity ($D + pR$) to observed net rainfall, cannot be uniquely determined because of interdependence between the model parameters [Calder 1977].

3) Most experimental methods for measuring interception losses are liable to large errors at high wind speeds because of the errors involved in the measurement of the precipitation input to the top of the canopy.

4) When precipitation is in the form of snow the error in the measurement of the precipitation input is likely to be particularly pronounced. Also little is known about the process of interception in these circumstances.

Conventional methods for measuring interception loss which rely on comparisons between measured values of precipitation above and below the canopy, when used on their own, are not sufficiently accurate to resolve these problems. However when these methods are used in conjunction with an independent method for determining either the canopy storage or the evaporation rate, much greater progress is possible. From measurements of the change in weight of wet shoots Rutter [1966] was able to independently measure evaporation rates in wet conditions. Similarly

Hancock and Crowther [1979] used displacement transducers to measure the change in weight of wet branches, and Harding and Rosier [1983] adapted a method developed by Roberts [1977] using load cells to measure the changes in weight of cut trees. To a greater or lesser extent each of these methods is subject to the limitations imposed by sampling size and spatial representivity. In principle at least, this limitation can be reduced using a gamma-ray attenuation method for determining canopy densities from which canopy storage and evaporation rates can be inferred.

Experimental method

The gamma-ray attenuation system was based on an original design by the Applied Physics department of Strathclyde University [Olszyczka 1979]. In the original system a collimated beam of 660 keV gamma rays, emitted by a 200 millicurie Caesium 137 radioactive source, was arranged to traverse a horizontal distance of tens of meters through the forest canopy before striking a detector, comprising a 0.3 square meter plastic scintillator attached to a photomultiplier. The source and detector, suspended from towers, were manually winched up and down to allow the beam to scan different levels in the canopy.

Subsequent developments have improved the stability of the detector and increased the data acquisition rate by automating the system and bringing the positioning of the source and detector under computer control. The computer also monitors, and can be configured to control, the temperature of the photomultiplier housing on the detector, measures the count rate of the pulses from the scintillation counter, applies an appropriate dead time correction to the rate and calculates the mass per unit area (M) of material in the beam from solution of the attenuation equation (see Notation):

$$M = \frac{1}{\mu} \log \left(\frac{n - nb}{na - nb} \right) \quad kg\ m^{-2} \tag{5}$$

where μ, the attenuation coefficient for water, is 0.008564 $m^2\ kg^{-1}$ [Hubbell 1969].

In addition the computer interrogates an automatic weather station [Strangeways 1972] to obtain standard meteorological information (solar and net radiation, air teperature and humidity, wind speed and direction) together with gross rainfall recorded with a 0.1 mm resolution tipping bucket and net rainfall measured with a 0.025 mm resolution plastic-sheet net-rainfall gauge [Calder and Rosier 1976]. The computer also pre-processes and performs online calculations of canopy density, drainage rates and estimates of evaporation calculated from the Penman-Monteith equation [Monteith 1965]. A schematic diagram of the present system is shown in figure 1.

Experimental Errors

The resolution and accuracy of the gamma-ray attenuation method for density determinations has been discussed by Clayton and Cameron [1966]. They classified the errors associated with the method into statistical random counting errors, proportional errors, for example errors due to changes in detector efficiency and zero errors caused by zero drift in amplifiers and analysers. For the present system zero errors are insignificant compared with proportional and random counting errors. Proportional errors in the count rate, when the detector housing is controlled at a constant temperature and the system is standardised by reference to count rates in air, are reduced to less than 1%, giving a typical relative error in the density determination of 1% (see Appendix). The relative random counting error with a 20 second counting time was 0.3% which increased the

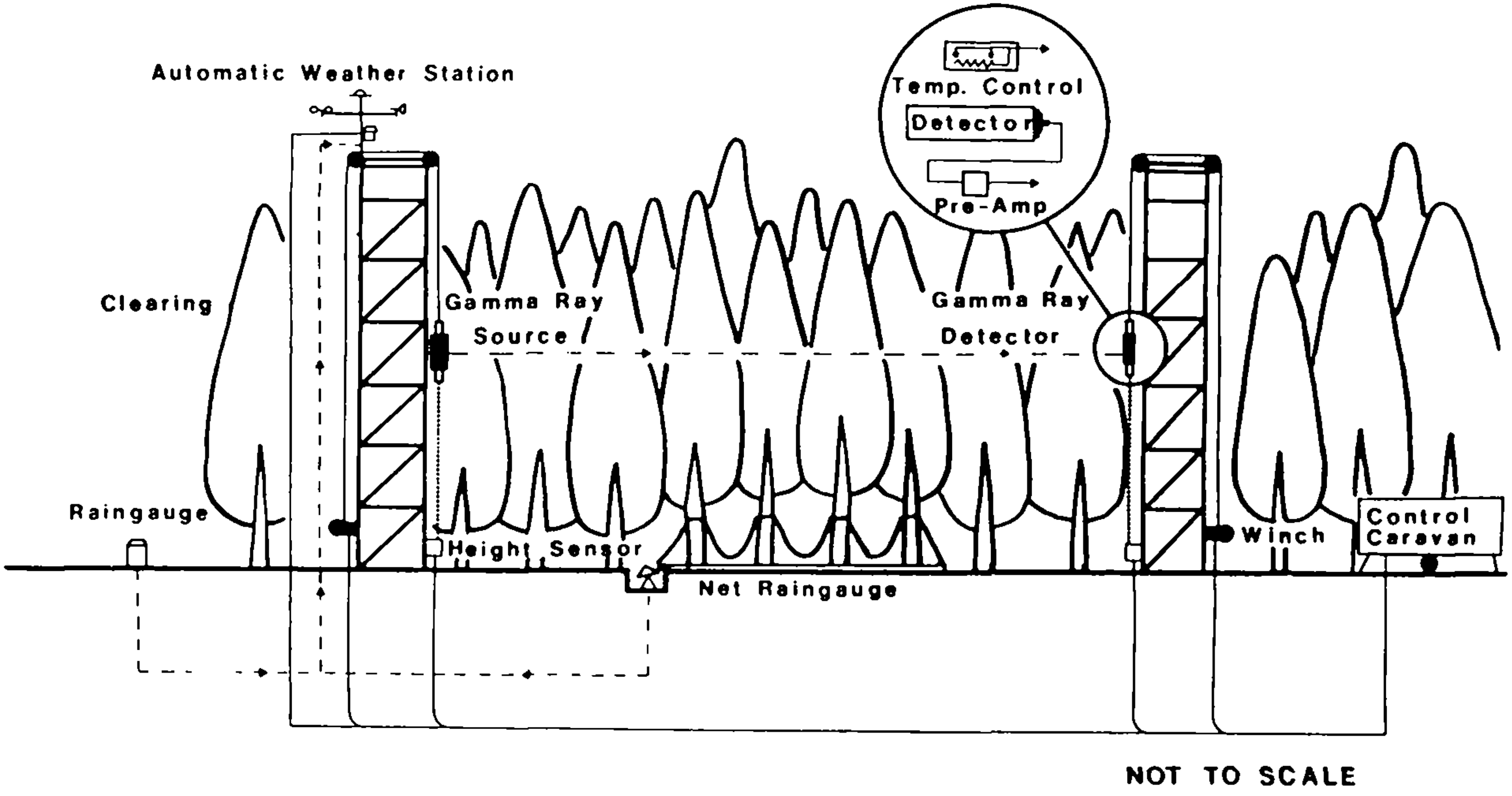

Figure 1. Schematic diagram of the forest gamma-ray attenuation system.

total relative error in the density determination to 1.1%. This represents an absolute density error at one scan level of typically 0.03 kg m^{-3}. If the errors at each level are assumed to be uncorrelated, the error in the measurement of the total mass per unit ground area will then be approximately 0.1 kg m^{-2} giving an error in the measurement of intercepted water of 0.1 mm depth.

Similar calculations can also be performed to calculate the sensitivity and accuracy of the method during conditions when snow is held on the canopy. Measurements of the maximum change in weight of a severed tree during snowfall [Harding and Rosier 1983] indicated depths of snow equivalent to 20 mm of water per unit ground area. With this depth of snow the total relative density error would be 0.7% which would result in an error in the measurement equivalent to a 0.18 mm depth of water.

The resolution, accuracy and general integrity of the system were also investigated experimentally at the Hafren site by carrying out a calibration experiment. This involved placing plywood sheets normal to the standard "air count" beam positioned at a height of 2 meters above the ground surface and mid way between the source and detector. Each sheet had dimensions of 2.44 by 1.22 by .01 meters and a mean weight per unit area of 5 kg m^{-2}. The experiment simulated in all respects the normal operation of the system except that the position of the source and detector were held fixed. The reference count rate with only air in the beam was initially obtained, then, without moving either the source or the detector, the number of sheets in the beam was increased and the new attenuated count rates recorded. The sheets were then removed, the "air count" rate remeasured and the mass per unit area of the sheets calculated with the operational computer analysis program which is based on the conventional attenuation equation (5). Figure 2. shows the results of this procedure which was carried out twice on each of two separate occasions. The calibration was found to

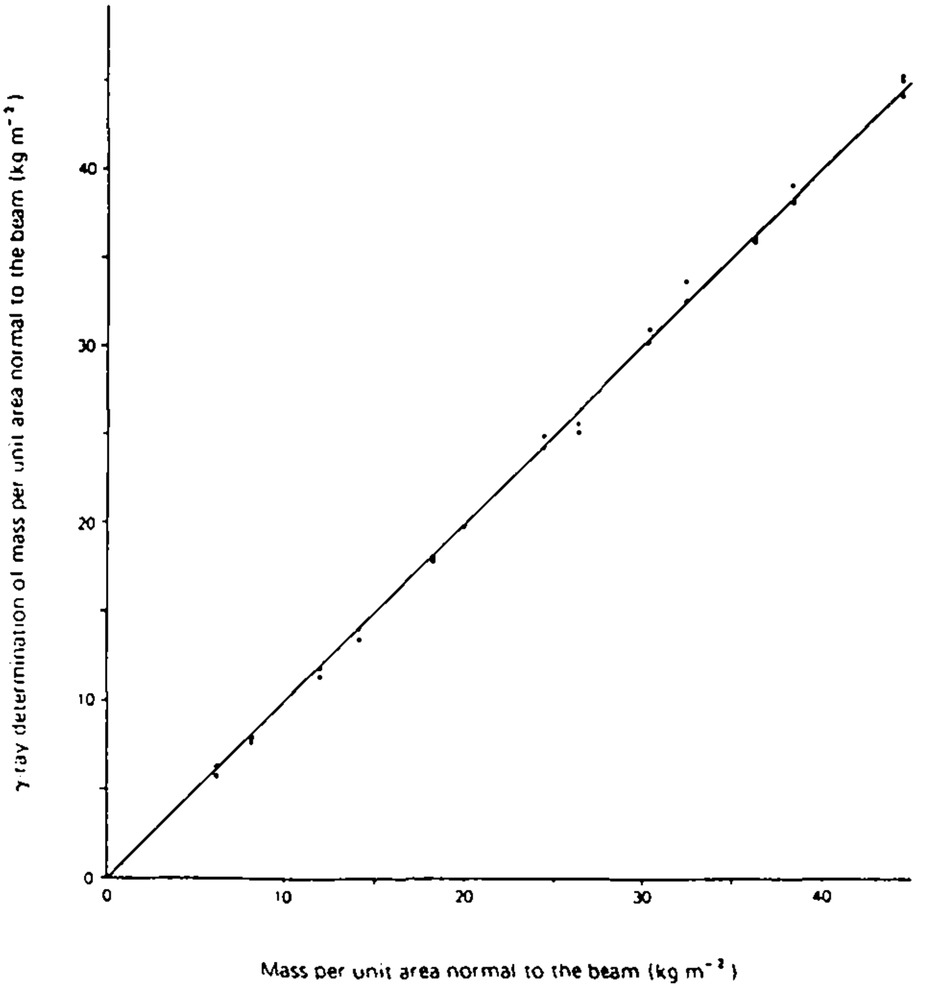

Figure 2. Gamma-ray determination ($\mu = 0.008564\ m^2\ kg^{-1}$) of the mass per unit area normal to the beam of plywood sheets plotted against gravimetric values.

TABLE 1. Forest site characteristics.

	Hafren Forest Site	Queen's Forest Site
Location	Long. 3 40' W., Lat. 52 28' N.	Long. 3 42' W., Lat. 57 11' N.
Altitude (m)	310	345
Tree Species	Sitka Spruce	Sitka Spruce
	[Picea sitchensis (Bong) Carr.]	
Planting Date	1950	1953
Maximum Tree Height(m)	14.5	15
Mean Tree Height (m)	13	14
Mean Tree Girth at chest height (cm)	45	46
Tree Density (stems per hectare)	3900	3100
Beam length from source to detector (m)	40	40
Beam length through absorber (forest) (m)	25	35

RESULTS

CANOPY DENSITY PROFILES

Density profiles of dry forest, measured at one meter height intervals, are shown for both sites in figure 3. At the Hafren site the beam did not intersect any tree trunks so the density profile relates only to the branches and leaves in the canopy and a peak in the profile is observed at the level where the closure of the live canopy occurs. At the Queens forest site the beam intersected both the canopy and three tree trunks and the presence of the trunks accounts for the gradual decrease in density with height; the total density of canopy and trunks per unit area was 26.6 kg m $^{-2}$. (The measured trunk density is not however representative of the forest as a whole as the proportion of tree trunks to horizontal beam area is less than that for the rest of the forest; at chest height the ratio of cross sectional trunk area to ground area is 0.0019 in the beam as compared with 0.0052 for the surrounding forest).

At the Hafren site the total mass per unit ground area of the canopy was found to be 8.0 kg m $^{-2}$. The measurements were obtained over the winter period from December to April, a period during which needle drop would have greatly exceeded new growth and the annual cycle of canopy density would have been expected to be close to the minimum. The measured canopy density value is therefore probably not inconsistent with the higher mean value of 11.0 kg m $^{-2}$ obtained by staff of the Macaulay Institute, Aberdeen [reported by Olszycka 1979] who used harvesting techniques in six different closed canopy stands of Sitka spruce.

WET CANOPY OBSERVATIONS

Changes in the total mass per unit ground area of the canopy, recorded during a typical storm event, at the Hafren site, are shown in figure 4. Consistent increases in the total mass of the wet canopy are recorded following the onset of be stable, reproducible and linear; a regression analysis indicated a value of 0.00859 $m^2 kg^{-1}$ for the attenuation coefficient of the plywood sheets. The attenuation coefficient of cellulose, the principal constituent of wood, is known to be 3% less [see Hubbell 1969] than that of water so the experimentally determined coefficient is perhaps one or two percent higher than expected but is within the error introduced by the uncertainty in the weight, the exact chemical composition and the spatial variation in density of the sheets.

To investigate the possibility of the calibration being sensitive to the position of the sheets in the beam, which would be expected if the primary beam contained a significant number of secondaries scattered from the vegetation or the ground, the sheets were also inserted at intermediate positions, both closer to and further away from the source but no significant differences in calibration were found.

In all subsequent analysis the attenuation coefficient for water (0.008564 $m^2 kg^{-1}$) was used; a small systematic error of 1-2% will therefore be introduced into the calculation of dry canopy densities for which no correction has been made.

DESCRIPTION OF SITES

The results presented here were obtained at two experimental sites; the first was located in the Hafren forest in Mid Wales, the second in the Queens forest near Aviemore in Scotland. At both sites the trees were mature sitka spruce, of a similar age, tree density and height.

At the Hafren forest site the beam was directed mid way between and parallel to the original lines of tree planting. This arrangement had the advantage that beam alignment could easily be set up and checked but had the disadvantage that the portion of the forest canopy scanned by the beam, which lay mid way between the tops of the trees, may have been unrepresentative of the canopy as a whole. A further disadvantage, which later became apparent, was that at high windspeeds, not only was random "noise" introduced into the canopy density measurements as tree branches swayed within the beam but a systematic increase was observed as the tree tops were displaced into the beam. At the Queens forest site the beam was arranged to intersect both the canopy and the trunks of the trees which ensured a more representative canopy sample. As was expected, errors in the measurement of canopy density were much reduced with this system.

Further details of site characteristics are given in Table 1.

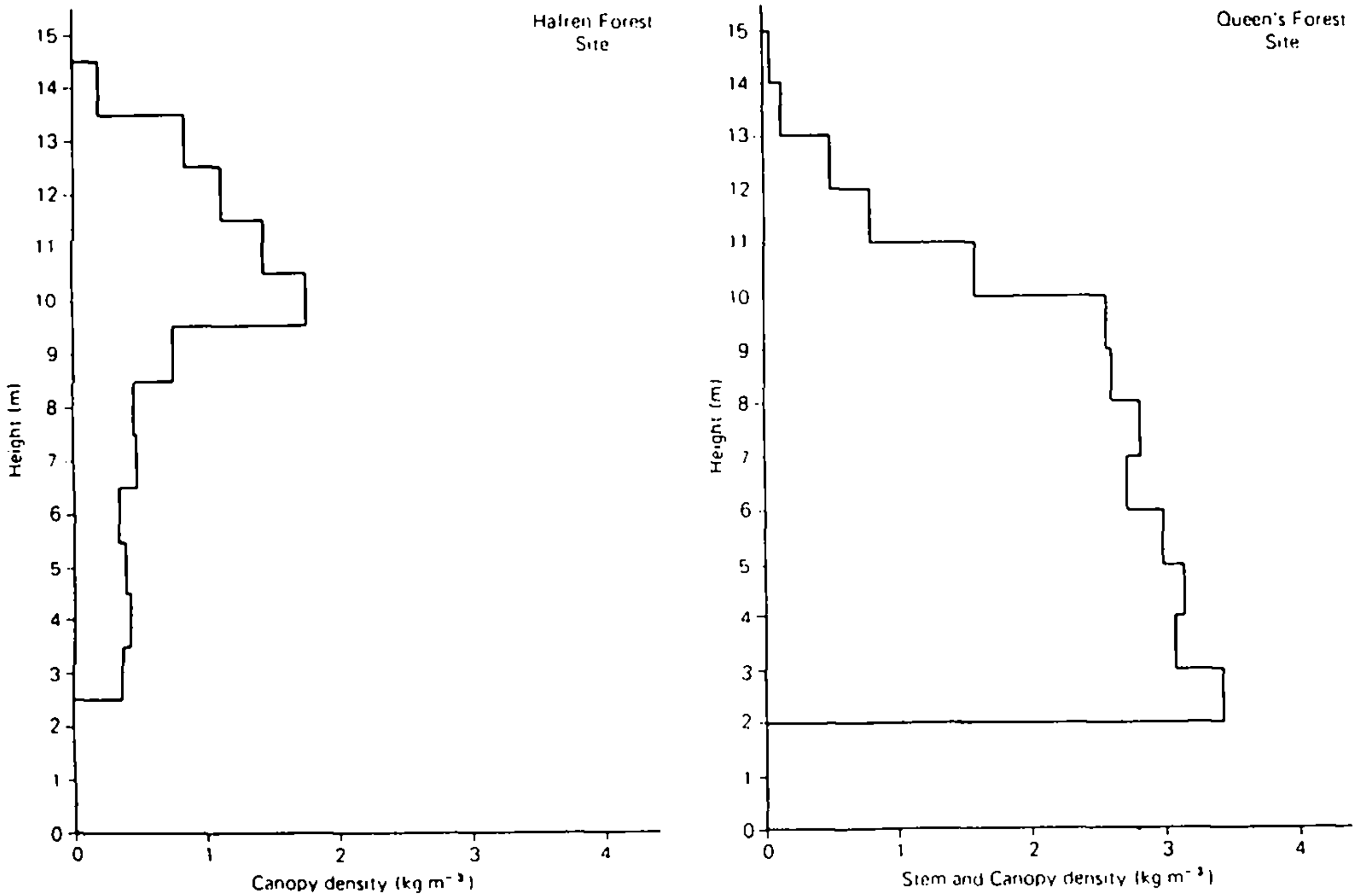

Figure 3. Density profiles under dry conditions, of the forest canopy at the Hafren site and of the stems and canopy at the Queen's forest site.

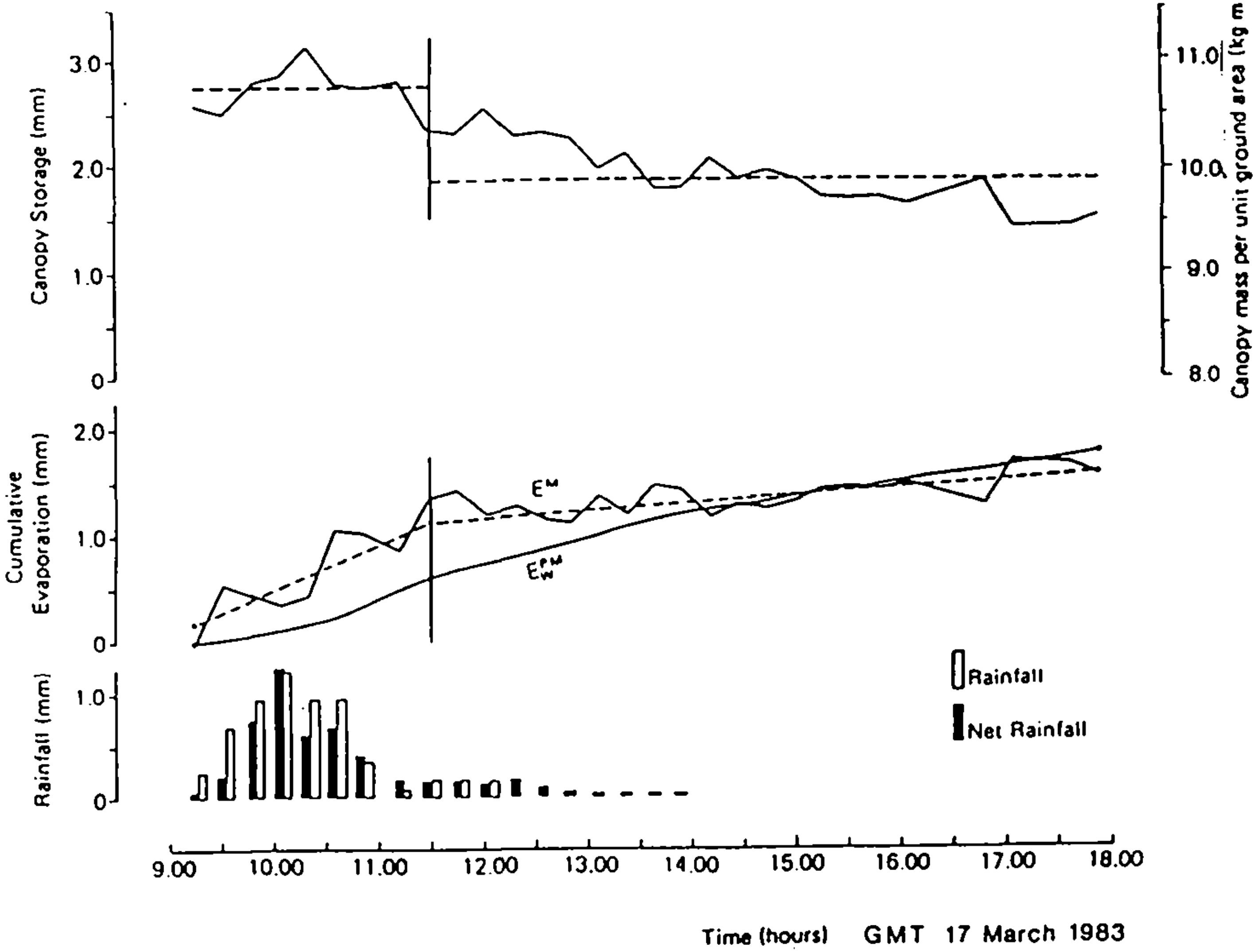

Figure 4. Rainfall, net rainfall, canopy storage, measured evaporation rate, E^M, and calculated evaporation rate, E_W^{PM} ($r_a = 3.5\ s\ m^{1}$), plotted against time. (The dashed lines indicate the average values of C and E^M, over the time periods selected for the subsequent calculation of evaporation rates).

rainfall. These increases, on subtraction of the dry canopy mass per unit ground area (26.6 kg m^{-2}), represent the storage of water on the canopy, which can be expressed more conveniently as a depth of water (mm). Figure 4 also shows that when the canopy storage is in excess of a value of about 2.0 mm, significant net rainfall occurs; this canopy storage value represents what is often (rather crudely) termed the canopy capacity. A more exact description of the canopy drainage characteristics can be given in terms of a canopy drainage function (see below).

Solution of the water balance equation allows evaporation rates from the canopy to be calculated from the difference between the measured rainfall and net rainfall rates minus the rate of change of canopy storage. The cumulative value of the measured evaporation, E^M, together with that predicted by the Penman-Monteith equation, E_W^{PM}, (using a value of $r_a = 3.5$ s m^{-1}) is also shown in figure 4. Both the measured and predicted values demonstrate similar trends, with higher evaporation rates during the early part of the event, reducing to lower rates later. The absolute magnitude of the predicted and measured evaporation rates are 0.28 and 0.38 mm h^{-1} respectively for the first two hours and 0.18 and 0.07 mm h^{-1} respectively for the remaining six hours.

CANOPY DRAINAGE FUNCTION

Six different events have been recorded in which significant drainage occurred and the relationship between drainage rate and canopy storage, for these events is shown in figure 5. The trends demonstrated by each of the events recorded at both the Hafren and Queens forest sites are similar with drainage rates rapidly increasing with increasing canopy storage when the "canopy capacity" value (2.0 mm) is exceeded. Also shown for comparison in figure 5 are the two optimised drainage functions which were previously derived by Calder [1977] by fitting the predicted net rainfall intensity from an interception model to that measured by

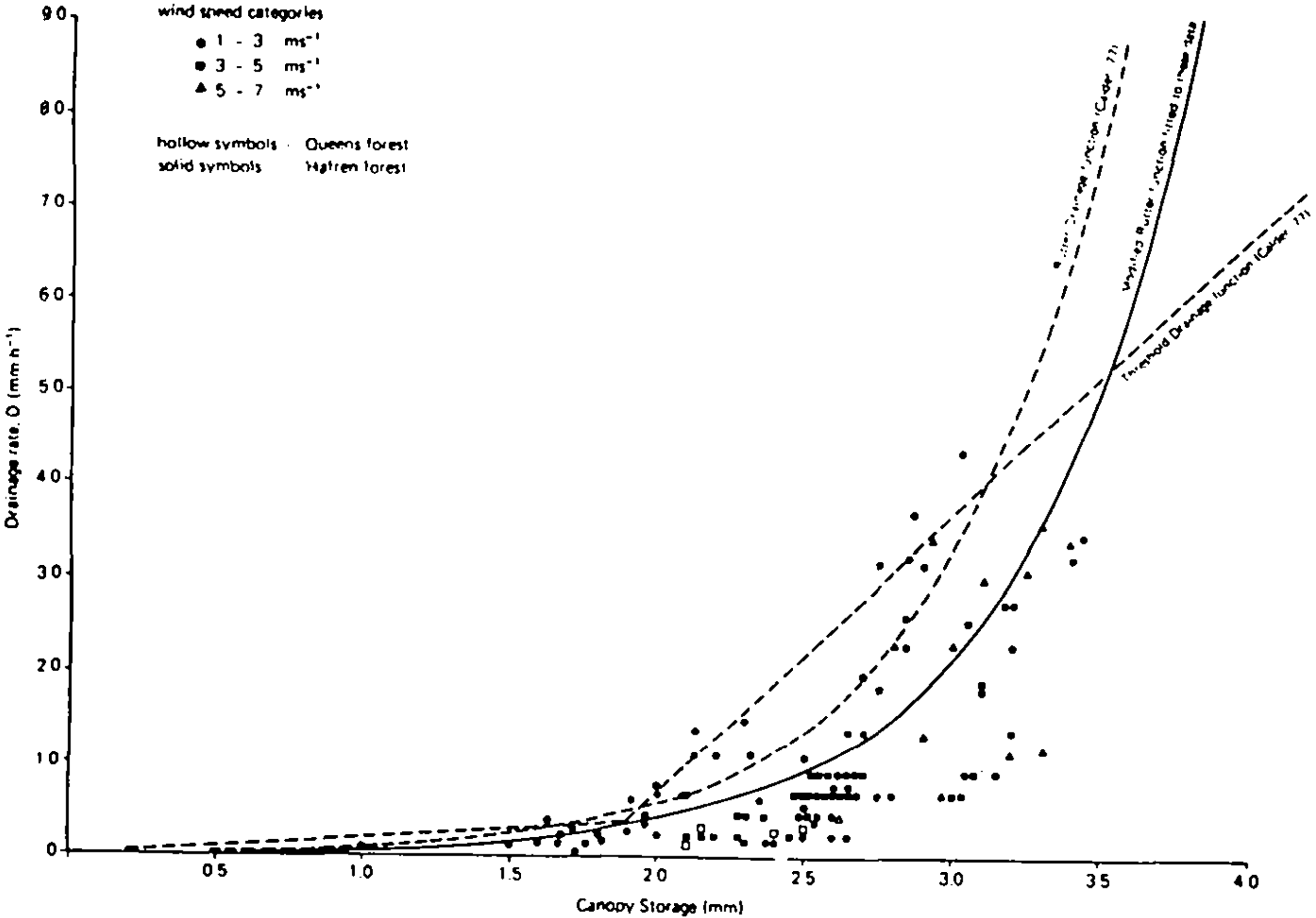

Figure 5. Net rainfall intensity, measured with plastic-sheet net-rainguages at the Hafren and Queens forest sites, plotted as a function of canopy storage together with the fitted drainage function (modified Rutter formula) shown by the solid line. Also shown for comparison are a), the Rutter form of drainage function and b), the threshold drainage function both of which were derived by optimisation methods using only rainfall , net rainfall and meteorological data from a different site in the Hafren forest [Calder 1977].

plastic-sheet net-raingauges at another site within the Hafren forest (predominantly Norway spruce with 10 % Sitka spruce). These functions are given by:

$$D = 0.018\, e^{1.71\, C} \qquad (6)$$

using the Rutter model [Rutter et al. 1971],

and $D = 0.21\, C$ $\quad$ mm h^{-1} $\quad$ for $C < 1.9$ mm $\qquad$ (7)

or $D = 3.2\, C - 5.6$ $\quad$ mm h^{-1} $\quad$ for $C > 1.9$ mm $\qquad$ (8)

using the threshold model [Calder 1977].

Even if the possibility of real site differences is discounted the agreement between the optimised functions and those derived by the gamma ray attenuation method, which involves an independent measurement of canopy storage, is good. However, of the two drainage functions the Rutter formulation appears best able to describe the trend exhibited by the data points. Fitting a modified form of the Rutter function to these data points by a least squares technique gives the following equation. (The modification ensures that no drainage is predicted when canopy storage, C, is zero).

$$D = 0.013\, (e^{1.71\, C} - 1) \quad \text{mm h}^{-1} \qquad (9)$$

EVAPORATION FROM PARTIALLY WET CANOPIES

The description of the evaporation process for conditions when vegetation is only partially wetted has not yet been adequately achieved. Many of the simplifications which allow the evaporation from either totally dry or totally wet vegetation to be modelled as a one dimensional process occurring from a flat surface are not valid in the partially wet situation. From visual obervations alone it is clear that drying takes place first at the top before moving down through the canopy. In these conditions both the mass transfers and the radiant and convective energy exchanges through the different levels of the canopy should, ideally, be taken into account. The situation is further complicated in that transpiration and the evaporation of intercepted water can take place concurrently during partially wet conditions.

Fortunately for practical purposes an exact description is not essential as the calculated interception losses for a storm event are insensitive to the predicted partially-wet evaporation rate except when rain occurs before the canopy has completely dried. The description of the drainage function is more critical as this governs how much water is left on the canopy following precipitation, which is then available for evaporation.

The description of evaporation from a partially wet canopy is nevertheless of great interest from a theoretical standpoint and has engaged the attention of many researchers, see for example Shuttleworth [1976,1977], Monteith [1977], Massman [1980], Sellers and Lochwood [1981], Hancock et al. [1983].

The gamma-ray attenuation method is capable of providing new insights into the interception process. Figure 6 shows the ratio of the measured to predicted evaporation rates, E^M/E_W^{PM}, in relation to canopy storage. The measured evaporation rates were calculated over time periods sufficient to reduce the proportional error to an acceptable value; these periods ranged from 1.5 to 7.5 hours. The ratio of E^M/E_W^{PM} reduces with decreasing canopy storage for values of storage which are less than 2 mm; above this value the observations are consistent with an E^M/E_W^{PM} ratio of unity. The turning point storage value of about 2 mm is close to the "canopy capacity" value at which drainage rates start to become significant (see figure 5). Figure 6 also shows that for canopy storage less than the capacity value the ratio E^M/E_W^{PM} is less than that predicted by the linear relationship with canopy storage that was assumed by Rutter et al. [1971],

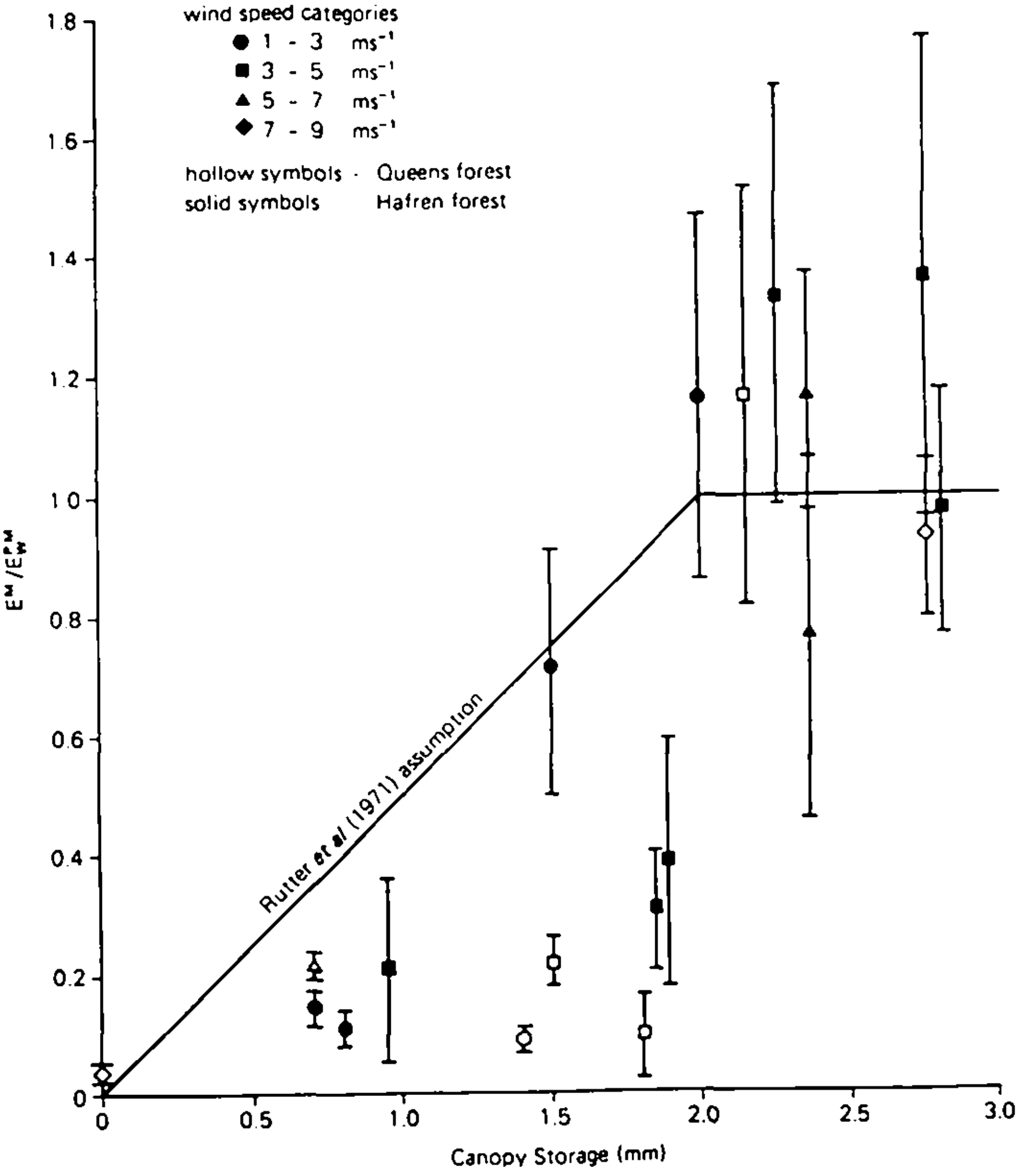

Figure 6. Measured evaporation rate, E^M, divided by calculated evaporation, E_W^{PM} ($r_a = 3.5\ \mathrm{s\ m^{-1}}$), plotted against canopy storage.

equation (4). Application of the Rutter assumption would therefore tend to underestimate the drying time for the lower levels of the canopy. More recent results from the gamma ray system which were obtained in conjunction with profiles of humidity and temperature allow a more detailed study of the process which will be discussed at greater length in a later paper.

DEPENDENCE OF DRAINAGE PARAMETERS ON WINDSPEED

The range of mean windspeeds recorded during operation of the gamma-ray system was from 1.5 to 8.0 $m\ s^{-1}$. Different symbols identify the windspeed ranges associated with the canopy drainage rates versus canopy storage points shown in figure 5. There is no indication from these results that drainage rates are significantly influenced by windspeed. Although considerable scatter exists in the relationship between drainage rate and canopy storage, much of it can be explained in terms of uncertainty in the measurement of the wet canopy mass per unit ground area which will be typically of the order of 0.1 mm depth of water equivalent and also in the dry canopy determination which will be of a similar magnitude. Few actual observations of the effects of windspeed on water retention by canopies have been presented other than in the present study and in the work of Perttu et al. [1980] who also reported only a weak dependence of drainage rates on windspeed. Clearly the modelling of forest interception losses is much simplified if windspeed dependence can be discounted.

DEPENDENCE OF AERODYNAMIC RESISTANCE ON WINDSPEED

Conventional eddy diffusion theory [see Monteith and Szeicz 1962] indicates that the aerodynamic resistance for momentum, heat or vapour transport from vegetation to a reference height z can be obtained (when the corrections for excess resistance and stability have been applied [see Thom 1972, Stewart and Thom 1973]) from the equation:

$$r_a = \frac{1}{k^2 u} \left[\log \left(\frac{z - d}{z_0} \right) \right]^2 \ s\ m^{-1} \quad (10)$$

where an inverse relationship between aerodynamic resistance and windspeed, u, applies. Rutter et al. [1975] assumed that for wet forests the corrections for excess resistance and stability were mutually compensating and suggested that aerodynamic resistance (to heat and vapour transport) could be calculated from the above equation with the roughness length, z_0, and the zero plane displacement, d, estimated from mean tree height, h, ie:

$$z_0 = 0.10\ h \quad (11)$$

$$d = 0.75\ h \quad (12)$$

For the Hafren site, where the majority of the results were obtained, h was 13 m and z, the height at which windspeed was measured, was 18 m. For $u = 3.75\ m\ s^{-1}$, the mean windspeed recorded during saturated conditions for the periods shown in figure 6, the calculated aerodynamic resistance (equation 10) is $5.4\ s\ m^{-1}$. Clearly application of this formula would result in much lower values of E_W^{PM} and higher E^M/E_W^{PM} ratios which are generally more divergent from unity than those shown in figure 6 (where $r_a = 3.5\ s\ m^{-1}$). For the range of windspeeds observed, which vary by a factor of four, this theory would also predict that the values of E_W^{PM} and E^M/E_W^{PM} would vary by a similar factor; even though the uncertainties in the E^M/E_W^{PM} ratios are large they clearly could not encompass such a variation. Indeed there is no indication that the scatter in the data points is correlated with windspeed.

(Although no strong wind dependence has been shown in these results it would of course be incorrect to assume that wind is unimportant to the evaporation process. Only if wind driven mixing is taking place (either by eddy diffusion or large gust penetration) will it be possible for dry air to be brought down from the atmosphere to canopy level to maintain the significant humidity deficits, which are necessary for the evaporation process.)

DISCUSSION AND CONCLUSIONS

Conventional interception studies rely on estimates of rainfall input to the top of forest canopies and net rainfall beneath. In windy upland areas the errors involved in using measurements of rainfall from a small forest clearing (as is usual practice) to estimate the above canopy rainfall, are difficult to quantify but may well exceed the errors in the net rainfall measurement. A major advantage of the gamma-ray attenuation method is that evaporation rates of intercepted water can be determined without reliance on an estimate of the above canopy precipitation; the method is therefore capable of providing an independent means of verifying the results of conventional interception studies.

The majority of the results from the gamma-ray attenuation system are in good agreement with generally accepted interception theory. In particular they confirm :

a) the high rates of evaporation, which can be of the order of 0.2 - 0.5 mm h^{-1} that are implied by conventional studies, see for example Calder [1976], Gash et al. [1980];

b) that for average wet time conditions, the aerodynamic resistance to the transport of heat and water vapour from spruce to a reference level 5 m above the mean tree height is well represented by the value of 3.5 s m^{-1} which was originally derived by optimisation methods using only measurements of rainfall, net rainfall and meteorological observations, Calder [1976];

c) that a modified form of the Rutter drainage function provides a reasonable representation of the relationship between drainage and canopy storage. Fitting the (modified) Rutter drainage function to the results from the Hafren and Queens forest gives:

$$D = 0.013 \left(e^{1.71\,C} - 1 \right) \quad \mathrm{mm\ h^{-1}} \tag{13}$$

The results do however suggest that in certain areas improvements to theory may be possible. They indicate that for canopy storages less than the capacity value, the proportional relationship between E^M/E_W^{PM} and canopy storage that was assumed by Rutter, will overestimate evaporation rates in partially wet conditions.

Although the possibility of genuine site differences within vegetation types makes the detailed comparison of the aerodynamic resistance results obtained using different methods both difficult and confusing there is, nevertheless, increasing evidence to suggest that a genuine disagreement between methods exists. The results obtained from the gamma-ray system, together with water balance interception studies in tropical rainforest [Calder et al. 1985] and results from other recent non-micrometeorological studies reported by Calder [1977], Hancock et al. [1979], Hancock et al. [1983], Calder et al. [1984] and Wallace et al. [1984] are generally mutually consistent within vegetation types but tend to be at variance with estimates derived from considerations of vegetation height and eddy diffusion theory and (or) with measurements made using micrometeorological methods (eddy correlation [Wallace et al. 1984], Bowen ratio [Miranda et al. 1984]). The reasons for these differences are not yet understood but the non-micrometeorological methods should not be dismissed solely on the grounds of inconsistency. They have the advantage that the calculation of aerodynamic resistance is inherently simpler and requires fewer assumptions than either the theoretical or the micrometeorological methods. Furthermore, the errors associated with the non-micrometeorological methods, although on occasions very large, can usually be identified as such. Real site differences may be partially resposible for the discrepancies: the non-micrometeorological methods have often been used in topographically rough hilly upland areas, whereas the micrometeorological methods have, of necessity, only been used in fairly flat locations.

For the purposes of calculating interception losses from short crops (eg. grass and heather) these discrepancies may not be important as predicted losses are only weakly dependent on aerodynamic resistance [Harding 1983 (personal communication), Wallace et al. 1984]. However, for trees, aerodynamic resistances are an order of magnitude less and interception losses are closely related to aerodynamic resistance: it is therefore necessary, both for practical and theoretical reasons, to resolve these differences.

The differences are manifest both as differences in magnitude and in windspeed dependence; the non-micrometeorological methods give values which are smaller and which tend to show less windspeed dependence than those of the other methods.

Lysimetric measurements of the aerodynamic resistance of heather at a hilly upland site in Scotland [Calder et al. 1984] suggested an inverse relationship with a power of 0.6 to 0.8 as compared with the theoretical value of unity. However, Wallace et al. [1984], who also used a lysimetric method, found a windspeed dependence for heather at a relatively flat site in North Yorkshire that was consistent with the theoretical value. For forests no clear windspeed dependence has been identified in either the present study or previous studies which involved water balance and interception modelling exercises, [Calder 1977, Calder and Wright 1985]. The lack of dependence may, however, be partially explained if "streamlining" of the canopy at high windspeeds is significant [Fraser 1962], or if the boundary layer resistence is altered at high windspeeds by a change in flow regime from one in which the flow passes through leaf shoots to one in which the flow is predominantly around the shoots (Grant 1983,1984). The existence of another transport mechanism (discussed below), in addition to eddy diffusion, may also tend to reduce the apparent wind dependence if this other mechanism is not functionally related to wind velocity.

The present results, the results of the previous interception modelling exercise, tropical rainforest interception studies [Calder et al. 1985], the forest aerodynamic resistance measurements of Hancock and Crowther [1979] and measurements of the aerodynamic resistance of heather [Calder et al. 1984a] all indicate aerodynamic resistances which are significantly lower (and evaporation rates higher) than would be expected from considerations of vegetation height and eddy diffusion theory. A transport mechanism operating in conjunction with eddy diffusion would provide a suitable explanation. Such a transport mechanism, which invokes the transport of heat and vapour by large scale eddies or gusts which penetrate the canopy, essentially a piston flow displacement, has been shown by Denmead [1984] to be a significant transport process at Uriarra forest (Australia); Crowther and Hutchings [1983] have also reported the presence of similar large scale eddies at Rivox forest in Scotland. The presence of these large scale eddies, which in hilly upland areas may well be associated with or enhanced by the local topography, might also explain the larger discrepancies with theory which are also observed for heather at an upland Scottish site as compared with a relatively flat site in East Anglia, see Calder et al. [1984b]. Clearly further studies are required to investigate this important phenomenon.

NOTATION

b	drainage parameter, mm $^{-1}$.
C	canopy storage, mm.
d	roughness length, m.
D	canopy drainage rate, mm h $^{-1}$.
E^M	measured evaporation rate, mm h^{-1}.
E_W^{PM}	Penman-Monteith estimate of evaporation from a wet surface ($r_s = 0$), mm h $^{-1}$.
h	tree height, m.
I_1	unattenuated gamma-ray flux at unit distance from the source, gamma-rays per second.
I_r	gamma-ray flux at distance r from the source, gamma-rays per second.
k	von Karman's constant, 0.41.
K	drainage parameter, mm h $^{-1}$.
M	mass per unit area, kg m $^{-2}$.
n	dead time corrected count rate of the gamma-ray beam attenuated by the forest canopy, s $^{-1}$.
na	dead time corrected count rate in air, s $^{-1}$.
nb	dead time corrected background count rate, s $^{-1}$.
p	"free throughfall" fraction, dimensionless. (For both sites considered in this study p is effectively zero).
Q	net input of water to canopy storage, mm h^{-1}.
r	distance from the source, m.
r_a	aerodynamic resistance to the transport of water vapour, s m $^{-1}$.
r_s	surface resistance to the transport of water vapour, s m $^{-1}$.
R	gross rainfall rate,mm h $^{-1}$.
S	canopy storage capacity, mm.
S_r	detector sensitivity, dimensionless.

u	wind speed, $m\ s^{-1}$.
z	height at which wind speed is measured, m.
z	zero plane displacement, m.
μ	attenuation coefficient for water, $m^{2}\ kg^{-1}$.
ρ	density of a homogeneous absorber, $kg\ m^{-3}$.

APPENDIX to APPENDIX 1

Calculation of statistical counting errors and proportional errors as a function of beam length.

If a homogeneous absorber of density ρ and attenuation coefficient μ is placed between a point source of gamma-rays and a detector, at distance r from the source, the flux of gamma-rays observed at the detector is given by:

$$I_r = \frac{I_1}{r^2} e^{-\mu\rho r}$$

where I_1 is the unattenuated flux at unit distance from the source. The sensitivity of the detector, S_r, at distance r is then given by

$$S_r = - \frac{\partial I_r}{I_r} \cdot \left(\frac{\partial \rho}{\rho}\right)^{-1} = \mu\rho r$$

on rearranging, the relative error in density determination is then given by:-

$$\frac{\partial \rho}{\rho} = - \frac{1}{\mu\rho r} \quad \frac{\partial I_r}{I_r}$$

If "dead time" effects in the analyser and rate scaler can be neglected the error in the count rate due to statistical counting errors is equal to the square root of the count rate and thus:

$$\left(\frac{\partial\rho}{\rho}\right)_{r,\ \text{statistical}} = \frac{1}{\mu\rho r} \cdot \frac{r e^{\mu\rho r/2}}{\sqrt{I_1}}$$

$$= \frac{e^{\mu\rho r/2}}{\mu\rho\sqrt{I_1}}$$

For errors which are proportional to the count rate, i.e. $\partial I_r = \subset I_r$, the relative error in the density determination is given by:-

$$\left(\frac{\partial\rho}{\rho}\right)_{r,\ \text{proportional}} = \frac{\subset}{\mu\rho r}$$

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APPENDIX 2

FURTHER INTERCEPTION STUDIES OF HEATHER USING A WET-SURFACE WEIGHING LYSIMETER SYSTEM

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ABSTRACT

Measurements have been made of the four canopy parameters required by Rutter type interception models for heather (Calluna vulgaris). The values obtained are 5.13 and 0.00085 for the drainage parameters b and k respectively, (0.13 ± 0.09) for the free throughfall coefficient p, and values of (1.1 ± 0.1) mm and (0.85 ± 0.1) mm for the canopy capacity S, derived from independent drainage and evaporation experiments respectively. It is suggested that the difference between the two values of S is significant and represents a real difference between the canopy storage at which drainage ceases and the smaller canopy storage necessary for a completely wet canopy. Studies of the wetting behaviour of heather provide evidence to support this hypothesis.

INTRODUCTION

The continuing afforestation of Scottish catchments, where the indigeneous vegetation is predominantly heather (Calluna vulgaris), has prompted the development of operational catchment response models for water resource management. These models themselves require inputs from physically based research models of the interception process. Of these, that due to Rutter et al (1971), (1975) and Rutter and Morton (1977) has been successfully employed, either in its orignal form or with slight modifications, by several workers (Calder 1977, Gash and Morton 1978, Gash et al 1980) to model the interception process in coniferous forest.

A full description of this model can be found in the references cited. For the present purpose it can be adequately summarised by the following equations which describe a version used by Calder et al (1980), (see also Perttu et al 1980) and Calder and Wright (1985) in which the water balance of the stems is included implicitly:

$$\frac{dC}{dt} = (1-p)R - k(\exp[bC] - 1) - E.\frac{C}{S} \qquad \text{for } C < S,$$

$$\frac{dC}{dt} = (1-p)R - k(\exp[bC] - 1) - E \qquad \text{for } C > S,$$

where in consistent units C is the canopy storage, R is the rainfall rate and E is the evaporation rate calculated from the Penman-Monteith equation (Monteith 1965) for a thoroughly wet canopy. The canopy parameters are: p, the free throughfall coefficient; S, the canopy storage capacity and k and b the drainage parameters. To apply the model to different species requires only the determination of the canopy parameters for that species. An accurate knowledge of the drainage parameters, and of the relationship between canopy storage and evaporation rate, may be of greater importance for modelling heather than conifers since the major part of interception loss from heather is likely to occur after rainfall has ceased. For conifers, because of their greater aerodynamic roughness a major part of the interception loss occurs during rainfall (in mid-Wales it is the major part: see Calder 1982). The following sections describe the measurement of the parameters for heather.

EQUIPMENT AND EXPERIMENTAL PROCEDURE

Apart from minor revisions described later, the equipment used was that described by Calder et al (1984) and more fully by Calder et al (1982). Briefly, a Sartorius balance monitoring the evaporative flux from a wet heather sample was interrogated by a Pet microcomputer which also interrogated an array of meteorological sensors at half-minute or minute intervals.

The experiments were performed in October and December 1983 in a large area of flat heathland, with a fetch in all directions of at least 0.5 km, at Berner's Heath, Norfolk (52° 21' N, 0° 38' W). The six-year-old stand of heather, from which representative samples were chosen was almost a monoculture and had a ground cover of (90 ± 5) % and a mean height, determined from a 63 point transect, of (0.32 ± 0.09) m.

The samples were 45 cm wide and 68 cm long and of two types: 1) a natural sample (NS) comprising heather plants and the top 10 cm of soil, prepared simply by digging around and beneath the sample and trimming off the surplus soil, and 2) heather plants supported by a paraffin wax substrate. Three of these artificial samples (AS1, AS2 and AS3) were prepared as follows:

A plastic, sample-sized rectangular mould was placed around a representative patch of heather and gaps between the mould and the soil were sealed with modelling clay. Waxoyl, a viscous solvent-based wax, was sprayed on the soil and litter layer avoiding contact with the heather leaves and stems and left to dry. Aluminium tubes were then pushed partly into the soil along the long axis of the plot to provide the base with drainage holes. A domestic washing boiler was used to melt paraffin wax which was carefully poured into the mould and allowed to solidify making a continuous seal over the soil, except at the sites of the drainage holes. (The Waxoyl prevented the litter and sandy soil absorbing large quantities of the liquid paraffin wax.) To ensure that water would drain rapidly from the heather into the drainage holes further wax was added, up to the top of the aluminium tubes, to produce a base of "V" shaped cross-section. This was created by digging around and beneath the samples and tilting them so that when additional wax was added a surface was formed at an angle to the existing wax surface; the method is illustrated in Fig. 1. Each sample took between 20 and 25 kg of wax. When the wax had solidified completely the mould was removed and the soil and heather roots were cut off the bottom of the wax.

After preparation of the samples, measurements commenced immediately and extended over a period of a few days. Visual checks of the canopy revealed no detectable leaf fall or canopy degeneration even over a period of two weeks.

Measuring the drainage rate

The wax-based samples were used in conjunction with a special drainer tray which supported the samples, flush with the surrounding heather, on top of the balance which was located in a pit. The drainer tray was designed to allow the water to flow rapidly off the sample and balance so that the drainage rate measured was controlled only by the drainage function of the heather.

The construction of the tray was of sheet aluminium braced with "L" shaped aluminium strip, to provide rigidity and support for the wax bases of the samples, and two lengths of plastic guttering held at an angle with their lower ends overlapping the short sides of the base by about 3 mm. Short lengths of wire attached to the lips of the guttering acted as drip sources to prevent water running back under the base of the tray. When the wax samples were in situ the holes in their bases were aligned so that water draining through them would fall into the guttering and thence drain rapidly off the tray.

Drainage runs were performed at night to minimise evaporative loss of water. The microcomputer interrogated the balance about once a second and meteorological sensors at half minute intervals. The mass readings were averaged over the period between sensor scans and these together with the meteorological data were stored on disc for later analysis. Sample AS3 was sprayed using a garden sprayer set to provide a high intensity until the heather was thoroughly saturated and the drainage process had attained equilibrium. The mass of the sample was monitored prior to and during spraying and throughout the subsequent drainage period.

To determine the drainage characteristics of the wax base and drainer tray the procedure was repeated but with water sprayed only beneath the heather directly onto the wax. The very rapid change in drainage rate made it necessary to print out the mass readings as the balance was monitored at intervals of 1.2 seconds.

Measuring the evaporation rate as a function of canopy storage

For this measurement the samples were held in the trays, essentially insulated glass-fibre boxes, described by Calder et al (1984). These ensured that water draining off the heather was retained on the balance so that the measured loss of mass was due solely to evaporation. Measurements were made with both types of sample which, when in situ, were flush with the surrounding heather. The samples were initially weighed dry, then sprayed until canopy saturation was achieved; the cessation of spraying was carefully synchronised with the timing of the monitoring program. The system continued to record both the mass of the sample and the meteorological variables at minute intervals while the canopy dried. Rainfall on one day made it possible to run the experiment under naturally wet conditions after the rain had ceased.

Estimating the throughfall coefficient

Colour slide photographs of the artificial samples were taken looking vertically downwards and a slide projector used to project images of the samples onto a 100 cm x 100 cm grid. The number of squares in which the white wax was visible then gave an estimate of p.

RESULTS

The heather

The results of an analysis of four representative 0.25 m^2 samples are given in Table 1. The Leaf Area Index (LAI) on a projected area basis was calculated from measurements using a leaf area meter (Model LI-3100, LI-COR Inc., Lincoln, Nebraska, USA). (Following Mackerron (1971), the LAI for the total leaf surface area results from multiplying the value in Table 1 by four.) The stem surface areas were calculated from the mean dimensions of stems and branches.

The drainage measurements

Curve A in Fig. 3 shows the decrease with time of the amount of water held on artificial sample AS3 for two consecutive runs. Within experimental limits the points from the two runs are indistinguishable, despite the second run occurring when the mean windspeed was 4.8 m/s compared with 2.8 m/s for the first run. There is, therefore, no evidence for a windspeed dependence of drainage rate.

The data of curve A have been compensated for evaporative loss to show, as curve B, the decrease in the amount of water on the canopy through drainage only. The evaporation rates were calculated using the Penman-Monteith equation with an aerodynamic resistance (r_a) calculated from the relationship

$$r_a = (68 \pm 9)/\ u \qquad (1)$$

where u is the mean windspeed. This relationship was obtained from a series of measurements made at Berner's Heath using the same procedure as described by Calder et al (1984). Curve B shows that all significant drainage had stopped at a total storage value of (1.2 ± 0.1) mm.

Drainage rates calculated from successive masses and compensated for evaporation rates are plotted in Fig. 4 versus the total equivalent depth of water ($C_t = C + C_w$) held on the heather canopy, wax base and drainer tray.

A simple iterative least squares algorithm, which assumed that the measured drainage rate D_w was given by

$$D_w = k''(\exp[b''C_t] - 1), \qquad (2)$$

was used to fit the data; the definition and values of k" and b" are given in Table 2 and the function is plotted as curve X in Fig. 4.

The drainage run on the wax and tray only (see Fig. 5), revealed that drainage was immediate and rapid, provided the equivalent depth of water on them exceeded about 0.1 mm. This was the quantity of water retained, when drainage had ceased, in small depressions on the wax surface where it touched the heather stems; no water was retained on the tray. The function

$$D = k'(\exp[b'(C_w - 0.1)] - 1), \qquad (3)$$

was fitted to the data using the least squares algorithm giving the parameter values shown in Table 2.

Since, for the drainage runs on the heather, the recorded masses include the mass of the water running over the wax and tray, it is necessary to use both (2) and (3) to determine the drainage function of the heather only. The algebra is given in the Appendix and the results, the drainage parameters for the heather canopy, are given in Table 2. The drainage function using these parameters is plotted as curve Y in Fig. 4.

Measurements of E/E_p and free throughfall coefficient

The variation of evaporation rate with canopy storage is shown in Fig. 6 which presents the results from a series of runs with three artificial samples and one natural sample. The results from just one run, using AS2, are shown in Fig. 6a where the ratio of the observed evaporation rate E, to the potential evaporation rate E_p, from wet heather in the same weather, is plotted versus the canopy storage C. The values of E were determined from the recorded masses which had been smoothed, to reduce the wind-induced random errors using the method of a linear moving average (11 point) which has been described elsewhere (Calder et al 1984). E_p values were calculated from the Penman-Monteith equation using the recorded meteorological data and r_a's given by equation (1). An allowance for drainage was made using the drainage function to give the true canopy storage C.

Figure 6b shows the results from all the runs in a simplified form in which, for most of them, just two points are plotted. They are first, the canopy storage at which E/E_p began to decline which, according to Rutter et al (1971), occurs at the canopy capacity S, and second, the average value of E/E_p determined for the period when the canopy storage was less than S. These points were obtained from two intersecting straight lines, as indicated in Fig. 6a, for each run. The point of intersection coincides with E/E_p at S and the midpoint of the sloping line is taken as the average value of E/E_p for $C < S$. An estimate of the uncertainties attached to each point, shown as error bars, was derived from the spread of the data either side of the lines.

For four runs it was only possible to fit one line to the data: three were terminated before the canopy storage had decreased as far as S (points representing E/E_p at the smallest value of C measured are shown in the figure by points with pecked lines to the left of the error bars) and the fourth run, using AS2, followed rainfall which did not completely wet the canopy. However, it has been possible to derive a value of S for this run by projecting its sloping line to intersect the line $E = E_p$.

With this one exception all the data were collected from runs when the samples were artificially wetted by spraying and therefore surrounded by an expanse of dry or partially dry heather. Thus for the spray runs, the values of E/E_p are likely to be overestimates since the measured evaporation rates were due to three-dimensional vapour fluxes whereas E_p is calculated on the basis of a one-dimensional flux. Runs with the natural sample may have another compensating systematic error arising from an allowance made for the evaporation from the soil. For these reasons the absolute magnitudes of E/E_p cannot be used to obtain E/E_p as a function of canopy storage.

The spray runs using sample AS2 gave systematically higher values of E/E_p than the other samples which probably reflects the differences between them in canopy density and morphology. All the samples were selected as representative of the patch of heather in which they were growing, but there was inevitably some variation between them. No measurements were made of the

LAI of the samples; however an indication of the relative densities is given by the free throughfall coefficients which were measured for three of the samples. These indicated that the density of AS2 was greatest with $p = (0.04 \pm 0.02)$ followed by the natural sample, $p = (0.08 \pm 0.03)$, and AS1, $p = (0.25 \pm 0.1)$. The throughfall coefficient for AS3, estimated by comparison with the other samples, was about 0.15. Taken together, the samples provided a good representation of the heather growing at Berner's Heath with a mean free throughfall coefficient of (0.13 ± 0.09) and for which there is a capacity S with a mean value of (0.85 ± 0.1) mm below which the ratio E/E_p declines.

DISCUSSION AND CONCLUSIONS

The drainage experiments demonstrated that the drainage rates from a heather canopy are well described by an exponential function the form of which, for a representative sample of the six-year old heather growing at Berner's Heath, is

$$D = 0.00085\ (\exp[5.13C\ ] - 1). \tag{4}$$

There was no evidence from the two drainage runs, at 2.8 and 4.8 m/s, of a windspeed dependence and this agrees with the findings of Calder and Wright (1985) for spruce; however, it is obvious that further measurements are required before it can be concluded that the drainage rate is independent of windspeed.

The drainage experiments also showed that all significant drainage had ceased at a total storage of (1.2 ± 0.05) mm or, correcting for the water retained on the wax, a canopy storage of (1.1 ± 0.1) mm. This value can be equated to the canopy capacity, defined as the amount of water stored on the canopy (including the stems) when rainfall and drainage have ceased in still air (see Zinke 1967). This definition was assumed by Leyton et al (1967), Calder (1977) and Calder and Wright (1985); a distinction between water held on the canopy and water held on the stems was made by Rutter et al (1975), Gash (1978), Gash and Morton (1979) and Gash et al (1980). As Rutter et al (1971), working with Corsican pine, pointed out the determination of the canopy capacity from drainage measurements is made difficult through wind effects. Drops of water dislodged from the foliage by the wind result in a small amount of drainage at storage values well below the canopy capacity, as seen in Fig. 4. With increasing gustiness the storage value at which drainage ceases will decrease. These effects are probably less important for heather than coniferous trees because it is shorter and also because, as discussed below, water adheres strongly to it. Nevertheless, it is propitious that an accurate assignation of a canopy capacity is unnecessary for understanding the drainage mechanism, which is adequately described by equation (4).

Rutter et al (1971) assumed that the canopy capacity could also be equated to the minimum amount of water required to wet all surfaces of the canopy and therefore to give evaporation rates equal to the potential, wet-surface rates. Assuming this to be correct, then it is possible to derive a mean value for S from the measurements of E/E_p versus canopy storage. However, the value of S derived from Fig. 6b may be biased towards a high value since it was not possible to use the information contained in the three runs which were stopped before E had begun to decrease consistently. Had the runs been allowed to continue, then at least one of them (AS3) must have yielded a value of S less than the mean value of (0.85 ± 0.1) mm. Comparison of this possibly high mean value with the (1.1 ± 0.1) mm obtained from the drainage experiment suggests that the true evaporation value of S is lower than the drainage value. Moreover, there are physical reasons, discussed below, to expect this difference.

It is usually assumed that the canopy capacity measured by drainage experiments can be used in the formulation $E = E_p.C/S$ when the Rutter model is employed. And the recent work of Calder and Wright (1985), who found S = 2 mm for Sitka spruce from both drainage and E/E_p measurements, provides evidence that for spruce this assumption is valid. However, there is no reason, per se, why evaporation and drainage experiments should give the same value of S and the results presented here suggest that for heather they do not.

A possible reason for this difference has been revealed by photographic studies of heather shoots using very weak solutions of rhodamine dye excited by an ultra-violet lamp. These show, in agreement with visual observations by Leyton et al (1967, p.173), that when water falls on heather a very thin film rapidly forms which covers the whole of the foliage. More water increases the thickness of this film, which is not easily shaken off, and also forms droplets which bridge the gaps between the leaves and the twigs; Fig. 7a shows the large amount of water that can be held in still air. Thus for heather, only a small amount of water, the canopy capacity as evaluated from E/E_p measurements, is required to wet the whole canopy surface and considerably more is needed before significant drainage occurs at and above the canopy capacity as evaluated from drainage measurements. The retentive nature of the heather foliage arises from its intricate small scale structure and the high wettability of the cuticle, presumably due to a lack of epicuticular wax. Studies of spruce leaves, using the same technique, showed that the water remained as a film as long as precipitation lasted after which it contracted into drops which lodged between the leaves and the leaf stalks (see Fig. 7b). The causes of this wetting behaviour are the large amount of epicuticular wax that has been found on the upper (adaxial) surface of spruce leaves (Jeffree et al 1971), and the spacing of the leaves which is generally too large to allow water to bridge the gaps between them.

The results presented herein show that the disposition of intercepted water is different for heather and spruce. The extent to which this affects the difference in the annual interception ratio for the two remains to be determined by, for example, modelling exercises using Rutter type models. It is proposed that for such exercises the drainage function given by equation (4) be used in conjunction with an evaporation rate which equals the Penman-Monteith wet-surface potential rate for canopy storage above S = 0.85 mm and below which the evaporation rate is given by $E = E_p.C/S$. A free throughfall coefficient of 0.13 should be appropriate, although it is probable that the model will be insensitive to this parameter and also possibly the canopy capacity; thus the errors attached to them will be of little consequence. Variation of the drainage parameters is likely to have a greater effect on the interception ratio but this will be the subject of a later paper.

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APPENDIX TO APPENDIX 2

Assuming the same exponential form of the drainage rate for the heather canopy as equation (3), the continuity equation for the water on the wax and tray, neglecting evaporation, can be written:

$$\frac{dC_w}{dt} = \text{rate of drainage from the heather } (D) - \text{rate of drainage from the wax and tray } (D_w)$$

$$= k(\exp[bC\ ] - 1) - k'(\exp[b'(C_w - 0.1)] - 1) \qquad \text{(A1)}$$

or to a very good approximation

$$k\exp[bC\ ] - k'\exp[b'(C_w - 0.1)]\ . \qquad \text{(A2)}$$

The results of the drainage run on the wax substrate and drainer tray showed that they worked well giving high drainage rates and only retained about 0.1 mm on the wax when drainage had finished. It is therefore reasonable to assume that drainage rates shown in Fig. 4 are equal to the drainage rates from the heather. So, to a very good approximation (for $C_w >$ 0.1 mm), $dC_w/dt = 0$ and the two exponential terms in (A2) can be equated giving,

$$k\exp[bC\ ] \approx k'\exp[b'(C_w - 0.1)] \qquad \text{(A3)}$$

and therefore

$$D = D_w = k\exp[bC\ ], \qquad \text{(A4)}$$

where D_w is the drainage rate off the wax and tray, the rate monitored by the balance . Taking logarithms gives

$$\ln D_w = \ln k + bC. \qquad \text{(A5)}$$

Multiplying (A3) by $\exp[b'C\ ]$ gives after rearrangement and taking logarithms

$$C = \frac{1}{b'+b}[\ln k' - \ln k + b'(C + C_w - 0.1)]$$

which when substituted into (A5) gives

$$\ln D_w = \ln k + \frac{b}{b'+b}\left(\ln \frac{k'}{k} - 0.1b\right) + \frac{b'b}{b'+b}(C + C_w) \qquad (A6)$$

$$\ln k'' + b''(C + C_w) \qquad (A7)$$

which is approximately the linearised form of equation (2), the relationship plotted in Fig. 4.

Equating the terms in (A6) and (A7) gives after rearrangement,

$$b = \frac{b'b''}{b'-b''} \qquad (A8)$$

and

$$\ln k = \frac{\ln k'' + 0.1\frac{b'b}{b'+b} - \frac{b}{b'+b}\ln k'}{1 - \frac{b}{b'+b}} \qquad (A9)$$

Finally substituting (A8) in (A9) gives

$$\ln k = \frac{\ln k'' + b''(0.1 - \frac{1}{b'}\ln k')}{1 - \frac{b''}{b'}} \qquad (A10)$$

The values of b and k calculated from (A8) and (A10) are given in Table 2.

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TABLE 1

The heather characteristics at the site studied at Berner's Heath, Norfolk. The values given are means and standard deviations.

Attribute		Value
Ground cover	(%)	90 ± 5
Age	(yr)	6 ± 0.5
Height	(m)	0.32 ± 0.09
LAI		1.8 ± 0.3
Areal stem density	(m^{-2})	766 ± 230
Stem length	(m)	0.37 ± 0.07
Stem surface area	(m^2 m^{-2})	4.1 ± 0.9

TABLE 2

The calculated drainage parameters

Symbol used in text	Meaning	Value
k''	drainage coefficient for total system	0.00133 $(\mathrm{mm\ hr}^{-1})$
k'	drainage coefficient for wax base and tray	0.21
k	drainage coefficient for heather canopy	0.00085
b''	drainage index for total system	4.31 (mm^{-1})
b'	drainage index for wax base and tray	27.09
b	drainage index for heather canopy	5.13

FIGURE CAPTIONS

Fig.1

The method used to create a "V" shaped wax base, used in the drainage measurements, involved tilting the sample and mould.

Fig. 2

The artificial sample AS3 in place on the drainer tray and showing the guttering and drip wires.

Fig. 3

Curve A: data from two drainage runs showing the decrease with time in the equivalent depth of water held on AS3 and the drainer tray due to drainage and evaporation. Each of the points was obtained from a mean mass calculated for a 30 second period.

Curve B: the same data but compensated for evaporative loss to give the decrease with time in total storage resulting from drainage only.

Fig. 4

The drainage rate calculated from the successive masses used in curve A of Fig. 3, and compensated for evaporation rates, is plotted against the total storage, expressed as an equivalent depth of water. (The negative drainage rates are the result of wind-induced random scatter on the masses not filtered out by the 30 second averaging period.) Curve X is the function $D_w = 0.00133(\exp[4.31C_t] - 1)$ fitted to the points. The drainage function derived for the heather, $D = 0.00085(\exp[5.13C] - 1)$, is also plotted as curve Y.

Fig. 5

The drainage function of the wax base and drainer tray. Drainage rates calculated from successive masses are plotted as a function of the equivalent depth of water held on the wax base and drainer tray. Also plotted is the curve $D_w = 0.21(\exp[27.09(C_w - 0.1)] - 1)$ fitted to the data.

Fig. 6

a) Experimental points, obtained using AS2, of E/E_p plotted against canopy storage C with two fitted lines to illustrate the method of obtaining the points plotted in b).

b) The relative evaporation rate E/E_p plotted in simplified form as a function of canopy storage from a series of experiments with four different samples. One point for AS2 was obtained by extrapolation, as shown by the dashed (- - - -) line.

Fig. 7

Water storage on (a) heather and (b) spruce in still air. The photographs, obtained using a UV lamp to excite a very weak solution of rhodamine dye, were taken 48 minutes after spraying the heather and immediately after spraying the spruce.

FIG.1

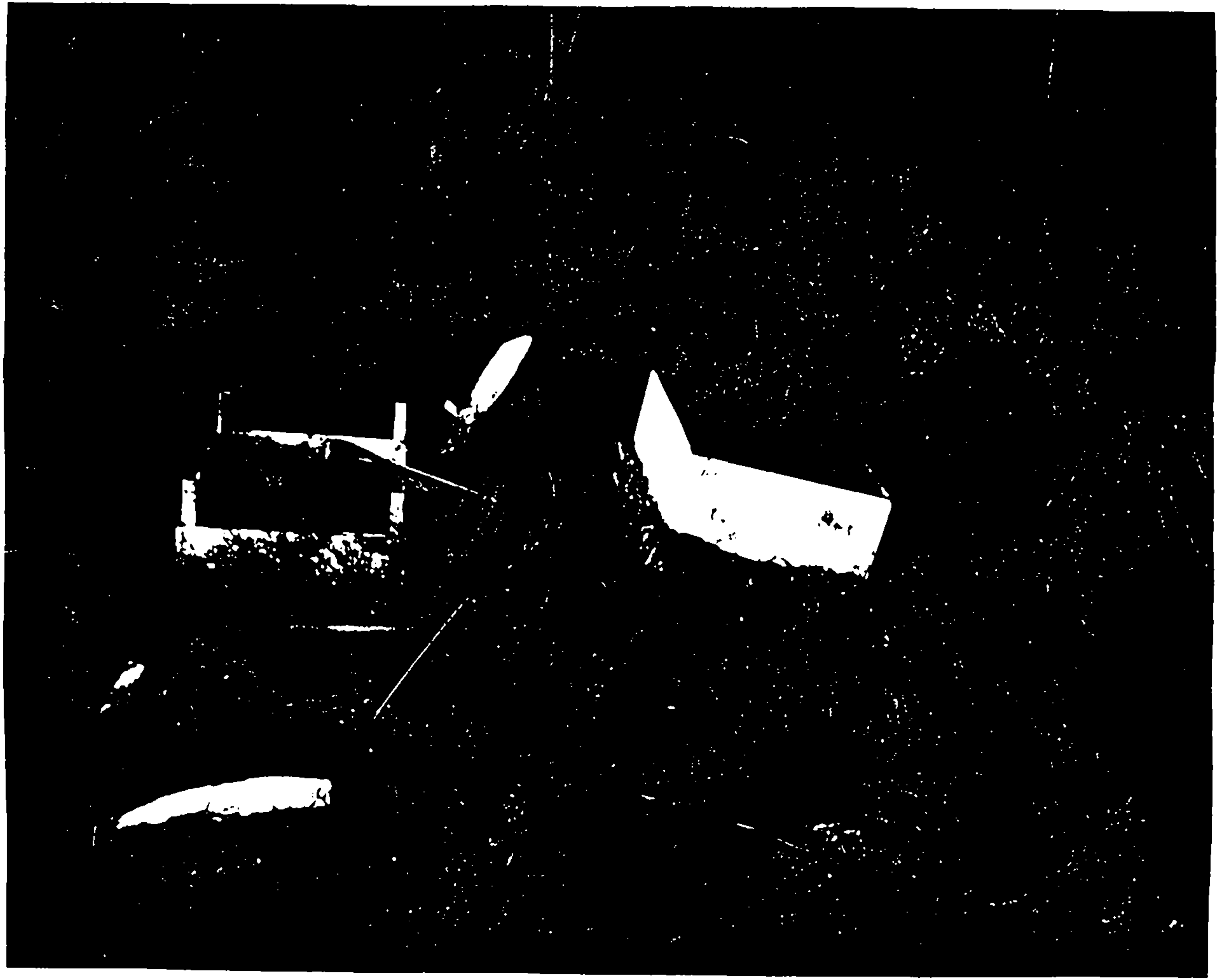
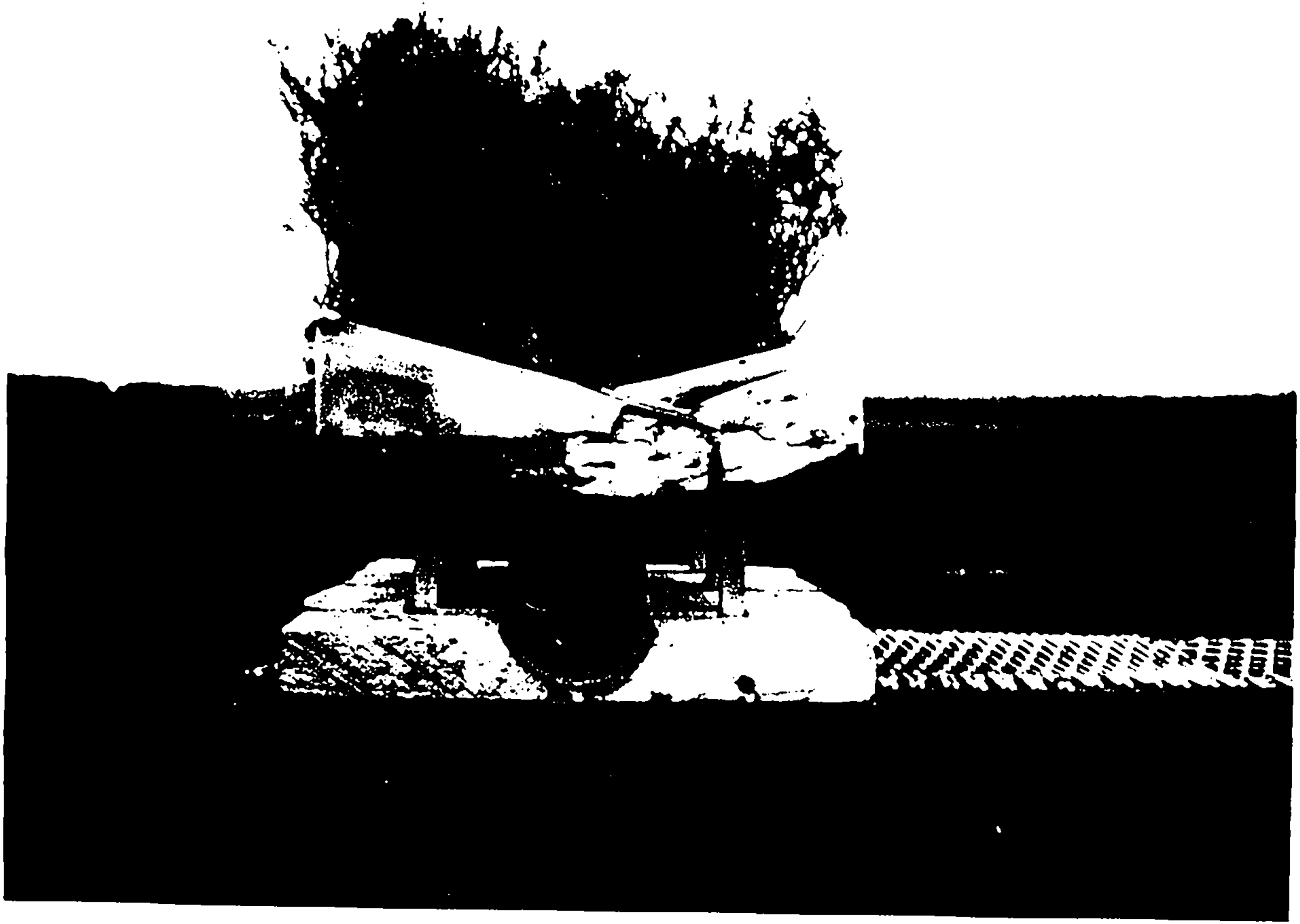


FIG. 2



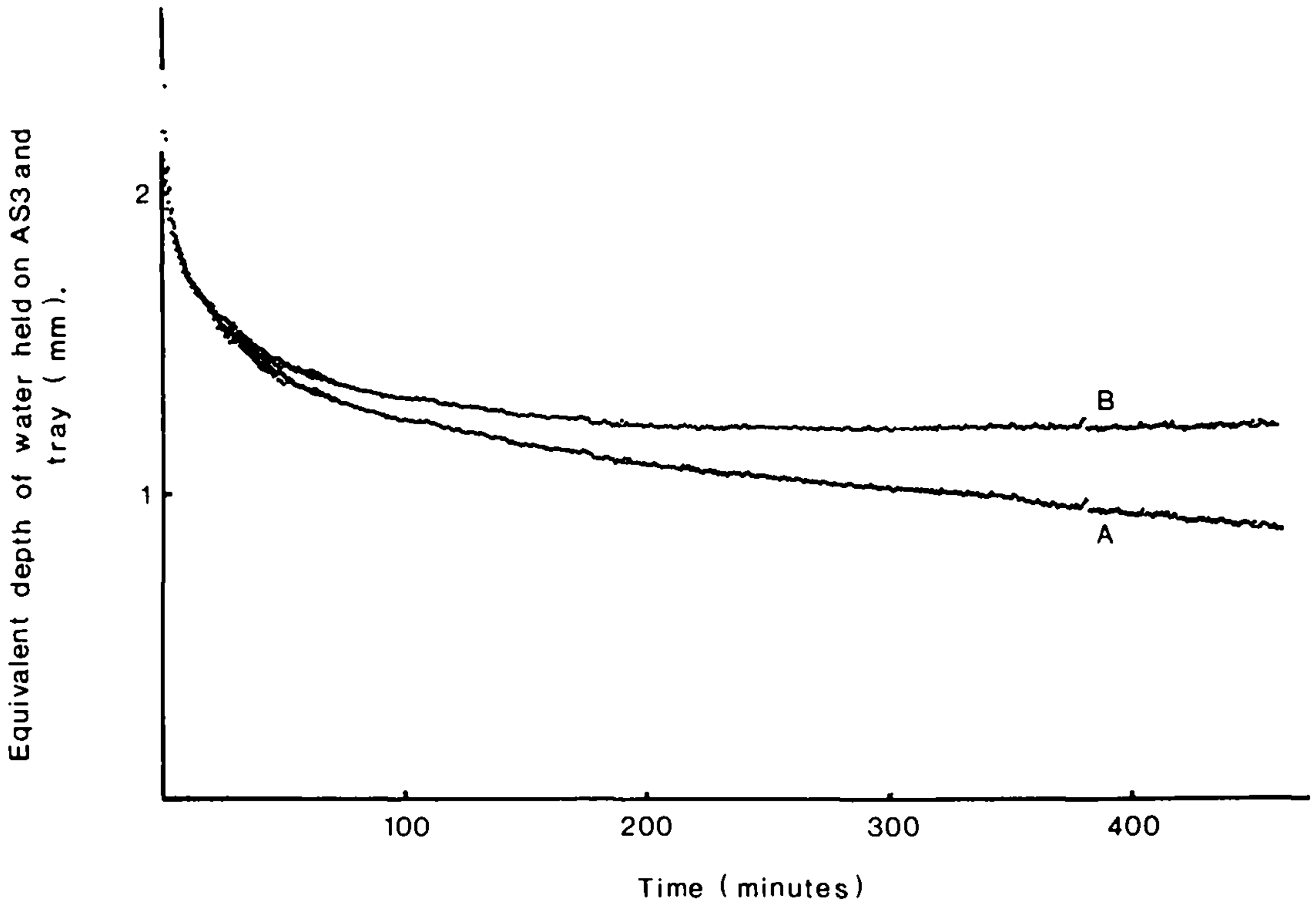

Equivalent depth of water held on AS3 and tray (mm).
2
1
100
200
300
400
Time (minutes)
B
A

FIG.3

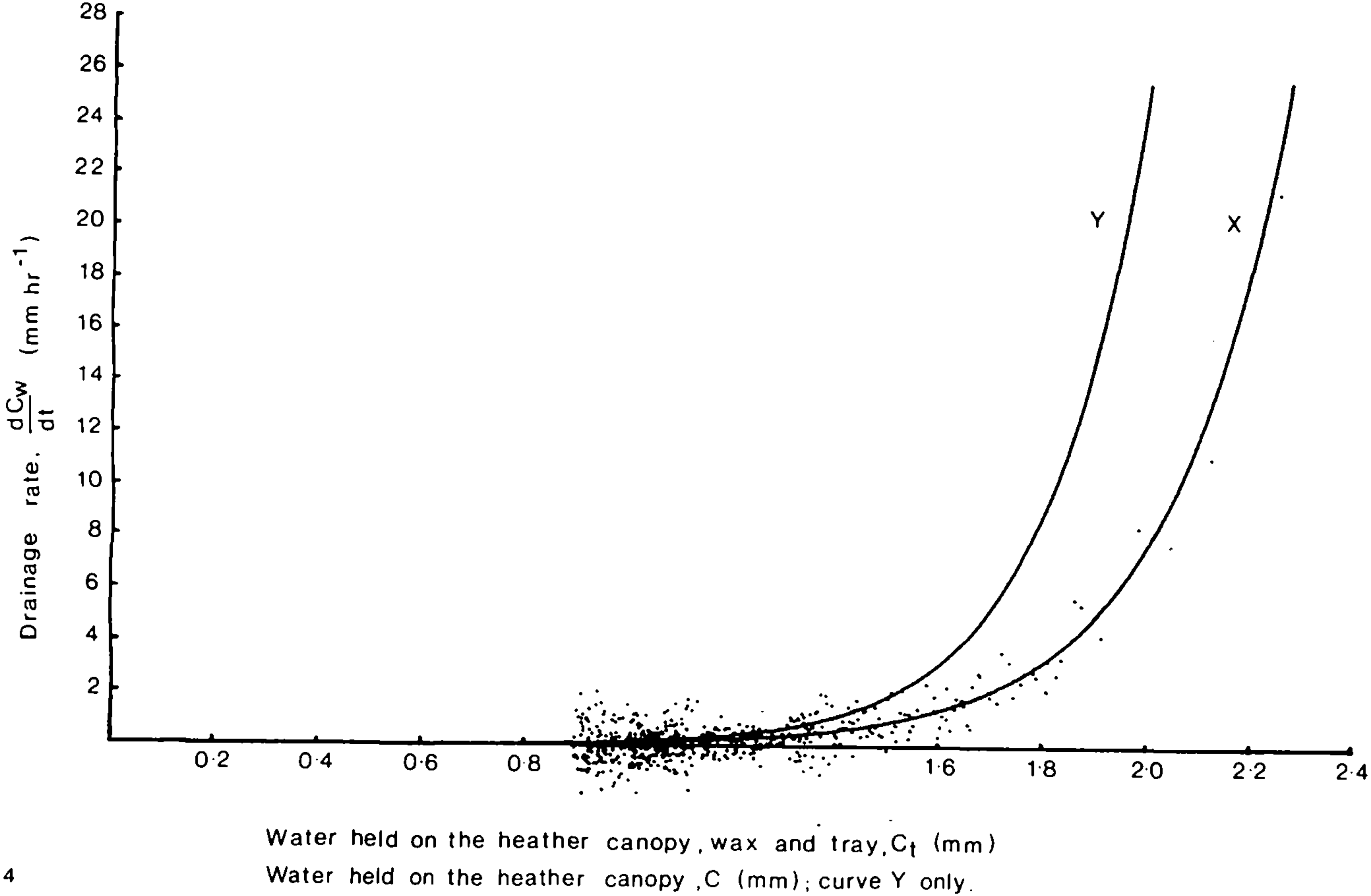

Drainage rate, $\frac{dC_w}{dt}$ (mm hr^{-1})
28
26
24
22
20
18
16
14
12
10
8
6
4
2
0·2
0·4
0·6
0·8
1·6
1·8
2·0
2·2
2·4
Y
X
Water held on the heather canopy, wax and tray, C_t (mm)
Water held on the heather canopy, C (mm); curve Y only.

FIG. 4

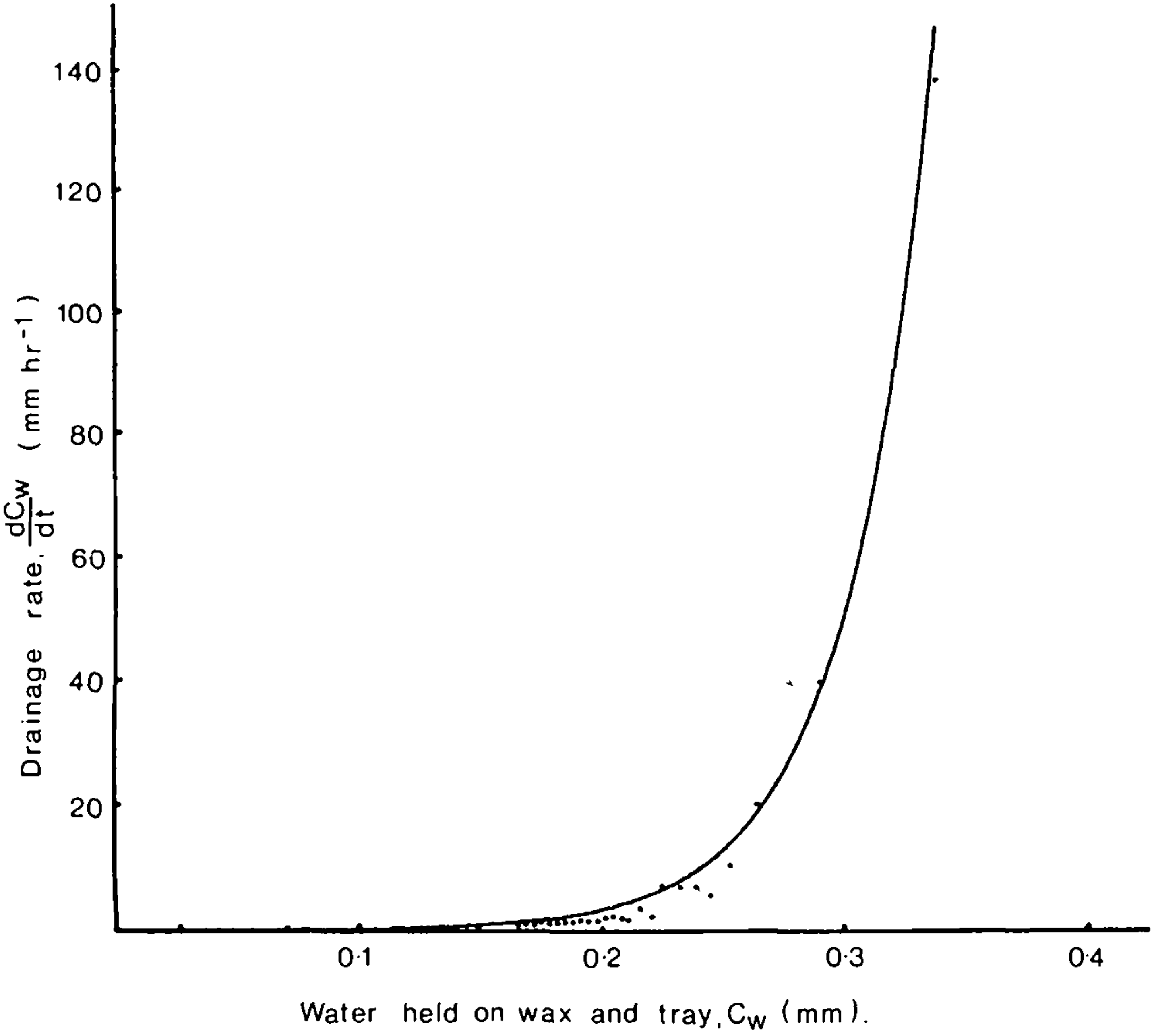

Drainage rate, $\frac{dC_w}{dt}$ (mm hr^{-1})
140
120
100
80
60
40
20
0·1
0·2
0·3
0·4
Water held on wax and tray, C_w (mm).

FIG.5

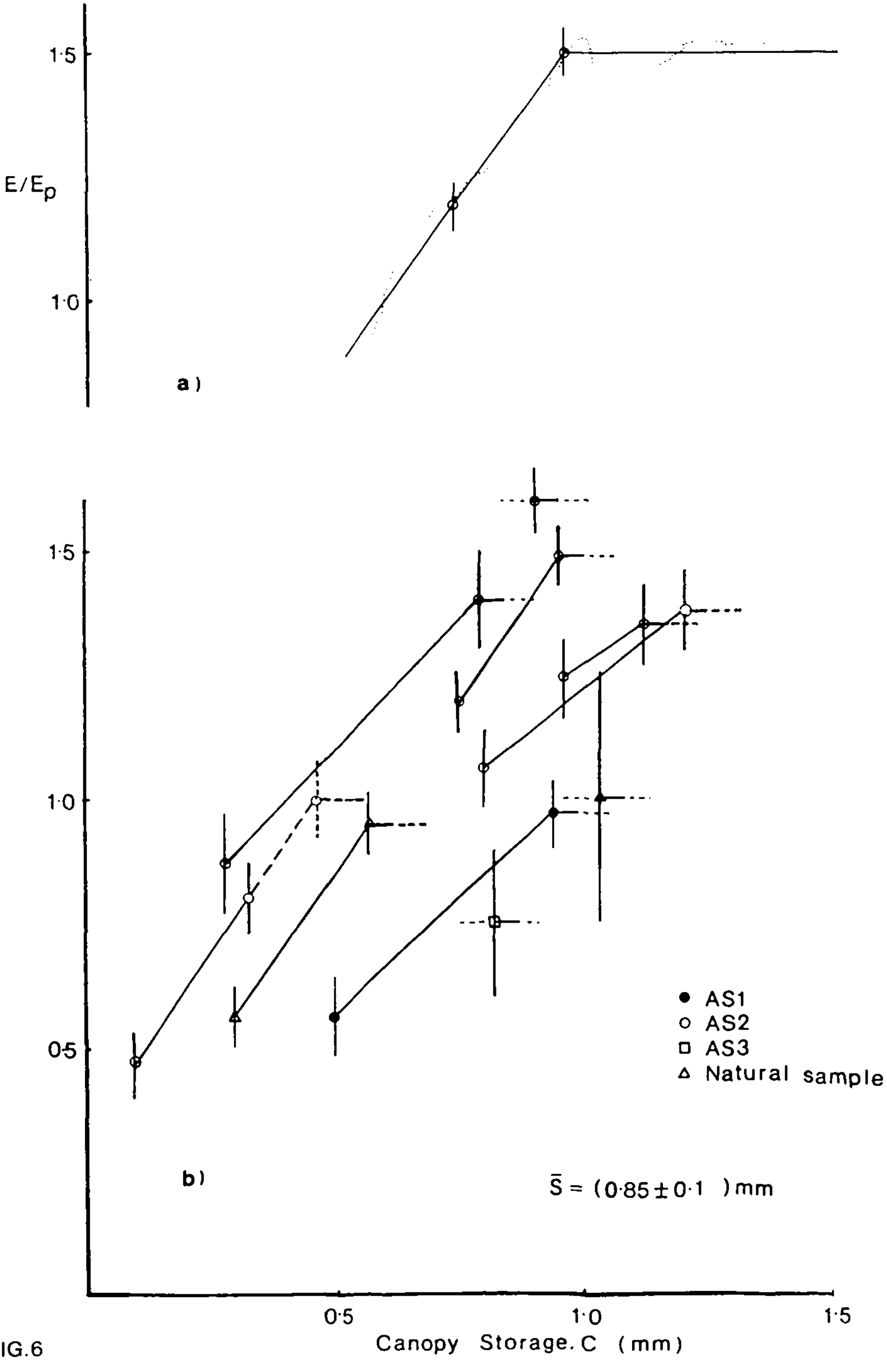
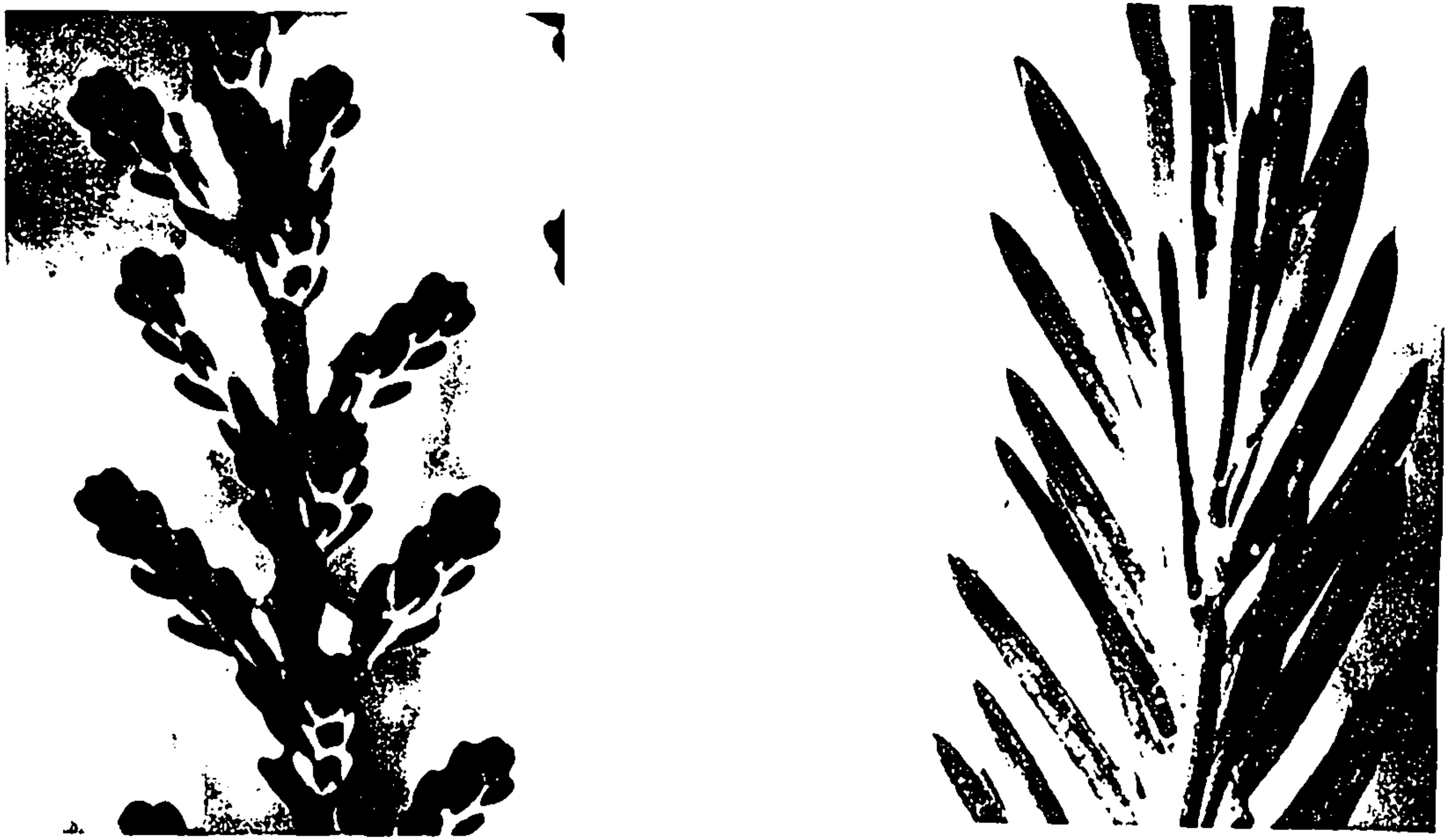

E/E$_p$
1·5
1·0
a)
1·5
1·0
0·5
b)
● AS1
○ AS2
□ AS3
△ Natural sample
$\bar{S}$ = (0·85 ± 0·1) mm
0·5
1·0
1·5
Canopy Storage. C (mm)

FIG.6



a) b)

FIG. 7

APPENDIX 3

INFLUENCE OF WOODLANDS ON WATER QUANTITY

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ABSTRACT

Recent developments in the study of evaporation from forests and woodlands are reviewed. Evidence is given for the inapplicability of the "potential evaporation" concept for use in estimating forest evaporation, particularly in wet climates where interception losses are large. Attention is drawn both to the importance and to the complexity of physiological controls on forest transpiration. It is suggested that, perhaps paradoxically, their existence greatly eases the task of obtaining long-term "broad brush" estimates of the influence of woodland on water quantity.

These recent developments also show that, within the UK at least, woodlands will generally reduce the quantity of runoff from catchments as compared with other vegetation types; in the wet upland regions of the UK the influence is most marked: annual evaporation rates from forests may exceed those from grassland by 100% and runoff will be reduced, typically by about 20%.

INTRODUCTION

The influence of the sun's warmth on evaporation is obvious to us all so intuitively it is perhaps not unreasonable to expect that the input of net solar radiation "tightly" controls the evaporation from vegetative surfaces. With the proviso that soil moisture is not limiting it could be, and often was, argued that all closed canopy vegetation would evaporate at similar rates, any differences being attributed to small differences in albedo.

Unfortunately nature is not so accommodating and many recent experiments have cast doubts on these simplistic views; some experiments, and particularly those concerned with the measurement of evaporation from forests growing in wet climates, have now totally destroyed them. No longer can we consider the evaporation loss to be passively determined by meteorological demand or limited by the "potential evaporation" concept.

These recent experiments on forests have revealed a different and considerably more complicated view of the evaporation process, a view in which advected energy plays a prominent role and one in which the vegetation itself plays an active part in modifying its transpiration response to changing meteorological and environmental conditions.

The development of these views has been brought about by workers of many disciplines; the story could perhaps start with the work of a British water authority engineer in the mid-fifties..

EARLY EVIDENCE FOR THE BREAKDOWN OF THE POTENTIAL EVAPORATION CONCEPT

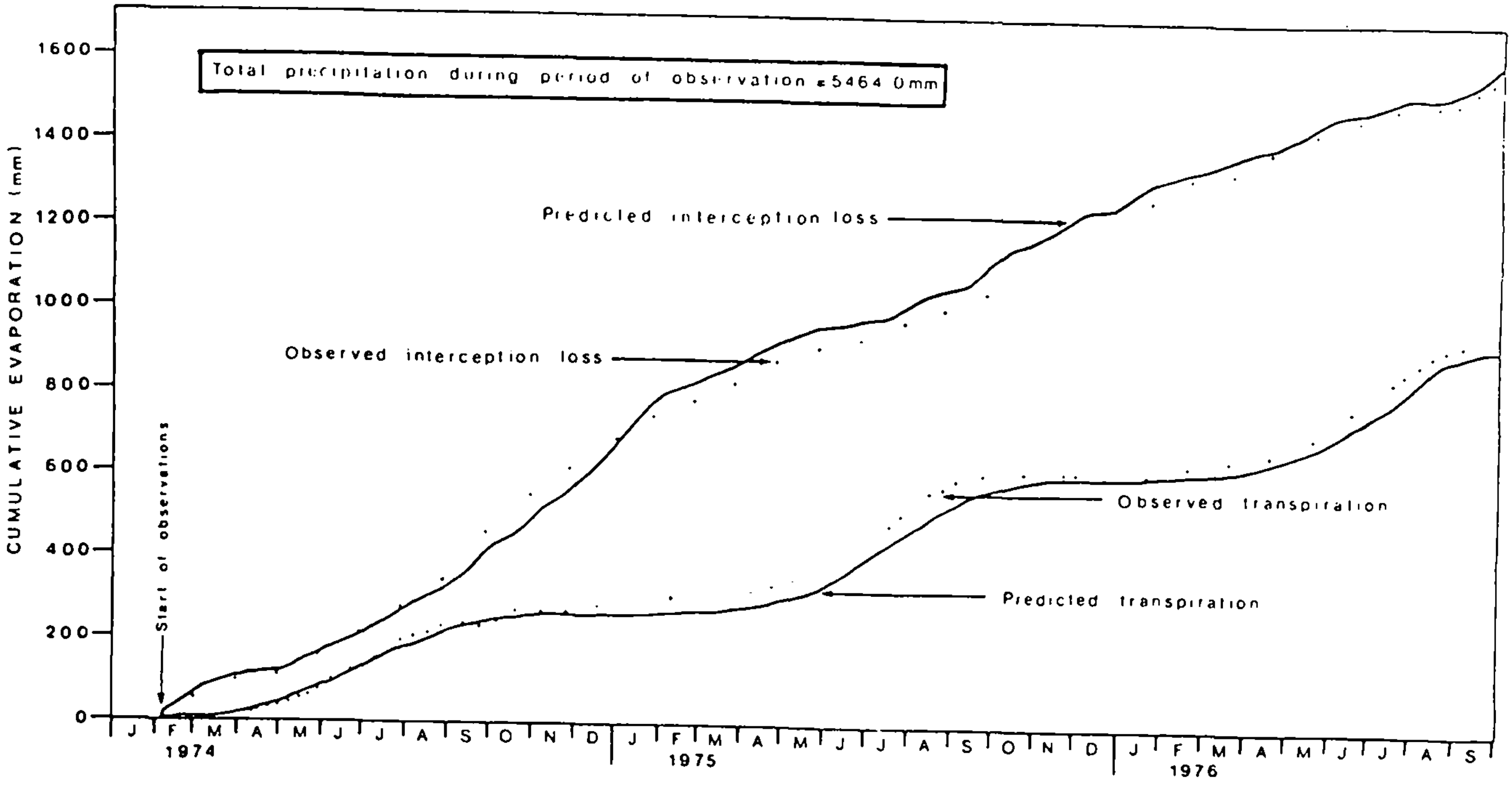
From experiments conducted on the Hodder catchments in the Yorkshire Pennines, Law (1956, 1957) presented a set of results which at that time caused considerable controversy amongst British hydrologists. He reported large differences in evaporation between different vegetation types. During the period 4 July 1955 to 8 July 1956, evaporation losses from a forested lysimeter of 371 mm interception and 340 mm of transpiration were recorded which, when taken together, exceeded the loss from the surrounding grassland by 290 mm. The results were not convincing because of doubts about the small size of the forest plantation and the consequent possibility of radiative and aerodynamic edge effects.

By the early sixties Rutter (1963) had published interception loss results from forest indicating loss rates higher than those indicated from the Penman (1948) potential formula and implying higher loss rates than could be sustained solely through the input net radiation. The experimental plot was in the Bramshill forest at Crowthorne, Berkshire, a forest of sufficient size to negate the possibility of edge effects. Similar results were also reported by Patric (1966), Helvey (1967) and Leyton et al. (1967) & oth

Towards the end of the sixties and during the early seventies results from a number of highly sophisticated and carefully designed micrometeorological studies over forests were published, Sziecz et al. (1969), Tajchman (1971), Gay (1972), Stewart and Thom (1973), McNaughton and Black (1973), Hicks et al. (1975). Some of these studies, Sziecz et al. (1969), Stewart and Thom (1973) show that latent heat fluxes due to transpiration, even when trees (Pinus sylvestris L were well supplied with water, could be significantly less than the net radiation, demonstrating that physiological controls were regulating the transpiration rates. Loss rates of intercepted water were shown to be higher than loss rates from a dry canopy; McNaughton and Black (1973) gave a conservative figure of 20% for a site in Canada whilst Stewart and Thom (1973) suggested a much larger figure of 500% for a site in the east of England.

The dominant role of interception in forest evaporation was perhaps most clearly demonstrated by the Institute of Hydrology's studies at Plynlimon in mid Wales. This is a high rainfall upland region receiving a yearly average 2200 mm of precipitation. Catchment studies indicated 75% greater losses from the partially forested Severn catchment compared with the adjacent grassland Wye catchment (Clarke and McCulloch, 1975). Interception experiments and a lysimeter set within the forest showed the cause of these increased losses (Calder 1976): annual interception losses were found to be almost exactly twice those due to transpiration (Fig. 1). The total loss, interception plus transpiration, was found to be approximately twice the Penman (1948) potential evaporation (Eo) estimate.

These results, regarded with some scepticism at the time, have been confirmed by other interception experiments in different high rainfall regions of the UK; they involve both conventional methods measuring the difference in quantity of rain above and below the forest canopy (Fig. 2) as well as more direct methods which use the attenuation of a γ ray beam to measure the change in storage of water on the forest canopy (Calder and Wright 1984). Confirmation is also given, perhaps more importantly, through a greater understanding of the mechanisms responsible for the high interception losses.



Cumulative observed and predicted transpiration losses from the forest lysimeter

Fig. 1

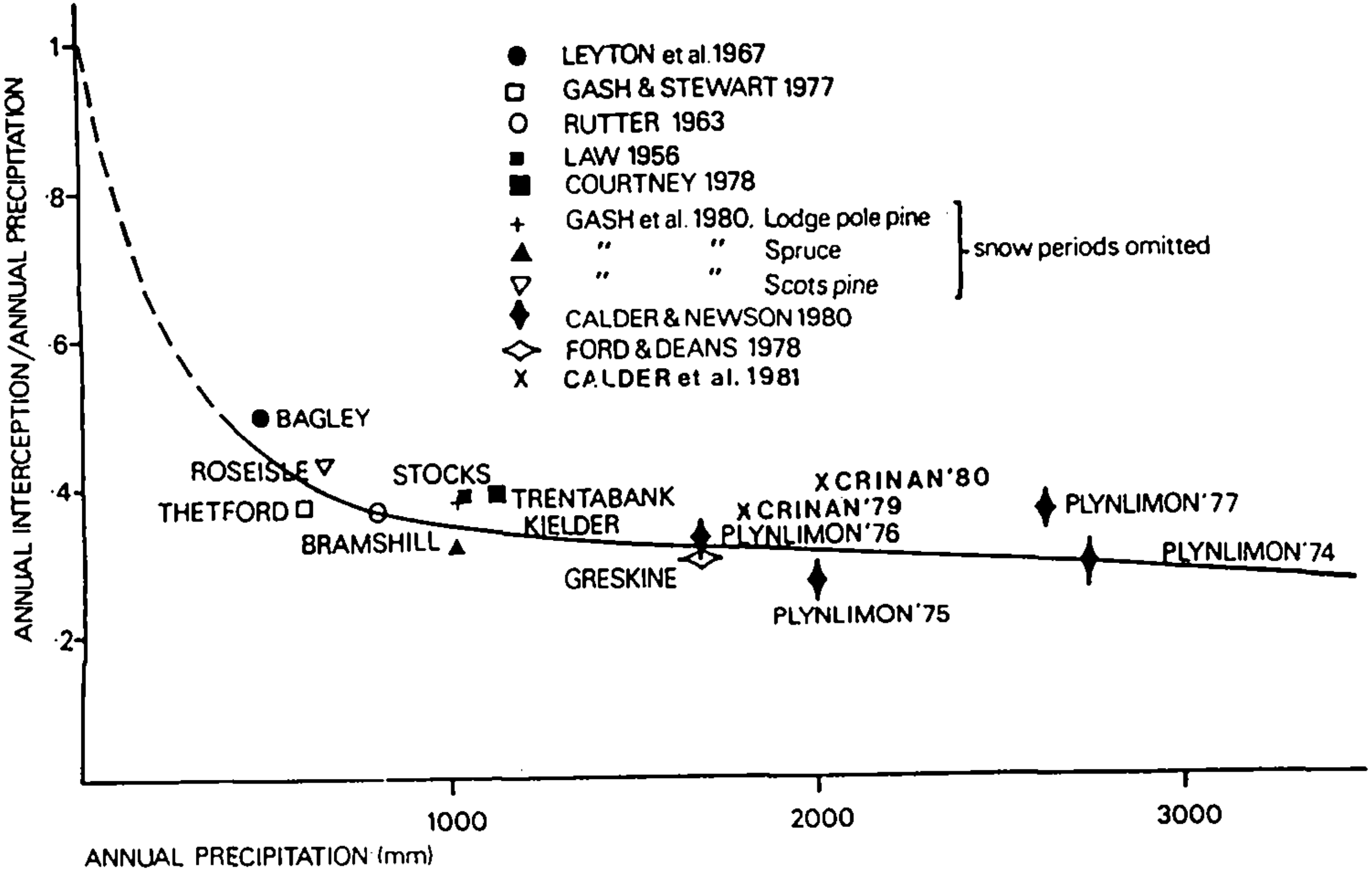


Figure 2. Measurements of annual loss by interception expressed as a fraction of the annual precipitation plotted against annual precipitation.

THE INTERCEPTION PROCESS

The interception process can be most easily interpreted within the framework of the Penman-Monteith equation (Monteith 1965, see also Thom 1975):

$$\lambda E = \frac{\Delta\ Rn + \rho C_p\ VPD/ra}{\Delta + \gamma\ (1 + rs/ra)}$$

where fluxes of latent heat λE can be calculated given the necessary meteorological data on vapour pressure deficit VPD, net radiation Rn, and air temperature for the estimation of the slope of the saturation vapour pressure curve Δ; γ is the psychrometric constant.

Two crop dependent parameters are also required; these are the surface resistance, rs, which for a living crop is a purely physiological resistance imposed by the crop itself on the movement of water through its leaf stomata, and the aerodynamic resistance, ra, which is a measure of the resistance encountered by water vapour moving from the outer surfaces of the crop into the atmosphere.

Under wet conditions, when a film of water covers the surfaces of leaves, the surface resistance is effectively "short circuited" and rs can be equated to zero.

For forests the aerodynamic resistance is normally an order of magnitude less than that of shorter crops (eg. grass); this is because trees present a very rough surface to wind and are more efficient in generating the forced eddy convection which, under the majority of meteorological conditions is the dominant mechanism for the transport of heat and water vapour from the external surfaces of leaves into the atmosphere.

The principal factors responsible then for the high interception losses observed from coniferous forest are simply that they have:

1) a low aerodynamic resistance, and
2) wettable surfaces which can support and sustain an almost complete surface film of water.

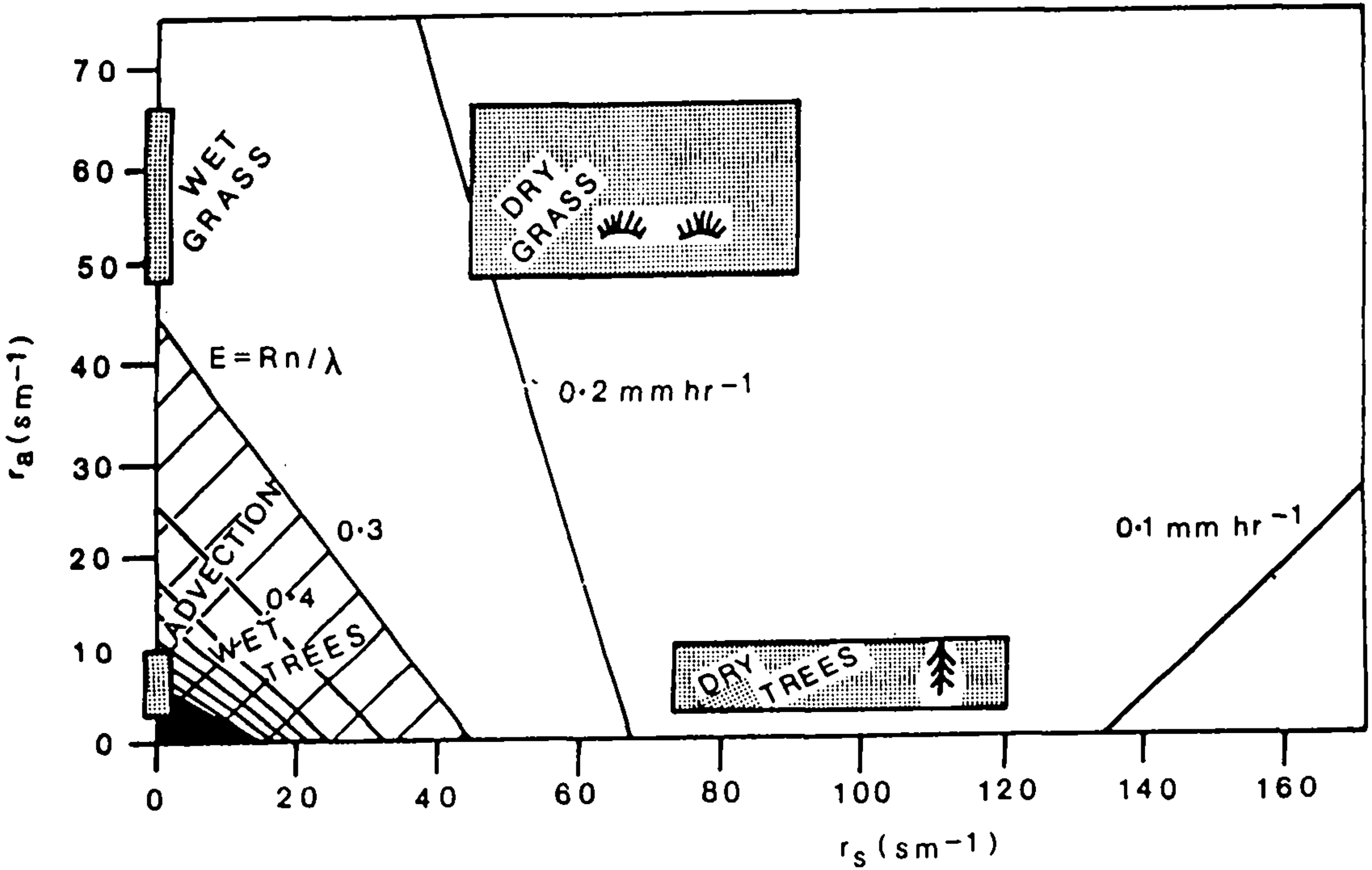


Fig. 3

Evaporation rates calculated from the Penman-Monteith equation as a function of ra and rs for cool summer daytime conditions (net radiation = 200 W m^{-2}, VPD = 5 mb, air temperature = 10°C)

The influence of these factors on evaporation rates can be most readily demonstrated by solving the Penman-Monteith equation for different values of ra and rs under a set of meteorological conditions, (Calder 1979, Fig. 3), chosen to represent those which could occur when either the vegetation is dry and transpiring or wet following rainfall. The increase in evaporation rates when trees are wetted in these conditions is by a factor of 5-15; for comparison the increase expected from grass is much less, a factor of 1.4-1.8. Even this modest increase is likely to be an overestimate for grass as most grass species seem unable to sustain a film of water on their leaves and the effective surface resistance in wet conditions probably never reduces to the zero value used in the calculation. (N.B. under average wet conditions which include rain periods,the atmospheric demand is likely to be less and the evaporation rates correspondingly less than those shown in Fig.3).

The aerodynamic mixing above forest canopies is so good that only small atmospheric humidity deficits are necessary to support significant evaporation rates; this ensures that, even during rainfall, evaporation will be taking place. Indeed at Plynlimon, where storms tend to be of fairly low intensity (1.4mm/hr) and long duration,the majority of the interception loss takes place during the rainstorm itself, the evaporation from the water remaining on the canopy at the end of the storm is a minor component of the total loss.

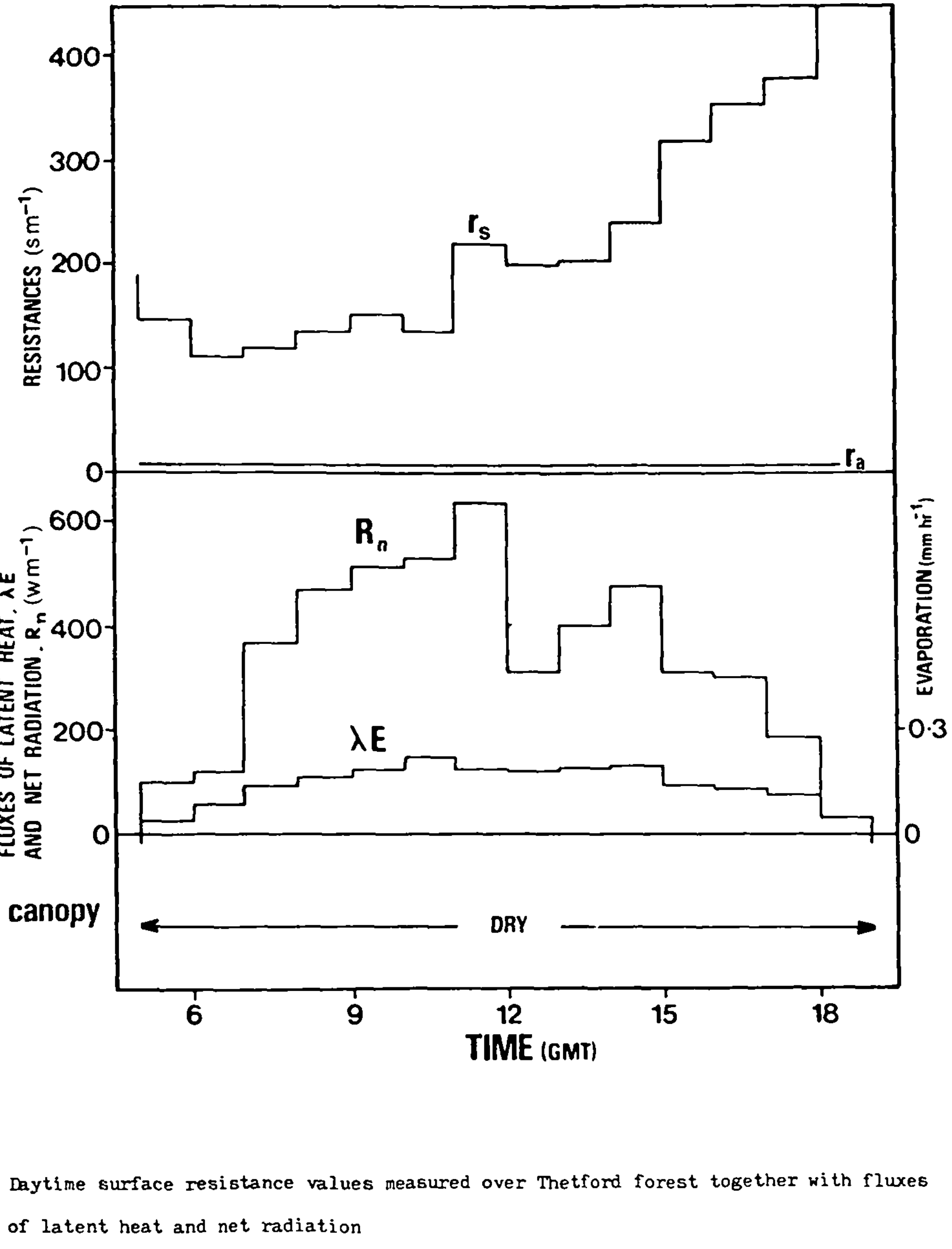
To sustain the rates of evaporation from wet trees implied by Figure 3, requires a considerable source of energy in addition to that available from net radiation. This additional energy source must be provided by advection, which results in a cooling of the air mass within and above the forest. The exploitation of this energy source by the forests at Plynlimon is so good that during wet canopy conditions typically 80% of the total energy input is derived from advection (Shuttleworth and Calder 1979); even on a long term basis advection is important at this site as the annual latent heat flux from the forest exceeds the supply of net radiation by 12%. If all this additional energy comes from the synoptic scale transport of energy from regions outside the forest, it may not be possible to support such rates from very large forested areas (e.g. the Amazon basin or some parts of Canada); alternatively, as Thom (1978) has suggested, energy loops within the planetary boundary layer (involving the latent heat energy released in the precipitation process) may make a significant contribution. Micrometeorological investigations together with interception studies in large tropical forests may be able to answer this question; winds are generally light in these regions and horizontal advection virtually absent; it awaits to be seen whether in these conditions evaporation rates can exceed the net radiation for significant periods.

EVIDENCE OF THE IMPORTANCE OF PHYSIOLOGICAL CONTROLS ON EVAPORATION

Physiologists have long recognised that plants can regulate the status of their leaf stomata and hence their transpiration rates and that the stomata respond to changes in many environmental variables and not solely to soil water stress. Stomatal response to changes in temperature, light intensity, leaf water potential and vapour pressure deficit are all well documented in the literature. It is therefore unreasonable to assume that plant transpiration rates are passively determined by atmospheric demand.

The importance of physiological controls on evaporation rates from natural forests was strongly confirmed by early micrometeorological studies. Micrometeorological experiments above a pine forest at Thetford in the east of England (Stewart and Thom, 1973), showed strong stomatal regulation: the surface resistance increased typically by a factor of three during the day (Stewart 1981, Fig. 4.) and there was some evidence of a seasonal variation. McNaughton and Black (1973) also found large diurnal changes in surface resistance and large day to day changes.

The importance of atmospheric humidity (or atmospheric evaporation demand) as a controlling variable on stomatal response was demonstrated at the individual leaf and sub-leaf (epidermal strip) scale by Lange et al. (1971) and Shulze et al. (1972) whereby an increase in atmospheric humidity deficit was observed to be correlated with a closing of stomata (an increase in stomatal resistance). This mechanism is of particular interest in evaporative studies since it represents a negative feedback mechanism; in situations where this mechanism operates,fluctuations in actual evaporation whether on a diurnal, day to day or seasonal basis would be expected to be much more conservative than fluctuations in atmospheric demand. Jarvis (1976) showed by using diffusion porometer techniques on the scale of individual shoots that this mechanism does indeed operate for trees, in this case sitka spruce (Picea sitchensis (Bong.) Carr.) trees, growing in natural surroundings. Tan and Black (1976), Calder (1977, 1978) and Roberts (1978) also confirmed the importance of this mechanism through micrometeorological scale experiments, lysimeter scale experiments using neutron probe techniques (40 trees), experiments on individual excised trees and again using diffusion porometers on individual shoots.



Daytime surface resistance values measured over Thetford forest together with fluxes of latent heat and net radiation

Fig. 4

The effect that this feedback mechanism has on evaporation rates can be illustrated (Calder 1978) by solving the Penman-Monteith equation with a surface resistance sub-model which incorporates the vapour pressure feedback mechanism for a range of values of net radiation and vapour pressure deficit, (Fig. 5). Clearly this feedback mechanism imposes an upper limit on transpiration rates of about 0.3mm/hr. In extreme conditions of atmospheric demand the model implies a reduction in evaporation rates. It has also been suggested that this mechanism is important to plants in conserving water use (Cowan 1977) and may even be a factor allowing survival in extreme sites for certain plant species (Johnson and Caldwell, 1976).

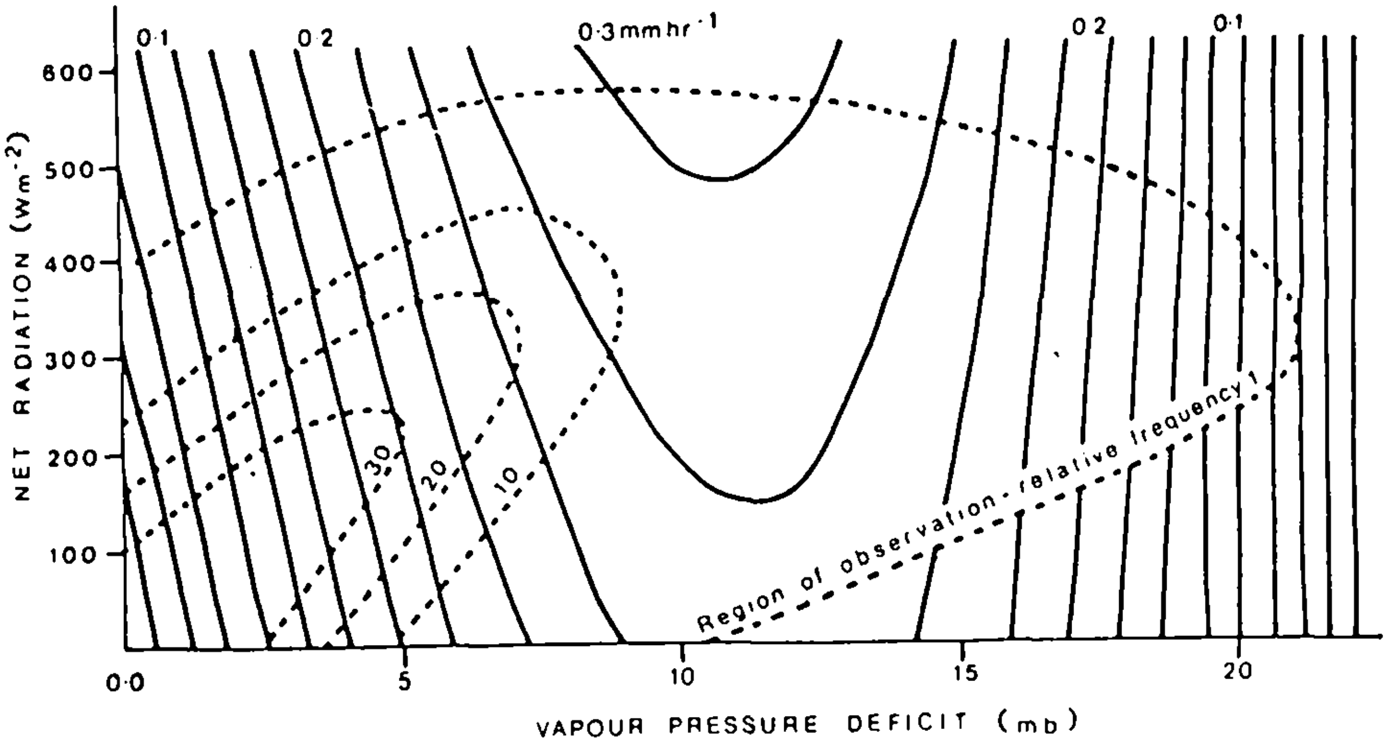
An important negative feedback control between soil moisture deficits and evaporation rates is to be expected but there is at present a dearth of information on this mechanism. Of particular value then are the results of Tan and Black (1976) who showed a halving of evaporation rates from Douglas fir (Pseudotsuga menziesii (mirb.) Franco) when soil water potential reduced to -10 bar; the effects of a given soil moisture stress become increasingly more pronounced under conditions of high atmospheric demand (high VPD). For Norway spruce (Picea abies (L.) Karst.), (Calder 1978) no dependence of surface resistance on soil moisture status was found within the total observational range of soil moisture potential of 0 to -6 bar.

There is a similar dearth of data on seasonal variation of surface resistance. Rutter (1967), however, reported measurements for Pine (Pinus sylvestris L.) growi in southeast England which showed a significant lowering of stomatal resistance during the summer. Calder (1977, 1978) also found a seasonal variation for Norway spruce, which, when the atmospheric humidity feedback effect was removed, could be fitted using an annual sinusoidal relationship, the trough occurring in the summer months. The relationship, used for estimating surface resistance on day No. D was:

$$rs = 74.5[(1-0.3\cos(2\pi(D-222)/365)]/(1-0.045VPD)$$

where VPD is the vapour pressure deficit (mb).

For most periods of the year this surface resistance sub-model gave predicted transpiration rates which agreed well with those observed (Fig. 1); close examination of the data showed that during emergence of new shoots in the springtime, predictions of the model were less than those observed which implied a reduction of stomatal control during this period.



ρ = 1·22 (kg m^{-3}) Δ = 1·10 (mb °C^{-1}) λ = 2·465 × 10^{6} (J kg^{-1})
c_p = 1010 (J kg^{-1} °C^{-1}) γ = 0·655 (mb °C^{-1}) D = 222 (day No.)

Model predictions of evaporation rates as a function of net radiation and vapour pressure deficit together with distribution of observation of these variables recorded during 1974 and 1975.

Fig. 5

ESTIMATION OF THE INFLUENCE OF WOODLANDS ON WATER QUANTITY

The task of estimating the effects that forests, growing in different climatic regions, will have on catchment runoff, is by no means a trivial exercise. Even if all the canopy parameters which control the complex evaporation process were well known there still remains a tremendous shortage of the detailed meteorological data that this type of "research" model requires.

If we are principally concerned with forests growing in regions of relatively high annual rainfall and low rainfall intensity and where snow is not a major component of the annual precipitation, as for example in the uplands of Wales and the north of England, and a semi-empirical approach is acceptable, the prospect of developing a "practical" evaporation model may not be quite so bad as it first appears. In these high rainfall areas interception losses dominate transpiration and it has been shown that for the U.K. at least, annual interception losses can be estimated quite accurately from a knowledge only of the local rainfall, Figure 2, (Calder and Newson 1980).

Paradoxically, the very complexity of the plant stomatal response mechanisms make the "broad brush" estimation of transpiration rates easier. The negative feedback responses brought about by increasing atmospheric vapour and soil moisture deficits both tend to make actual transpiration rates conservative in comparison with atmospheric demand. Roberts (1982, 1983) has shown that the mean of the observations of annual transpiration loss from European forests, both coniferous and broad leaf is 326mm with a standard deviation of only 24mm. It may be possible to improve on this estimate if we are prepared to let the arguments above concerning the inapplicability of potential evaporation to forest evaporation go full circle.

For the spruce forest at Plynlimon, transpiration losses are broadly in agreement (at the 10% level) with the long term Penman potential transpiration values when these values are reduced in proportion to the average fractional time the canopy is wet (and transpiration will not be taking place). This observation together with the observations that interception losses from forests in the U.K. can be roughly estimated from a knowledge only of the local rainfall and that the Penman E_t estimate provides a reliable estimate of annual losses from grass and other short crops formed the basis of a simple evaporation equation (Calder and Newson 1979, 1980) for estimating the effects on water resources of afforestation in the uplands of the U.K. Annual losses from a catchment with a fractional canopy coverage of f and an annual precipitation of P, are then given by:

$$\text{annual loss} = E_t + f\,(P.\alpha - w.E_t)$$

where:

α = interception fraction (from Fig. 2),
w = fraction of year when canopy is wet.

It was suggested that by making use of the observation that at Plynlimon the forest is wet for about 50% longer than the duration of rainfall w can be estimated from the equation:

$$w = \text{annual precipitation} \times 1.71 \times 10^{-4}/\text{mean rainfall intensity}$$

The model has been used in the U.K. (see e.g. CAS report 1980) to predict the effects of upland coniferous afforestation on runoff for such diverse interests as hydroelectric power, canal and water authorities, Figure 6.

The model outlined above is strictly only applicable when it is required to estimate the influence of woodlands as compared with grassland, on water quantity in high rainfall regions. Application of the model to much of the Scottish uplands is therefore difficult, land which is considered suitable for afforestation often has a cover of rougher, intermediate height vegetation, e.g. heather, or is subject to a climate where snow may form a significant proportion of the annual evaporation.

The Institute of Hydrology is currently carrying out a research programme, funded largely by a consortium of Scottish interests, to investigate these aspects. Experiments using lysimeter and neutron probe techniques at sites in Scotland and the North of England all suggest that heather, one of the

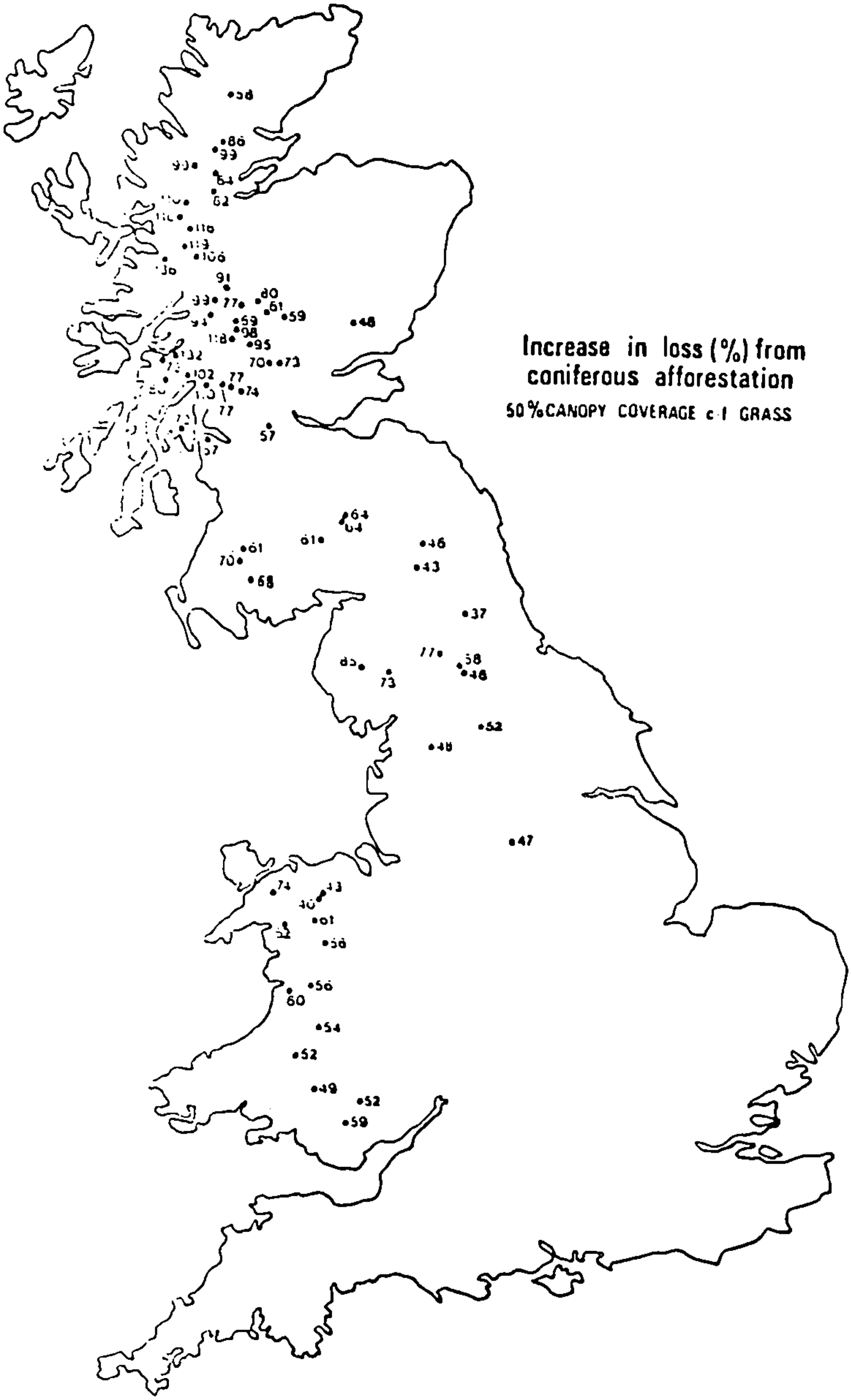


Figure 6.

Predicted percentage increase in evaporation loss from afforesting to 50% canopy coverage the catchments supplying the major U.K. upland reservoirs.

upland vegetation types the evaporation characteristics of which were formerly poorly known, transpires relatively little, especially during the early part of the year, but experiences relatively high interception losses. These observations suggest (see Table 1) that annual evaporation losses from heather could be estimated with an equation of the form:

$$\text{annual loss} = \beta . E_t (1-w) + \alpha . P$$

where:

$$\beta = \text{transpiration}/(\text{Penman's } E_t \text{ for grass } x \ (1-w))$$

$$\simeq 0.5$$

and $\alpha \simeq 0.2$

The model implies that for upland regions of moderately high rainfall, say 1500 mm, the evaporation from heather would be similar to that from grass but in wetter climates the interception losses from heather will dominate and result in greater total losses.

The full significance of snow interception from forests has yet to be determined but preliminary results from studies carried out at a site in the Queens Forest, near Aviemore, Scotland, indicate that the effects are important. Experiments using "weighing tree" techniques, heated plastic-sheet net-rainfall gauges and a γ ray attenuation rig which scans the snow covered forest canopy all indicate that the canopy capacity for snow is an order of magnitude greater than that for water and evaporation rates can be of a similar magnitude to those from wet canopies: evaporation rates of 0.5 mm per hour were recorded with the γ ray attenuation rig during the night of 12-13 December 1983 from a snow covered canopy with the arrival of a frontal system which introduced warm dry maritime air.

Further research is required to determine fully the significance of snow interception and also to investigate other grey areas of our knowledge such as the seasonal distribution of evaporation losses from forests as compared with other vegetation types. The overall picture however remains clear - woodlands in wet upland areas will reduce water quantity compared with other vegetation types.

TABLE 1 Simple evaporation model parameter values for heather (Calluna vulgaris (L.) Hull)

Source	Period	Rainfall rate over period (mm/yr) P	Interception fraction α	Transpiration fraction β
Model estimate derived using automatic weather station data from Crinan, Argyll and a measured aerodynamic resistance for heather	March-Sept 1981	843	0.21	
Neutron probe measurements of S.M.D. beneath heather at Crinan (Calder et.al. 1980, 1984b)	1981-1983			0.38-0.67
Optimised parameter values obtained using data from Law's heather lysimeter at Stocks Reservoir (Calder et. al. 1983)	1964-1968 freezing periods during winters excluded	1575	0.16	0.47
Heather lysimeters, Sneaton Moor, North Yorkshire (Wallace et al 1982)	May-July 1980	786		0.25-0.5*
(Roberts and Wallace, 1984, Wallace et al 1934)	348 days 1980	992	0.19	0.55*

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* + 10% correction made to the published data to express transpiration as a percentage of Penman E_t estimate for <u>grass</u> rather than <u>heather</u>)

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APPENDIX 4.

THE EFFECT OF THINNING A STAND OF SITKA SPRUCE UPON THE INTERCEPTION RATIO.

Two plastic-sheet net-rainfall gauges have been in continuous operation at a site 300m from the Institute´s office at ,Dolydd, Plynlimon, mid-Wales since March 1980. Four complete years of data (1981-1983 pre-thinning and 1984 post-thinning) for the net-rainfall gauges are presented in Tables 1 to 4. Thinning was carried out according to normal Forestry Commission practice for this area of removing every third row.

A canopy-cover survey at two different sites within the same stand was carried out in October 1984 and a value of p (the free throughfall coefficient) of 0.75 was obtained from both sites, indicating that canopy cover was uniform. The survey of the canopy was carried out using an anascope (an instrument consisting of a mirror and cross wires, mounted on gimbals, which is designed to allow the assessment of whether vegetation is directly overhead or not). Point measurements of canopy cover were made at 1m intervals along transects 1m apart. Site 1 with 147 observations gave p = 0.748 and Site 2 with 147 observations gave p = 0.755.

Results so far from the net-rainfall gauges indicate that the annual average interception ratio was unaffected by the thinning; for the pre-thinned forest it varied between 0.38 and 0.42 compared with 0.40 after thinning, see Tables 1 to 4. An analysis of the daily measurements similar to that developed for the daily interception model (see main text) demonstrates in detail the effects of the thinning. The pre-thinned forest (Figures 1 and 2) shows an interception loss equal to the rainfall when the rainfall is less than 2 mm per day and an average loss on days of high rainfall of between 5 and 6 mm. In contrast the post-thinned forest (Figure 3) shows an interception loss of approximatly 75% of the gross rainfall at low intensities but on average a higher loss (7 mm) than the pre-thinned forest on days with high rainfall.

FIGURE CAPTION.

Figures 1 to 3 show daily interception loss plotted against daily rainfall at Plynlimon for the years 1982, 1983 and 1984 respectively. Also shown are the curves fitted to the data using a simple interception model.

TABLE 1.

DOLYDD 1981 NET-RAINFALL DATA.

PERIOD	RAIN	NRAIN	IR*	REMARKS
010181-310181	177.8	99.96	0.44	data loss 010181-050181 use 0.38 as IR
010281-280281	145.0	100.34	0.31	
010381-310381	396.5	266.25	0.31	data loss 200381-230381 use 0.38 as IR
010481-300481	63.7	31.14	0.51	
010581-310581	132.4	69.93	0.47	
010681-300681	66.7	27.09	0.58	
010781-310781	76.1	30.10	0.60	
010881-310881	45.5	27.17	0.40	
010981-300981	247.9	150.64	0.39	data loss 300981-300981 use 0.38 as IR
010081-311081	375.1	265.39	0.29	
011181-291181	211.4	138.56	0.34	
301181-311281	161.5	90.36	0.44	
TOTAL	2099.6	1295.93	0.38	

*INTERCEPTION RATIO

TABLE 2.

DOLYCD 1982 NET-RAINFALL DATA.

PERIOD	RAIN	NRAIN	IR*	REMARKS
010182-310182	193.5	99.62	0.48	
010282-280282	121.2	70.31	0.42	
010382-310382	267.5	168.83	0.37	
010482-300482	50.9	21.04	0.58	
010582-080682	87.8	45.67	0.48	data loss 190582-080682 use 0.42 as IR
090682-300682	120.4	75.04	0.38	
010782-310782	36.8	17.34	0.53	
010882-310882	1903.1	104.64	0.46	data loss 110882-160882 use 0.42 as IR
010982-300982	137.4	104.64	0.46	
011082-301082	128.2	66.90	0.48	
311082-301182	332.7	186.18	0.44	data loss 211182-241182 use 0.42 as IR
011282-010183	297.6	195.69	0.34	
TOTAL	1967.2	1138.49	0.42	

*INTERCEPTION RATIO

TABLE 3.

DOLYDD 1983 NET-RAINFALL DATA.

PERIOD	RAIN	NRAIN	IR*	REMARKS
020183-300183	392.8	258.11	0.34	data loss 120183-120183 use 0.42 as IR
310183-280283	135.6	94.70	0.30	
010383-310383	143.8	79.23	0.45	
010483-300483	117.2	61.89	0.47	
010583-310583	133.7	63.03	0.53	
010683-300683	95.2	47.78	0.49	data loss 170683-300683 use 0.42 as IR
010783-300783	42.6	25.58	0.40	
310783-310883	70.5	39.44	0.44	
010983-300983	280.4	142.93	0.49	data loss 030983-040983 use 0.42 as IR
011083-311083	287.8	163.40	0.43	
011183-301183	134.2	77.84	0.42	data loss 011183-301183 use 0.42 as IR
011283-311283	282.0	185.00	0.34	
TOTAL	2116.0	1238.73	0.41	

*INTERCEPTION RATIO

TABLE 4.

DOLYDD 1984 NET-RAINFALL DATA.

PERIOD	RAIN	NRAIN	IR*	REMARKS
020384-260384	45.5	28.60	0.37	
270384-300484	12.1	4.41	0.64	
010584-220584	45.2	31.04	0.31	
230584-260684	80.2	25.69	0.57	
270684-300784	26.0	9.84	0.63	
310784-290884	74.2	45.71	0.38	
300884-260984	190.5	117.30	0.38	
270984-241084	233.0	139.08	0.40	
251084-231184	280.2	186.72	0.33	
241184-181284	156.2	96.16	0.38	
191284-301284	67.9	41.83	0.38	
311284-310185	102.5	63.19	0.38	Snow period 080185-270185
010285-280285	75.7	43.34	0.43	Snow period 080285-240285
TOTAL	1389.2	832.91	0.40	

*INTERCEPTION RATIO

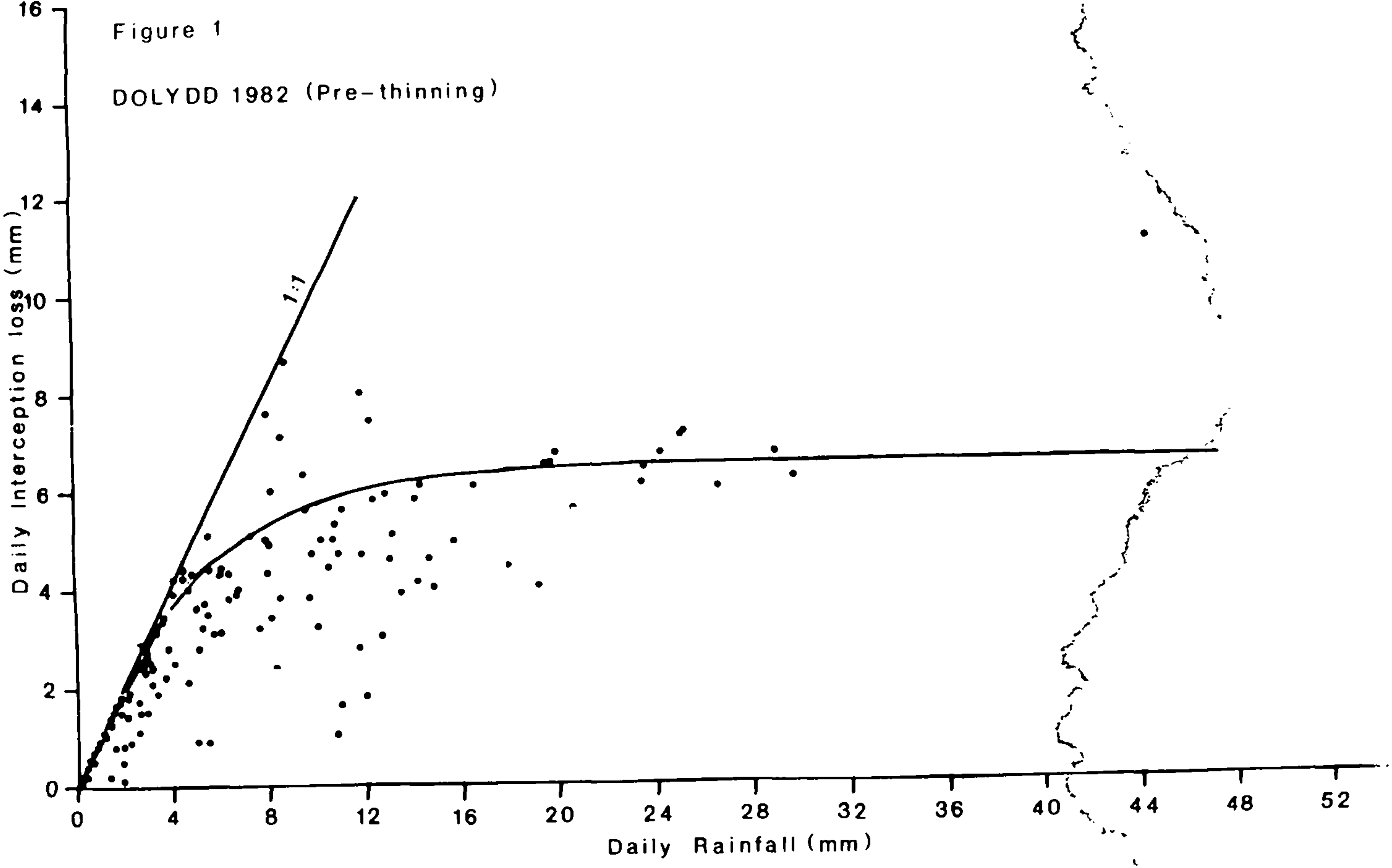
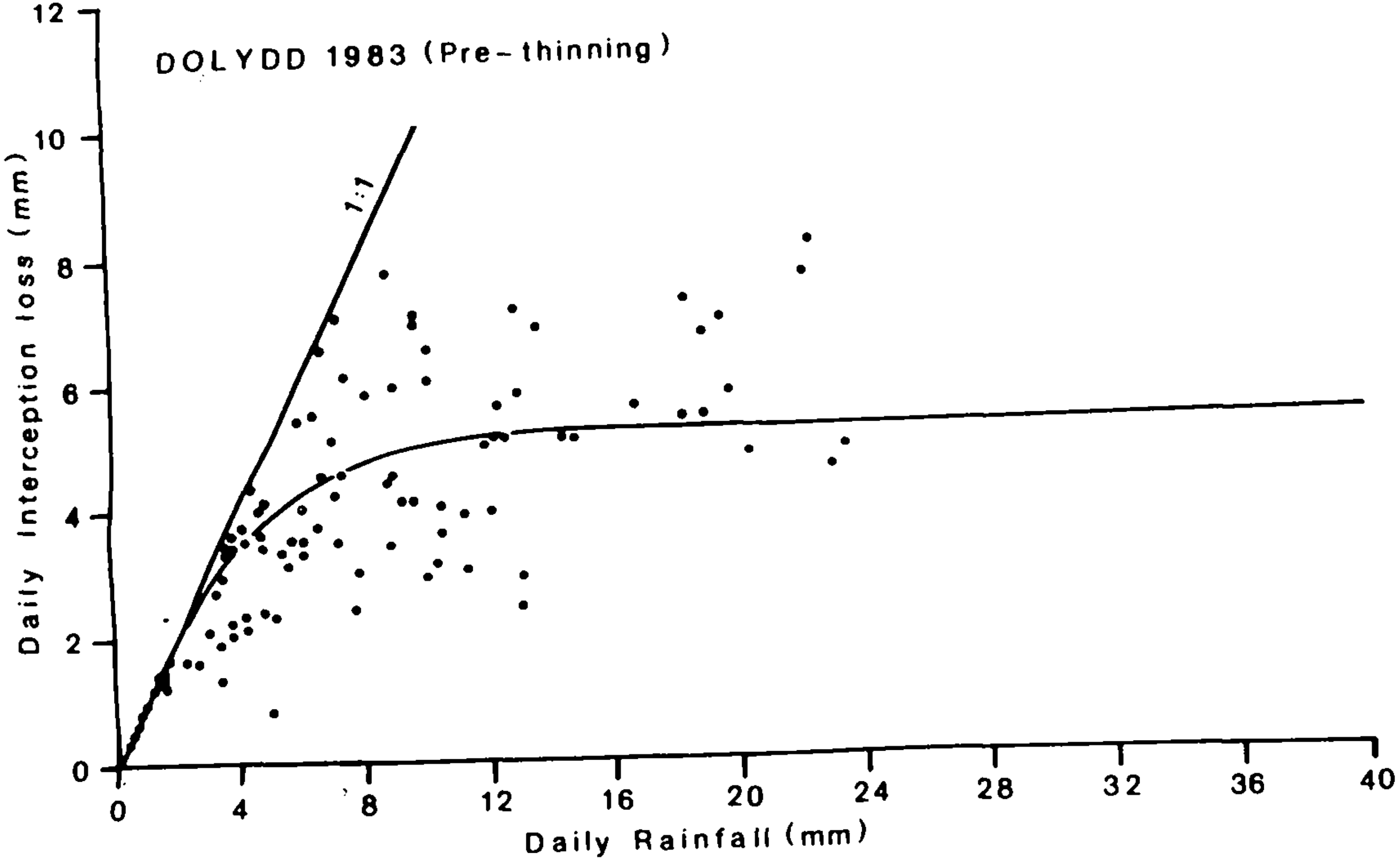


Figure 1

DOLYDD 1982 (Pre-thinning)

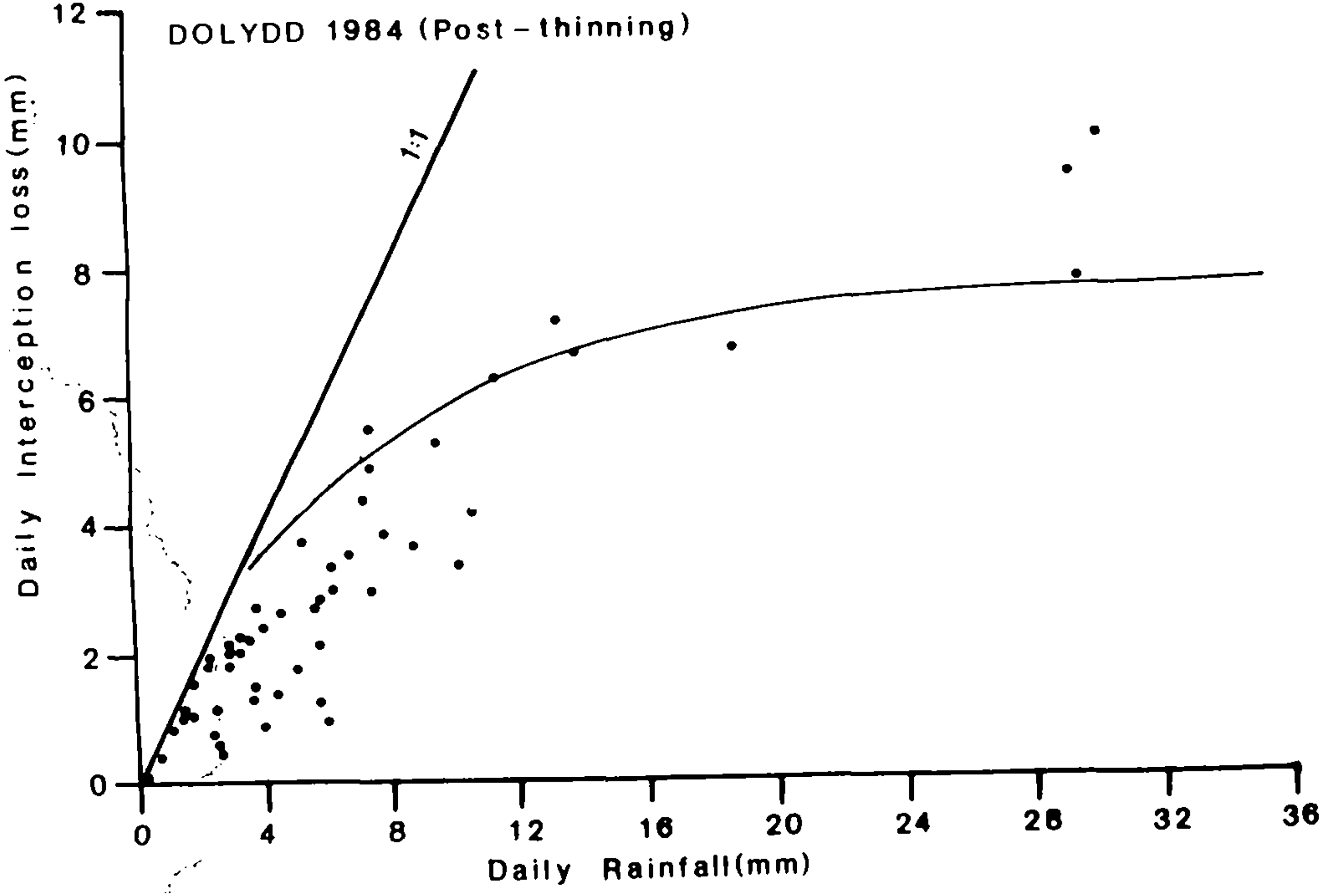
Figure 2

DOLYDD 1983 (Pre-thinning)



1

Figure 3



DOLYDD 1984 (Post-thinning)

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