1983/002

UPLAND AFFORESTATION AND WATER RESOURCES

Progress Report 1982/83

on

The Balquhidder Catchment Studies

and

The Physical Process Studies

Progress Report on the Balquhidder Catchment Studies

1982/83

By

J. R. Blackie

INTRODUCTION

The Monachyle and Kirkton catchments at Balquhidder, located as shown in Figure 1, were chosen by the Consortium to study in a typical Scottish Highland catchment area the effects on the hydrology of plantation forestry as compared with the indigenous grass/heather/bracken vegetation. The aspects of particular interest in the initial 5 year phase of the study are the differences in vegetative water use, both annual and seasonal, the difference in range and time distribution of flow and the differences in sediment transport attributable to these two forms of land management. A second phase of the study, in which the effects on these aspects of initial forest planting in part of the Monachyle and of progressive felling and replanting in the Kirkton will be monitored, has been discussed and provisionally agreed.

In a report to the Consortium in 1982 the first stages of instrumentation of the catchments were described. This report covers later stages of that work, describes the continuing evaluation of the data collection techniques and discusses some of the points of interest arising in the preliminary analysis of the accumulating data base.

FIELD OPERATIONS

Streamflow structures

As of March 1982 the major construction work outstanding was that of the streamflow structures on both catchments. Preparatory work had been carried out on the Kirkton site but work was brought to a halt until April by the severe winter conditions. Rapid progress was made from then on by Forestry Commission and Institute of Hydrology staff on the main structure, a Crump weir with 7 m stainless steel crest, and construction was completed late in June. Concurrently Forth River Purification Board installed a parallel pair of low flow flumes downstream of the main structure. After installation and testing of the electrical water level recorders which record on magnetic tape at 5 minute intervals on both structures, data collection began early in July 1982. No major problems have been encountered with these structures other than the need to clear sediment from the low flow structures after flood events. Much of the early accumulation was of loose material left in the streambed after the construction work.

The next priority was the installation of the main and low flow structures five months respectively. Otherwise all these gauges were read at approximately monthly intervals. The only exception to this was during Autumn 1982 when the three gauges in the upper Monachyle were not read for a period of eight weeks. This arose from a request from the landowner to stay away during deer culling operations.

The original network of six snow gauges in Kirkton forest clearings was reduced to five during the year. Despite considerable access difficulties during January and February these were read after each major snow event. During the rest of the year frequent readings were made of three of these gauges and the adjacent ground level gauges to assess their performance as raingauges. Similar comparative readings were done with the snowmelt gauges in both catchments. The positions of a number of the networks of snow poles installed in 1981 were changed during the year to make them more easily visible by telescope from key observation points. These poles are used to assess the depth of lying snow in major events when access to the upper parts of the catchments is restricted.

Weather Stations

The third and final automatic weather station was installed at the Tulloch farm site (figure 1) in March 1982 followed by the manual meteorological equipment, supplied by the Meteorological Office, in mid-April 1982. More detailed comment on the performance of the weather stations is given later.

Sediment yield studies

During Summer 1982 the Fluvial Geomorphology Unit within IH began studies of the suspended and bed sediments carried by both the Kirkton and Monachyle streams in flood. This work is funded by NERC although the fieldwork is done by the resident observer on the Balquhidder project. Mr. Johnson has been provided with USDH-48 (suspended) and Helley-Smith (bed) samplers which he operates from bridges during flood events. To ensure suspended load sampling during "unsocial hours" an automated sampler has also been provided. After major floods, observations are made of any changes in channel morphology and an estimate made of the volume of any sediment deposited in the flow-gauging structures.

ANALYSIS

It is now some eighteen months since the first rainfall data were obtained from the Balquhidder catchments. The Kirkton and Monachyle automatic weather stations were installed at the same time but the data run from these is patchy over the first six months. Streamflow measurement began in July 1982 in the Kirkton and began effectively in December 1982 in the Monachyle. Obviously at this stage the analytical work on the data is concerned mainly with checking the performance of the instrumentation, assessing the adequacy of the design theory and determining the relationships within and between networks. In the following paragraphs brief descriptions are given of some aspects of this work.

Precipitation data

Whilst the design and installation of the streamflow structures have consumed a major portion of the effort and funding of this catchment study so far, it is the accurate estimation of the volume input of precipitation to the catchments that presents the major scientific challenge. It presents problems at every level from the philosophical to the very practical.

At the philosophical level there is a profound difference in approach between the estimation of the volume input to a small experimental catchment and the estimation of regional rainfall. In siting gauges in a sparse network to obtain regional estimates one would tend to avoid areas of steep rugged terrain such as these catchments. They would be considered likely to give anomalous results, in regional terms, because of the local topographic effects. Yet it is these 'anomalous' inputs that have to be measured in the catchments and areal estimates accurate to the order of 5% on an annual basis have to be derived if the water balance is to determine differences in water use between the catchments with acceptable accuracy.

This difference of approach starts with the method of point measurement of precipitation and extends to the network design. Catchment domain theory accepts that local variations in rainfall will occur within the catchment not only with altitude but also with aspect and slope. Depending on the topography, these variations will bias the areal rainfall relative to the regional mean. Thus instead of seeking raingauge sites which will give a reasonable representation of the regional mean a network is designed to sample, on an area weighted basis, all the major altitude aspect and slope domains within the catchment. Whilst the individual gauges are nominally

(f) A further check on (c) will be provided by the 'within network' relationships, derived retrospectively, for periods when precipitation falls as rain at lower and as snow at higher altitudes.

Against this theoretical background much of the initial analytical effort has been devoted to cross-checking the various types of precipitation gauges in use and to developing within network and between network relationships.

Time distribution of the monthly network readings is done on a proportional basis using the recording gauges nearest to the storage gauge in question. With the intermittent performance of the weather stations and also of the rainfall event recorder in the Monachyle over much of the initial period of record, accurate time distribution of the monthly readings has yet to be fully achieved. Tentative monthly estimates for the period April - October 1982 are given in Table 1.

The current best estimates of catchment total precipitation from October 1981 to September 1982 are

Monachyle catchment	2625 mm
Kirkton catchment	2338 mm

These, it must be stressed, are subject to progressive revision as the 'within' and 'between' network relationships are refined. They do however bear out the evidence from regional gauge records that a considerable West to East rainfall gradient exists in this area.

Tables 2 and 3 give details of the location, slope and aspect of the ground level raingauges in each network. In Table 4, within network comparisons of cumulative totals over periods free of snow and when the individual totals are directly comparable are presented. For each catchment the pattern of departure from the catchment mean of the individual gauges is similar in each of the two periods. Comparison of this pattern with the site details in Tables 2 and 3 confirms that there is a weak but positive correlation with altitude, but indicates also that other factors significantly effect the distribution. Work will continue on quantifying these patterns.

TABLE 2. Kirkton GL Raingauges

Gauge Code	C1W	C3W	C3Y	D3Y	D2Y	B3Y	A3Y	B3W	A3W
ALT(m)	670	580	600	780	710	540	380	420	370
GRID EAST	5135	5145	5385	5395	5320	5260	5350	5245	5273
GRID NORTH	2290	2372	2255	2350	2422	2405	2240	2275	2195
ANGLE°	05	13	19	18	13	21	22	15	15
* $CF(\frac{1}{\cos\theta})$	1.004	1.026	1.058	1.051	1.026	1.071	1.078	1.035	1.035
$DIR^{n}.°$	350	080	230	260	210	210	270	110	090

*CF is the slope correction factor by which the observed catch is multiplied

Table 4. Within catchment comparisons of period rainfall totals

(a) KIRKTON CATCHMENT

Period		C1W	C3W	C3Y	D3Y	D2Y	B3Y	A3Y	B3W	A3W	Catchment Mean
31/7/81	TOTALS	864	821	653	780	805	702	640	722		749
to	xCF	868	843	691	820	826	752	690	747		780
3/11/81	% Dep.	+11.3	+8.1	-11.3	+5.2	+6.0	-3.6	-11.5	-4.2		
5/5/82	TOTAL	919	895	709	892	902	782	714	814	(764)	828(8)
to	xCF	923	918	751	937	925	838	769	842	(791)	863(8)
6/10/82	% Dep.	+6.9	+6.4	-13.0	+8.6	+7.2	-2.9	-10.8	-2.4	(-8.3)	

(b) MONACHYLE CATCHMENT

		A1X	A3X	B2W	B1W	B2X	B1X	B1Y	B2Z	B3Z	C2Z	C2W	Catchment Mean
3/8/81	TOTAL	860	896	882	884	802		790	731	834	871	912	846
to	xCF	865	910	895	885	853		798	736	850	890	921	860
6/11/81	% Dep.	+0.5	+5.7	+4.1	+2.9	-0.8		-7.2	-14.4	-1.2	+3.5	+7.0	
6/5/82	TOTAL	466	476	529	495	443	(494)	434	399	449	469	536	470(10)
to	xCF	469	483	537	496	471	(495)	438	401	457	479	542	477(10)
2/9/82	% Dep.	-1.8	+1.3	+12.6	+4.0	-1.3	(+3.8)	-8.2	-15.9	-4.2	+0.4	+13.5	

%Dep. is the departure from the mean expressed as a percentage.

Table 5

Comparison of GL and snow gauge rainfall catches at two forest sites in Kirkton

Period	A3Y			A3W		
1982	GL	Snow gauge	$\frac{S-GL}{GL}$ %	GL	Snow gauge	$\frac{S-GL}{GL}$ %
Feb/Mar	359.5	319.3	- 11.2	349.3	306.4	- 12.3
Apr/May	129.1	94.8	- 26.6	138.3	100.8	- 17.1
Jun/Aug	198.9	129.9	- 34.6	187.3	120.3	- 35.8
Aug/Sept	196.2	159.0	19.0	199.8	156.0	- 21.9
Sept	248.6	228.6	8.0	258.1	241.2	6.5
Oct	304.7	284.7	6.6	341.3	337.3	1.2
Nov	126.4	120.0	5.1			
TOTAL	1563.4	1336.3	- 14.5	1474.1	1262.0	- 14.4

Ground level (GL) readings are corrected for angle.

TABLE 6. Kirkton daily streamflow, Sept. 1982
(Provisional only, based on theoretical ratings)

DATE	RAINFALL DISTRIBUTION		STREAMFLOW	
	AWS(T) (mm)	AWS(K)	CRUMP (mm)	LOW FLOW
1	0.0	0.5	1.53	-
2	0.0	0.0	1.40	1.50
3	8.0	7.5	1.46	1.56
4	4.5	5.0	1.41	1.51
5	18.5	19.0	7.23	x
6	9.0	12.5	5.84	x
7	13.0	10.5	6.17	x
8	2.0	2.0	4.24	4.63
9	7.0	9.0	4.06	4.40
10	23.0	31.5	16.58	x
11	0.0	0.0	4.83	x
12	23.5	36.0	15.49	x
13	0.0	0.0	5.37	x
14	0.5	1.0	3.63	3.95
15	1.0	3.0	3.08	3.65
16	3.0	5.5	3.27	3.54
17	0.0	0.0	2.59	2.83
18	1.0	1.5	2.21	2.76
19	17.5	16.5	3.46	x
20	27.5	33.0	16.86	x
21	6.0	6.0	9.13	x
22	7.0	9.0	4.60	x
23	12.0	16.5	10.65	x
24	31.0	34.5	17.80	x
25	6.0	7.0	11.45	x
26	25.5	32.0	14.67	x
27	29.0	35.0	24.51	x
28	21.0	31.5	21.89	x
29	3.5	2.0	9.70	x
30	5.5	9.0	6.17	x
TOTAL	305.5[1]	376.5[1]	241.9	

Midnight Midnight as compared to 0900 - 0900 in Table 1
Flow out of structure range for all or part of day.

TABLE 7 Monachyle (M) v. Tulloch Farm (T) AWS regressions, April to June 1982

Variable	Units	Regression		r^2	$\bar{M}$	$\bar{T}$
Daily mean temperature	^{o}C	M = 1.062T-2.40	76	0.979	8.3	10.0
Daily max temperature	^{o}C	M = 1.079T-2.76	76	0.973	13.3	14.9
Daily min temperature	^{o}C	M = 1.050T-2.57	74	0.922	3.1	5.4
Daily solar radiation	MJm^{-2}	M = 0.875T+0.29	75	0.852	12.4	13.8
Windspeed	ms^{-1}	M = 0.870T+1.04	76	0.629	2.69	1.89
Spec. humidity deficit	$gm\ kg^{-1}$	M = 0.937T-0.22	76	0.896	1.70	2.05

compare this with the winter correlation of radiation. Kirkton windspeeds are much higher than those at the E-W and N-S valley bottom sites of Tulloch and Monachyle respectively. The correlation with Tulloch is significantly higher than that of the Monachyle site. Both Kirkton and Monachyle have significantly lower humidity deficits than Tulloch, presumably because the lower temperatures, higher rainfall and longer duration of hill fog outweigh the effects of the proximity of Kirkton to the loch.

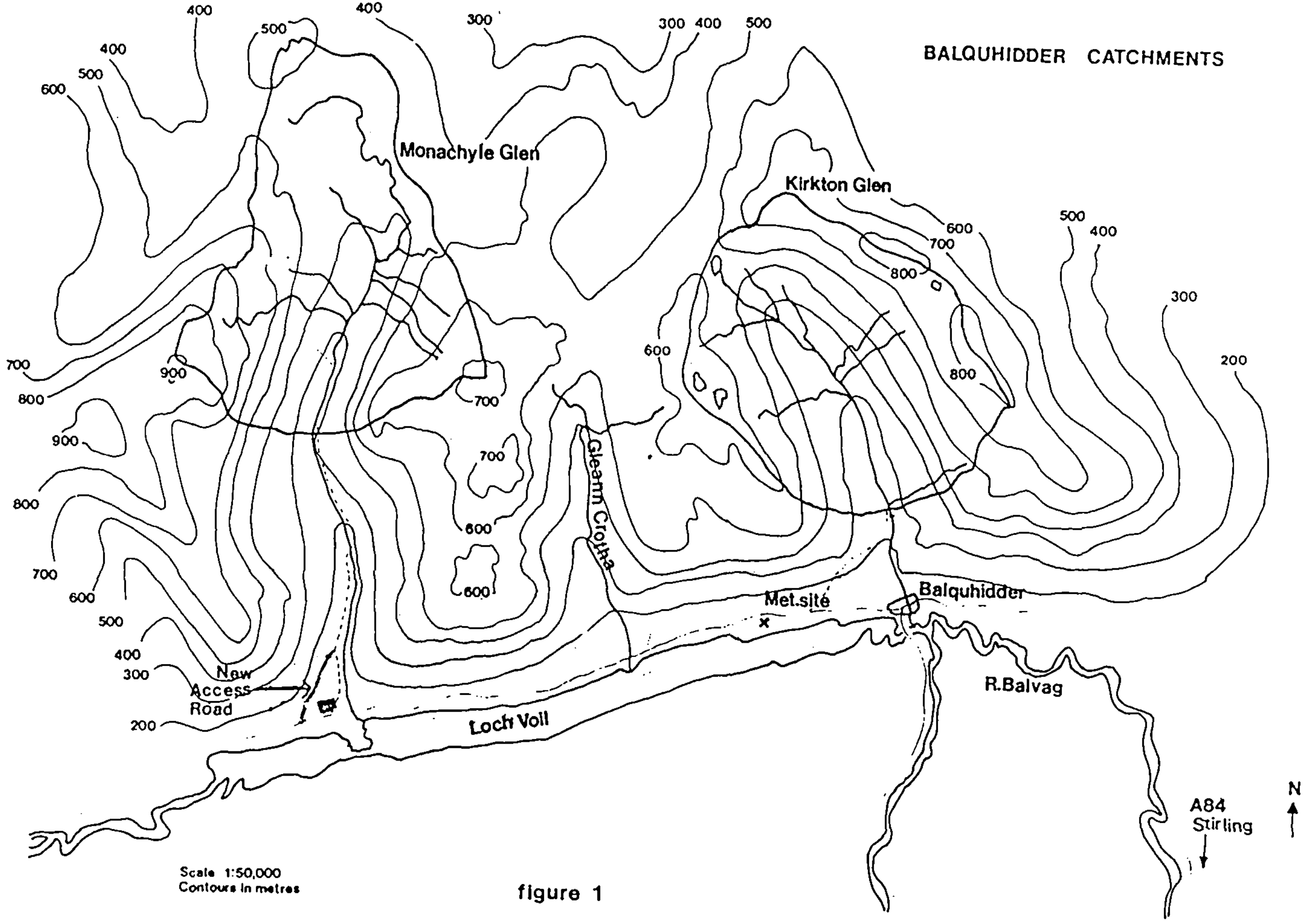
The Met. Office supplied manual meteorological equipment at the Tulloch site provides useful back-up to the weather station and also provides 'instant' data which is of general value to the observer on site. Comparison of temperatures can be done most conveniently using the daily maximum and minimum values. Those from the weather station are in fact the extreme values recorded at the 5 minute sampling intervals during the 24 hour period whereas the manual values are from the screen mounted maximum and minimum thermometers. Monthly means of the daily values together with the extremes in each month for the period May-October 1982 are listed in Table 9. This indicates that the weather station sensor consistently reads 0.5°C higher than the manual instruments. This is double the minimum discrimination level of the AWS data logging system of ±1 logger step which, for the present temperature range used, is equivalent to ± 0.25°C. The extreme maximum temperatures reached on 5/6/82, 21/7/82 and 5/8/82 are the only occasions when significantly greater differences occurred. In each case windspeed was negligible at the time of maximum temperature, suggesting that the shielding and ventilation effects of the Stevenson and AWS screens differ under these extreme conditions.

SUMMARY

1982 has seen the completion of the instrumentation of the Monachyle and Kirkton catchments, with the exception of the second streamflow structure on the Monachyle which is scheduled for Spring 1983. As the data collection problems have been solved progressively, preliminary analysis of the accumulating data has begun. From this, patterns of spatial and temporal distribution are beginning to emerge which, when fully quantified, will form the basis of methods for progressive refinement of the estimates of precipitation and meteorological inputs to the catchments. Preliminary analysis has also identified the need for some checking of the ratings of the streamflow structures on Kirkton and for some modifications to the combined snow/rainfall gauges in the forested area of the Kirkton. Preliminary estimates of annual precipitation suggest that this is higher than was anticipated originally but confirm that the area is subject to a pronounced West to East gradient.

The study is now well launched and gives every indication of producing accurate hydrological information on land use effects.

In conclusion IH wishes to thank SDD, FC and FRPB in particular for their active assistance in tackling design and field installation problems.



BALQUHIDDER CATCHMENTS
Monachyle Glen
Kirkton Glen
Gleann Crotha
Met.site
Balquhidder
R.Balvag
Loch Voil
New
Access
Road
A84
Stirling
N
Scale 1:50,000
Contours in metres
200
300
400
500
600
700
800
900

figure 1

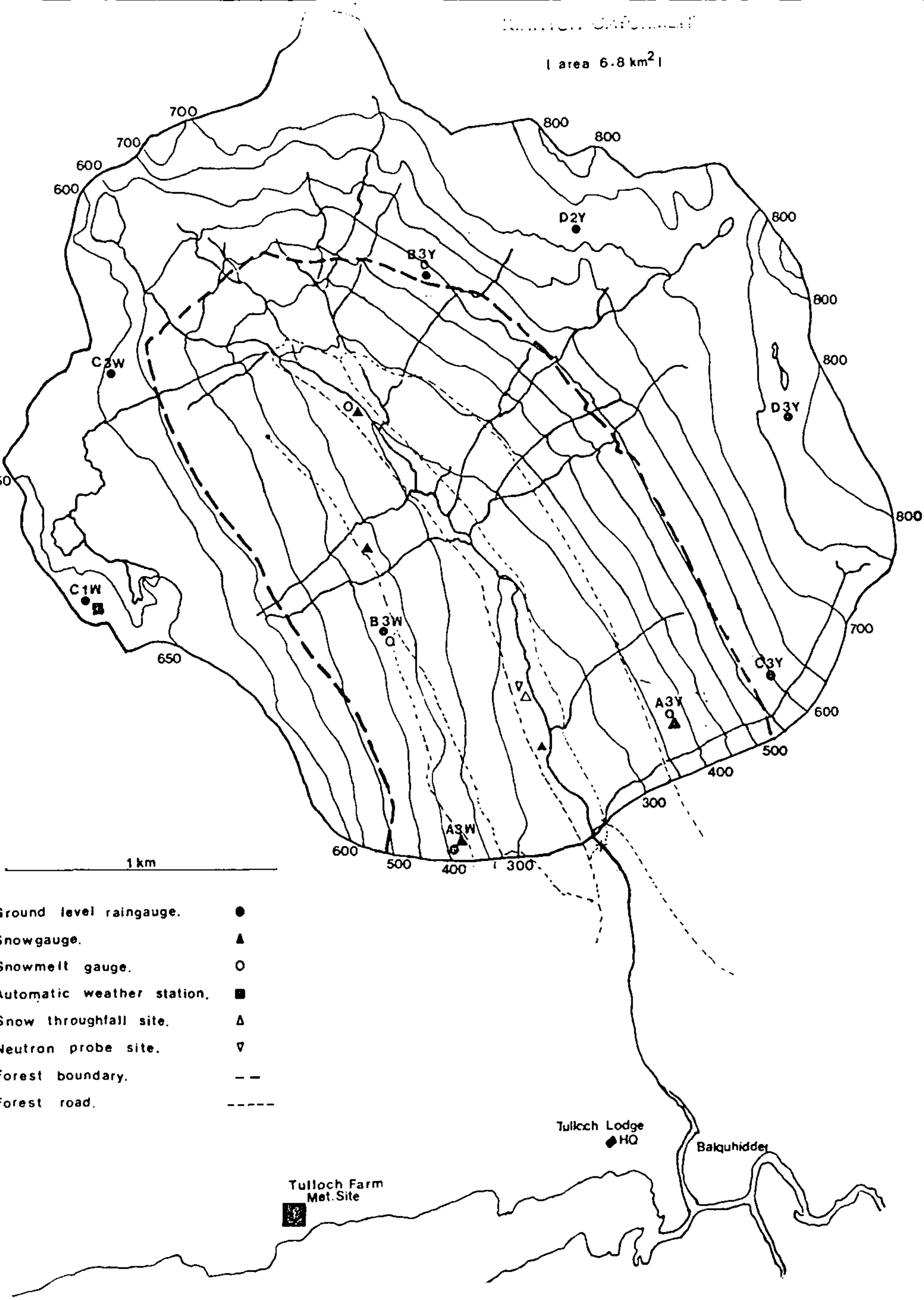
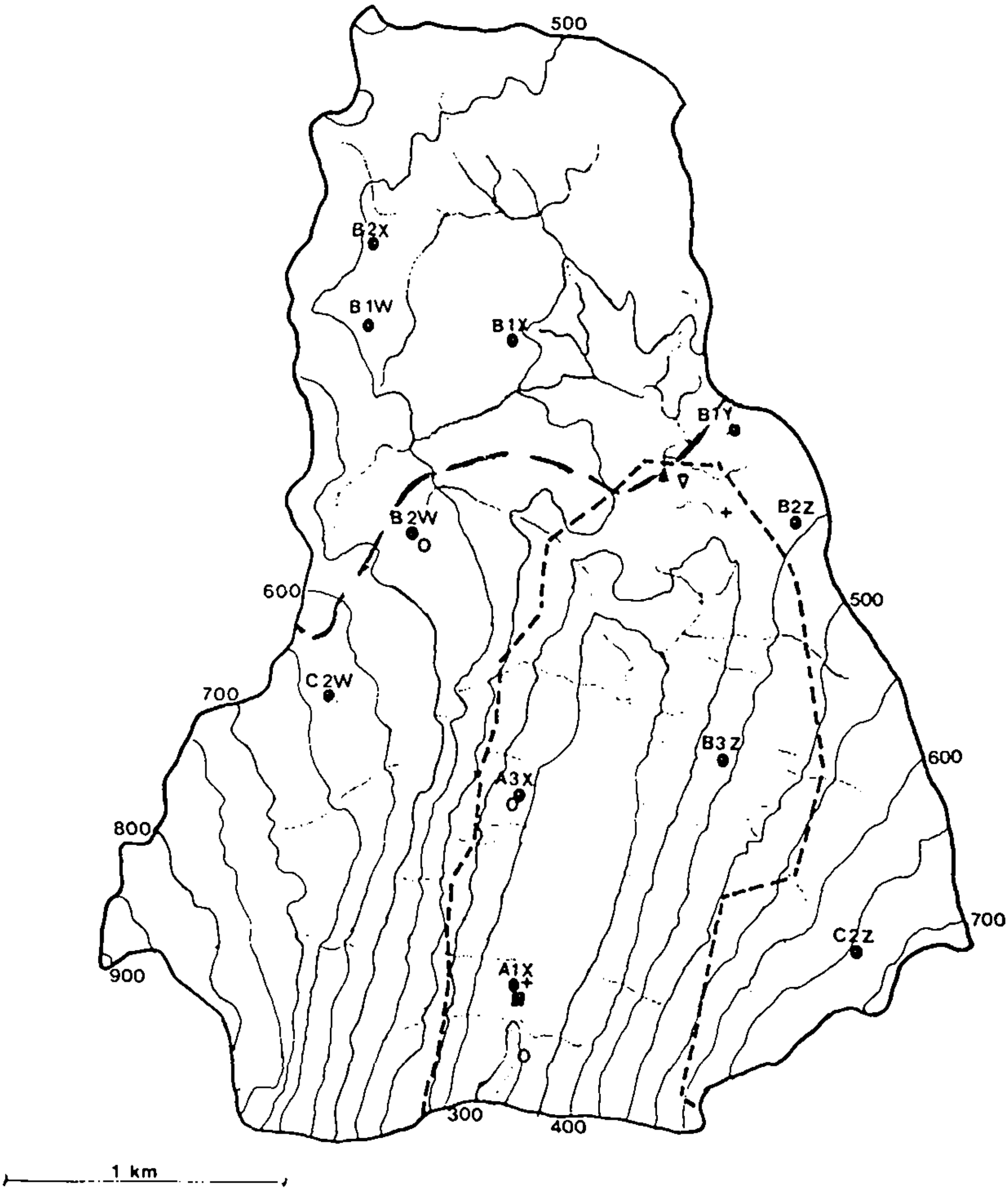

(area 6.8 km²)
700
700
600
600
800
800
800
800
800
800
650
650
700
600
500
400
300
600
500
400
300
D2Y
B3Y
C3W
D3Y
C1W
B3W
A3Y
C3Y
A3W
1 km
Ground level raingauge.
Snowgauge.
Snowmelt gauge.
Automatic weather station.
Snow throughfall site.
Neutron probe site.
Forest boundary.
Forest road.
Tulloch Lodge
HQ
Balquhidder
Tulloch Farm
Met. Site

figure 2

MONACHYLE CATCHMENT (area 7.7 km^2)



Ground level raingauge ●
Snowmelt gauge O
Recording raingauge +
Automatic weather station ■
Neutron probe site ▽
Proposed site for second streamflow structure ▲
Forestry Commission fence – –
Upper Catchment boundary

figure 3

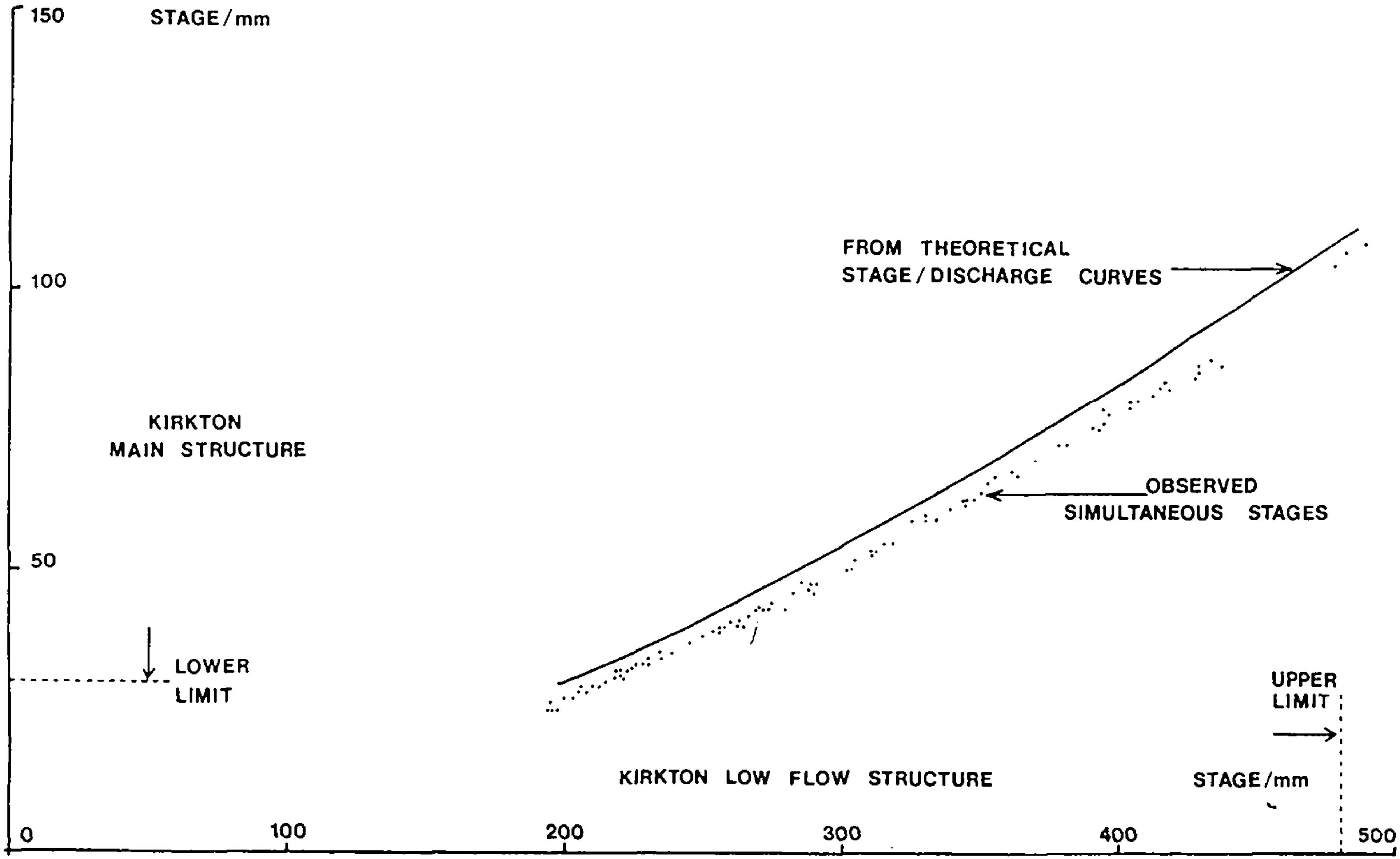


figure 4 Observed and theoretical stage relationships on the Kirkton structures

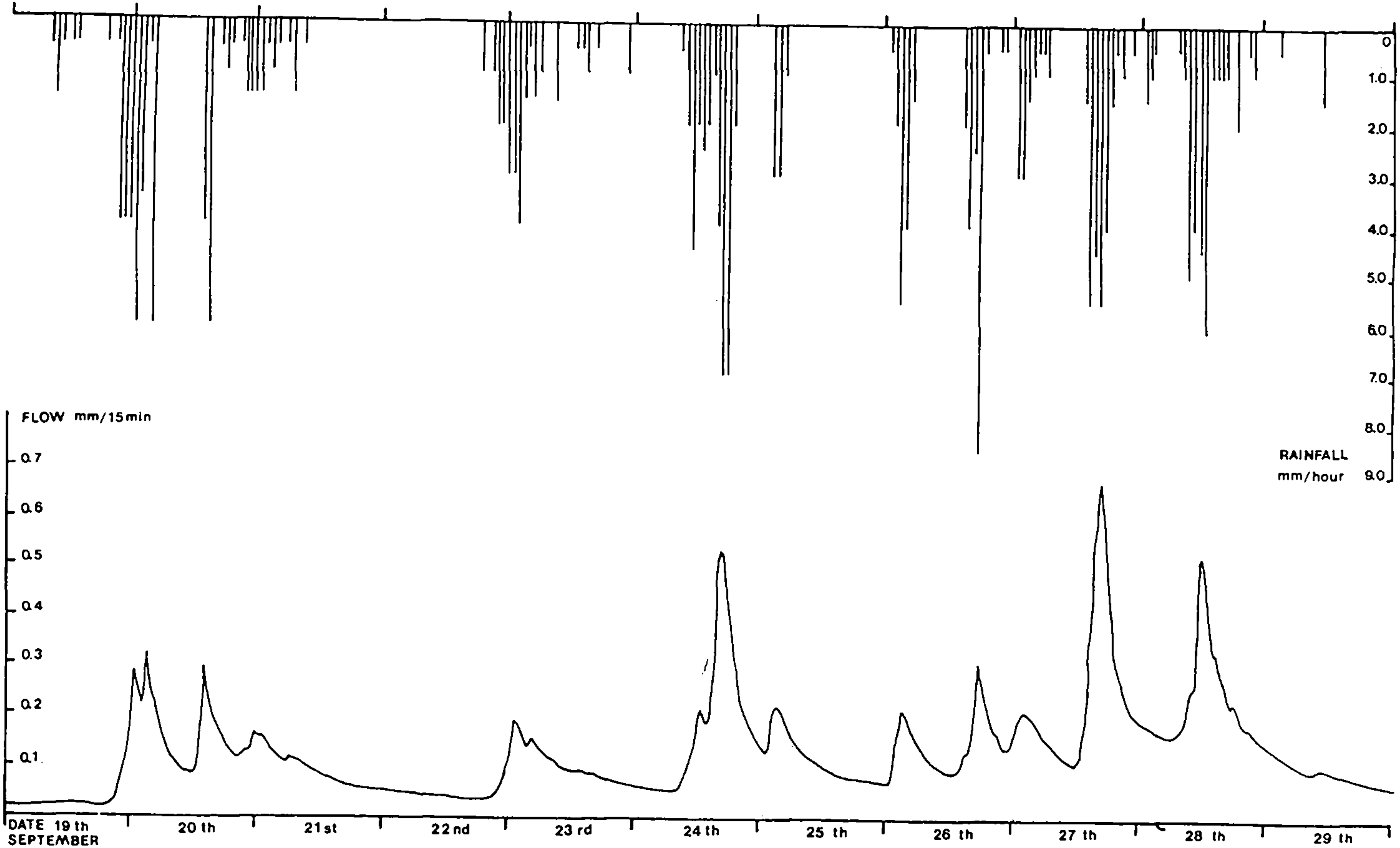


figure 5. Hydrographs from Kirkton using the theoretical Crump rating.

UPLAND AFFORESTATION PROGRESS REPORT. PROCESS STUDIES 1982-1983

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

INTRODUCTION

During the past year the development of field experiments has continued at sites in Scotland, England and Wales. Preliminary results and conclusions from some of these studies have already been included in publications (see Appendices 1 and 2) entitled:

The application of catchment, lysimeter and hydrometeorological studies of coniferous afforestation in Britain to land-use planning and water management., I.R. Calder, M.D.Newson and P.D.Walsh, 1982, Proceedings of the International Symposium on hydrological research basins and their use in water resource planning. Berne 1982.

Forest evaporation., I.R.Calder, 1982, Proceedings of the Canadian Hydrology Symposium 82, Hydrological processes of forested areas, pp173-193.

The results of some of the wet-surface weighing lysimeter studies will be submitted for publication in the Journal of Applied Meteorology. A lecture describing the snow interception studies and their preliminary results was presented by Dr. R J Harding at the annual meeting of the Society of Glaciology in September.
The progress of the individual experiments is outlined below. All of the experiments are on schedule except for the snow interception, gamma ray attenuation project which has required considerably more instrumental development than was originally anticipated. This experiment will not now be operational at the Aviemore site before the winter of 1983/84 and an extension of the project to allow operation of this experiment and to complete the necessary evaporation modelling for an extra year would be desirable.

determining aerodynamic resistance. There was also collaboration at Berner's Heath with members of the Applied Physics department of Strathclyde University who used a gamma ray attenuation experiment to measure the change in mass of intercepted water on the heather canopy. It is expected that the results from these combined studies will greatly enlarge understanding of the evaporation characteristics of heather.

SNOW INTERCEPTION

The experimental study started in 1981 in Aviemore is continuing; a report describing the experiment and the results from the winter of 1981/82 has been prepared.
The main experiment, consisting of heated plastic sheet net rainfall gauges and a weighed tree, is again operational this winter and it is planned to continue operation in 1983/84. In the winter 1983/84 it is also planned to operate a gamma-ray detection system to measure the weight of snow on the forest canopy.
The Meteorological Office, Aviemore is thanked for their cooperation in the provision of routine climatalogical data.

SOIL MOISTURE DEFICIT STUDIES

Balquhidder

Very few observations were obtained during 1982; other demands on manpower within the catchment left little time for neutron probe observations at the upper Monachyle site. It is expected that in 1983 storage facilities for the probe at the Monachyle site will be available and regular soil moisture readings will be possible.

Crinan

As in previous years, observations have been maintained under different

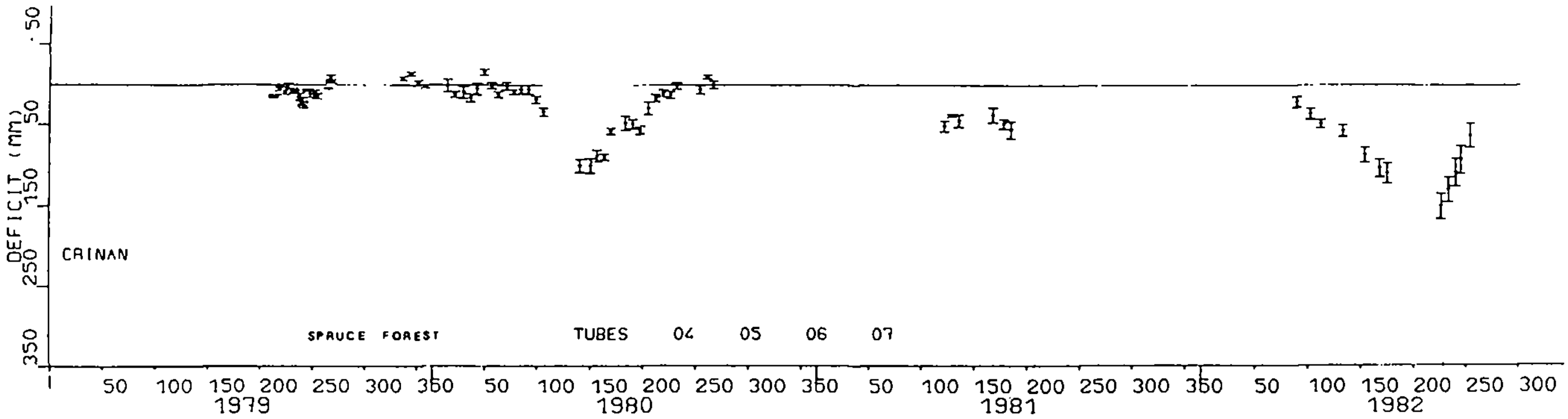


Figure 1

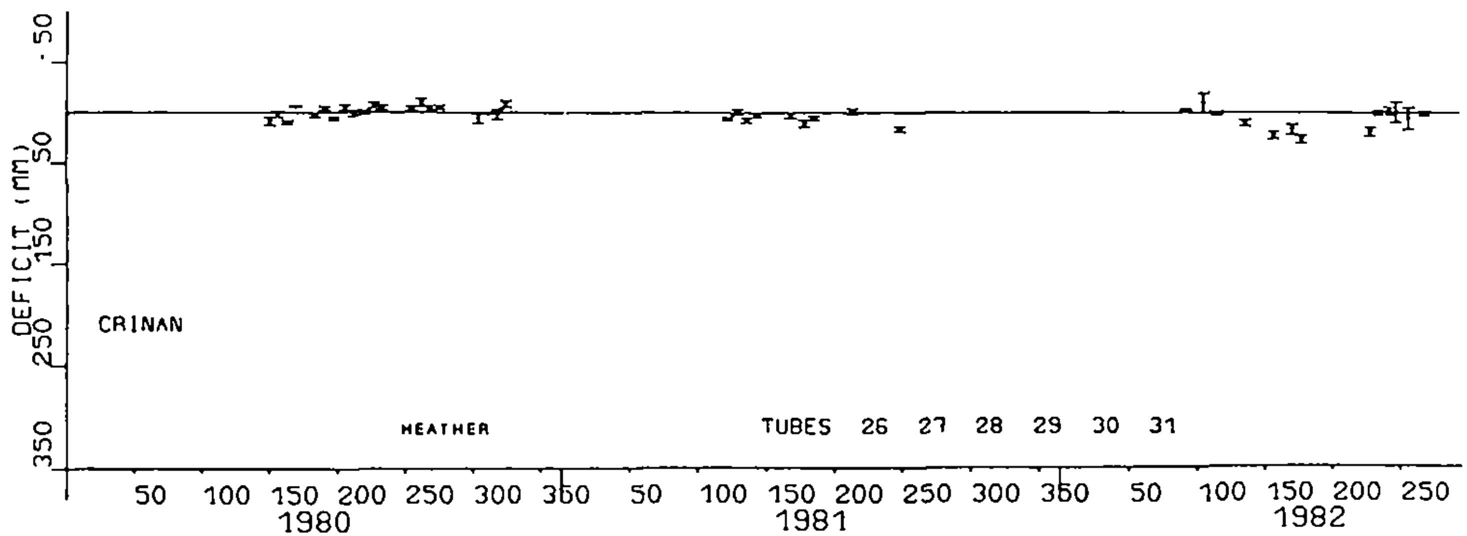


Figure 2

ANALYSIS OF HISTORICAL DATA FROM FRANK LAW'S EXPERIMENTS AT STOCKS RESERVOIR

Historical data from Frank Law's grass and heather lysimeter experiments have been reanalysed to provide additional information on the evaporation characteristics of these crops.
The experimental site is at Stocks Reservoir, near Slaidburn, Yorkshire, 20 miles north-east of Preston.
Six years of data (1964-1970) from four grass drainage lysimeters, two grass weighing lysimeters and two heather weighing lysimeters have been quality controlled and analysed.
Periods selected for detailed analysis were 1964 (25th May - 31st Dec), the whole of 1965, 1967 and 1968 and the first six months of 1969.
Optimisation methods have been used to compare the operation of different evaporation models with the data from the heather lysimeters.
The models, based on the methods developed by Calder and Newson (1979)(see Appendix 3), took the form:

$$E = R.ET.(1-w) + \alpha.P$$

where,

E	=	evaporation rate	(mm/day)
R	=	transpiration ratio	
ET	=	Penman's potential transpiration for grass	(mm/day)
w	=	fraction of day canopy is wet	
α	=	interception ratio	
P	=	precipitation rate	(mm/day).

An estimate of w can be calculated from the relation:

$$w = P.1{\cdot}5/(i.24)$$

where i is the mean rainfall intensity (mm/hr) and w is not allowed to exceed unity.

Table 2

MODEL NO.	LYSIMETER	α			R.M.S. ERROR (mm)
	R	0.2	0.36		28
1	S	0.2	0.32		42
1	R and S	0.2	0.34		33
2	R	0.18	0.41		27
2	S	0.13	0.52		28
2	R and S	0.16	0.47		27
3	R	0.18	0.39	0.21	27
3	S	0.13	0.51	0.15	28
3	R and S	0.16	0.45	0.18	27

APPENDIX I

THE APPLICATION OF CATCHMENT, LYSIMETER AND HYDROMETEOROLOGICAL STUDIES OF CONIFEROUS AFFORESTATION IN BRITAIN TO LAND-USE PLANNING AND WATER MANAGEMENT.

I.R. Calder[1], M.D. Newson[2] and P.D. Walsh[3]

[1]Institute of Hydrology, Wallingford, U.K., [2]Institute of Hydrology, Staylittle, Powys, U.K., [3]North West Water, Warrington, U.K.

ABSTRACT

The paper is based upon an application of the pioneering study by Law at Stocks Reservoir, north-west England, and its subsequent development in the Plynlimon Experimental Catchments, mid-Wales. The context is the important upland zone for water conservation in Britain, in which rates of land-use change have accelerated rapidly since the major period of reservoir construction. Examples are given of the pressures which now exist to make more effective economic use of the semi-natural grassland and moorland which characterizes the British uplands. Afforestation is treated as the land-use change most likely to affect the availability of water resources from the uplands since evaporation from interception storage is an efficient process in the prevailing climate.

Site-specific research to compare the water balance of rough grassland and mature coniferous forest is described by summarizing the most recent analyses of data from Stocks Reservoir and Plynlimon. Extrapolation as a basis for practical advice to the water supply and hydro-power industries has been based on process studies of interception and evaporation and their incorporation in models, the most useful of which is very simple. Confirmation of the models has been achieved by case studies in collaboration with a variety of authorities throughout Britain. The implications of the findings are described from the points of view of the planning of the use of natural (land based) resources (as yet poorly developed in the upland areas of Britain) and the specific case of water management in north-west England.

Finally, the remaining gaps between research and application are listed in an attempt to specify research priorities in the period during which land and water use strategies are being formulated for the next century.

THE CONTEXT OF WATER RESOURCES AND CATCHMENT LAND-USE IN UPLAND BRITAIN

The hydrological picture

Situated across the path of prevailing moist Atlantic winds and with most of its mountains and hills in the west, Britain experiences a wide range of climates from the relatively cold, wet, "hyper-oceanic" west to a moderately warm, dry, more continental east. With a range of annual rainfalls of 2,500 mm - 500 mm, west-to-east, and one of 350 mm - 575 mm of annual potential evaporation from north-east to for amenity, or to supplement incomes, but little concern was expressed about afforestation on a larger scale until after World War II. The international literature on the hydrological effects of afforestation was marked by discrepancies in results between climatic zones, crops and treatments; no catchment studies had been initiated in Britain to provide first-hand evidence, although Ovington (1954) had measured the interception effect of several tree species in southern England, recording up to 93% reduction of precipitation reaching the ground under trees in some rain storms.

The Stocks lysimeter and other experiments

The prospects of increasing demands for water and timber at a time of hydrological ignorance (only one quarter of today's flow stations then existed) makes the work of Frank Law of key importance in Britain. In 1954, as Engineer of the Fylde Water Board in north-west England he commenced his experiments at Stocks Reservoir to try and resolve the conflict of opinions (Law, 1956) then being expressed; foreign research results and those of Ovington were at variance with the views of many British hydrologists on water losses from forests.

Stocks Reservoir which is now owned by North West Water Authority was completed in 1933 and has a catchment area of 37.5 sq kms; it is between 180 and 540 metres above sea level and receives an average annual rainfall of 1650 mm. Runoff into the reservoir is calculated from the balance of reservoir storage and all abstractions and outflows; almost 50 years of daily data are now available. Measurement of rainfall commenced in 1910 with 5 gauges, but for the last 25 years 22 gauges have been in use. Runoff from a neighbouring non-afforested catchment, Croasdale, has been measured since 1957; subsequently in 1960 a flume was constructed to measure flows from the main afforested (70%) sub-catchment of the reservoir, Bottoms Beck.

In 1947 22% of the catchment was leased to the Forestry Commission who have since 1953 planted Sitka spruce, Picea Sitchensis. The lysimeter (450 m^2) was established in a smaller area of older trees at an elevation of 183 metres. In addition to a full climatological station nearby, a second was established in 1955 on an exposed promontory with twice the wind run. This site also housed grass and heather weighing lysimeters and a range of experimental raingauges.

The foresight to gather all these data to fill gaps in the perceived needs of a water supply undertaking through applied research is even now proving useful to other researchers. Despite only 18 months of measurement Law appreciated the significance of his results and challenged the policy of afforestation of catchments with data showing that over a 12 month period 290 mm* less rainfall was converted to runoff from the lysimeter; he suggested that if the whole catchment were to be afforested the effect would be to reduce water supplies by 42%.

These early results were challenged most vigorously on the grounds that Law's small plot was unrepresentative. They prompted other research of a more fundamental nature; most notably that undertaken by the Institute of Hydrology at Thetford and Plynlimon. Nevertheless, his experiments were continued and a recent appraisal has produced 11-15 years of valid data. Table 1 extends the information given by Law in 1957 for the lysimeter, the whole of the

TABLE 1: Summary of Data from Stocks Reservoir - Sitka Lysimeter and Catchment Areas (Units: mm)

	Calendar Years															AVERAGES	
	1956	1957	1958	1959	1960	1961	1962	1963	1964	1965	1966	1967	1968	1969	1970	All Years shown	6-years 1961-64 1966,67
SITKA PLANTATION LYSIMETER (450 m^2)																	
1. Rainfall: mean of 3 outside gauges	1374	1557	1491	1245	1588	1615	1468	1367	1323	1552	1651	1915	1547	1184	1565	1496	1556
2. Throughfall: stemflow & plantation gauges	871	1003	1039	757	1001	993	902	836	828	955	1008	1062	1072	678	897	927	938
3. Interception: (1-2)	503	554	452	488	587	622	566	531	495	597	643	853	475	506	668	569	618
4. Lysimeter Runoff	411*	734	762	447	523	538	531	457	510	#	531	663	#	#	#	555	538
5. Gross Losses: (1-4)	963	823	729	798	1065	1077	937	910	813	-	1120	1252	-	-	-	953	1018
6. Nett (evapotranspiration) Losses:(2-4)	460	269	277	310	478	455	371	379	318	-	477	599	-	-	-	381	400
STOCKS RESERVOIR CATCHMENT (22% afforested) (37.5 km^2, including Bottoms Beck)																	
7. Estimated Area Rainfall	1471	1725	1665	1370	1785	1811	1640	1519	1412	1740	1841	2133	1737	1328	1750	1662	1726
8. Catchment Runoff	1038	1208	1200	907	1375	1439	1212	1143	979	1270	1355	1565	1289	881	1254	1208	1282
9. Losses: (7-8)	433	517	465	463	410	372	428	376	433	470	486	568	448	447	496	454	444
BOTTOMS BECK CATCHMENT (70% afforested) (10.6 km^2)																	
10. Estimated Areal Rainfall						1674	1458	1405	1269	1575	1684	2065	1593	1224	1494	1544	1592
11. Catchment Runoff						1250	1016	993	808	1092	1191	1341	1123	734	945	1049	1100
12. Losses (10-11)						414	442	412	460	483	493	724	470	490	549	495	492

Notes: 1.* Not recalculated from original field sheets
2.# Runoff data thought to be unreliable for all or major part of year
3. 21 trees removed from lysimeter in March 1962 and a further 17 in December 1967 leaving 57 thereafter.
4. In May 1957 there was a severe loss of needles from trees in the lysimeter due to an aphid.

can be extrapolated to other regions, regions which may have different climates, different natural vegetation, different forest management practices or forest species.

Just two variables are responsible for the major differences in interception loss rates between different vegetation types, the aerodynamic resistance and the surface area of wet vegetation. For coniferous forests these two variables in conjunction result in an almost optimal mix for supporting high interception loss rates. The aerodynamic resistance, the resistance encountered by water vapour moving from the external surfaces of leaves into the atmosphere, is low because forests with rough canopy surfaces are very effective in generating the turbulent forced eddy convection which,under the majority of meteorological conditions, is the dominant transport mechanism. The wettable surface area of forests is high in comparison with most other crops, they have high leaf area indices and have leaf surfaces which are effective in supporting water films.

Our understanding of the interception process has been gained from a number of experiments carried out in the U.K. and sophisticated mathematical models are now available for predicting these losses given detailed hourly meteorological data as an input. For situations where only basic meteorological data are available a simple empirical model has been proposed which requires only annual measurements of rainfall and estimates of potential transpiration for estimating both interception and total evaporation losses from forests in the U.K. (Calder and Newson 1979, 1980); it has been used as an initial basis for predicting the effects on water resources of further afforestation in the uplands.

PRESENT AND FUTURE FOREST COVER: THE EFFECT ON BASIN MANAGEMENT

Mapwork on reservoir catchments

Clearly the prerequisites of coordinated resource planning are those of accurately predicting reduction of yield (and its timing) on reservoir catchments with existing relatively small forest covers and of assessing the likelihood of future afforestation and hydrological change on reservoir catchments which at present have a minimal forest cover (the majority in Britain).

The problems of refining our hydrological predictions are dealt with below: those of a successful assessment of future land-use include imponderable economic trends but also the relative scarcity of land-use capability mapping. Fortunately an agricultural classification now exists (M.A.F.F., 1980). Foresters, too, have used land classification to aid selection of sites for forest expansion (Locke, 1980).

For a developed country there is a clear discrepancy between the economic claims of rival, single-resource agencies and the notion of resource planning. The idea of rural planning has been largely stillborn in the nation which first institutionalised town planning.

At present map analysis of overlapping areas of importance for forest expansion and water catchments produces the pattern shown in Figure 1. Understandably, the water industry has taken a protective attitude to those areas on the map until the full consequences of

PROBLEMS IN THE APPLICATION OF RESEARCH RESULTS AND THE NEEDS FOR FURTHER INFORMATION

Our understanding of the mechanisms which control evaporation from wet upland catchments, both in terms of transpiration and interception loss, has increased in recent years and the overall picture concerning the effects of afforestation on water resources is clear: afforestation of grass pasture will significantly increase losses, (Calder 1979) sometimes by as much as 100% (resulting in reductions in runoff of about 20%).

However, the application of research results to real problems frequently raises new questions, especially if extrapolation beyond the range of conditions examined is necessary (i.e., to more extreme rainfall zones and to other vegetation types - heather, myrtle, bracken). In some cases the details in the picture are not clear and have not been examined fully (e.g. the seasonal distribution of interception loss). Another gap in our knowledge is the magnitude of evaporation loss from snow covered vegetation under British conditions.

The Institute of Hydrology is currently carrying out a research programme, funded largely by a consortium of Scottish interests, to investigate these aspects. Some results from this research are already available. Experiments using lysimeter and neutron probe techniques at sites in Yorkshire (Wallace et al 1982), Scotland (Calder et al 1981), and at Stocks Reservoir all suggest that heather, one of the 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. The balance is such that for upland regions of moderate rainfall, say 1500 mm, the annual losses are expected to be similar to those from grass but in wetter climates the interception losses from heather will dominate and result in greater total losses.

Preliminary results are also becoming available on interception losses during snow conditions. Measurements of the weight of a cut tree, using the technique developed by Roberts (1978) indicate that a spruce tree can support an order of magnitude more water in the form of snow (20 mm water equivalent) than of liquid water and therefore has the potential, given the necessary meteorological conditions, for high interception losses. Measurements obtained from heated plastic-sheet net-rainfall gauges also indicate the potential for high interception losses from snow.

The need for a seasonal picture of interception loss, and the problems of applications, which will follow, illustrate the problems in the transfer of results from catchment research to water resources planning and management. Calder and Newson, 1979 present a practical, albeit simple model of the annual loss which can be used to appraise the overall magnitude of the impact of afforestation on runoff. In detail, however, the water engineer must first translate this into a seasonal picture since, for example, increased loss in winter would be of little consequence for a reservoir which invariably overflows at that time of year.

CALDER, I.R., HALL, R.L., HARDING, R.J., and WRIGHT, I.R. (1980). Report on collaborative project with the British Waterways Board on the effects of afforestation on the runoff from the catchments supplying the Crinan Canal Reservoirs. Institute of Hydrology Report.

CENTRE FOR AGRICULTURAL STRATEGY. (1980). Strategy for the U.K. forest industry. CAS Report 6.

FORESTRY COMMISSION (1977). The wood production outlook in Britain. U.K. Forestry Commission, Edinburgh.

GASH, J.H.C. and STEWART, J.B. (1977): The evaporation from Thetford Forest during 1975. Journal of Hydrology, Vol. 35, 385-396.

LAW, F. (1956). The effect of afforestation upon the yield of water catchment areas. Journal of the British Waterworks Association, 489-494.

LEYTON, L., REYNOLDS, E.R.C. and THOMPSON, F.B. (1967). Rainfall interception in forest and moorland. International Symposium on Forest Hydrology. (W.E. Sopper and H.W. Lull, Eds.), Pergamon Press, Oxford, 163-168.

LOCKE, G.M.L. (1980) Land Assessment for Forestry, Proceedings of The Royal Scottish Geographical Society Symposium, 25 May 1979, Edinburgh, In: Land Assessment in Scotland, Aberdeen University Press 63-68.

MINISTRY OF AGRICULTURE, FISHERIES AND FOOD. (1980). The classification of land in the hills and uplands of England and Wales. M.A.F.F. Booklet 2358.

MINISTRY OF HEALTH. (1948). Report of the Gathering Grounds Committee: Gathering grounds - public access to gathering grounds, afforestation and agriculture on gathering grounds. His Majesty's Stationery Office London.

OVINGTON, J.D. (1954). A comparison of rainfall in different woodlands. Forestry, 27, 41-53.

PEARSON, D. and WALSH, P.D. (1982). The derivation and use of control curves for the regional allocation of water resources. Proc. Exeter Symposium IAHS.

ROBERTS, J.M. (1978). The use of the "Tree Cutting" technique in the study of the water relations of Norway Spruce, Picea abies (L.) Karst. Journal of Experimental Botany, Vol. 29, 465-471.

SEARCY, J.K. and HARDISON, C.H. (1960) Double mass curves hydrology, Part 1: General surface-water techniques. Manual of USGS, Water Supply Paper 1541-B.

WALSH, P.D. (1977). The Practical Analysis and Operation of Multi-source Water Supply Systems with particular reference to the Lancashire Conjunctive Use Scheme. Ph.D. Thesis, University of Birmingham.

WALSH, P.D. (1980). The impacts of catchment afforestation on water supply interests. Aqua, 4, 0082-0085.

WALLACE, J.S., ROBERTS, J.M. and ROBERTS, A.M. (1982) Evaporation from heather moorlands in North Yorkshire, England. Proceedings of Berne International Symposium on Hydrological Research Basins and their use in Water Resources, Planning & Management.

C 82
H
SCH

• CANADIAN HYDROLOGY SYMPOSIUM: 82
• ASSOCIATE COMMITTEE ON HYDROLOGY
NATIONAL RESEARCH COUNCIL OF CANADA
• JUNE 14-15, 1982
FREDERICTON, NEW BRUNSWICK

• SYMPOSIUM CANADIEN D'HYDROLOGIE: 82
• COMITÉ ASSOCIÉ D'HYDROLOGIE
CONSEIL NATIONAL DE RECHERCHES CANADA
• LES 14 ET 15 JUIN 1982
FREDERICTON, NOUVEAU-BRUNSWICK

FOREST EVAPORATION

Ian R. Calder[1]

ABSTRACT

Recent developments in the study of forest evaporation 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 the complexity of physiological controls on forest transpiration and it is suggested that, perhaps paradoxically, their existence greatly eases the task of obtaining long-term "broad brush" estimates of forest evaporation which are required for practical applications.

[1] Institute of Hydrology, Wallingford, England

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. The attraction of these views is obvious, especially to the physicist or meteorologist, as it places the task of estimating or predicting evaporation solely in physical terms that he understands.

Unfortunately nature is not so accommodating and many recent experiments have cast doubts on this simplistic view; 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...

at the Water space amenity commission in May 1975). Results from 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.

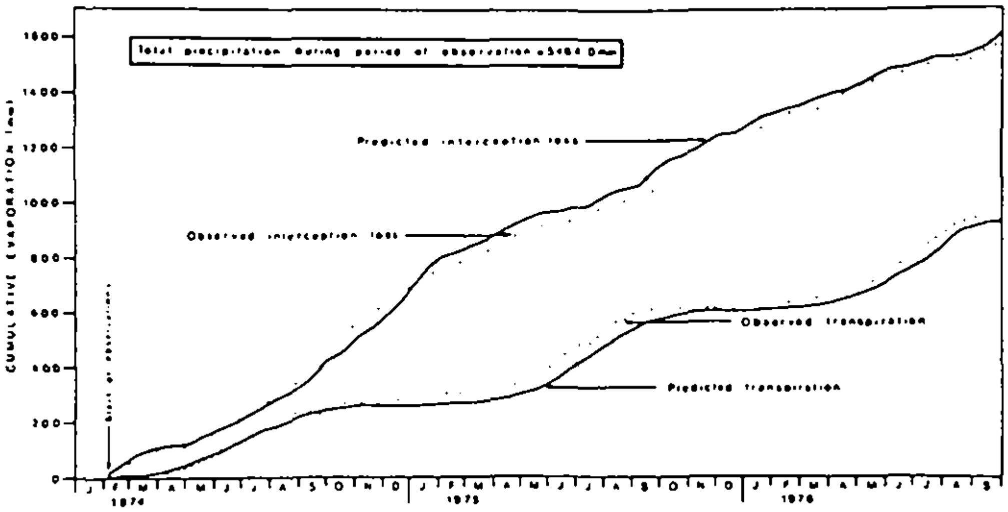


Figure 1. Cumulative observed and predicted transpiration losses from the forest lysimeter.

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):

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

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 saturated vapour pressure curve Δ and the psychrometric constant γ.

Two crop dependent parameters are also required; these are the surface resistance, rs, which for a living crop is purely a 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 (ie. the assumption that rs is zero is good in the case of most coniferous forests and remains so for quite a large range of canopy storage).

small atmospheric humidity deficits are necessary to support significant evporation rates and 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 being a minor component of the total loss.

To sustain the evaporation rates from wet trees that Figure 3. implies does, however, require 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 it is found that the annual latent heat flux from the forest exceeds the supply of net radiation by 12%. It is not yet clear if all this additional energy comes from the synoptic scale transport of energy from regions outside the forest, in which case it may not be possible to support such rates from very large forested areas (e.g. the Amazon basin or forested areas in Canada) or whether, 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.

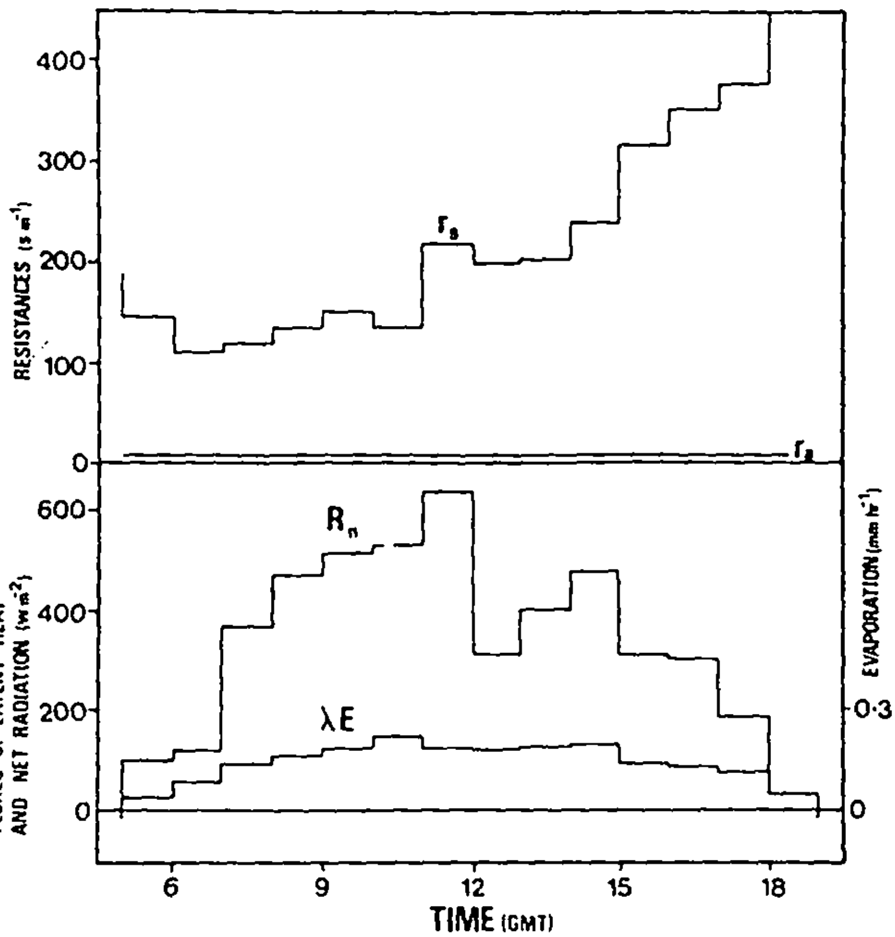


Figure 4. Daytime surface resistance values measured over Thetford forest together with fluxes of latent heat and net radiation.

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).

sylvestris growing in southeast England which showed a significant lowering of stomatal resistance during the summer. Calder (1977, 1978) also found a seasonal variation for spruce, which, when the atmospheric humidity feedback effect was removed, could be fitted using an annual sinusoidal relationship, the trough of the sinusoid occurring in the summer months. The exact relationship, used for estimating surface resistance on day No. D was found to be:

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

where VPD is the vapour pressure deficit (mb).

Surface resistance values calculated from this function are shown in Figure 6.

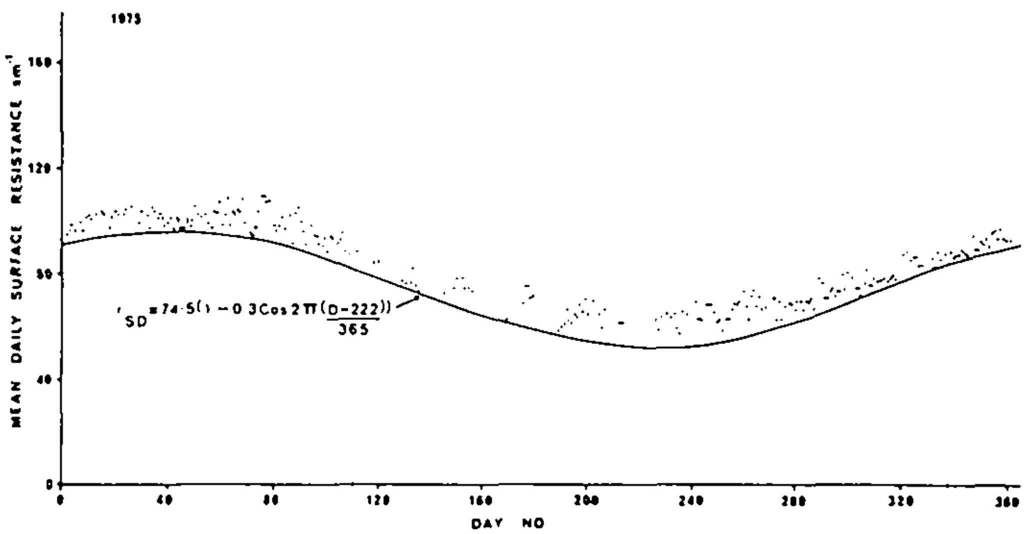


Figure 6. Mean daily surface resistance calculated from the surface resistance function (for hours when net radiation is positive) for 1975.

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

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:

$$\text{annual loss} = Et + f(P\alpha - wEt)$$

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:

$$w = \text{number of rain hours per year} \times 1.5 \,/\, \text{number of hours in year}$$

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

Within the limitations of the model (as discussed above and in more detail in Calder and Newson 1980) the method has two further advantages over the Penman-Monteith approach in addition to its much more limited data requirement (annual data rather than hourly). Firstly the model can be more safely used in a predictive mode to estimate losses from areas which may undergo afforestation as it is essentially interpolating between measurements of evaporation loss from existing typically sized U.K. forests. The Penman-Monteith equation, on the other hand, requires estimates of the meteorological conditions above the actual evaporating surface and if it is required to investigate changes in evaporation resulting from changes to the surface the concurrent change in the meteorological conditions produced by the evaporation/atmosphere interaction must also be taken into account. Secondly, the model predictions are not unduly sensitive to measurement errors in the input meteorological data whereas estimates obtained by the Penman-Monteith method, particularly in wet conditions, tend to be very sensitive to measurement errors of atmospheric humidity. It has been shown that errors of as little as 0.3 degrees Celcius in psychrometer wet bulb determinations can lead to prediction errors in interception loss of approximately 25% (Calder 1977).

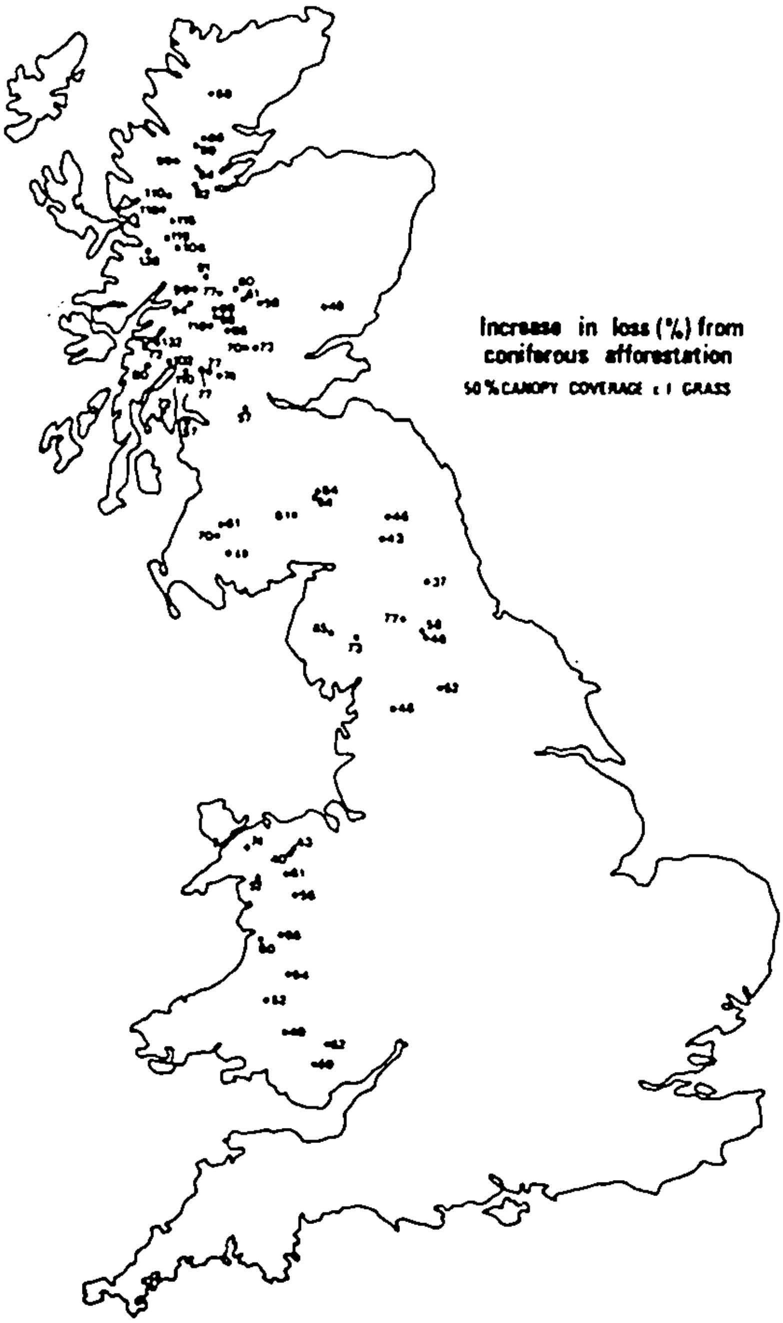


Figure 7. Predicted percentage increase in evaporation loss from afforesting to 50% canopy coverage the catchments supplying the major U.K. upland reservoirs.

Helvey, J.D. (1967): Interception by Eastern White pine. Water Resources Research, Vol. 3, pp. 723-729.

Hicks, B.B., Hyson, P. and Moore, C.J., (1975): A study of eddy fluxes over a forest. Journal of Applied Meteorology, Vol. 14, pp. 58-66.

Jarvis, P.G. (1976): The interpretation of the variations in leaf water potential and stomatal conductance found in canopies in the field. Philosophical Transactions of the Royal Society London,Ser. b, 273, pp. 593-610.

Johnson, D.A. and Caldwell, M.M. (1976): Water potential components,stomatal function, and liquid phase water transport resistances of four arctic and alpine species in relation to water stress. Physiologia Plantarum, Vol. 36, pp. 271-278.

Lange, O.L., Losch, R., Schulze, E.D. and Kappen, L. (1971): Responses of stomata to changes in humidity. Planta, Vol. 100, pp. 76-86.

Law, F. (1956): The effect of afforestation upon the yield of water catchment areas. Journal of the British Waterworks Association, pp. 489-494.

Law, F. (1957): Measurement of rainfall interception and evaporation losses in a plantation of Sitka spruce trees. In: IUGG/IASH, General assembly of Toronto, Vol 2, pp. 397-411.

Leyton, L., Reynolds, E.R.C. and Thompson, F.B. (1967): Rainfall interception in forest and moorland. International Symposium on Forest Hydrology. (W. E. Sopper and H. W. Lull, Eds.), Pergamon Press, Oxford, pp. 163-168.

McNaughton, K.G. and Black, T.A. (1973): A study of evapotranspiration from a Douglas fir forest using the energy balance approach. Water Resources Research, Vol. 9, pp. 1579-1590.

Monteith, J.L. (1965): Evaporation and the environment. Symp. Society of Experimental Biology, Vol. 19, pp. 205-234.

National Water Council (1980): Forest policy and the water services. Written Evidence to the sub Commmittee on forestry of the House of Lords Select Committee on Science and Technology. In: Scientific Aspects of Forestry. 2nd Report. Volume II. Minutes of

Szeics, G., Gabriella Endrodi and Tajchman, s. (1969): Aerodynamic and surface factors in evaporation. Water Resources Research, Vol. 5, No. 2, pp. 380-394.

Tajchman, S.J. (1971): Evaporation and energy balances of forest and field. Water Resources Research, Vol. 7, No. 3, pp. 511-523.

Tan, C.S. and Black, T.A. (1976): Factors affecting the canopy resistance of a Douglas-fir forest. Boundary Layer Meteorology, Vol. 10, pp. 475-488.

Thom, A.S. (1975): Momentum, mass and heat exchange of plant communities. In: J.L. Monteith (Editor), Vegetation and the atmosphere, Vol. 1, Academic Press, London, pp. 57-109.

Thom, A.S. (1978): Evaporation from forests in relation to climate and hydrology. In: Proceedings of the Symposium on Forest Meteorology, August 21-25, 1978, Ottawa, Ontario, pp. 80.

WATER RESOURCES BULLETIN
VOL. 15, NO. 6 AMERICAN WATER RESOURCES ASSOCIATION DECEMBER 1979

LAND-USE AND UPLAND WATER RESOURCES IN BRITAIN – A STRATEGIC LOOK[1]

I. R. Calder and M. D. Newson[2]

ABSTRACT: Recent results from the Institute of Hydrology's hydrometeorological and hydrological studies on water use by forest and grassland confirm earlier predictions of a reduction in water yields following afforestation. This reduction is due primarily to the increased interception losses from forests. This paper shows how the water yield from uplands is related to the relative proportions of land under forest and hill farming, and estimates how water yields will change if a greater proportion of hill land is afforested.
(KEY TERMS: afforestation; experimental catchments; interception; reservoirs; water resources; evaporation models.)

THE IMPORTANCE OF WATER YIELDS FROM UPLAND AREAS

Although Britain is a relatively highly developed land, its uplands, which constitute a fifth of the land surface, have always been economically marginal and their resources exploited sporadically. These 'less favored areas' (EEC, 1975) are, however, receiving close attention at present from the resource planners. One of the reasons for this is that the high water yield in surface streams draining the uplands is one of the principal resources of such areas, and by impoundment this water yield frequently supplies large industrial and domestic demands in the lowlands. Although possible sites for further impoundment reservoirs in upland areas may now be largely exhausted (Water Resources Board, 1973) there is scope for improving the reliability of existing reservoirs through the development of better operating rules. It is also essential that changes in land use and hence in the water lost by crops through evaporation in the catchment areas, will not seriously threaten either quantity or quality of water available for impoundment. Changes in the relation between forestry and farming in the uplands, which are at present determined largely by market forces and handled by individual resource agencies (Wibberley, 1976; Davidson and Wibberley, 1977), may well have important consequences for upland water yields. Such changes deserve the most careful planning and clearly require full information of the water use by forest and hill pasture. However, hydrological networks in the uplands are particularly sparse, so that the operation of the Institute of Hydrology's experimental catchment areas of the rivers Wye and Severn in mid-Wales during the last decade has provided much valuable data. The two adjacent catchment areas are on the east flank

[1] Paper No. 78160 of the *Water Resources Bulletin*. Discussions are open until August 1, 1980.
[2] Institute of Hydrology, Maclean Building, Crowmarsh Gifford, Wallingford, Oxon OX10 8BB, United Kingdom.

Results from a lysimeter close to the center of the Severn catchment, for which transpiration and interception components of the water balance were measured separately (Calder, 1976; Calder and Rosier, 1976) show that during the period of observation from February 1974 to September 1976, interception losses exceeded those from transpiration by 75 percent (Table 2).

TABLE 1. Annual Values of P, Q, and P–Q: Wye and Forested Area of the Severn Catchment Only, Years 1970-77 (units: mm).

Year	P: Precipitation		Q: Streamflow		P–Q: Losses		Difference in Losses (Severn-Wye)
	Wye	Severn	Wye	Severn	Wye	Severn	
1970	2869	2485	2415	1636	454	849	+395
1971	1993	1762	1562	797	431	965	+534
1972	2131	2124	1804	1342	328	782	+454
1973	2606	2380	2164	1581	442	799	+357
1974	2794	2703	2320	1785	474	918	+444
1975	2099	2035	1643	1213	456	822	+366
1976	1736	1645	1404	921	332	724	+392
1977	2561	2573	2236	1638	325	935	+610
Mean	2348	2213	1944	1364	405	849	+444

TABLE 2. Evaporation Measurements From the Forest Lysimeter, February 1974 – September 1976 (units: mm).

Period	Precipitation	Interception	Transpiration
6 February 1974 – 31 December 1974	2328	685	289
1 January 1975 – 31 December 1975	2013	529	335
1 January 1976 – 1 October 1976	1103	366	277
TOTAL	5444	1580	901

LAND-USE IN RESERVOIRED CATCHMENTS

The 1948 Report of the Gathering Grounds Committee (Ministry of Health) dealt exclusively with the influence of land-use on pollution of upland water supplies. The replacement of farming by forestry has become a way of obtaining 'sterile' catchments by limiting human access. In its note on afforestation, the Committee also comments on the advantages of tree cover in preventing erosion and in regulating streamflow by encouraging infiltration. There is also a hint that forests are likely to induce increased rainfall, although transpiration losses are also mentioned; in fact the Committee characterized the whole field by the phrase 'shortage of evidence.' Their conclusion, nevertheless, was that 'land which is incapable of agricultural use should if possible be afforested, but with due regard to amenity and the requirement of adjacent agriculture.'

planted by the target date of 2025, 1.44 million hectares of new coniferous forest will have been planted in Scotland and 0.28 million hectares in England and Wales (the balance being hardwoods, unlikely to be planted in the uplands). The total coverage of forestry in the uplands will then be approximately 50 percent, but only small changes in agricultural and timber prices are required to put large areas under forestry (Bowman, 1977). However, both forestry and farming are financed by Government sources and by using a discount rate on forest investment of 10 percent it can be shown that farming activity in the uplands is cheaper to sustain (Treasury Office, 1972) although this result depends heavily on the discount rate adopted (Price, 1973).

It seems, therefore, that water resource planners and engineers should allow for the possibility that some upland catchments may be at least 50 percent afforested by 2025; there is a need, therefore, to consider the consequences not only for water supply to domestic and industrial users but also, especially in Scotland, for hydroelectric power generation.

ESTIMATION OF THE EFFECTS OF FURTHER AFFORESTATION ON WATER YIELDS

The principal causal mechanism for the reduced water yield from upland forests, relative to hill pasture, is the greatly increased evaporation rates from wetted forest canopies during and following precipitation (Rutter, 1963; Rutter, *et al.*, 1971, 1975; Rutter and Morton, 1977; Stewart and Thom, 1973; Shuttleworth, 1975, 1976; Thom, 1975; Stewart, 1978; Calder, 1977, 1978, 1979; Gash and Morton, 1978; Gash, 1979). Numerical models of the evaporation process based on the Penman-Monteith equation (Monteith, 1965) exist for determining the magnitude of the reduced yield for catchments where necessary hourly meteorological data are available; because such data are commonly lacking, however, it is difficult at present to apply them on catchments where no automatic weather station is sited. Research is in progress to enable the models to be used with more readily available meteorological data, but until this work is completed it is necessary to resort to more empirical methods to estimate evaporation losses, such as that described below.

Measured interception losses, expressed as a fraction of the annual precipitation, from British forests are shown in Figure 1 plotted against annual precipitation. A consistent trend is demonstrated: the interception fraction decreasing with increasing rainfall.

The Penman E_t estimate (Penman, 1948) is generally accepted as a reliable method for estimating annual evaporative losses from grass and other short crops. Results from the Plynlimon forest lysimeter indicate that during periods when the forest canopy is dry, Penman's E_t also provides an approximate estimate of transpiration from spruce forest.

These observations provide the basis of a simple evaporation model and suggest that the evaporation loss from an upland catchment may be estimated from the sum of the proportional losses arising from the forested and nonforested areas, such that:

annual evaporation = fraction of catchment under grass x grass annual evaporation + fraction of catchment under canopy coverage x (forest annual transpiration + forest annual interception loss)

$$= \frac{\text{annual precipitation (mm)}}{\text{mean rainfall intensity (mm hr}^{-1})} \times 1.71 \times 10^{-4}$$

This model required knowledge of only four variables; the Penman estimate E_t of annual potential evapotranspiration, the mean annual rainfall, the mean rainfall intensity, and the fraction of the catchment area with complete canopy coverage. Model predictions of percentage reduction in runoff and percentage increase in loss are shown in Figure 2 and Figure 3 as a function of two of these variables, annual rainfall and Penman E_t, whilst assuming the constant values of 1.4 mm per hour (that observed at Plynlimon) for the mean rainfall intensity and 50 percent for the forest canopy coverage. (Mean rainfall intensities throughout Britain are low (Atkinson and Smithson, 1976), and the use of the constant value of 1.4 mm per hour is unlikely to introduce serious errors in the evaporation model predictions.)

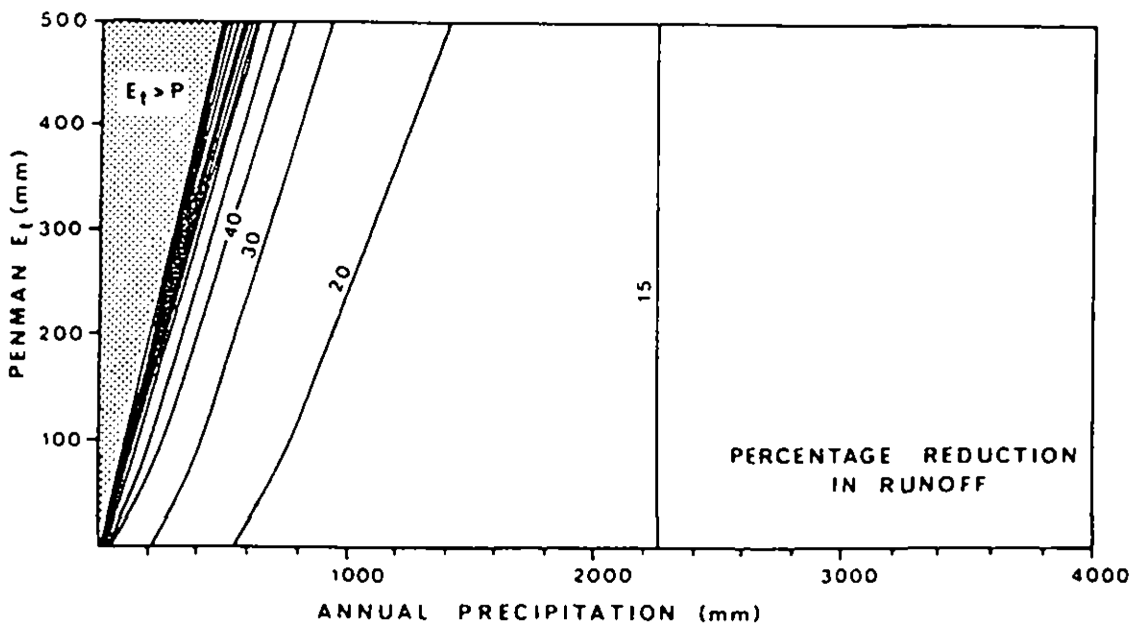


Figure 2. Model Predictions of Percentage Decrease in Runoff as a Result of Afforestation to 50 Percent Canopy Coverage Plotted Against the Penman E_t Estimate and Mean Annual Rainfall.

In the drier lowland areas, where interception is a smaller component of the total evaporation, this simple model cannot be used with confidence. In these areas, differences between forest and grassland evaporation are likely to be much smaller; more complex evaporation models, taking into account the different transpiration characteristics of forest and grass will be needed to determine the magnitude of any difference.

The effect of afforestation on water yields, as estimated by the above procedure, has been calculated for those catchments with streams feeding the major reservoirs (greater than 10 million m^3, Rodda, Downing, and Law, 1976) located in the uplands. The percentage increase in loss which application of the model predicts for these catchments, when afforested to an extent of 50 percent canopy coverage, is shown in Figure 4.

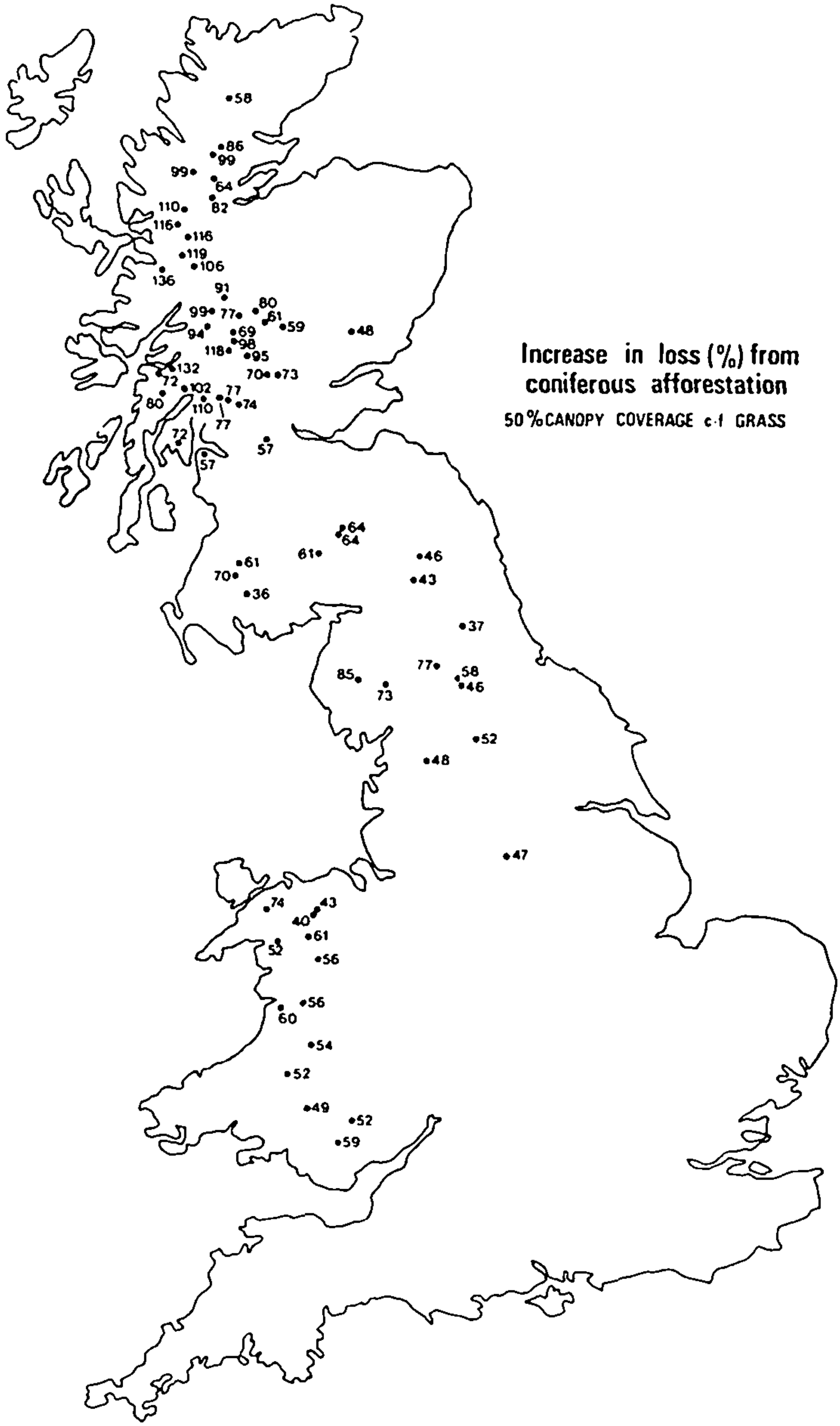


Figure 4. Predicted Percentage Increase in Loss From Afforesting (to 50 percent canopy coverage) the Catchments Supplying the Major Upland Reservoirs.

Calder, I. R., 1978. Transpiration Observations From a Spruce Forest and Comparisons With Predictions From an Evaporation Model. J. Hydrol. 38:33-47.

Calder, I. R., 1979. Do Trees Use More Water Than Grass? Water Services 83:11-14.

Calder, I. R. and P. T. W. Rosier, 1976. The Design of Large Plastic Sheet Net Rainfall Gauges. J. Hydrol. 30:403-405.

Courtney, F. M., 1978. Personal Communication.

Davidson, J. and G. Wibberley, 1977. Planning and the Rural Environment. Pergamon.

EEC, 1975. Directive 268/75/EEC -- Mountain and Hill Farming and Farming in Less-Favoured Areas.

Forestry Commission, 1977. The Wood Production Outlook in Britain.

Gash, J. H. C., 1979. An Analytical Model of Rainfall Interception for Forests. Quart. J. Roy. Met. Soc. (in press).

Gash, J. H. C. and A. J. Morton, 1978. An Application of the Rutter Model to the Estimation of Interception Loss From Thetford Forest. J. Hydrol. (in press).

Gash, J. H. C. and J. B. Stewart, 1977. The Evaporation From Thetford Forest During 1975. J. Hydrol. 35:385-396.

Gibson, C. E., 1976. An Investigation into the Effects of Forestry Plantations on the Water Quality of Upland Reservoirs in Northern Ireland. Water Research 10(11):995-998.

Law, F., 1956. The Effect of Afforestation Upon the Yield of Water Catchment Areas. Jnl. Br. Waterworks Assn. 38:484-494.

Law, F., 1957. Measurement of Rainfall, Interception and Evaporation Losses in a Plantation of Sitka Spruce Trees. IASH, Toronto, pp. 397-411.

Leyton, L., E. R. C. Reynolds, and F. B. Thompson, 1967. Rainfall interception in forest and moorland. *In:* Int. Symp. on Forest Hydrology, W. E. Sopper and H. W. Lull, Editors. Pergamon, Oxford, pp. 163-178.

Lloyd, D., 1950. The Effect of Forest on Streamflow With Reference to Afforestation at Vyrnwy. British Assn. Meeting, Liverpool.

Lloyd, D., 1953. (In Discussion) The Lynmouth Flood of August 1952, by C. H. Dobbie and P. O. Wolf. Proc. Instn. Civ. Engrs. 2(3):522-588.

Mather, A. S., 1978. Patterns of Afforestation in Britain Since 1945. Geography 63(3):157-166.

Ministry of Health, 1948. Report of the Gathering Grounds Committee: Gathering Grounds: Public Access to Gathering Grounds, Afforestation and Agriculture on Gathering Grounds. HMSO.

Monteith, J. L., 1965. Evaporation and the Environment. Symp. Soc. Exp. Biol. 19:206-234.

Penman, H. L., 1948. Natural Evaporation From Open Water, Bare Soil and Grass. Proc. R. Soc., London, Ser. A, 193:120-146.

Penman, H. L., 1963. Vegetation and Hydrology. Technical Communication No. 53, Commonwealth Bureau of Soils, Harpenden, Commonwealth Agricultural Bureau.

Price, C., 1973. To the Future: With Indifference or Concern – The Social Discount Rate and Its Implications for Land-Use. Jnl. Ag. Econ. 24(2):292-298.

Rodda, J. C., R. Downing, and F. Law, 1976. Systematic Hydrology. Newnes-Butterwork.

Rutter, A. J., 1958. Effect of Afforestation on the Water Yield of Catchment Areas. Water and Water Engrng. 62:96-102.

Rutter, A. J., 1963. Studies in the Water Relations of *Pinus silvestris* in Plantation Conditions. I. Measurement of Rainfall and Interception. Jour. Ecol. 51:191-203.

Rutter, A. J., K. A. Kershaw, P. C. Robins, and A. J. Morton, 1971. A Predictive Model of Rainfall Interception in Forests. I. Derivation of the Model From Observations in a Plantation of Corsican Pine. Agric. Meteorol. 9:367-384.

Rutter, A. J., A. J. Morton, and P. C. Robins, 1975. A Predictive Model of Rainfall Interception in Forests. II. Generalisation of the Model and Comparison With Observations in Some Coniferous and Hardwood Stands. J. Appl. Ecol. 12:367-380.

Rutter, A. J. and A. J. Morton, 1977. A Predictive Model of Rainfall Interception in Forests. III. Sensitivity of the Model to Stand Parameters and Meteorological Variables. J. Appl. Ecol. 14: 567-588.

Shuttleworth, W. J., 1975. The Concept of Intrinsic Surface Resistance Energy Budgets at a Partially Wet Surface. Boundary-Layer Meteorol. 8:81-99

Shuttleworth, W. J., 1976. A One-Dimensional Theoretical Description of the Vegetation-Atmopshere Interaction. Boundary-Layer Meteorol. 10:273-302.

Natural
Environment
Research
Council