The Effect of Afforestation on Water Runoff in the Woodburn Catchment Area

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SUMMARY

Weekly runoff and rainfall records for 1960–71 are analysed in this paper for two catchments: a forest area, planted between 1958 and 1960, of 111·5 ha and a grass area kept permanently for grazing of 26·5 ha. Analysis of the data failed to detect any significant changes in the water yield from the forested catchment. The experiment has demonstrated the difficulties of making precise measurements and comparisons from data collected in areas of rolling topography where soils among other factors differ.

1. INTRODUCTION

THE aim of the experiment described in this paper was to determine the long-term effects of a forest crop on the quantity and periodicity of water reaching the Woodburn reservoirs, which are located north of Belfast in Co. Antrim, Northern Ireland. It was hoped that this catchment would be representative of other similar afforested areas in Northern Ireland.

The experiment was started in 1960. At that time there was very little knowledge about the effects of forests on runoff in the British Isles and a good deal of debate was taking place as to the best form of land use on catchment areas. This was stimulated by a paper by Law (1958) who suggested that a Sitka spruce crop used much more water than the existing moorland vegetation in the Pennines, to the detriment of water supplies. The results of Law's catchment experiment, together with those of several others, have been reviewed by Penman (1963). In the late 1950s a great deal of land was available in Northern Ireland on catchments which had good afforestation potential. Several water authorities were reluctant to allow the ground to be planted because they thought forests would reduce the total quantity of water available for water supplies. Because of the lack of evidence about the effects of trees on runoff, particularly in the very maritime climate of Northern Ireland, and to help allay fears of water engineers, it was decided that some local research was essential; the experiment described here was, as a result, set up jointly by the Belfast City and District Water Commissioners and the Forestry Division, Department of Agriculture. Plans for two other similar projects were eventually abandoned because of problems of setting up acceptable experiments.

There are many difficulties associated with catchment experiments which have been discussed by Reynolds and Leyton (1967). They include: the time and expense involved in setting up and running experiments, the difficulty of finding 'representative' sites, geological leaks from catchments which preclude valid water balance determinations, measurement accuracy,

and the design and analysis of experiments. However, catchment experiments provide a real integration of precipitation and flow processes on both a time and a real basis in terms of stream flow at predetermined points. The information is of immediate relevance to the water user.

2. DESCRIPTION OF AREA AND EXPERIMENTAL METHODS

Site. Part of the catchment area of the Woodburn reservoirs is divided into two sections. A forest area of 111·5 ha lies between 200 and 260 m (650–850 ft) in elevation and has a southerly aspect, and a grass area of 26·5 ha lies at about the same elevation but has a south-easterly aspect. A 1960 aerial photograph of the catchment (Fig. 1) shows that before planting the area consisted of a large number of rather small fields. Some idea of the topography may be gained from the contours drawn on Fig. 2. These indicate that the forest area has a greater proportion of high ground above it from which water could possibly flow via surface drainage or springs into the catchment.

2.1. *Recording Runoff.* Three outlet streams in the forest area and one in the grass area were fitted with Lea flow recorders in 1959 in order to measure surface runoff. The type of weirs used have 90-degree V-notches to record the lower flows and rectangular weirs measure the flow above predetermined levels. The maximum measurable flows of the various weirs vary between 180,000 and 316,000 ml/second (150,000 and 250,000 gallons/hour). These have generally proved adequate; each recorder pen has overtopped the charts on about 25 occasions over the 12 years of operation. The recorders have proved reliable and generally trouble-free. On some occasions breakdowns of one or other of the mechanisms have occurred. In such cases an estimate of runoff was calculated from regressions obtained from other runoff measurements taken at the same time. Intercorrelations of runoff between the four recorders were of the order of 0·95.

2.2. *Isolation of area.* It proved possible to isolate the east and west sides of the catchment and to ensure that pick-up drains along the south side were adequate to divert all surface water into the various streams on which recorders were placed. Isolation of the higher northern boundary was more difficult. It was necessary to provide some intersecting drains to catch surface water and direct it out of the catchment. A spring emerges near the northern boundary of the forest area which was diverted into a catch well and subsequently metered and the readings deducted from the total. A small stream had been diverted out of it many years previously to provide a domestic water supply. This was also metered and added to the total.

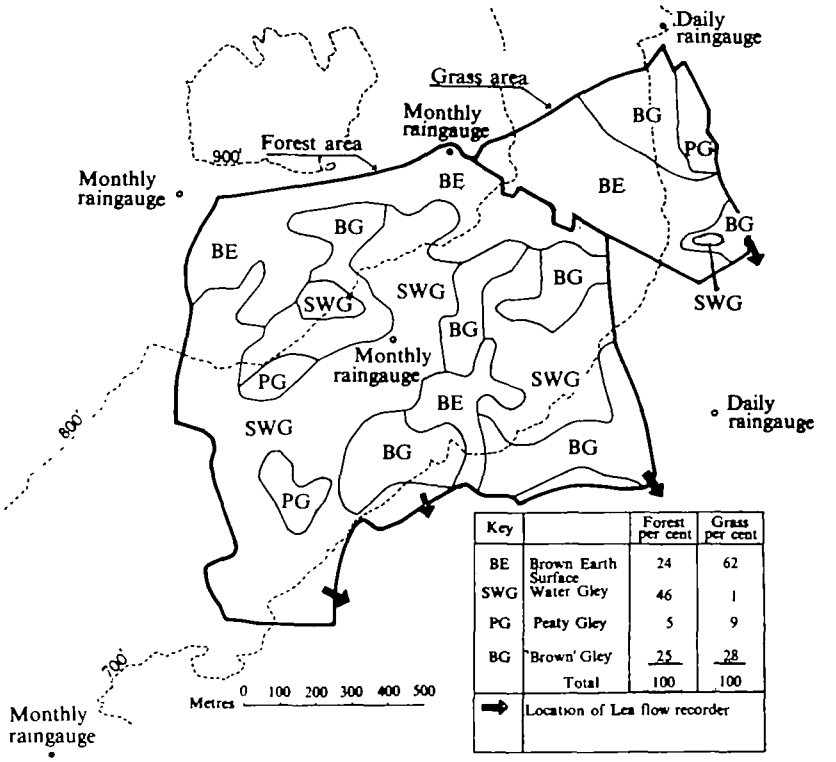
Largely on account of cost it was decided not to make impermeable cut-off trenches round any part of the catchment.

2.3. *Soils.* A soil survey (Fig. 2) indicated that a high proportion of the soils in the west of the catchment were relatively impermeable and structureless gleys while those in the east, particularly in the grass area, were more fertile and permeable brown earths.

FIG. 1. Aerial photograph of the Woodburn reservoirs and experimental water catchment. Crown Copyright reserved.

PLATE I

2.4. *Crops and treatments.* About 4 ha of the forest area had been established in 1948 but the majority of it was planted between 1958 and 1960 with coniferous crops, mainly Norway spruce (*Picea excelsa*) and Japanese larch (*Larix leptolepis*). Some poplars planted in 1958 were replaced by Norway spruce in 1964. At the end of the 12 years under consideration about two-thirds of the tree crops had closed canopy; the trees were on average about 6 m tall; the remaining ones were quite near canopy closure.



Key		Forest per cent	Grass per cent
BE	Brown Earth	24	62
SWG	Surface Water Gley	46	1
PG	Peaty Gley	5	9
BG	'Brown' Gley	25	28
	Total	100	100
➡	Location of Lea flow recorder		

FIG. 2. The Woodburn water catchment; soil map and contours. The area delimited by the heavy black line corresponds to that delimited by the broken white line in Fig. 1, and shows the boundary of the experimental catchment area.

Before planting most of the forest area was artificially drained. Trees were planted on ridges thrown up by ploughing at spacings of just over 1·5 m. These treatments were expected to result in rather faster runoff from the forest than the undrained grassland. The fact that the soils of the forest area were, on average, much less permeable than those of the grass area also made the likelihood of faster runoff from the forest a strong possibility, even had no drainage been carried out.

The grass area was maintained as a permanent pasture for cattle-grazing for the whole period.

2.5. *Recording rainfall.* Two daily rainfall gauges just outside the experimental catchment in open situations have been in operation since 1881. At the start of the experiment they were supplemented by four new monthly gauges, two within the catchment and two outside it. Those inside the forest area were located in clearings. Using all six gauges rainfall was calculated for the period 1965–70 by the method described by Thiessen (1911). Differences between the figures obtained by this method and the much simpler one of taking rainfall in the forest area as the mean of that of the two daily rain gauges and in the grass area as the actual readings of the rain gauge near it were so small that it was decided to use only these two gauges in the full analysis. Comparisons are shown in Table I.

TABLE I. *Comparison of rainfall measurements on grass and forest areas at Woodburn using six and two rain gauges*

Year	Rainfall calculated by Theissen method using six rain gauges		Rainfall calculated using two rain gauges	
	Forest mm	Grass mm	Forest mm	Grass mm
1965	1,100	1,125	1,131	1,151
1966	1,373	1,398	1,383	1,408
1967	1,289	1,308	1,291	1,321
1968	1,244	1,250	1,229	1,244
1969	1,049	1,030	1,004	995
1970	1,266	1,267	1,228	1,243

2.6. *Weaknesses of experiment.* Three main weaknesses of the experiment should be noted:

1. The grass area is only about a quarter the size of the forest and has a different aspect and soil type.
2. It would have been desirable to compare flow records for a number of years before planting.
3. The catchments are almost certainly not isolated. Water derived from precipitation may be lost through seepage to adjoining areas in some parts and augmented in others. Wicht (1957) states that this is permissible provided it can be assumed that the water lost through underground seepage remains constant before and after treatment throughout the period of the experiment, or that it will vary as the result of treatment only, and that in either case any variation that does occur will also be reflected in variations in the superficial discharge which is being gauged. These assumptions had to be made; it was thought that the quantities of water lost or gained would be small in relation to the total.

In view of these weaknesses there was a case for a more suitable experimental site to be found. This proved not to be possible, however. The initiators of

TABLE II (A). *Summary of rainfall and runoff at Woodburn, 1960–5*

	Correlation coefficients			Min. (mm/week)	Max. (mm/week)	Mean (mm/week)	% loss	Standard deviation (mm/week)
	Forest runoff	Grassland rainfall	Grassland runoff					
1960								
Forest rainfall	0·45	0·94	0·35	0·0	192·6	28·2		24·2
Forest runoff		0·51	0·93	1·1	143·2	15·9	44	12·3
Grassland rainfall			0·42	0·0	191·6	27·6		28·2
Grassland runoff				3·5	66·5	11·4	59	5·8
1961								
Forest rainfall	0·58	0·99	0·49	0·0	166·0	24·7		17·9
Forest runoff		0·56	0·98	1·4	133·3	13·7	44	11·5
Grassland rainfall			0·47	0·0	171·1	25·8		18·6
Grassland runoff				3·6	66·8	9·9	62	5·3
1962								
Forest rainfall	0·68	1·00	0·58	0·0	166·2	22·5		18·9
Forest runoff		0·68	0·97	1·6	132·0	11·6	48	9·5
Grassland rainfall			0·57	0·0	171·3	23·3		19·9
Grassland runoff				2·8	77·7	8·3	64	4·5
1963								
Forest rainfall	0·54	1·00	0·40	0·0	154·8	23·3		18·0
Forest runoff		0·55	0·94	3·9	118·2	14·5	38	9·8
Grassland rainfall			0·41	0·0	168·6	23·9		18·4
Grassland runoff				4·1	86·0	9·6	60	4·6
1964								
Forest rainfall	0·59	1·00	0·55	0·0	76·2	20·1		17·6
Forest runoff		0·58	0·96	2·6	69·9	11·9	41	11·8
Grassland rainfall			0·53	0·0	76·2	21·0		18·2
Grassland runoff				3·7	31·6	7·7	63	4·8
1965								
Forest rainfall	0·54	1·00	0·45	0·0	61·1	21·8		15·6
Forest runoff		0·55	0·97	3·3	59·7	15·2	30	12·5
Grassland rainfall			0·46	0·0	57·7	22·1		16·1
Grassland runoff				3·2	30·0	9·3	58	5·6

TABLE II (B). *Summary of rainfall and runoff at Woodburn, 1966–71*

	Correlation coefficients			Min. (mm/week)	Max. (mm/week)	Mean (mm/week)	% loss	Standard deviation (mm/week)
	Forest runoff	Grassland rainfall	Grassland runoff					
1966								
Forest rainfall	0·67	1·00	0·63	0·0	65·5	26·6		17·3
Forest runoff		0·66	0·98	4·1	62·4	19·2	28	14·4
Grassland rainfall			0·61	0·0	65·0	27·1		17·6
Grassland runoff				5·4	27·2	11·2	58	5·6
1967								
Forest rainfall	0·56	1·00	0·49	0·0	91·3	24·8		18·6
Forest runoff		0·55	0·97	3·1	77·8	16·4	34	13·1
Grassland rainfall			0·48	0·0	87·6	25·4		18·4
Grassland runoff				4·7	39·9	10·6	58	5·8
1968								
Forest rainfall	0·70	1·00	0·64	0·0	118·0	23·6		22·0
Forest runoff		0·69	0·97	3·9	80·0	17·0	28	13·1
Grassland rainfall			0·63	0·0	117·8	23·9		22·2
Grassland runoff				3·9	40·3	10·2	57	6·1
1969								
Forest rainfall	0·56	1·00	0·51	0·0	54·2	19·3		14·4
Forest runoff		0·55	0·97	3·4	51·8	14·2	27	10·5
Grassland rainfall			0·50	0·0	54·6	19·1		14·4
Grassland runoff				3·9	24·2	9·1	52	4·7
1970								
Forest rainfall	0·64	1·00	0·64	0·0	127·2	23·6		20·6
Forest runoff		0·64	0·97	3·7	54·9	17·0	28	11·6
Grassland rainfall			0·64	0·0	126·5	23·9		20·7
Grassland runoff				4·1	24·9	10·5	56	5·0
1971								
Forest rainfall	0·74	1·00	0·68	0·0	114·6	19·0		21·0
Forest runoff		0·73	0·91	4·5	69·2	11·7	38	9·5
Grassland rainfall			0·67	0·0	117·3	19·6		21·7
Grassland runoff				3·5	29·3	8·5	57	4·0

the experiment felt that though the Woodburn area was not ideal it should be able to yield some useful results.

3. EXPERIMENTAL DATA

Data were summarized on a weekly basis; records for the 12 years 1960–71 (624 weeks) are analysed in this paper.

A summary of the rainfall and runoff data for the two areas together with their intercorrelations is given in Table II. It can be seen that forest runoff is about twice as variable as grass runoff and that rainfall on both areas is more variable than runoff from either. There is a tendency for forest runoff to be more closely correlated with rainfall than is the grass-area runoff, indicating that rainfall appears as runoff more quickly from the forest than from the grass area, probably for the reasons explained in section 2.4 above.

4. ANALYSIS

For the purpose of analysis the time span of the observations was divided into two periods 1960–5 and 1966–71. They were chosen because it was felt that for the first period, when most of the trees were small, differences due to a forest crop could scarcely be expected. Separate analyses were carried out for each period and also for the complete time span 1960–71. A summary of the analyses is given in Table III.

TABLE III. *Results of analyses of rainfall and runoff variance*

	Degrees of freedom (6 years)	Degrees of freedom (12 years)	Rainfall			Runoff		
			1960–5	1966–71	1960–71	1960–5	1966–71	1960–71
Grass area								
Years	5	11	NS	NS	NS	•••	••	•••
Years linear	1	1	NS	•	NS	•••	••	NS
Years scatter	4	10	NS	NS	NS	••	NS	•••
Slope (mm/year)			−61·26	−69·06	−21·14	−23·61	−22·15	−1·46
S.E. (slope)	311	623	33·31	33·10	11·62	6·81	7·24	2·46
Forest area								
Years	5	11	NS	NS	NS	NS	••	NS
Years linear	1	1	•	•	NS	NS	••	•••
Years scatter	4	10	NS	NS	NS	NS	NS	•••
Slope (mm/year)			−65·50	−68·12	−20·56	−9·39	−56·67	5·66
S.E. (slope)	311	623	33·81	32·8	11·64	16·52	17·65	5·98

Probability levels: NS = not significant, •$P < 0.05$, ••$P < 0.01$, •••$P < 0.001$.

4.1. *Analysis for trend.* Figs. 3 and 4 show the rainfall and runoff trends for the two periods of time and for the over-all time span on both areas. During 1960–5 the downward trend in rainfall on the grass area just failed to reach significance at the five per cent level but was accompanied by a significant downward trend in grass runoff. During the same period there was a significant downward trend in forest rainfall but no significant trend in forest runoff. These trends were reflected in a smaller percentage loss from the forest area compared with the grass area towards the end of the 1960–5 period (Table II).

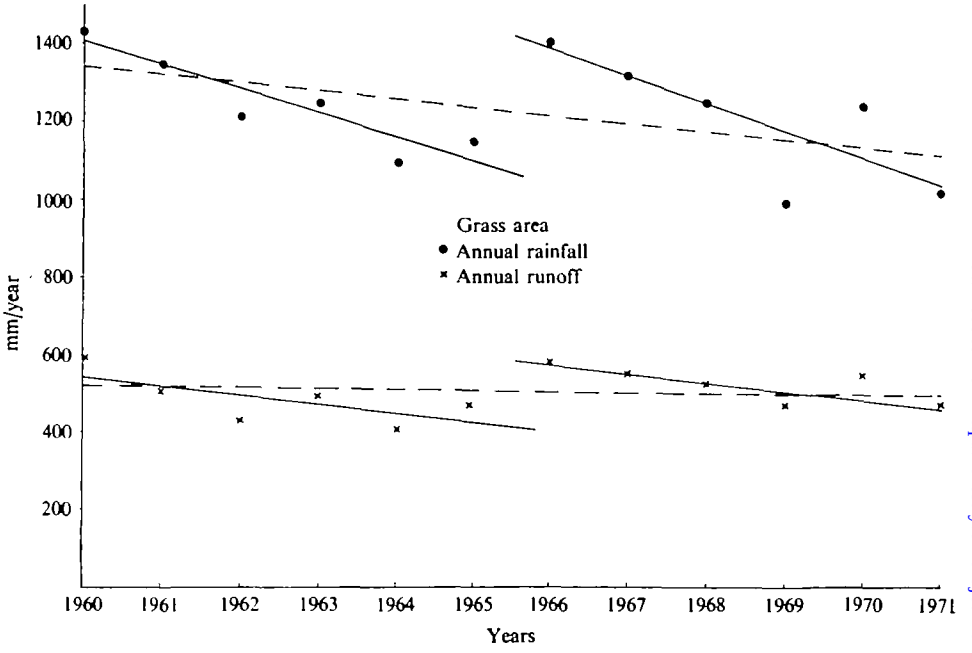


FIG. 3. Annual rainfall on and runoff from the grass area for 1960–5 and 1966–71.

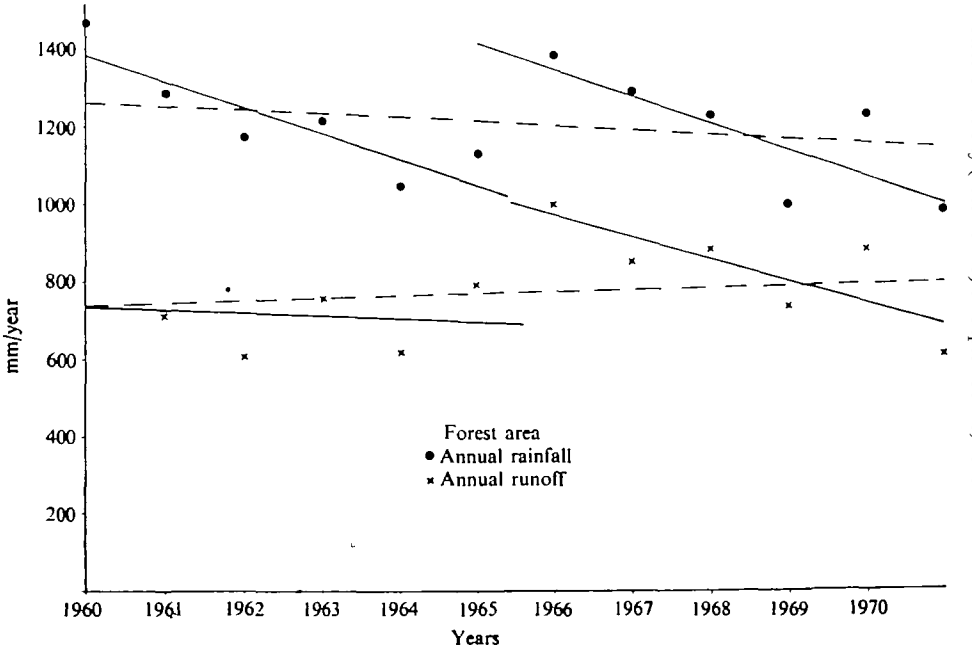


FIG. 4. Annual rainfall on and runoff from the forest area for 1960–5 and 1966–71.

The year 1966 had an exceptionally high rainfall compared with the years immediately preceeding. This was followed by reduced rainfall in later years. Consequently both the grass and forest areas experienced significant downward rainfall trends during the period 1966–71. Forest runoff followed the rainfall trend much more closely during 1966–71 than in the earlier period. Runoff from both the forest and grass areas fell significantly during this period.

Over the total time span 1960–71 there were no significant rainfall or runoff patterns on either area.

4.2. *Harmonic analysis.* In an attempt to determine whether the timing and magnitude of maximum and minimum flows were changing in the forest as the crop developed, compared with the grass area, harmonic analyses were carried out. As data would be expected to follow a cyclic pattern about the trend line with a fundamental period of one year, Fourier curves of the form:

$$y = a_0 + a_1 \cos(2\pi t/52) + a_2 \sin(2\pi t/52) + b_1 \cos(2\pi t/26) + b_2 \sin(2\pi t/26)$$

were fitted to the rainfall and runoff data, where a_0, a_1, a_2, b_1, and b_2 are constants and t is the time in weeks from the beginning of the year.

Although the phase and amplitude of the runoff curves varied significantly in the forest area from year to year during the 1966–71 period and over all, there was as much variation in the annual pattern of runoff from the grass area. Variations would of course be expected on both sites as the annual weather pattern changed. However, the differences between the two harmonics remained reasonably similar throughout the whole period. There was no sign, for example, of the maximum flows from the forest becoming less as the crop developed, nor of minimum flows increasing.

As the annual harmonic curves did not vary very much relative to each other it is reasonable to illustrate the differences in runoff patterns between the two areas in terms of the average curves derived for the whole period of 12 years. These are shown in Fig. 5. It will be seen that in the grass area runoff tended to vary much less about the mean than in the forest. This is probably caused by differences in soils and cultivation treatments.

5. DISCUSSION

The analysis of data for the first 12 years of the Woodburn runoff experiment has clearly failed to detect any significant changes in water yield from the forested catchment. The experiment has demonstrated the difficulty of making precise measurements and comparisons from data collected under conditions of rolling topography. Climatic trends, particularly trends in rainfall, contribute to a lesser degree in making comparisons difficult.

In examining the differences between rainfall and runoff over the years (Table IV) there is an indication that progressively more water has been accounted for by stream gauging from the forest area. During the 1960–5 period about 41 per cent of the water which fell as rainfall was not accounted for through the flow recorders. In the 1966–71 period this fell to 31 per cent.

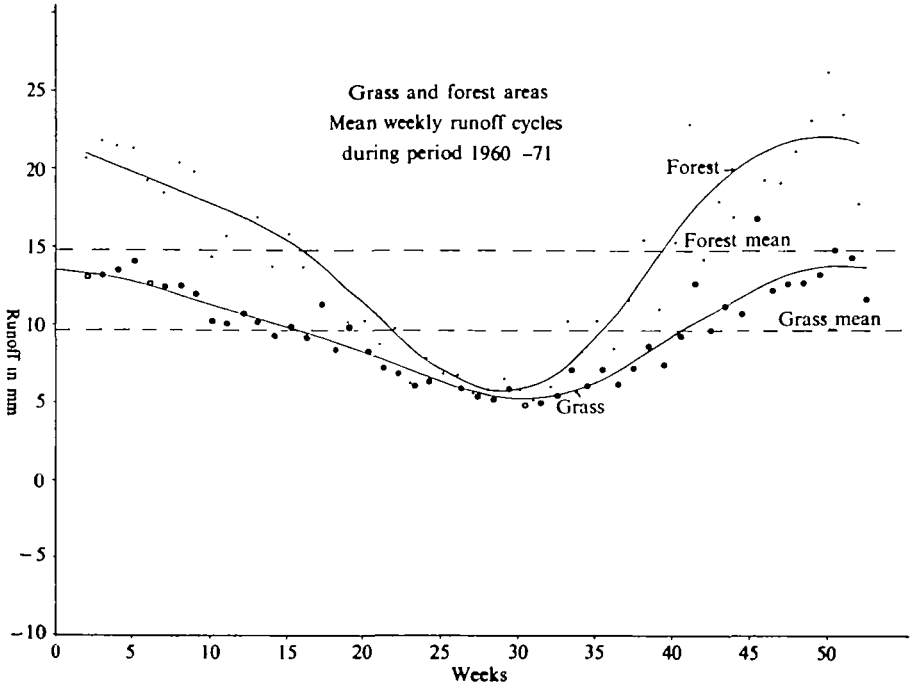


FIG. 5. Annual cycle of runoff from the forest and grass areas as shown by mean weekly values, and by curves derived by harmonic analysis of the values.

TABLE IV. *12-year water balance data for Woodburn catchment (mm)*

Year	Forest area			Grass area		
	Rainfall R	Runoff r	R-r	Rainfall R	Runoff r	R-r
1960	1,468	828	640	1,435	594	841
1961	1,285	714	571	1,344	517	827
1962	1,172	602	570	1,212	433	779
1963	1,212	754	458	1,244	499	745
1964	1,046	617	429	1,095	402	693
1965	1,131	790	341	1,151	484	667
1966	1,383	998	385	1,408	583	825
1967	1,291	852	439	1,321	552	769
1968	1,229	882	347	1,244	529	715
1969	1,004	737	267	995	472	523
1970	1,228	883	345	1,243	548	695
1971	990	611	379	1,020	470	550
Mean	1,203	772	431	1,226	507	719

Annual amounts unaccounted for from the grass area remained much more steady over the twelve years, averaging 59 per cent. It is not at present possible to account fully for this trend but it is likely to be caused by changes in the drainage pattern of the forest catchment rather than changes in the rate of evapotranspiration. Meteorological Office estimates suggest that annual evapotranspiration in the Woodburn area is unlikely to be less than 400 mm whether the ground is covered by a crop of trees or grass. During the period 1966–71 the difference between measured rainfall and runoff exceeded 400 mm only once and during most of the years concerned it was substantially less. There is therefore a strong possibility that large quantities of water were coming into the forest catchment unrecorded from neighbouring land and finding their way out via the flow recorders. The grass catchment has, in contrast, proved to be much more reliable and if it were planted with trees might prove a more rewarding area for a study of this kind. But by doing this only a time comparison would be possible so that climatic trends over several years would confuse results.

In the analyses certain differences between the forest and grass areas have appeared. In the forest even from the start of the experiment when the ground was largely covered with grass, runoff was always greater in terms of mean and maximum flows and more variable. Minimum runoff was normally lower. It is almost certain that these differences were caused solely by differences in soils and possibly in underlying geology between the two sites although the pre-planting drainage of the forest area may have had some influence. The predominantly brown earth soils of the grass area allow much quicker and deeper penetration by water than the gleys elsewhere. It is likely that considerable quantities have been lost by underground leakage from the grass area. This view is supported if the seasonality of loss is considered. In the winter months (taken as weeks 1–16 and 41–52 inclusive) when evapotranspirational losses are at a minimum and rainfall generally high, gleyed soils tend to be at or near field capacity most of the time. In such circumstances runoff should be at a maximum.

In 1965, 1966, 1967, and 1968 data indicated that of the total annual quantities of water unaccounted for, winter losses were about 21, 21, 25, and 18 per cent of the total respectively in the forest area and 44, 53, 45, and 71 per cent in the grass area. The latter with its small proportion of gleyed soils is unlikely to be at field capacity except after prolonged periods of rain. It is worth noting that losses from the grass area do not vary very much with season indicating that water movement is relatively independent of the time of year.

On the forest catchment it is possible that after a further period of growth some detectable differences may appear as the extent and depth of the forest canopy increases.

ACKNOWLEDGEMENTS

The authors acknowledge in particular the help given by Mr. R. E. D. Bain. His summary (Bain, 1965) of the first five years' recordings has been

incorporated into this report. Minor discrepancies in figures for runoff and rainfall between his paper and this one have been caused by a different method of calculating rainfall and a rechecking of the weekly runoff charts prior to punching data for computer analysis. The work of Mr. J. E. McEwen who carried out the soil survey is acknowledged and the authors thank Dr. E. R. C. Reynolds for his helpful criticism of the paper.

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