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HYDROLOGICAL IMPACTS OF CONVERTING TUSSOCK GRASSLAND TO PINE PLANTATION, OTAGO, NEW ZEALAND

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ABSTRACT

The hydrological impacts of converting lightly grazed mid-altitude tussock grassland to *Pinus radiata* plantation are examined using data collected from two medium-sized catchments in upland east Otago. After a 3-year calibration period, 207 ha of one catchment (310 ha) were planted at 1250 stems/ha in 1982. No change in water yield was observed until late 1988. In 1989 annual runoff from the planted catchment was 100 mm less than that from the adjacent control catchment in tussock (218 ha). The same was true in 1990, representing a 20% reduction in water yield each year. Land preparation before planting had a much earlier effect on the quickflow component of annual runoff, causing it to fall by about 9% in 1983. The peak flow rates of small storms (< 10 L s^{-1} ha^{-1}) were most affected by afforestation and showed an average reduction of up to 50% for the 1988–1990 period. Storm quickflow volumes showed a 29% reduction over the same period. Flow-duration curve analysis suggests that less water is now being released as low flow from storage in the planted catchment than in the control catchment. Higher interception loss through increased evaporation rates from a wetted forest canopy is believed to be the main reason for reduced water yields after almost 8 years of tree growth.

INTRODUCTION

The long-term effects of converting tussock grassland to pine plantation on water yield, storm flows, flood peaks, and low flows, as well as water chemistry and sediment yields have been examined by the Forest Research Institute in a paired-catchment study in the Waipori River headwaters (Fig. 1). One of the catchments (G1) was set aside as a control, and the other (G2) was planted. Rainfall and runoff were monitored in both catchments from 1980 to 1982 for calibration purposes (O'Loughlin *et al.*, 1984; Pearce *et al.*, 1984). Natural isotopic tracers were used to identify the mechanisms producing runoff from G1 (Bonell *et al.*, 1990). In addition, Campbell (1987, 1989), and Campbell and Murray

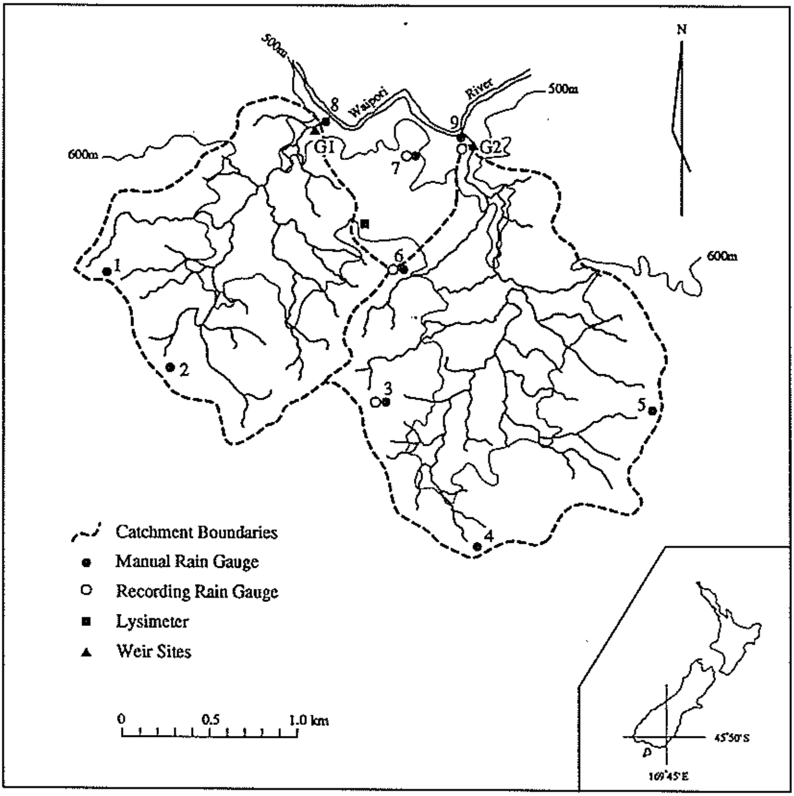

FIG. 1.—Topographic map showing Glendhu experimental catchments (G1 on left, G2 on right), and instrument locations.

(1990) investigated evaporation and the water balance of snow tussock in a large (6-m^2) weighing lysimeter installed on the boundary between the two catchments (Fig. 1).

In this paper, we assess the impact of afforestation on water yield and streamflow characteristics for the period since planting (1983–1990), and examine the water balance for the two catchments over 11 years (1980–1990).

STUDY AREA

The two catchments are on the southern-most end of the Lammerlaw Range in the upper Waipori catchment, 70 km west of Dunedin (Fig. 1). They are both north-facing, and comprise rolling-to-steep topography with an elevational range of 460 to 670 m. The bedrock is quartzo-feldspathic schist (McKellar, 1966). A weathered discontinuous mantle of colluvium fills many fossil gullies and depressions in the schist basement. Soils on the plateau-like summits are well-drained silt loams, commonly with a significant loess component (Hewitt, 1982). Soil depths range between 0.2 and 1.5 m. Valley-bottom soils tend to be poorly drained and peaty, but retain their silt-loam texture. Bogs and wetlands are common along major stream courses, particularly in their upper reaches, and occupy about 10% of the two catchments. Narrow-leaved snow tussock (*Chionochloa rigida*) is the dominant indigenous species, but it now occurs in association with an extensive ground cover of introduced grasses. Red tussock (*Chionochloa rubra*) is common in the more poorly drained valley bottoms.

The climate is dominated by a sequence of frontal systems in a prevailing westerly flow. Cold fronts are often preceded by strong dry north-westerly winds. The nearest climatological station is at Lake Mahinerangi (400 m a.s.l.), 20 km east of the catchments. The mean annual temperature at this site is 8.6° C, and the January and July means are 12.7° C and 3.6° C, respectively (New Zealand Meteorological Service, 1983). The average annual rainfall at Lake Mahinerangi is 960 mm, and the monthly means range from a low of 62 mm in September to 98 mm in May. Snow falls on an average of 11 days each year. The rainfall regime is one of many small events of long duration and low intensity (Murray *et al.* 1990). Occasional dry spells in the summer are associated with slow-moving anticyclones.

Catchment G2 (310 ha) was contour-ripped to a depth of 60 cm at approximately 3.5-m intervals in the winter of 1981, and the interfluves were planted the following winter with *Pinus radiata* at 1250 stems/ha, giving a total planted area of 207 ha. In the summer of 1989–1990 approximately 34 ha in the lower reaches of the catchment were pruned and thinned to 270 stems/ha. Both catchments were lightly grazed until late 1982. Catchment G1 (218 ha) has continued to be lightly grazed, but the stock density has never exceeded one sheep/ha.

METHODS AND INSTRUMENTATION

Between 1980 and 1987 rainfall was estimated from a network of nine 127-mm manual gauges (Fig. 1), which were read at least weekly. Catchment average rainfall for this period, calculated using the Thiessen weighting procedure after Pearce *et al.* (1984) showed precipitation (P) for the two catchments to be virtually identical (± 2% per annum). Five gauges were removed at the end of 1987, and the catchment rainfall from 1988 to 1990 was estimated by regression analysis. Three Belfort weighing-bucket gauges with Alter shields were also installed down the altitudinal transect between the two catchments in 1980. Those at sites 3 and 6 were removed at the end of 1987. At the same time, two tipping-bucket gauges were located at sites 8 and 9.

Runoff (R) was measured at the outlet of both catchments by broad-crested V-shaped concrete weirs. Pearce *et al.* (1984) are confident that no water by-passed either weir, and claim that runoff accuracy is ± 40 mm (5%). The quickflow and delayed-flow contributions to runoff were calculated after Hewlett and Hibbert (1967).

In the assumed absence of groundwater loss (because of the impermeable schist basement), the catchment water balance may be written as $R = P-E-\Delta S$, where E is evaporation and ΔS is the change in soil-water storage. Evaporation has two components: wet-canopy evaporation or interception, and transpiration from the dry canopy. For selected 2–3 month winter periods, we estimated

TABLE 1—Annual rainfall and runoff figures for catchments G1 and G2 for 1980 — 1990 (mm).

Year	Rainfall	Runoff G1	Runoff G2	Difference G1–G2	% Reduction in runoff
1980	1555	911	907	4	1
1981	1265	728	707	21	3
1982	1482	837	825	12	1
1983	1572	1115	1145	–30	–3
1984	1388	946	883	63	7
1985	958	488	476	12	2
1986	1487	799	810	–11	–1
1987	1591	1008	959	49	5
1988	1321	718	681	37	5
1989	1222	705	574	131	19
1990	1063	533	428	105	20
Mean	1355	799	761		

evaporation from P–R, after Pearce *et al.* (1984). All periods chosen for analysis were immediately preceded by rainfalls ranging from 91 to 139 mm. We believe that these were all sufficient to fully recharge the soil, thereby validating the assumption in the water balance calculations that $\Delta S = 0$.

CHANGES IN WATER YIELD

Annual Runoff

Annual runoff was similar for the two catchments from 1980 to 1988 (Table 1). However, in 1989 and 1990, after 6–7 years of tree growth, runoff for G2 was over 100 mm lower than that for G1. A decline of this size is consistent with those noted in afforestation studies elsewhere in New Zealand (e.g., Dons, 1986; 1987; Duncan, 1979; Smith, 1987). These show a range in water-yield reduction from 83 mm to 289 mm when scrub and pasture is converted to pines.

For the pre-planting period (1980 to 1982) monthly runoff differences between the two catchments seldom exceeded 5 mm (Fig. 2) and were not statistically significant (paired "t" test; $p > 0.05$). However, G1 yielded on average about 1 mm more water each month than G2 in this period. From the beginning of 1983 until the end of 1986 monthly runoff at G1 averaged only 0.6 mm above that at G2. However, for a few months, notably in early 1984, runoff at G2 was well below that at G1 (Fig. 2). There is no obvious explanation for this. Similarly, in February 1987, G2 runoff was well below that at G1. This month had the highest rainfall total (307 mm) during the study period, suggesting that higher interception at G2 may have been responsible for the difference. Through 1987 the monthly differences increased to an average of 3.9 mm. Although from January to September 1988 they decreased to an average of 1.7 mm per month, in the subsequent 27-month period to December 1990 they increased steadily to an average of 9.5 mm. The monthly differences since

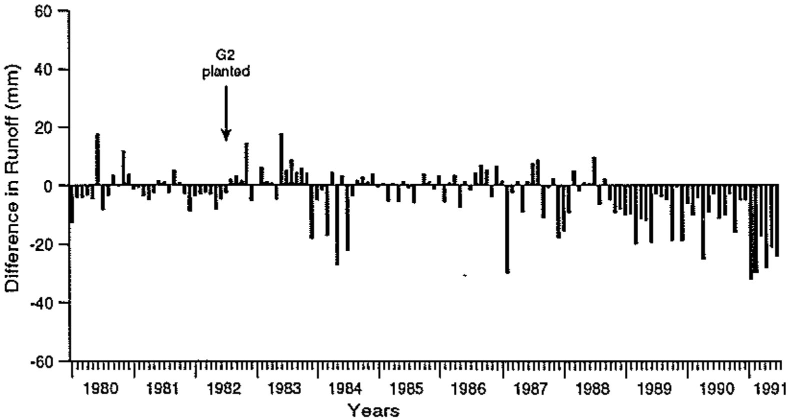

FIG. 2.—Monthly differences in runoff between catchment G1 (in tussock), and G2 (planted in *P. radiata,* winter 1982) at Glendhu Forest, 1980–1990.

TABLE 2—Evaporation estimates for G1 and G2, expressed as a percentage of rainfall, based on water-balance calculations during selected winter periods, after Pearce *et al.* (1984)

Year	Period	Days	Rainfall (mm)	Evaporation (% of rainfall) G1	G2
1982	18 Jul–27 Oct	99	492.6	31	30
1986	22 May–08 Jul	47	186.6	30	32
1987	22 May–11 Aug	81	287.4	26	21
1988	27 Jun–28 Aug	62	267.6	43	42
1989	11 Apr–26 Jun	75	229.8	27	44
1990	25 Apr–14 Jul	80	200.8	41	51

September 1988 were significant ($p < 0.05$), and all the monthly totals for G2 have been below those of G1 since this date, suggesting that tree growth was now having a significant impact on water yield.

Total Evaporation

Evaporation expressed as a percentage of rainfall, although varying from year-to-year, was reasonably similar for the two catchments up to 1988 (Table 2). However, for 1989 and 1990 evaporation increased markedly for the planted catchment compared with the control.

Annual interception was estimated at 20% of rainfall during the calibration period (Pearce *et al.,* 1984). This figure agrees well with the interception loss of 21% of rainfall measured from April 1985 to March 1986 for nine tussock plants in the large weighing lysimeter (Campbell, 1987). In their interception calculations, Pearce *et al.* (1984) assumed a winter transpiration rate of 10 mm per month, based on Penman evaporation estimates, whereas the water-balance data from the lysimeter suggests transpiration from tussock in winter is at least 15 mm per month (Campbell and Murray, 1990). Applying this rate to the periods listed in Table 2 showed that interception loss from tussock averaged 19%. Thus, despite using the higher transpiration estimate, interception loss from the tussock cover in the control catchment can still be assumed to be about 20%.

The problem here is to determine the relative contributions of transpiration and interception to the water balance for the planted catchment. There is some evidence that when soil water is not limited, transpiration rates from tussock grassland will resemble those from young coniferous forest (Campbell, 1987; Murray *et al.*, 1990). Thus, as a first approximation, for the planted catchment in 1989 and 1990 we have assumed a transpiration rate of 15 mm per month for winter (May to August), 35 mm per month for summer (January to March), and 25 mm per month for the remainder. This gives an annual total of about 275 mm, which for 1989 is 23% of total rainfall, leaving for that year a residual of 373 mm (31%) to be assigned to interception.

The above figures suggest that the increase in interception from young pines exceeds the increase in transpiration. There is support in the literature for assigning losses in runoff after afforestation to increased interception rather than to higher transpiration rates. Following on from the pioneer work of Law (1956) into afforestation influences in Britain, Newson (1979), Calder and Newson (1979), Blackie and Newson (1986), and Calder (1990) have shown that wet-canopy evaporation in wet upland forested catchments in central Wales can be up to twice the loss from transpiration.

Estimates of canopy storage-capacity for tussock and forest are remarkably similar, although water is normally evaporated more quickly from a forest canopy than from tussock and interception loss from forest may be twice that from tussock during rainfall (Murray *et al.*, 1990). Interception measurements from mature *Pinus radiata* stands in New Zealand and Australia range from 18 to

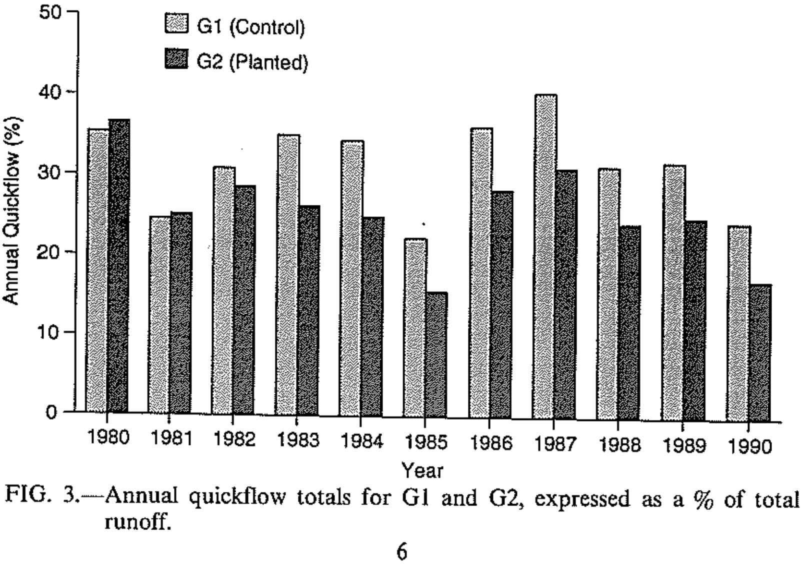

FIG. 3.—Annual quickflow totals for G1 and G2, expressed as a % of total runoff.

49% (Fahey, 1964; Smith, 1974; Feller, 1981; Crockford and Richardson, 1990; Kelliher *et al.*, 1992). The variation in these figures may be explained by differences in stand density, tree height, and local climate, but it does suggest that interception at Glendhu under young pine forest is high, particularly in view of the short time since G2 was planted. In addition, the steeper slopes and valley bottoms, which make up over 100 ha (or one-third of the catchment), were not planted. On a strictly areal basis, if all 310 ha had been planted, interception loss could be approaching 46% by now. A factor contributing to the high interception figure is the retention of the original tussock cover in the planted catchment, which continues to intercept precipitation. Exactly how long this will persist is uncertain. Canopy closure will eventually lead to the demise of the tussock understorey, although rainfall interception by dead tussock surfaces could continue indefinitely.

Further thinning and pruning may alter the trend towards lower water yields. However, the presence of slash (tree stems and branches left over from thinning and pruning) will further reduce understorey evaporation under dry conditions, and offer additional surfaces for interception during rainfall (Kelliher *et al.*, 1992).

CHANGES IN FLOW REGIMES

Annual Quickflow

Annual quickflow averaged 30% of total runoff for both catchments over the 3-year pre-planting period (Pearce *et al.*, 1984). However, in 1982 annual quickflow for the planted catchment fell marginally below that for the control, then remained lower by an average of 8% per year between 1983 and 1990 (Fig. 3). Changes in surface runoff characteristics after the ripping of the catchment in mid-1981, possibly coupled with the cessation of grazing, are believed to have caused the reduction in annual quickflow over this period. The reason why

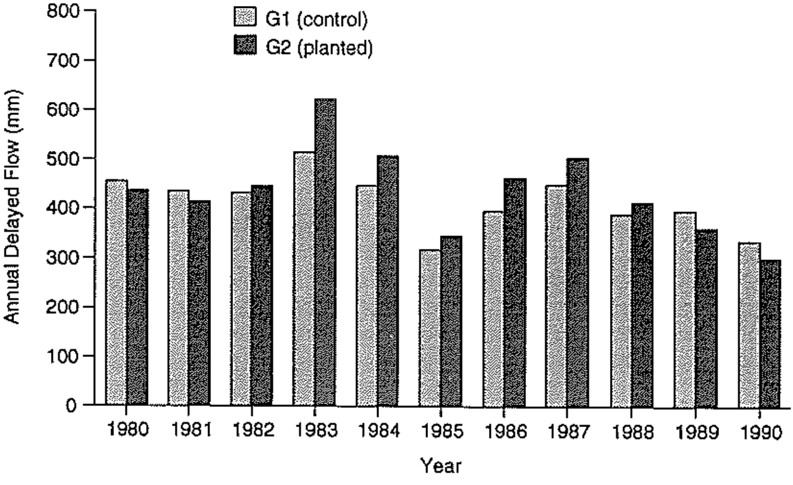

FIG. 4.—Annual between-storm delayed flow totals for G1 and G2 in mm.

TABLE 3—Average storm peak flows (L s^{-1} ha^{-1}) and associated quickflows (mm) for G1 and G2 in two storm size classes for three periods (pre-planting, early post-planting, and later post-planting). The analysis is restricted to storms with uninterrupted recession curves.

		Peak Flows			Quickflows		
Period	n	Size Class (L s^{-1} ha^{-1})	G1	G2	Size Class (mm)	G1	G2
1980–82	6	5 — 9.9	7.2	6.7	5 — 19.9	6.6	6.3
	3	>10	14.2	13.5	>20	34.0	37.0
1984–86	6	5 — 9.9	6.3	4.3	5 — 19.9	14.3	12.3
	6	>10	13.3	10.6*	>20	28.3	21.2*
1988–90	10	5 — 9.9	6.3	3.3	5 — 19.9	11.0	7.5
	5	>10	18.6	14.7*	>20	34.6	25.9*

* Means for G1 and G2 significantly different ($p < 0.05$)

annual quickflow showed only a small reduction in 1982 immediately after ripping, is not known.

Annual Delayed Flow

Delayed flow totals for the two catchments during storms differed little from year to year. This was not the case, however, with delayed flow between storms (Fig. 4.). Annual totals were much the same before ripping and planting, but in 1983 delayed flow between storms at G2 exceeded that at G1 by 108 mm (21%). Thereafter, the difference between the two catchments declined progressively until by 1989 annual between-storm delayed flow at G2 had fallen below that at G1 as tree growth began to have an effect. Delayed flow between storms occurred on virtually the same number of days each year in both catchments. The reduction in quickflow after ripping and planting in G2 was balanced by an increase in delayed flow between storms, compared with G1.

Storm Peak Flows and Quickflows

The effect of tree growth on storm peak flows and associated quickflows was examined for two size classes of storms, using flow at G1 as the basis for the classes (Table 3). For the pre-planting period (1980–1982), mean peak flows in both size classes for the two catchments were similar. For the early period after planting (1984–1986) average peak flows for G2 had fallen by 32% and 20% for the two size classes, respectively. For the most recent period (1988–1990), average peak flows for the planted catchment showed a further reduction (48% and 21% for the two size classes, respectively). Quickflow averages did not differ significantly for the 1980–1982 period. However, during 1984–1986 quickflows at G2 had fallen by 14% and 25% for the two classes, and during 1988–1990, the reductions were 32% and 25%. In percentage terms, the biggest impact of planting on peak flows was for the smaller events (< 10 L s^{-1}

TABLE 4—Quickflow response ratios (quickflow expressed as a percentage of gross storm rainfall) for catchments G1 and G2 at Glendhu for selected classes of quickflow over the periods 1980–1982 and 1988–1990.

Quickflow Classes (mm)	Sample size		1980–1982 Quickflow response ratio		Sample size		1988–1990 Quickflow response ratio	
	G1	G2	G1	G2	G1	G2	G1	G2
1 — 4.9	52	52	17.1	13.8	38	52	15.9	9.5
5 — 19.9	25	24	29.7	32.2	28	16	35.8	30.0
>20	8	9	47.7	47.8	4	3	48.8	42.1

ha^{-1}). However, the impact was more uniform across the range of quickflows on a storm-by-storm basis.

The two sets of quickflows for all events > 5 mm were compared for the same three periods listed in Table 3. For the pre-planting period the 32 events had statistically similar means of 15.0 mm and 16.4 mm, for G1 and G2 respectively. For 1984–1986, the 38 events had significantly different means of 16.5 mm for G1 and 12.3 mm for G2 ($p < 0.05$). For 1988–1990, the 32 events had lower means than those previously recorded (13.1 mm and 9.1 mm, respectively) but these were still significantly different ($p < 0.05$).

Storm quickflows for G1 and G2 from January 1980 to November 1981 (pre-ripping) showed no consistent differences. From the beginning of 1982, however, (i.e., after ripping but before planting), virtually all storm quickflows from G1 exceeded those from G2, confirming that ripping reduced the potential for quickflow.

Quickflow Response Ratio

For the control catchment the relationship between the quickflow response ratios (quickflow/rainfall) and quickflow yields was similar to that noted by Pearce *et al.* (1984) (Table 4). However, for the 1988–1990 period, the average quickflow response ratios for medium-to-large runoff events at G2 were consistently lower than those at G1.

Low Flows

Flow-duration curves identify the percentage of time that a given streamflow is equalled or exceeded (Searcy, 1959). In addition the shape of the curve reflects the ability of a catchment to store water. Flat slopes, for example, (particularly at the lower end of the curve) indicate substantial storage capacity and stable flows. A comparison of curve shape at different times in a catchment's history should make it possible to determine whether flow characteristics are responding to changes in land use, assuming separate accounting for temporal variations in climate.

The Glendhu catchments sustained high flow rates between rainfall events for 1980–1982 (Pearce *et al.,* 1984). For example, average flow was sustained at > 0.1 L s^{-1} ha^{-1} for 96% of the time. Low flows were up to 6 times higher than those for comparable catchments in indigenous forest (McKerchar and Waugh, 1976).

Flow-duration curves are used here to determine the extent to which low flow characteristics have changed in response to tree growth in G2 (Fig. 5). For the pre-treatment period at G2 the minimum flow was at least 0.1 L s^{-1} ha^{-1} for 93% of the time, and 0.07 L s^{-1} ha^{-1} for 99.9% of the time. For 1988–1990 the minimum flow fell to 0.08 L s^{-1} ha^{-1} and 0.04 L s^{-1} ha^{-1} for 93% and 99.9% of the time, respectively. This suggests that less water is now available from storage in the planted catchment. However, while the 1988–1990 curve for G2 occupies the lowest position on the graph, the reduction in flow for the later period may also be partly attributable to the lower average annual rainfall in this period compared with 1980–1982. This is suggested by the position of the flow duration curve for G1 (1980–1982) which is above that for 1988–1990.

The lowest average flow for 7 consecutive days has also been proposed as a useful parameter for establishing the impact of land-use change on low flows (Riggs, 1972). The differences between the minimum 7-day means from 1980 to 1987 showed no significant pattern, apart from those for G2 being slightly higher than those for G1 (Table 5). However, over the last 3 years this was reversed, suggesting that low flows for the planted catchment are now being reduced by afforestation.

CATCHMENT WATER BALANCE

For ease of comparison with data presented by Pearce *et al.* (1984), catchment water balances were calculated for calendar years (Table 6). It is possible that the assumption $\Delta S = 0$ may be violated by having the period begin and end in summer when soil moisture deficits are more common. To check the validity of the above assumption, the water balance was also calculated over the 12-month period 1 September to 31 August, and the results compared with those in Table 6. Run-off totals were all within 4% of one another using the two calculation periods, suggesting that any errors arising from the use of a calendar year are small.

Apart from a higher transpiration loss, the average annual water balance for the control catchment over the period 1980–1990 differs little from that calculated by Pearce *et al.* (1984) as the annual average between 1980 and 1982 (Table 6). However, a comparison of the annual water-balance components for 1981 and 1989 reveals the impact that tree growth has had on the water balance. Quickflows show a marked decline. Estimated interception increased from 20 to 31% of gross rainfall. Transpiration is assumed to have remained virtually unchanged.

SUMMARY AND CONCLUSIONS

It has taken almost 8 years for tree growth at a stocking rate of 1250 stems/ha in tussock grassland to have a detectable effect on water yield over time scales of 1 month to 1 year. Annual runoff from the planted catchment is now slightly over 100 mm less than that from the catchment left in tussock. This amounts to a 20% reduction in water yield after planting two-thirds of the catchment in *Pinus radiata*. In contrast, the impact of land preparation on

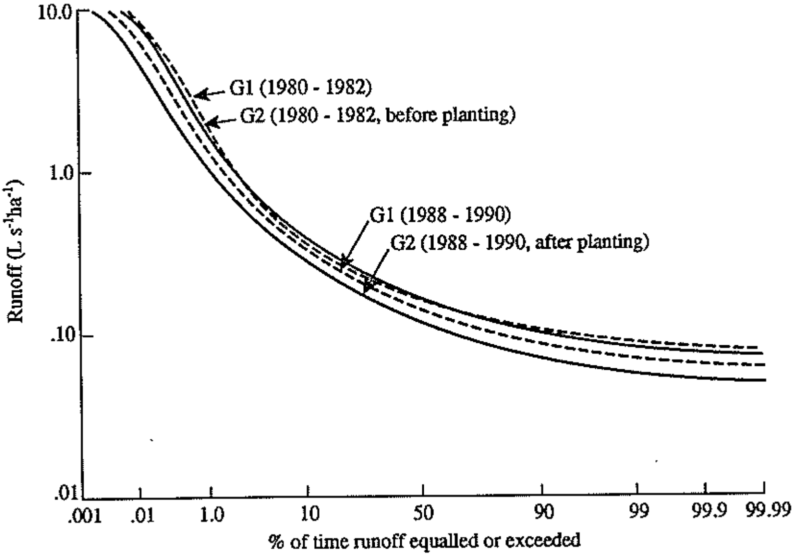

FIG. 5.—Flow duration curves for catchments G1 and G2 before planting (1980–1982), and after planting (1988–1990).

TABLE 5—Minimum annual 7-day low flows (mm) for G1 and G2 from 1980 to 1990.

	Minimum annual 7-day low flows (mm)		
Year	G1	G2	G1–G2
1980	1.03	0.95	0.08
1981	0.85	0.90	-0.05
1982	0.81	0.72	0.09
1983	1.09	1.18	-0.09
1984	0.97	1.15	-0.18
1985	0.68	0.72	-0.04
1986	0.47	0.59	-0.12
1987	0.77	0.89	-0.12
1988	0.68	0.54	0.14
1989	0.80	0.57	0.23
1990	0.65	0.53	0.12

quickflows was more immediate. However, although ripping and planting may cause a reduction in quickflow, most of the change at the outset was balanced by an increase in delayed flow between storms. The net effect was to keep total flow reasonably constant as a percentage of rainfall, until interception loss from tree growth was sufficient to cause a decline in water yield.

TABLE 6—Average annual water balances at Glendhu for (a) 1980–1982 for the two catchments combined (after Pearce *et al.*, 1984); (b) 1980–1990 for the control (G1); and (c) annual water balances for 1981 and 1989 for both catchments. Interception and transpiration are shown as a percentage of gross precipitation, and quickflow as a percentage of total runoff.

Catchment		Period	Precip.	Interception		Transpiration		Quick-flow		Delayed flow
			(mm)	(mm)	(%P)	(mm)	(%P)	(mm)	(%R)	(mm)
(a)	Combined	1980–1982	1305	260	(20)	210	(16)	250	(19)	585
(b)	Control	1980–1990	1355	271	(20)	285	(21)	260	(19)	539
(c)	Control	1981	1265	253	(20)	285	(23)	175	(25)	548
	Planted	1981	1265	253	(20)	305	(24)	178	(25)	529
	Control	1989	1222	244	(20)	273	(22)	224	(32)	481
	Planted	1989	1222	373	(31)	275	(23)	143	(25)	431

After 7–8 yr of tree growth, peak flows for moderate-sized storms declined by 20%, and for small storms by 50%. Quickflows and the quickflow-response ratio showed a similar but less pronounced trend. The percentage of quickflow appearing as runoff was low compared with storm runoff responses presented by Pearce and McKerchar (1979) for a variety of catchments and cover types in New Zealand, and conversion to pines has the effect of reducing it even further.

The effect of afforestation on low flows is more difficult to discern. However, the results from the flow duration curves and the minimum 7-day average suggest that less water is now being stored in the planted catchment for slow release as delayed flow, but the magnitude of the impact is masked by slightly drier conditions for 1988–1990 than for 1980–1982. The main factor causing the decline in runoff in the planted catchment since 1988 is believed to be an increase in interception by tree canopy development and growth. Thinning and pruning of the tree crop in the catchment may modify the interception response, but as long as tussocks continue to survive beneath the trees and slash intercepts rainfall, any reduction in interception loss from thinning and pruning is not expected to be significant.

The observed 20% reduction in water yield after 7–8 years of tree growth can be critically important, particularly in summer when demand for water for recreation, irrigation, and domestic supplies is at a peak. Moreover, even allowing for thinning and pruning, interception losses will continue to grow as the trees mature and canopy closure is finally achieved. Land managers should be aware of these effects when planning future forestry development in the area.

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