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Hydrological impacts of converting pasture and gorse to pine plantation, and forest harvesting, Nelson, New Zealand

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Abstract

The hydrological impacts of converting hill country pasture and tall dense gorse to *Pinus radiata* plantation and subsequent felling of the mature forest are examined using data collected from five small (4.0 - 7.7 ha) catchments in Moutere Gravel hill country near Brightwater, Nelson. After a six-year calibration period one pasture catchment and two tall dense mature gorse catchments were planted at 1500 trees/ha in 1970/71. The trees were pruned and thinned at various times until in 1981 all catchments were stocked at 300 trees/ha. The trees were felled in the winter of 1991. Annual water yield increased by 219-358 mm/y in the three years after the gorse catchments were cultivated or line dozed for planting. Water yield reduced to pre-planting values 4-5 years after planting. Over the next 2-3 years annual water yield continued to decline, as the canopy closed. Thereafter annual water yields were relatively constant with some response to annual rainfall variation and silvicultural practices. These water yields averaged 63 mm/y less than would be expected from gorse. Water yields in the former pasture catchment started to reduce 3 years after planting and beyond 7 years averaged 167 mm/y less than expected from pasture. Four months after clear felling, when soil moisture levels had been replenished, runoff rates had increased to be greater than those from pasture. In the first and second years after harvest flows increased 0-60 mm/y and 226-343 mm/y respectively above those expected from pines, to yield in the second year flows similar to those expected from bare land.

The small catchments are all ephemeral, and those with gorse or pine cover can be expected to be dry for 3 months per year more on average than pasture catchments. When all catchments are flowing, pine or gorse catchments have less than half the flow expected from pasture catchments.

Peaks of freshes from pine/gorse catchments are 20% of those from pasture catchments. As annual flood exceedance probability (AEP) decreases the difference in flood size also decreases until for AEPs of 0.02 flood peaks from pines/gorse catchment average half of those from pasture catchments. The differences in runoff between pines and pasture catchments are primarily attributed to greater interception by the pine trees and greater soil moisture storage potential under pines because of their greater rooting depth.

Introduction

This study was initiated in the 1960s when the effects on water yield of planting new forests were poorly understood, and there were prospects of large areas of scrub and pasture land in New Zealand being converted to *Pinus radiata* forest. A decade later, the understanding was much improved and the cumulative experience from 94 catchment experiments worldwide was reviewed by Bosch and Hewett (1982). The concerns that lead to this study spawned many others in New Zealand and they have been reviewed by Fahey and Rowe (1992). This is the first New Zealand study to assess the effects of a full forestry cycle on water yield and stream flow.

Study Area

The six study catchments are on the north-eastern edge of the dissected Moutere Gravel hill country, 20 km south-west Nelson City (Fig. 1). Five catchments are north facing and one, catchment 8, is southeast facing. The

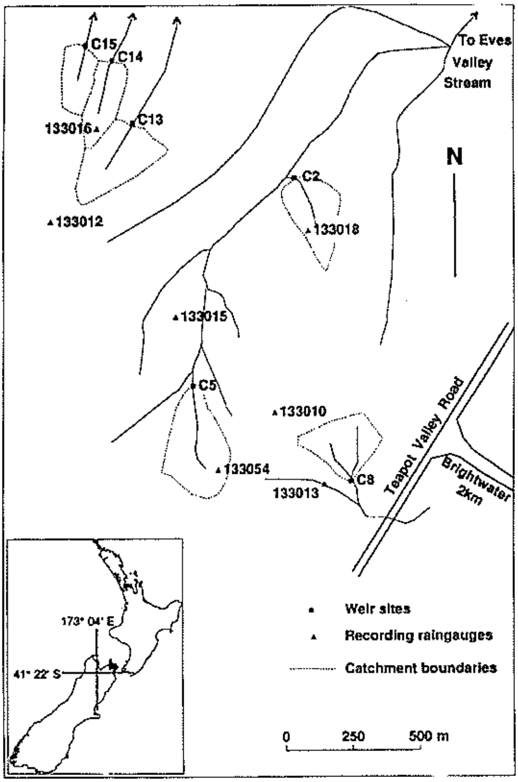

FIG. 1 — Location map of the Moutere experimental catchments.

topography is rolling to steep (mean hill slope 18°) with an elevation range from 60 to 140 m. Mean channel slope is 10-18°. The Moutere Gravel Formation is composed of deeply weathered early Pleistocene gravels, sand, silt and clay. The weathering and size range of the materials have combined to form an essentially impervious foundation to the catchments. This deep formation extends over an area of 1200 km^2 and its geology has been described by Grindley (1961) and Beck (1964).

The soils are strongly enleached, moderately clay illuvial surfulvic soils (Gillingham, 1968). The soils are rarely less than 400 mm thick and the subsoil is usually a clay loam 350-400 mm thick that is commonly underlain by a 500 mm thick layer of dense clay. Subsoils of lower slopes are often gleyed, indicating poor aeration and drainage.

The climate is dominated by gentle to fresh south to southwest winds, but most rain comes from the north. The mean annual temperature at the site is 12.9°C and the January and July means are 17.8°C and 8.0°C respectively. The average annual rainfall (1960-86), is 1018 mm, and the monthly means range from a low of 53 mm in February to 103 mm in August. Mean potential evapotranspiration (Penman, 1963) for Moutere normally exceeds precipitation from November to February.

Storm flow runoff from pasture-covered catchment 5 is considered by Pearce and McKerchar (1973) to be generated by saturation overland flow for small storms and by Hortonian overland flow for intense rainfalls. The author has seen, during an intense rain storm, Hortonian overland flow on a large portion of a pasture catchment adjacent to the study catchments. Because of a thick organic layer of decaying needles and an absence of soil compaction by stock in gorse and pine catchments, Hortonian overland flow is probably less important in pine- and gorse-covered catchments.

Catchments 2 (C2, 3.96 ha) and 5 (C5, 6.96 ha) have had a cover of improved ryegrass/white clover pasture for the entire time of the study. Gorse in the gullies of C2 and C5 was eliminated by spraying during 1964-68.

The tall dense gorse cover of catchment 8 (C8, 4.41 ha) was burnt in March 1970..*Pinus radiata* was planted in dozed lines at 1500 trees/ha in September 1970. The trees were pruned and thinned to 600 trees/ha in October 1978, and to 300 trees/ha in February and March 1981. The trees were skidder logged in June/July 1991 when the trees were 25.5 m high. New trees were planted amongst the slash.

Catchment 13 (C13, 7.65 ha) was covered in mature gorse from 1964 to March 1970, when it was incompletely burnt. Gorse regrowth was vigorous. The catchment was root raked, the soil cultivated and two contour banks constructed in winter 1971. *Pinus radiata* was planted at 1500 trees/ha in August 1971. Gorse regrowth was again vigorous. The trees were pruned

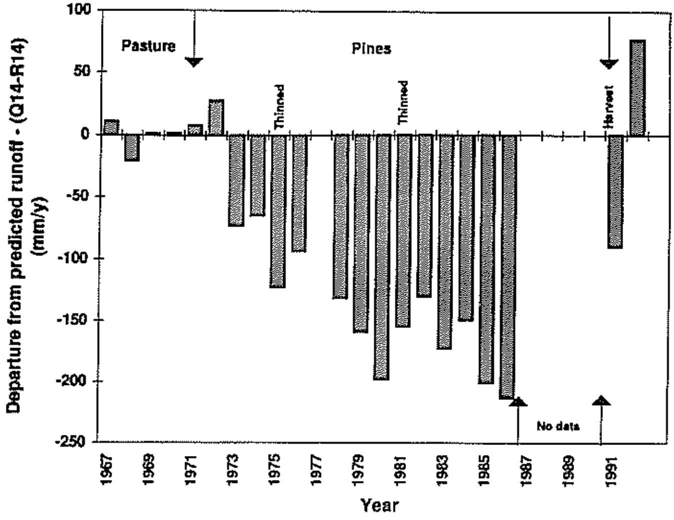

FIG. 2 — Annual differences between runoff from C14 and predicted runoff using the relationship P14 = 0.5*Q5 + 79.7 ($r^2 = 0.88$) where P14 is the predicted runoff from C14 and Q5 is the runoff from C5 and r^2 is the regression coefficient. Data for 1991-93 is for June to July years.

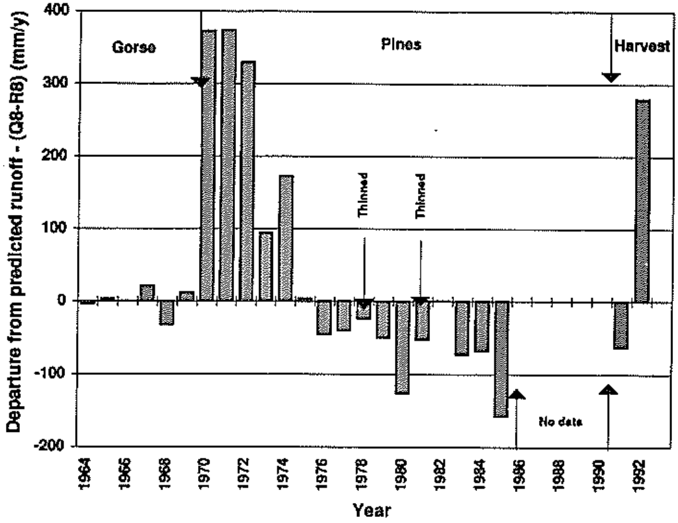

FIG. 3 — Annual differences between runoff from C8 and predicted runoff using the relationship P8 = 0.92*Q5 - 73.6 ($r^2 = 0.92$) where P8 is the predicted runoff from C8 and Q5 is the runoff from C5 and r^2 is the regression coefficient. Data for 1991-93 is for June to July years.

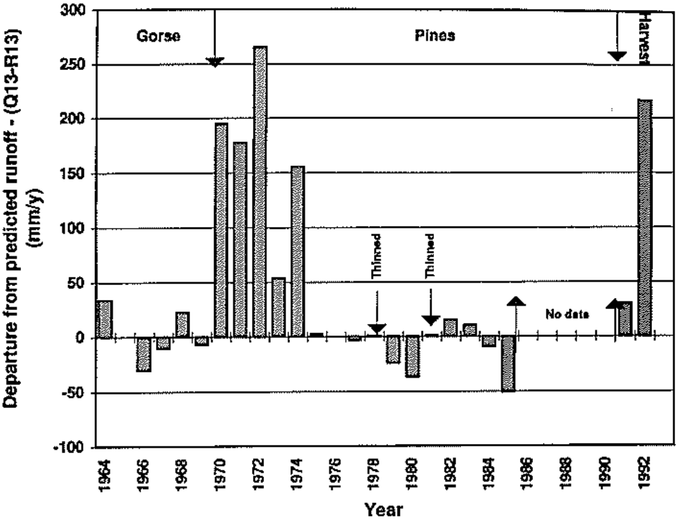

FIG. 4 — Annual differences between runoff from C13 and predicted runoff using the relationship P13 = 0.47*Q5 - 34 (r^2 = 0.65) where P13 is the predicted runoff from C13 and Q5 is the runoff from C5 and r^2 is the regression coefficient. Data for 1991-93 is for June to July years.

and thinned as detailed for C8. The trees were harvested by skidder on the east side of the catchment and cable on the west side in August/September 1991 when the trees were 29 m high, and new trees replanted soon after.

Catchment 14 (C14, 4.34 ha) had a sparse pasture cover in 1964, and the cover was reported as complete in 1967-68. The catchment was cultivated in August 1970 and *Pinus radiata* was planted at 1500 trees/ha the following month. Vigorous pasture regrowth occurred that spring. The trees grew well and by May 1975 there was almost complete canopy cover, but in July they were pruned and thinned to 500 trees/ha. Pruning and thinning to 300 trees/ha took place in March 1981. The trees were harvested by cable hauler in July/August 1991 when the trees were 33 m high, and replanted soon after.

Catchment 15 (C15, 2.71 ha) was in pasture from 1964 to 1978 when the gully and adjacent area covering 20% of the catchment area were planted in pines at 1200 trees/ha. The remainder of the catchment kept its pasture cover. The trees were pruned to 3 m in December 1983 and thinned to 500 trees/ha in February 1984.

Methods and Instrumentation

Initially (1962-1966) ten manual rain gauges, 127 mm diameter, were installed in the catchments and read daily. Catchment average rainfall for this

TABLE I - Annual runoff from catchments at Moutere (mm).

Year	Rainfall	C2	C5	C8	C13	C14
1964	1116	277	280	181	131	462
1965	810	132	124	44	23	163
1966	1105	184	279	184	66	221
1967	958	326	289	215	91	234
1968	1054	316	282	155	121	199
1969	1065	205	306	222	102	233
1970	1115	365	426	693	361	293
1971	1006	209	244	525	258	209
1972	1051	252	339	569	390	276
1973	653	22	60	76	48	35
1974	1232	321	475	538	345	250
1975	1123	209	274	184	97	92
1976	1232	237	302	160	108	135
1977	919	155	178	51	46	35
1978	831	100	143	35	34	18
1979	990	159	184	47	28	11
1980	1025	197	280	59	60	20
1981	921	102	193	52	58	20
1982	791	102	160	75	56	28
1983	1219	296	406	229	167	108
1984	942	154	202	45	51	30
1985	1140	263	339	82	74	47
1986	1127	345	416			73
1987	869	176	213			
1988						
1989						
1990						
1991/92	804		136	136	60	56
1992/93	1174		296	460	237	215

period, calculated using the Thiessen weighting procedure, was correlated with each gauge. The network was then reduced to a single automatic rain gauge on the site with the best correlation with catchment average rainfall. The original Dines tilting siphon gauges were replaced with 0.5 mm tipping bucket gauges and Fischer and Porter recorders in the early 1970s. Before the growing pines could significantly affect rain gauge catches, the automatic rain gauges were relocated in grassed paddocks by each pine catchment. Annual rainfall (1964 - 1985) varied less than ±2.5% between catchments.

Runoff was measured using several structures. Two-foot H-flumes recording on daily Kent chart recorders were replaced with compound V-notch weirs (C5 in 1967, and C13, C14 and C15 in 1968) or 9-inch H-flumes extended to 3 feet (C2, C8 in 1969). The H-flumes in C2 and C8 were replaced by compound V-notch weirs in 1976. The Kent recorders were replaced with Fischer and Porter digital punched-tape event recorders in 1970 and 1971 (Duncan, 1990).

Neutron probe soil moisture measurements began in C5, C8, and C14 in 1974. One access tube allowing measurements to 2.2 m and two to 1.4 m were installed in each catchment. The neutron probe was calibrated with gravimetrically determined soil moisture contents of cores taken next to the tubes. Measurements were taken every 100 mm between the depths of 100 mm and 600 mm and every 200 mm below 600 mm. Sites were sampled twice per month until 1979 and monthly until 1986.

Interception in the growing pine forest in C14 was calculated as the difference between mean basin rainfall, and stem flow plus throughfall. Throughfall was measured by 20 troughs, each with an area of 0.186 m^2, set in a line, 1 m above ground, at 10 m intervals, along one side of the catchment. The catch from all troughs drained into a single container. Stem flow was collected by channels formed of spiral strips of water-proof foam rubber and celluloid glued to the smoothed bark of trees, and taken by tubes to a single container. Initially stem flow was collected from 30 trees on a 204 m^2 plot. As the trees were thinned, the number of trees from which stem flow was collected was reduced in proportion to the number of trees removed.

Annual water balance calculations for C5 and C14 are based upon rainfall, runoff, interception and neutron probe soil moisture measurements. Evapotranspiration from the vegetation and soil for C5 is calculated from rainfall less runoff and soil moisture change. For C14 a distinction is made between total evaporative losses, called here evaporation, and transpiration from trees added to evaporative losses from the soil, called here evapotranspiration. C14 evaporation is calculated as for evapotranspiration in C5, and C14 evapotranspiration is calculated as C14 evaporation less C14 interception.

In 1988 all measurements ceased. Rainfall, runoff and soil moisture sampling recommenced in July 1991 in C5, C8, C13 (no soil moisture samples) and C14 immediately prior to the felling of the trees, and continued until July 1993. The weirs had been left in place in anticipation of the resumption of recording when forest harvesting was planned. The neutron probe access tubes in the forested catchments (C8, C14) were damaged by forest harvesting and new tubes were installed close to the location of the old tubes. The new tubes penetrate only to the gravels, and thus give soil moisture data from 0-900 mm below the surface.

Results and Discussion

Changes in Annual Water Yield

Annual runoff from the catchments is shown in Table 1. The effects of the land-use changes on annual yields were examined by developing linear regression equations describing the relationship between yields in the control catchment (C5) and the experimental catchments for the period 1964 - 69 (C8, C13) and from 1967-71 (C14). C14 uses a later period because the pasture was poorly developed before 1967 and planting pines in the pasture had no significant effect on water yield before 1972 (Fig. 2). Yields after afforestation were then predicted using the regression equations, and the afforestation effect calculated as the difference between predicted yields and measured yields. C8 showed a marked increase in runoff following the gorse burning and line dozing in preparation for planting in 1970 (Fig. 3). In each of the first two years after scrub clearance annual runoff increased 373 mm. Runoff then decreased until in 1975 it was similar to that before planting. The anomalous behaviour of 1973 runoff is explained by a severe drought that year (Table 1) when all catchments had reduced runoff. From 1976 runoff has been less (average 1976-85 of 102 mm) than it was when the catchment was gorse covered. Differences were lower than average during 1978 and 1982 when annual rainfall was also low (Table 1). Thinning of the stand in 1978 and 1981 may also have had some effect in increasing runoff in those years. Yield changes occurring after harvesting are considered later.

Annual runoff departures in C13 (Fig. 4) show a similar pattern to those from C8, averaging 212 mm for 1970-72. Runoff returned to pre-treatment levels in 1975 and averaged 26 mm (1975-85) less than gorse. Differences in behaviour between C8 and C13 are attributed to differences in aspect with C8 facing southeast and C13 facing north. As C8 is steep, it is in shade for most of the day and evaporation is lower, leaving a greater proportion of the rain available for runoff. The calibration period runoff from C8 thus averaged 167 mm/y compared to 89 mm/y for C13.

Departures from predicted runoff in C14 (Fig. 2) increased from 1973 to 1978 when the canopy closed. From then until 1986 the magnitude of the departure reflects annual rainfall (Table 1) and averages 169 mm.

Changes in Peak Floods

Duncan (1980) showed that the peaks of freshes from these small catchments are about 80% smaller from gorse or pine catchments than from pasture catchments. The question arises whether more extreme floods from gorse/pine catchments are also smaller. The long record period (1964 - 86) allows standard extreme value analysis to predict confidently the expected magnitude of floods with annual exceedance probabilities (AEP) down to 0.02. For all catchments the Log Pearson 3 extreme value distribution fitted the annual maximum series better than other distributions, and the fits were considered good (not shown). Peak flows according to the distribution, for a range of AEPs from each catchment, are shown in Figure 5. C14 data are for 1973 - 93 when it was planted in pines. C15 is included in this analysis to supply data from another pasture catchment: data from 1983 on was not used as the small portion of its catchment area planted in pines could have affected that portion of the record.

There is a clear separation of the flood peaks from pasture and gorse/pine catchments (Fig. 5). However, the data from C5 and C14 are the primary cause of the wide separation of the mean pasture and pine curves; data from the remaining catchments are not significantly different (5%). Nevertheless, the data as a whole indicate floods from pine catchments can be expected to be smaller those from pasture catchments over a wide range of AEPs. The mean annual flood (AEP 0.43) peaks from pines average about 35% of those from pasture and the 0.02 AEP peaks average about 50% of those from pasture. This result is not consistent with the commonly held view that extreme flood magnitudes are independent of catchment cover. This view is primarily based on the premise that the differences in interception capacity between tall and short vegetation are small compared with the volumes of rain required to produce extreme floods. This simplistic view does not take

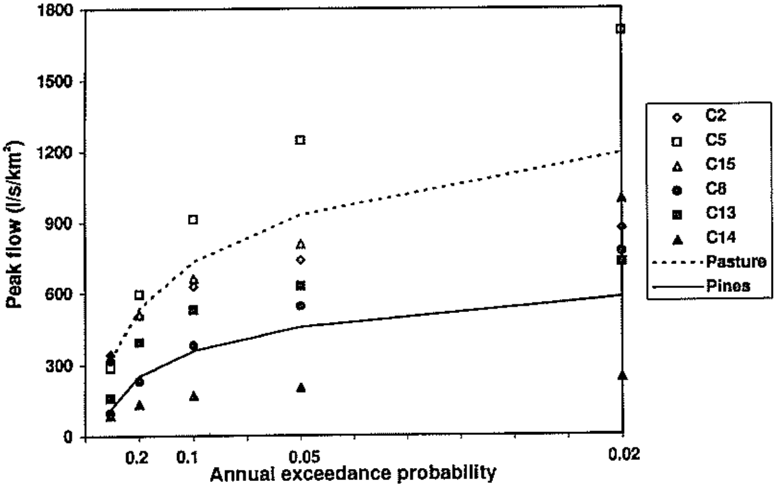

FIG. 5 — Relationship between annual peak flow and return period for catchments that were either predominantly pasture or gorse/pines between 1964 and 1993. Pasture catchments have open symbols and pine catchments filled symbols. Open and filled circles indicate the mean for each group.

into account evaporation of the intercepted water during a rainstorm (Pearce et al., 1980a) which is significant in locations where relatively modest rainfalls cause floods. The argument also fails to consider the differences in soil moisture beneath vegetative covers. At Moutere where evapotranspiration normally exceeds rainfall from November to March, a soil moisture deficit builds up beneath each cover type. However, as the pasture has an effective rooting depth of 300 mm and the trees exploit water from at least a depth of 2300 mm, a substantial difference in soil moisture can build up. From 1974 to 1978/9, when the trees were having an increasing effect on reducing water yields, the soil moisture levels in the two pine catchments became substantially less than in the pasture catchment (Fig. 6B). The change in the pattern from 1981 is attributed to thinning the pines in February and March of that year. The moisture under the pasture may have been low then because of the

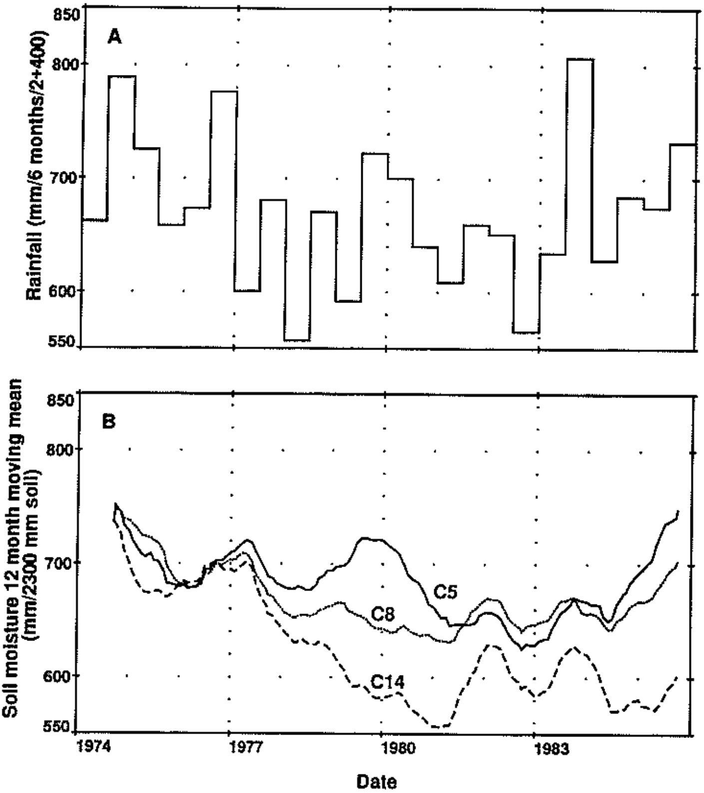

FIG. 6 — Relationship between 6-month moving average of rainfall (A) and 12-month moving mean of soil moisture depth (mm) in the top 2300 mm of soil from C5 (pasture) and C8 and 14 (pines)(B).

persistently lower than average rainfall in 1981 and 1982 (Fig. 6A, Table 1). Once higher than average annual rainfalls occurred, the soil moisture under pasture increased towards levels monitored at the start of the record. By this time the remaining trees are assumed to be exploiting the soil volumes formerly occupied by the thinned trees where the soil moisture levels remain lower than under pasture. The data imply that for most of their life soil moisture levels beneath mature trees will be substantially lower than under pasture. For 1979, 1980, 1984 and 1985 when the canopy was closed and the trees not affected by silvicultural operations, the soil moisture levels averaged 46 and 115 mm less in C8 and C14 respectively than in C5. The difference between the two forested catchments is attributed to aspect.

Hydrographs from a storm in June 1980 (Fig. 7) and water balances (Table 2) for the three catchments with neutron probe measurements illustrate how interception and soil moisture differences can effect extreme floods. This flood was the largest from the catchments with pine trees. The AEPs for the flood peaks are 0.088, 0.085, 0.194, 0.291, 0.042, and 0.096 for C2, C5, C8, C13, C14 and C15 respectively. The flood peaks for the pine catchments average 32% of those from the pasture catchments. A water balance (Table 2) is calculated for 9 June to 7 July, dates when neutron probe soil moisture measurements were made to a depth of 2300 mm in C5, C8, and C14. The rainfall causing the floods (Fig. 7) was 80% of the total for this period. Runoff from C8 and C14 came only, and for C5 primarily, from the flood-producing storm (Table 2): rainfall was measured in or adjacent to each catchment; throughfall was measured in C14, assumed to be the same proportion of rainfall for C8 and assumed to be zero for C5. The balance, assumed to be evapotranspiration, gives values of 0.43 mm/d for pasture and 0.75 and 1.07 mm /day for pines. The evapotranspiration rates are similar to winter rates of 0.8 mm/d reported by Whitehead and Kelliher (1991) for central North Island pines and 0.6 mm/d reported by McAneney et al. (1982) for pasture at Hamilton. As water for evapotranspiration comes from the soil, the evapotranspiration totals can be added to the measured soil moisture differences to give total soil moisture flux during the period. Of the 75.5 mm runoff reduction in runoff between the pasture and the mean of the pines catchments, 6 mm (8%) is attributed to rainfall differences, 24.5 mm (32%) is intercepted and evaporated by the pines, and 45 mm (60%) enters the soil under the pines.

The average soil moisture difference between pine and pasture catchments (Fig. 6B) is of the same order as the 0.02 AEP-24 hour rainfall at Moutere of 153 mm, and the mean peak discharges for 0.02 AEP floods from pine and pasture catchments of 51 mm and 104 mm per day respectively. While the relationship of infiltration rates and rainfall intensities as well as the nature of the flood source areas are important determinants of flood peak magnitudes

TABLE 2 - Catchment water balances for 9 June - 7 July 1980 (mm)

Catchment	C5	C8	C14	Mean C8, C14	Difference C5-Mean
Rainfall	125	134	104	119.0	6.0
Less					
Interception	0	28	21	24.5	-24.5
Runoff	101	38	13	25.5	75.5
Soil Moist. Change	12	47	40	43.5	-31.5
Equals					
Evapotranspiration	12	21	30	25.5	-13.5
Soil Moist. Change + Et.	24	68	70	69.0	-45.0

from small catchments, the relative size of the soil moisture deficits of soils under different vegetation types, as well as interception differences, offer explanations for the differences in size of floods of a wide range of exceedance probabilities.

Changes in Low Flows

The impervious Moutere Gravels, with their low water storage characteristics, and the summer soil moisture deficit, have low runoff rates during base flow periods. The streams are ephemeral, with the pasture catchments C2 and C5 averaging 71 days per year without flow (1964-85, range 0-180 days). The catchments with gorse cover (C8, C13) (1964-69) averaged 158 days per year of zero flow compared to 52 days per year from pasture (C2, C5) (Fig. 8). When the trees were young their catchments flowed a little longer than the pasture catchments. As canopy closure approached, the pine catchments had more zero flow days than the pasture catchments. During canopy closure (1978-85) the pine catchments had 64 more zero flow days than the pasture catchments (93 zero flow days). After the trees were felled the pine catchments flowed more often than the pasture catchments. These findings are consistent with the depletion of soil moisture beneath the pine trees.

Flow duration curves (Fig. 9) show the relative flow rates from semi-mature (closed canopy) pines and pasture from 1978 to 1985. For much of the time the flow from pine catchments is about 25% of that from pasture catchments. This supports Duncan (1980) who showed, using low flow distributions from C8 and C14, that pines reduced specific discharges by more than 50% over most of the low flow range.

Changes in Seasonal Runoff

Seasonal changes in runoff can be important, especially in summer and autumn when demand, particularly for irrigation water, is high, and water yields are naturally low. Figure 10 shows the seasonal changes, both in percentage terms and as millimetres of runoff, using 3-month seasons with summer starting in December. Clearly, in most seasons, mature pine catchments have between 50 and 90% less runoff than pasture catchments. However, there are wide fluctuations in the water yield difference between seasons. Most winters and some springs show large differences in runoff between catchments with different cover types, while summers and autumns show small differences. The season's runoff difference reflects the total runoff normally occurring during a season, eg. the higher flows typical of winter give the opportunity for a high reduction in runoff.

Water Balance

Neutron probe soil moisture data from C5 and C14 and interception data from C14 and the impervious nature of the catchments allow the calculation

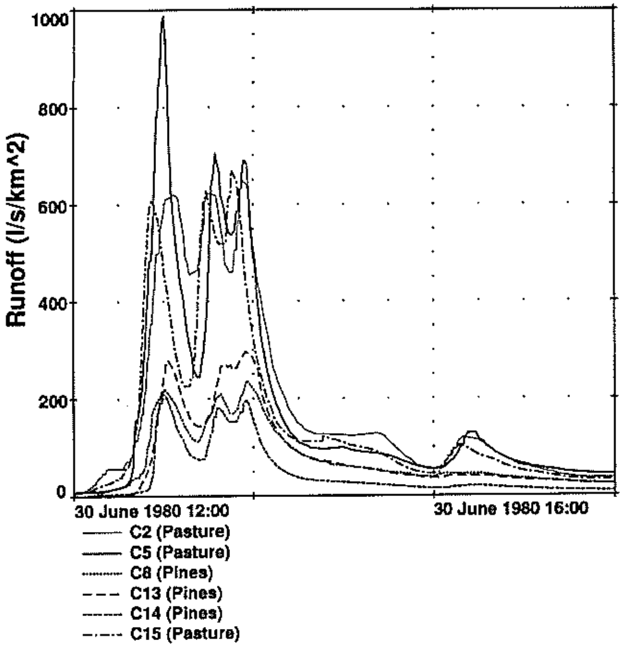

FIG. 7— Hydrographs from pine and pasture catchments for the flood of 30 June 1980.

TABLE 3 - Annual water balance at Moutere (1975 - 1985) for a pasture catchment (C5) and a pine catchment (C 14).

Year	Rainfall (mm)	CS RO (mm) (mm)	C14 Ro (mm) (mm)	CS SM change	C14 SM change	C14 Inter. (mm)	C14 Et. (mm)	CS Et. (mm)	C14Evap'n (mm)
1975	1167	274	92	-91	5	130	940	984	1070
1976	1300	302	135	147	147	307	7]1	851	101
1977	963	178	35	-97	-148	177	899	882	1076
1978	855	143	18	-8	-38	236	639	720	875
1979	1028	184	11	74	-10	284	743	770	1027
1980	1082	280	20	-92	-57	491	628	894	1119
1981	938	193	20	-4	123	134	661	749	795
1982	834	160	28	-70	- 108	183	731	744	914
1983	1284	406	108	70	108	179	889	808	1068
1984	1027	202	30	29	- 104	273	828	796	1101
1985	1214	339	47	85	78	259	831	790	1089
Totals	11692	2661	544			2652.7	8499.3	8988	11152
% of rainfall		22.8	4.7			22.7	72.7	76.9	95.4

of evapotranspiration losses without some of the assumptions often made in water balance studies. Soil moisture data (0-2300 mm depth) show that the assumption of little change from year to year, even after the end of winter when the soil moisture store is often assumed to be filled, is rarely true (Fig. 6B).

Over the eleven year period for which data are available (Table 3, Fig.11A, B) the trees were close to providing a full canopy cover. Runoff from the pasture catchment (C5) was 22% of rainfall and from the pine catchment (C14) 4.6% of rainfall. Since pines and pasture had similar transpiration rates of 72.7% and 76.9% of rainfall respectively averaged over the 11 years, the lower runoff rate from pine catchments occurs primarily because of interception, which averaged 22.7% of rainfall over the period. Because of the impervious underlying catchment, losses to deep ground water were assumed to be negligible.

Transpiration losses from pasture average 817 mm/y and were more consistent than those from the pines, which averaged 773 mm/y. This was primarily because annual interception varied widely; when there were large interception losses, transpiration was restricted. Interception tended to increase as the trees got older, but this trend was interrupted by pruning in 1977 and thinning in 1981. One curious result is that for some years evaporative losses (evapotranspiration plus interception) in C14 exceeded annual rainfall. In these years total soil moisture was less at the end of the year than at the start.

Calculated interception in seven year old pines in Otago (Fahey and Watson, 1991) was 31% of the annual rainfall of 1222 mm. At the same age, pine trees at Moutere intercepted only 18% of rainfall but the pines had been thinned that year from 1500 to 500 trees/ha. The following year interception had increased to 28% of rainfall, similar to the Otago pines. In contrast, the transpiration rates in Otago for tussock and 7 year pines are much less at 273 and 275 mm/y than the average at Moutere of 817 and 773 mm/y for pasture and pines respectively.

Interception and Stemflow

Replacement of pasture by pines alters both interception and transpiration. Evaporation is controlled primarily by the bulk surface resistance and aerodynamic resistance (Monteith and Unsworth, 1990). Bulk surface resistance is a measure of the ease at which water vapour moves to a leaf surface from within a plant. When leaf surfaces are dry, pines have about 3 times the bulk resistance of pasture, and they normally transpire less than pasture, providing they have equal access to soil moisture. Aerodynamic resistance is a measure of the ease with which water vapour moves from the leaf surface to the atmosphere (Fahey and Rowe, 1992). It is inversely

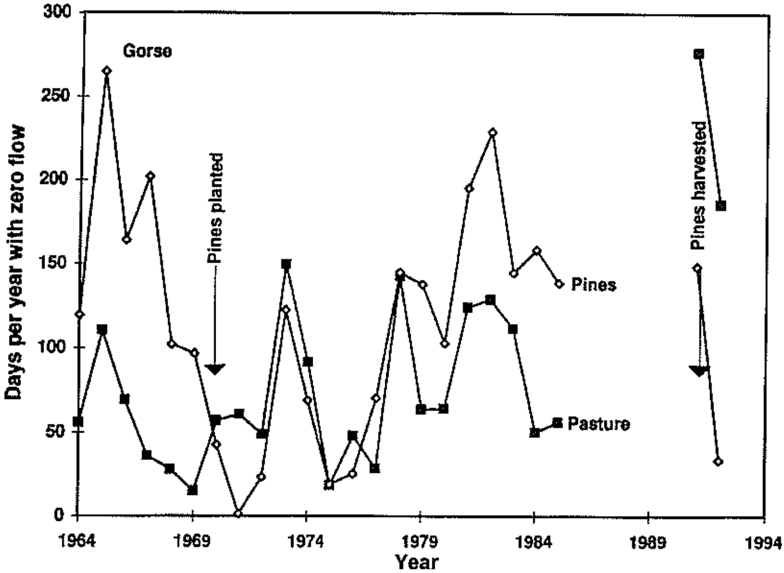

FIG. 8 — Days per year with zero flow in pasture and gorse/pine catchments.

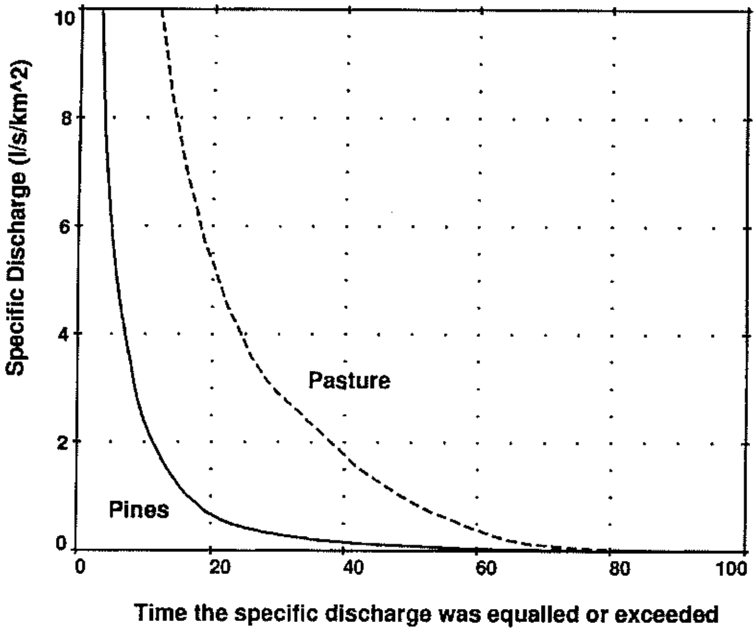

FIG. 9 — Flow duration curves for 1978-85 from mature pine and pasture catchments.

proportional to vegetation height and wind speed. Thus intercepted water is more easily removed from pine forest than pasture. It is this increased removal of intercepted water from tall vegetation that appears to be responsible for the reduced flows in pine catchments compared to pasture catchments.

The results of the interception study in C14 indicate the magnitude of the interception losses. Figure 12 shows throughfall and stem flow plotted as a percentage of rainfall by 3-month season, with summer beginning in December. Interception averaged 22% of rainfall during the study period. There is an obvious seasonality with interception being 24%, 27%, 20%, and 18% of rainfall for autumn, winter, spring and summer respectively.

Seasonal effects are more obvious after thinning, and interception was greater and more consistent when the foliage density was greater in 1978-80 and after 1984. During the post-thinning phases (winter 1975 to autumn 1978 and autumn 1981 to summer 1983) interception was 17% and 14% of rainfall, while in the post-thinning time of winter 1978 to summer 1981, and after summer 1983, interception was 28% and 26% respectively of rainfall. The amount of interception is within the range of 18 to 49% for interception measurements from mature *Pinus radiata* in New Zealand and Australia. (Fahey, 1964; Smith, 1974; Feller, 1981; Crockford and Richardson, 1990a; Kelliher et al., 1992).

Stemflow was not measured from summer 1978 to autumn 1980. The amount of stemflow has been low and a function of tree stocking density and age. It averaged 5.5%, 3.1% and 0.9% of rainfall when stocking density was 1500, 600 and 300 trees/ha respectively. These stemflows are within the range of 1% to 11.2% of stem flow for *Pinus radiata* reported by Crockford and Richardson (1990b) (11.2%, 1700 trees/hectare) Langford and O'Shaughnessy (1978) (11.00%, 1500 trees/ha), Feller (1981) (1%, 670 trees/ha) and Smith (1974) (3%, 98 trees/ha).

The difference between the stemflow proportion of rainfall reported here of 5.5% and the 11.2% and 11.0% for tree densities of 1500 trees/ha found by Crockford and Richardson (1990b) and Langford and O'Shaughnessy (1978) is attributed to differences in age and hence size of trees. The trees in this study were 4-5 years old, while in the Australian studies they were about 17 years old.

The Effects of Forest Harvesting on Water Yield

The experimental area was sold in June 1991, and the new owner immediately proceeded to harvest the forests, thus denying hydrologists the opportunity to monitor the runoff before harvest to establish whether or not runoff relationships had altered since monitoring ceased 5 years earlier. C5, C8, C13 and C14 were monitored from shortly before harvesting (July 1991) until nearly two years after harvest (June 1993). To maximise the use of this data, annual yields for July to June water years are used in the following section. Because of the limits of the plotting programme, June 1991 to July 1992 data are plotted as 1991 data (and so on) in Figures 2,3 and 4.

The Effects of Forest Harvesting on Annual Yield

For C14 and C8 respectively, in the year (July 1991 to June 1992) including harvest, runoff was in the range of data that had been measured for a full forest canopy in those catchments (Figs. 2 and 3). In C13 (Fig.4) runoff was a little more than might have been expected from mature forest. However runoff in all catchments was more (departure less) than might have been expected had the forest been growing for the entire year. In the second year after harvest runoff departures for C8 and C13 were similar to those measured when the land was prepared for planting, and when the trees were very young. C14 had more runoff than would have been predicted had it been in pasture. The positive departures for C8 and C13 are larger than for C14 because they are compared with flows from gorse, whereas the departures from C14 are in relation to pasture catchments which have a greater yield than gorse. Contrary to expectations (Waugh, 1980; Herald, 1979; Duncan, 1980; Rowe and Fahey, 1991; Pearce et al., 1980b ; Pearce et al., 1982) the increase in

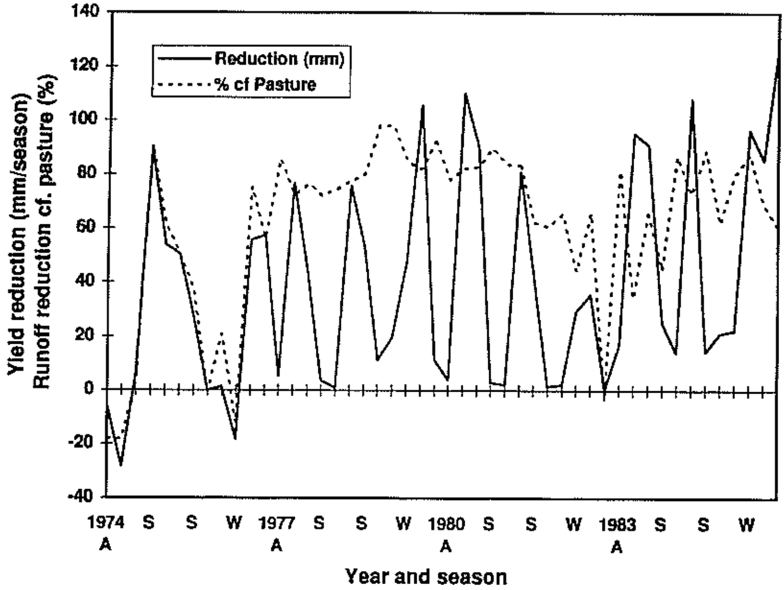

FIG. 10 — Seasonal water yield differences between pine and pasture catchments as runoff and percent reduction. "A", "S", "S", and "W" on the X axis refer to autumn, spring, summer and winter.

runoff in the second year was greater than in the first. The response was delayed because the normally low soil moisture levels under the trees were exacerbated by low rainfalls in the previous six months. The January to June rainfall at Appleby, 7 km north of Moutere, was 282 mm compared to the 1932-93 mean for the period of 475 mm. It was not until rainfall had increased soil moisture levels that the former pine catchments were able to respond in the expected manner.

The water yield departures for C8 were less after harvesting than after gorse clearance. There are three likely explanations. Firstly, the line dozing gorse clearance bared the subsoil from ridge top to gully and was more conducive to producing surface runoff than the slash- and needle-covered catchment left after forest harvesting. Secondly, the line dozing suppressed grass and gorse growth until the end of 1971, whereas there was vigorous growth of weeds in C8 following harvest. Both factors give rise to more evapotranspiration and less runoff after forest harvesting. Thirdly, C8 is also very responsive to rainfall once sufficient rain has fallen to saturate the soil. The different water yield responses to the two episodes of vegetation clearance may have been due to subtle differences in rainfall intensity, and to soil moisture.

C8 was harvested by skidder and C14 by hauler, so it is tempting to attribute the larger increase in runoff from C8 compared to C14 to more severe soil compaction and disturbance caused by skidder logging in C8. However C8 has a shaded south-east aspect and normally has more runoff than the north-facing C13 and C14 when they have had similar vegetation (Table 1, 1976 - 1986). Thus the effects of harvesting methods on runoff rates cannot be easily separated from the effect of aspect.

The Effects of Forest Harvesting on Monthly Water Yield

Until November 1991 there was more runoff from the pasture (C5) than the former pine catchments (Fig. 13). From November 1991 till April 1993, except for October 1992 when the relative difference was small, there was more monthly runoff from the former pine catchments. For May and June 1993 runoff from the pasture catchment was greater than for the former pine catchments. In the first period, while the trees were standing or only recently felled, the soil moisture levels in the former pine catchments were lower than in C5 (Fig. 14) so they were less responsive to rainfall. From about November the soil moisture in the former pine catchments was replenished, and as the replanted trees used little soil moisture, and weeds had not become established, most of the rain ran off. In contrast, the pasture in C5 was transpiring as much as soil moisture will allow and had little runoff. In March to June 1992 only 172 mm of rain fell (average is 357 mm), so there was little runoff from any of the catchments. From August 1992, when weeds had become established in the former pine catchments, runoff from all catchments is similar. In May and June 1993, when the trees and weeds on the former pine catchments continued to grow and the pasture in C5 was short, there was more runoff from the pasture catchment.

The Effects of Forest Harvesting on Soil Moisture

Three of the catchments (C5, C8, C14) had 3 neutron probe soil moisture access tubes each to at least 900 mm below the soil surface. Because there

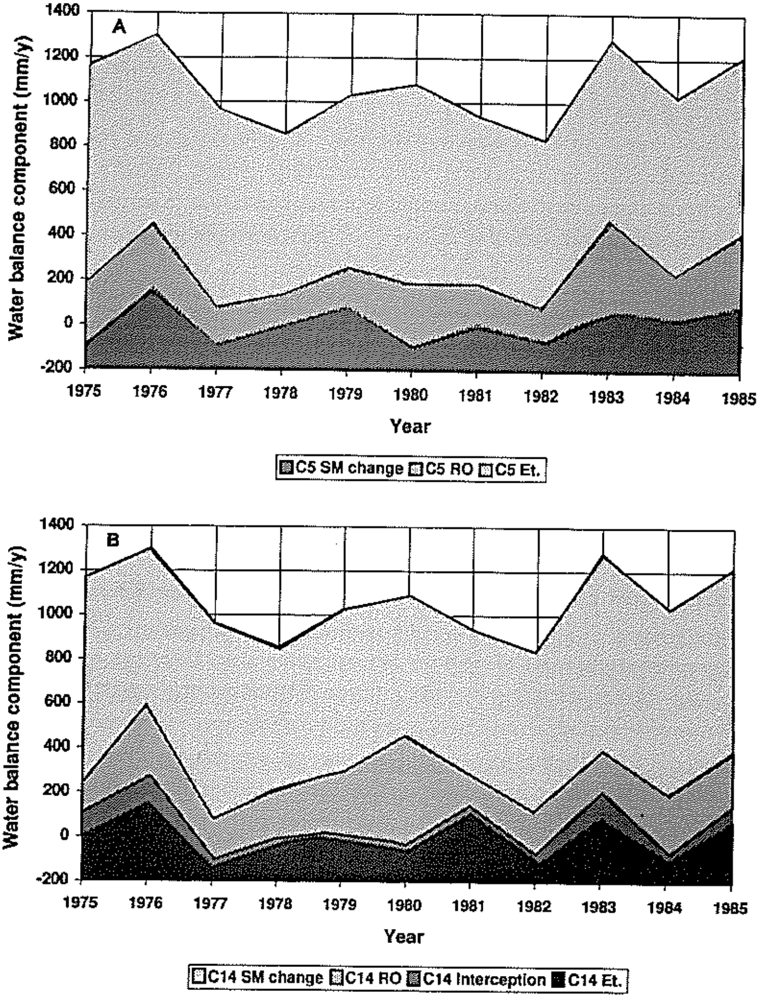

FIG. 11 — Annual water balance components for a pasture (C5) (A) and a pine (C14) (B) catchment.

are so few access tubes per catchment, the mean of the soil moisture readings per catchment may not give an accurate assessment of the amount of soil moisture in a catchment, but the relative changes will be indicative of the change in the catchment.

Before and shortly after the trees were felled there was less soil moisture in the pines catchments (Fig. 14). During October 1991 to January 1992, C8 and C14 soil moisture levels remained high and static, in contrast to the declining levels in C5. From October 1991 for the rest of the period, soil moisture levels were higher in the pine's catchments, compared to the levels in C5, than they were prior to felling. From December 1991 to July 1992 the soil moisture in C5 was less, relative to the pines, than from August 1992 to June 1993.

The times of lesser, greater, or near-equal soil moisture in C8 and C14 compared to C5 are coincident with times of lesser, greater, or near-equal runoff in the former pine compared to the pasture (C5) catchments (Fig. 13).

The Effects of Forest Harvesting on Evapotranspiration

Monthly evapotranspiration (Fig. 15) for C5, C8, and C14 during the post-harvest period was calculated as monthly rainfall, less runoff and change in soil moisture storage.

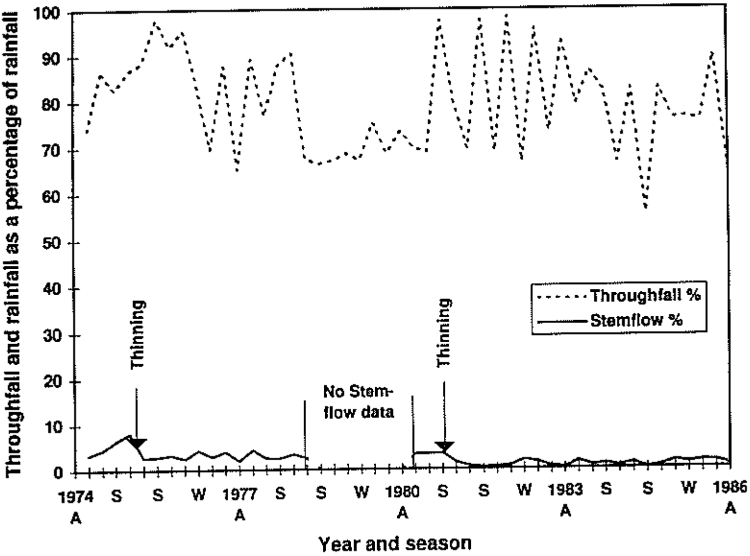

FIG. 12 — Seasonal throughfall and stemflow in C14 as a percentage of rainfall. "A", "S", "S", and "W" on the X axis refer to autumn, spring, summer and winter.

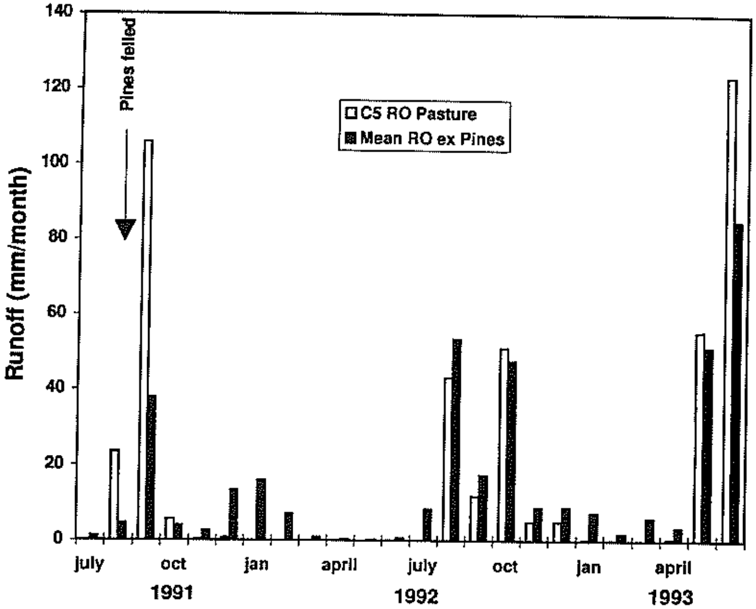

FIG. 13 — Monthly runoff from a pasture catchment and the mean of three treated catchments after harvesting the pine trees.

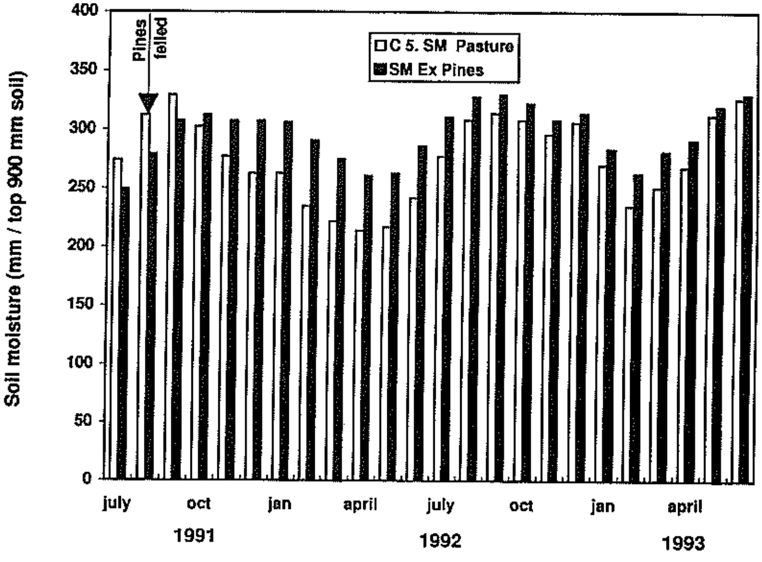

FIG. 14— Monthly soil moisture from a pasture catchment and the mean of two treated catchments after harvesting the pine trees.

In July-September 1991, when the trees were still standing, transpiration was higher in the pines than in the pasture catchment, except in July, when low soil moisture levels limited transpiration. Once the pines were felled there was an immediate drop in evapotranspiration relative to that from pasture. This persisted through to February 1992. From March to June 1992, when all soil moisture levels were low, evapotranspiration was also low and similar from all three catchments. From July to December 1992, when soil moisture levels were higher, there is no clear pattern of greater evapotranspiration of one cover over another. In January to April 1993, at a time of decreasing and/or low soil moisture levels, the pasture had greater evapotranspiration. This perhaps indicates continued growth of the pasture, extracting soil moisture from deeper in the profile; shallower rooting weeds by this time of year would be setting seed and growing less vigorously than in the spring. The relatively low evapotranspiration in C5 in May and June may be a response to close grazing of the pasture, while the weeds would be able to grow and respond to increased soil moisture levels.

Summary and Conclusions

Burning and clearing gorse in preparation for tree planting had a large and immediate effect on water yield, which increased an average over three years of 212 mm per year in one case and 358 mm per year in another. Increases in water yields persisted for four years, after which they were similar to or slightly less than would have been expected from gorse in one case and 50-158 mm per year less than gorse in the other. In the pasture catchment planted in pines, yields were reduced in the third year after planting, and by the seventh year were 133 mm less than from pasture and averaged 167 mm per year less for the remaining monitored period. Thinning, especially the reduction from 600 to 300 trees per hectare, appears to have increased water yield slightly, but analysis was confounded by a persistent drought coincident with thinning.

Forest harvesting did not immediately increase water yield. The increase occurred in the second year after harvest, when the former gorse catchments had 220-280 mm more runoff than would be expected from gorse and the former pasture catchment had 80 mm more runoff than would be expected from pasture. Monthly runoff and soil moisture measurements indicated that the soil moisture deficit build up underneath the trees had to be replenished before more runoff occurred from the catchments where the trees were harvested, than from the pasture catchment. This took from July 1991, when harvesting started, to November 1991. From November to June there is normally little runoff from any catchment, despite its cover, because of the seasonal soil summer/autumn moisture deficit, hence the lack of obvious runoff response in the first year after harvest.

The impact of the mature pines on flood flows has been similar to the effect of the gorse in reducing freshes about 80% compared with those from pasture catchments. An unexpected result is the relative size of extreme flows (e.g. AEP 0.02), which are 50% less from the pine/gorse catchments. This is attributed to the difference in rooting depths of pine/gorse and pasture which results in the pine/gorse cover, with greater rooting depths, exploiting soil moisture to a greater depth than pasture, and keeping deep soil moisture persistently lower than under pasture. Interception by pines during storm rainfalls is also a factor.

Low flows in these ephemeral-drainage catchments are 50-80% lower from mature pines than from pasture. Pine catchments have on average 64 more days per year without flow than pasture catchments.

Seasonal water yields from the mature pine catchments are consistently 50-80% less than from pasture. However the difference in yield fluctuates markedly from season to season, with winter and spring showing large yield changes and summer and autumn showing low yield changes.

The differences in water yield between the pines and pasture catchments are attributed primarily to interception by the pines, and secondarily to the greater soil moisture storage potential under pines. In large pines with near full canopy cover interception has been measured at 30% of annual rainfall. Thinning has reduced interception in the remaining standing pines to 20% of

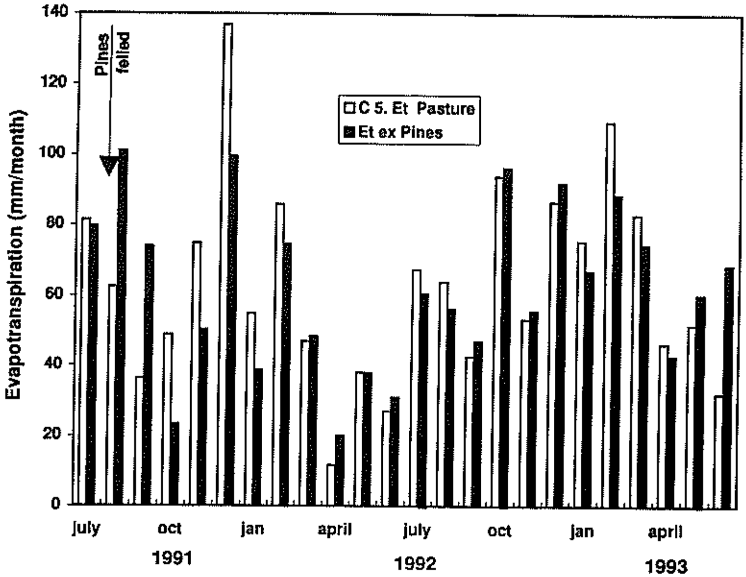

FIG. 15 — Monthly evapotranspiration from a pasture catchment and the mean of two treated catchments after harvesting the pine trees.

annual rainfall. Paradoxically the persistently lower soil moisture under pines may lead to increased transpiration from pines, because it allows precipitation to be stored for later transpiration, rather than to run off immediately.

New Zealand has a long history of land-use change which began with the fires of the moa hunters. Change continues with conversions from pasture, tussock and scrub to exotic plantations. The hydrological responses reported here have implications for a wide range of land and water users. Through the effects on ground water recharge, land-use changes can affect downstream uses. Resource managers in particular need to be aware of the effects of land-use change on water yields if they are to make meaningful decisions on the allocation of water resources in water-short areas.

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