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WATER USE BY MANAGED STANDS OF *PINUS RADIATA*, INDIGENOUS PODOCARP/HARDWOOD FOREST, AND IMPROVED PASTURE IN THE CENTRAL NORTH ISLAND OF NEW ZEALAND

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ABSTRACT

Streamflow data from a catchment study located in the central North Island of New Zealand were analysed to determine the effect of land-use and forest management on water yield. Land-uses compared included pasture, pasture converted to *Pinus radiata* D. Don, and evergreen indigenous forest. The catchments ranged in area from 6 to 37 ha. Rainfall and streamflow were monitored from 1969 to 2000. Leaf area index of three pine stands with different silvicultural management regimes was measured from 1975 to 1985.

Annual flows from pine catchments were lower than from pasture, with an average maximum difference of approximately 400 mm after canopy closure. Thinning of the pine stands reduced the difference and harvesting reversed this trend, with the flow from pine catchments exceeding flows from pasture for the 3 years after harvesting of the pines. Annual flows varied over time, depending on tree age, the silvicultural regime, and variations in annual rainfall (approximately 1200–2100 mm/year).

Evapotranspiration and interception losses increased linearly with the increase in canopy leaf area index of the pine stands, but transpiration was not significantly related to leaf area index or rainfall. Annual variation in rainfall accounted for approximately 60% of the variation in flow across all land-uses. A simple model incorporating pine leaf area index in addition to rainfall accounted for 91% of the variation in streamflow in pasture and pasture/pine catchments.

Water yield averaged approximately 160–260 mm/year, less from pine than pasture, depending on the silvicultural regime. Water yield from the pine forest averaged around 100 mm/year less than from indigenous forest.

Keywords: streamflow; evapotranspiration; leaf area index; land-use change; models; water yield; interception.

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INTRODUCTION

Water yield has been examined in a number of small- and large-scale catchment studies installed in New Zealand in the late 1960s and 1970s to determine the effects of land-use and management (Dons 1986, 1987; Pearce & Rowe 1979; Pearce *et al*. 1982; Fahey *et al*. 1997). Results from these studies generally support the findings in the many reports on this topic, that afforestation or reforestation of grassland substantially reduces water yield, and deforestation increases water yield (Hornbeck *et al*. 1997; Lesch & Scott 1997; Cornish 1989; Smith 1987). The impact of afforestation with intensively managed pine plantations on water yield depends on factors including stand age, silvicultural management, and harvesting, which influence canopy cover measurements such as leaf area index (LAI) (Bosch & Hewlett 1982; Baker 1986; Whitehead & Kelliher 1991; Sahin & Hall 1996; Duncan 1995).

Parameters relevant for making water balance calculations — including rainfall, streamflow, and groundwater loss — are normally recorded in catchment studies, and the effects of land-use and management are determined using a paired catchment approach. Canopy leaf area index is known to influence interception of precipitation, and leaf area index has been used to predict the effects of thinning *Pinus radiata* stands on water yield from catchments using a process-based model (Whitehead & Kelliher 1991). Because it is difficult to measure, leaf area index data over a full rotation of pine forest are non-existent, and consequently the role of leaf area index on water yield has not been well documented in catchment studies. In addition, existing process-based models for use by water-resource managers are considered by some to be too complex (Swanson 1998), and so simple methods and models to integrate the effects of site, climate, and forest management practices on a geographical basis are required.

In this study we analysed the influence of land-use and land-use change (afforestation of pasture) on annual water yield. Land-uses compared included evergreen indigenous podocarp/hardwood forest, improved pasture, and intensively managed *P. radiata*. The effects of variation in pine leaf area index, silvicultural management, and forest harvesting on water yield from adjacent sub-catchments are shown as simple functions of rainfall and leaf area index, which can be incorporated into leaf-area-based stand growth models.

MATERIALS AND METHODS

The research was undertaken at the Purukohukohu Experimental Basin, which is one of several sites covering the range in hydrological variation in New Zealand that have been set up to provide catchment data. The general background and research objectives of the experimental basins programme have been described previously by Beets & Brownlie (1987).

Purukohukohu Experimental Basin

The Purukohukohu Experimental Basin is located in the Paeroa Range in the central North Island of New Zealand, approximately 30 km south of Rotorua (Fig. 1). The basin incorporates three land-uses: unlogged indigenous forest (Puruorakau and Puruwai catchments), improved pasture (Purutakaiti and Purutaka catchments), and pine plantation (Puruki catchment). The species-rich podocarp/tawa forest in the indigenous catchments has a three-tiered structure of variable canopy density (Beets & Brownlie 1987) with a history of browsing by possums (*Trichosurus vulpecula* Kerr) and deer (*Cervus* spp.). The original indigenous vegetation in the Purutakaiti, Purutaka, and Puruki catchments was cleared and converted to pasture in the 1920s, and developed into improved pasture in 1957. Subsequent farm management included grazing of both sheep and cattle, with regular topdressing. Puruki catchment was planted in pine in 1973. A detailed description of the

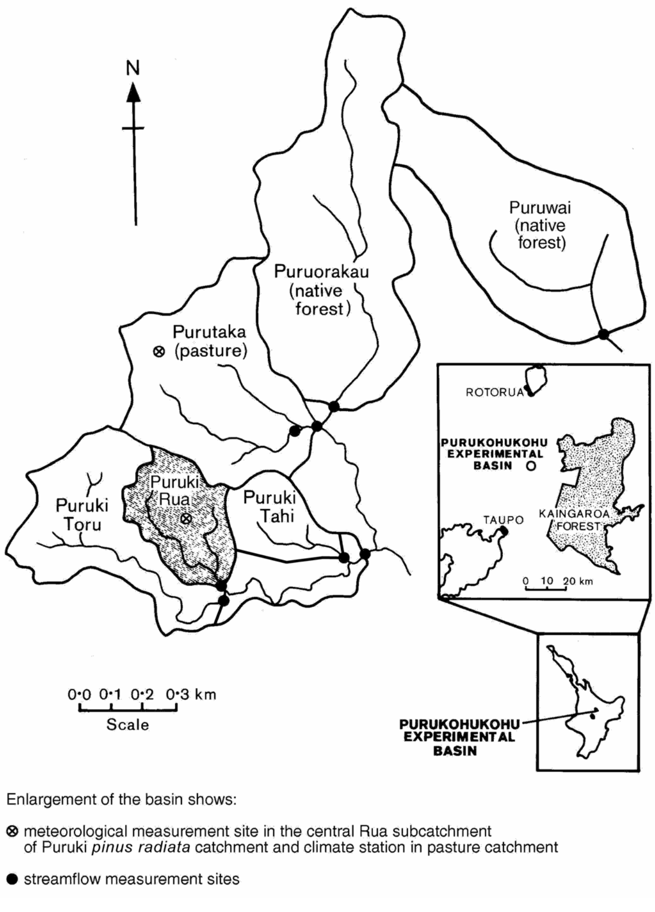

FIG. 1–Location of Purukohukohu Experimental Basin and Landuse Catchments. Purutakaiti pasture subcatchment (not shown) is a tributary within Purutaka.

vegetation, soil, climate, and the history of the pine stand management has been given by Beets & Brownlie (1987). The main soil parent material originated from the Taupo volcanic centre (1860 ± 100 BP), but older ash showers from Taupo and Okataina volcanic centres have a significant presence. Soils are classified as Pumice Soil in the New Zealand Soil Classification System (Hewitt 1998); they belong to the Oruanui series, and are highly permeable, consisting of loamy sand, silty sand, and gravel (Taupo lapilli). Elevation ranges from 500 to 700 m a.s.l., and topography ranges from gently rolling land (slopes under 12°) to moderately steep (slopes up to 23°) to steep (slopes up to 30°). Topography has had a major influence on erosion and hence the thickness of the pumice layers (Rijkse & Bell 1974). Rainfall averages 1500 mm/year, and average annual temperature varies between 9° and 11°C, with monthly averages ranging between 5° and 15°C. It was calculated that there was sufficient soil moisture available to meet evapotranspiration (ET) demands through the severest drought on record for similar soils in the central North Island (Will & Stone 1967).

Silvicultural Management

Puruki catchment was converted from improved pasture to *P. radiata* in 1973 when the stand was established at an initial stocking of 2200 trees/ha, and fenced to exclude grazing animals. Puruki is subdivided into three subcatchments (Tahi, Rua, Toru) plus an adjoining area to the south-east (Fig. 1).

The Puruki subcatchments were all pruned and were thinned to different stockings to give a wide range in pine canopy leaf area index over time, following the silvicultural management regime described by Beets & Brownlie (1987) and summarised here in Table 1. Early invasions of thistles (*Cirsium vulgare* (Savi) Ten.), ragwort (*Senecio jacobaea* L.), and flatweeds were replaced by pasture grasses by 1975 when the pines were well established (Beets & Brownlie 1987). Ground vegetation was largely suppressed by the pines by 1979, but thinning resulted in vigorous regrowth of bracken (*Pteridium esculentum* (Forst. f.) Kuhn.), particularly in the heavily thinned Tahi subcatchment. Harvesting occurred during

TABLE 1–Silvicultural operations (month/year completed) in Puruki subcatchments, which were planted with *P. radiata* in 1973 at 2200 trees/ha.

Catchment	Date pruned to 2.2 m height	First thinning		Second thinning		Third thinning	
		Date	Trees /ha	Date	Trees /ha	Date	Trees /ha
Puruki-Tahi*	3/1979	5/1979	500	8/1983	160	10/1987	60
Puruki-Rua	4/1980	4/1980	550	–		–	
Puruki-Toru	4/1981	11/1981	550	9/1984	290	10/1988	180

* Adjoining area in Puruki catchment managed as for Tahi

January–July 1997 and replanting with *Pinus radiata* was undertaken in September and October of 1997. Puruki was largely weed-free after harvesting, but weed growth, including grasses, ferns, and shrub hardwoods was prolific within 2 years of harvesting, except on extraction tracks and skid sites.

Rainfall and Streamflow Measurement

Rainfall was measured with an automatic tipping bucket gauge with a 6-minute recorder, located 0.6 m above ground-level in Purutaka pasture catchment (Dons 1987), and with an automatic tipping bucket gauge located above the pine canopy in Puruki catchment (Brownlie & Kelliher 1989). Rainfall data primarily from the Purutaka gauge (with its longer record) were used in this analysis, supplemented by data from the Puruki gauge where necessary.

All catchments (including the three subcatchments of Puruki) were instrumented in the late 1960s and early 1970s using H flumes following the detailed description given by Dons (1987). H flume water level to flow conversions were developed for each flow station and periodically checked by gauging flows. Water level was recorded to within ±3 mm at 15-minute intervals by a Fisher and Porter digital recorder (Dons 1987). The flow data were converted to annual flows (litres), based on a water-yield year running from 1 January to 31 December. During the monitoring period 1969–2000, only Puruki and Purutaka catchments were measured continuously — other catchments were measured periodically (Table 2).

Leaf Area Index of Pine Stands in Relation to Silvicultural Management and Water-yield Year

Leaf area index for Puruki subcatchments was reported by Beets & Pollock (1987) as part of a larger study of stand dry matter accumulation over time. Total leaf area on an all-surfaces basis was measured in June and July 1975–85, as described by Beets & Lane (1987), at the middle of each water-yield year. Leaf area index was strongly influenced by pruning and thinning operations, which usually extended over several months (Beets & Pollock 1987).

Throughfall and Stemflow Measurement

Interception was derived from measurement of precipitation, throughfall, and stemflow, the latter being measured in part of Rua subcatchment prior to and after the pruning and thinning operations conducted in 1980. Throughfall and stemflow measurements commenced on 13 December 1979, and thinning in this area occurred on 16 October 1980, a few months later than the rest of Rua, to provide sufficient pre-thinning data. Post-thinning measurements were completed on 1 April 1982. Throughfall was measured using 20 rainfall gauges, which were randomised weekly on a 10 × 10-point grid under the canopy. Stemflow was

TABLE 2–Catchment land-use, area (topographic and hydrologic), and duration of monitoring in the Purukohukohu Experimental Basin. A land-use change from pasture to pine occurred within Puruki during July 1973.

Catchment	Land cover	Area			Monitoring date		Duration (years)
		Topographic (ha)	Hydrologic (ha)	Change (%)	Start	Finish	
Puruki	Pasture /pine	34.4*	31.4	–8.7	1969	2000	32
Puruki-Tahi	Pasture /pine	5.9	5.0	–15.2	1973	1993	21
Puruki-Rua	Pasture /pine	8.7	8.7	0	1971	1993	23
Puruki-Toru	Pasture /pine	13.8	11.0	–20.3	1972	1994	23
Purutaka	Pasture	22.5	9.2	–59.1	1969	2000	32
Purutakaiti	Pasture	11.3	9.1	–19.5	1986	1991	6
Puruorakau	Indigenous forest	37.2	20.0	–46.2	1969	1986	18
Puruwai	Indigenous forest	28.0	20.0	–28.6	1973	1993	21†

* Puruki weir measures flow from Tahi, Rua, Toru, and the adjoining 6 ha to the south-east.
† Not continuous

measured using collars placed around 16 trees, and this reduced to seven trees after the thinning operation. The throughfall and stemflow measurements were divided into three periods related to changes in leaf area index with canopy biomass due to thinning (Beets & Pollock 1987, Table 7):

(1) A leaf area index of 16.8 was applied to the period prior to thinning from 13 December 1979 to 16 October 1980.

(2) Post-thinning, a leaf area index of 5.4 was applied to the period from 17 October 1980 to 23 December 1980.

(3) A leaf area index of 9.0 was applied to the period from 24 December 1980 to 1 April 1982, to allow for tree growth during the year.

Canopy interception was predicted as a function of leaf area index and rainfall, using the GLM procedure in SAS (SAS Institute Inc., Cary, NC, USA, www.sas.com).

Calculations and Statistical Analysis

All flow information given in this paper was based on annual flows after an allowance was made for groundwater losses. Leakage can be large in these catchments, as discussed in detail by Dons (1987). Groundwater loss from individual catchments was allowed for by reducing the topographic area to the hydrologic area. To determine the hydrologic area of a catchment, it was assumed that Puruki Rua was watertight and that annual streamflows from Puruki Rua were identical to flows from other catchments concurrently under the same land-use (Table 2). The years selected for cross-catchment calibrations were; Purutaka 1971–73, Toru 1972–73, Tahi 1973, Puruki 1971–73. Takaiti was calibrated using Taka flows from 1971 to 1973. Dons (1987) assumed that Puruki catchment as a whole was watertight, but this does not seem to be so (Table 2). Although groundwater can be lost or gained by flows occurring across topographic boundaries (Dons 1987), hydrologic areas at Purukohukohu were all less than topographic areas (Table 2), which indicates that only losses occurred. Leakage is expected to be related to the amount and spatial variability of fractured rock within the catchment.

Puruki catchment was expected to be effective at showing hydrological changes due to land-use because it was monitored both prior to and after the change of land-use from pasture to pine. However, the effect of indigenous forest on water yield was not well documented at this site because no land-use change occurred during the period of this study, and therefore cross calibration of flows while catchments were under the same land-use was not possible. Furthermore, the leaf area index of the indigenous forest was not known but was derived using the model based on pine leaf area (*see* Results section) to give predicted flows that matched the actual flows from native forest. The leaf area index of indigenous forest was assumed to be stable over time. The hydrologic area of the indigenous catchments therefore remains uncertain.

The effects of land cover (pasture, pine, indigenous forest), annual rainfall, leaf area index, and year on annual flows were tested using the GLM procedure in SAS. For pine catchments, land cover was pasture up until 1972 and pine from 1973 onwards, with pine leaf area index assumed to be zero in 1973. The effect of pine afforestation on flow was tested using two pasture catchments (Purutaka, Purutakaiti) and three pine subcatchments (Tahi, Rua, Toru). Silvicultural effects were tested using the three pine subcatchments (Tahi, Rua, Toru). Land-use effects were tested using all the catchments (Purutaka, Purutakaiti, Puruki, Puruorakau, Puruwai).

Annual flow and rainfall data were used to calculate annual evapotranspiration (ET) in each catchment (where evapotranspiration = rainfall – streamflow), which assumes no change in soil water storage on an annual basis. Evapotranspiration was partitioned into its interception and transpiration components for the pine subcatchments, based on the rainfall, throughfall, and stemflow data measured weekly over a 2-year period in Rua subcatchment. Canopy interception (I) (where interception = rainfall – throughfall – stemflow) in Rua was fitted to the pre- and post-thinning leaf area index and rainfall data. The resulting function was applied to the Tahi, Rua, and Toru pine subcatchments to predict interception in years when leaf area index and rainfall data were available, and annual transpiration (T) was derived by difference (transpiration = evapotranspiration – predicted interception).

RESULTS

Annual Water Balance

Average annual rainfall, streamflow, and evapotranspiration by catchment are summarised in Table 3. Puruki rainfall averaged 1579 mm over the 32-year period from 1969 to 2000 inclusive, with annual totals ranging between 1201 and 2115 mm (Fig. 2). Annual total rainfall data were available in all years except 1994. Long-term average annual water balance calculations were applicable to the catchment-specific monitoring periods specified in Table 2. Although the monitoring periods of the pine and pasture catchments did not overlap exactly with the indigenous catchments, these long-term data (Table 3) show that land-use apparently affected the water balance. For example, in Purutaka pasture catchment annual rainfall averaged 1579 mm, streamflow 772 mm (49% of rainfall), and evapotranspiration 807 mm (51% of rainfall). In contrast, streamflow averaged 32% of rainfall in the Rua and Toru pine subcatchments, while Puruki averaged slightly higher (38%) because the monitoring period included 3.5 years under pasture, prior to planting the pines. Streamflow from the indigenous forest catchments was about midway between pine subcatchment and pasture flows.

TABLE 3–Average annual water balance (mm) of land-use catchments* at Purukohukohu Experimental Basin for monitoring period specified in Table 2. Annual streamflow and evapotranspiration losses are also shown as a percentage of annual rainfall.

Catchment	Land-use	Rainfall	Streamflow	Evapotranspiration
Puruki	Pasture/pine	1579	598 (38%)	981 (62%)
Puruki Tahi	Pasture/pine	1543	518 (34%)	1026 (66%)
Puruki Rua	Pasture/pine	1554	503 (32%)	1050 (68%)
Puruki Toru	Pasture/pine	1542	500 (32%)	1042 (68%)
Purutaka	Pasture	1579	772 (49%)	807 (51%)
Purutakaiti	Pasture	1535	721 (47%)	814 (53%)
Puruorakau	Indigenous forest	1559	608 (39%)	951 (61%)
Puruwai	Indigenous forest	1545	596 (39%)	948 (61%)

* Based on catchment hydrologic areas

Afforestation with *Pinus radiata*

Annual streamflows from Puruki and Purutaka are summarised in Fig. 2. Streamflow from Puruki catchment was initially similar to that from the pasture catchment until the pines were established in 1973; then annual flow from the pine forest decreased

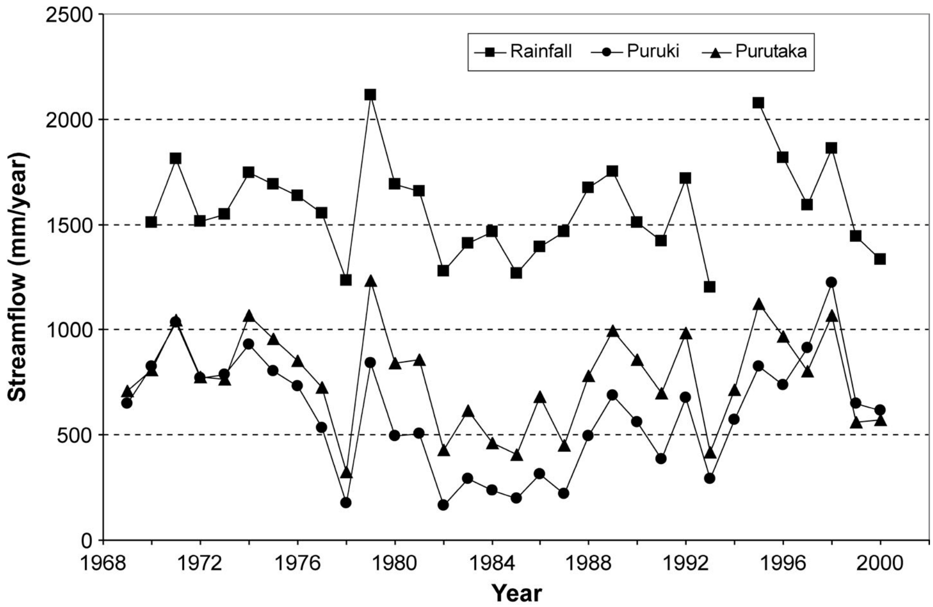

FIG. 2–Annual rainfall and streamflow for Puruki and Purutaka catchments. Puruki was converted from pasture to pine in 1973, and harvested and replanted in 1997. Purutaka was in pasture throughout this period.

to 100–400 mm less than that from pasture. This situation reversed after harvesting of the pines in 1997 when Puruki flows exceeded Purutaka for 3 years, but flows were again similar by 2000 when revegetation of Puruki had occurred.

Silviculture

Annual flows from the subcatchments within Puruki (Fig. 3) were similar before the pines were planted in 1973, but after that the flow from Tahi declined more than the flow from Rua and Toru until the first thinning operation in 1979. Streamflows were variable until 1983 when flow from Tahi increased after the second thinning. From 1984 to 1991 flows were in the order Tahi>Toru>Rua, which was inversely related to stocking. From 1991 streamflows from Toru and Tahi converged. Heavy understorey growth may have contributed to reduced water yield in Tahi.

Pine *versus* Indigenous Forest

Puruki (shown from planting date in 1973) initially had higher annual flows than the pine and indigenous forest catchments (Fig. 4), but this situation reversed when the pine stands were 5 years old. The flow from Puruki pine forest remained about 250 mm less than flows from indigenous forest until 1986 when monitoring of indigenous forest ceased. When monitoring recommenced in Puruwai in 1992,

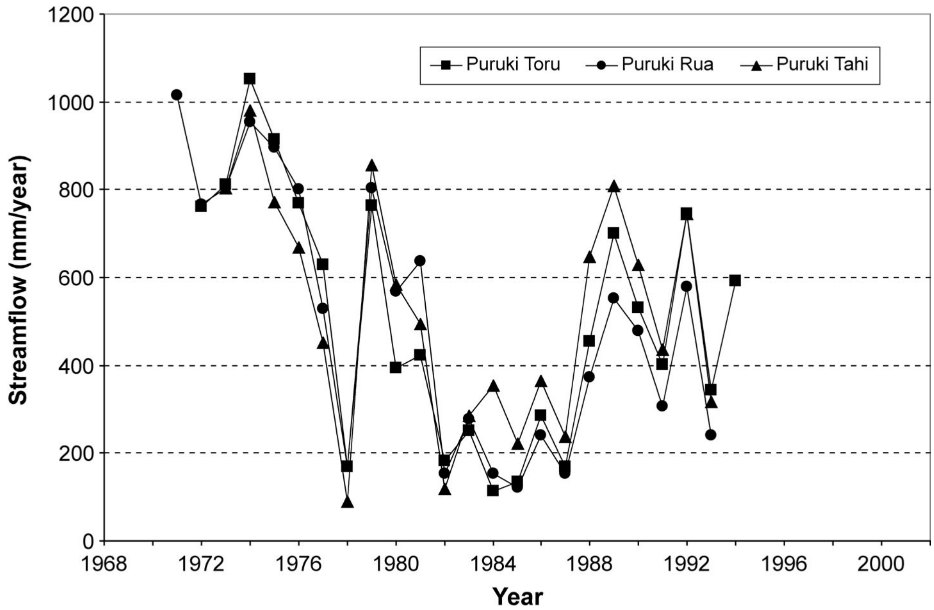

FIG. 3–Annual streamflow from three pine subcatchments. Timing of silviculture operations is given in Table 1. Final stockings differed between subcatchments, with Tahi thinned to 60 trees/ha, Toru to 180 trees/ha, and Rua to 550 trees/ha.

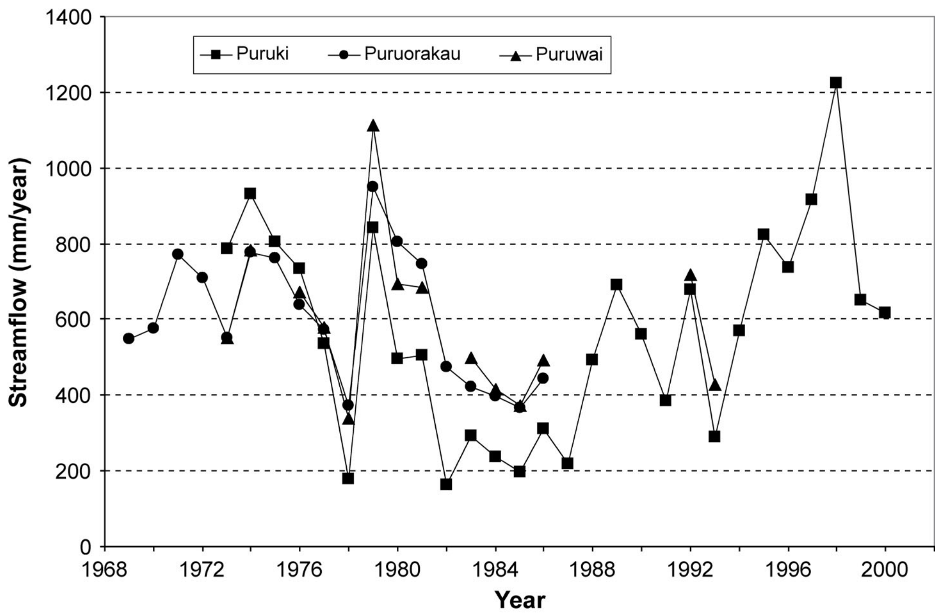

FIG. 4–Streamflow from indigenous forest (Puruorakau, Puruwai) and pine (Puruki) catchments.

annual flows from Puruki were only about 150 mm less than flows from the indigenous forest.

Models for Predicting Streamflow from Site Data

Models were developed to predict streamflow from rainfall and additional selected variables including cover type and leaf area index (Table 4). All variables included in these models were statistically significant. According to the models, rainfall and leaf area index were the two key variables that determined most of the variation in streamflow, with Models 3, 5, and 7 accounting for 89–92% of the variation in annual flow. Cover type was not as effective as leaf area index (compare Models 2 and 3). Afforestation reduced flow, with the pine leaf area index coefficient equal to –21.5 (Model 3). Silvicultural effects were most precisely tested when the pine subcatchments were analysed on their own. However, the coefficients of Model 3 (where pasture catchments were included with pine catchments) were almost identical to those of Model 5 (pine alone) and Model 7 (all land-use catchments). The land-use test demonstrated a small improvement in the root mean square error when cover type was included with rainfall and leaf area index (Model 8).

Interception in Rua

Throughfall and stemflow data are shown in relation to periodic rainfall prior to thinning of the Puruki Rua stand (Fig. 5). Thinning increased throughfall by approximately 50% and decreased stemflow (data not shown). Analysis of the pre- and post-thinning interception data showed that rainfall, leaf area index, and rainfall × leaf area index interaction influenced rainfall interception by the pine canopy, with the model accounting for 76% of the variation. The function (s.e. in parentheses) for predicting interception is given by:

$$I = -2.455(1.83) + 0.308(0.14) \times LAI + 0.017(0.03) \times rainfall + 0.012(0.0027) \times LAI \times rainfall$$

where the Prob. > T for the intercept, leaf area index, rainfall, and interaction terms were 0.18, 0.035, 0.63, and <0.0001, respectively.

Predictions using this function gave annual interception/rainfall ratios that were almost identical to those derived from annual sums of the interception/rainfall pre- and post-thinning data.

Evapotranspiration and Its Components

Evapotranspiration, predicted interception (using the above function), and transpiration (by difference) were calculated in relation to leaf area index for the pine stands, with pine canopy leaf area index changing markedly with stand age and silviculture (Fig. 6). Pasture leaf area index was unknown but was assumed to be

TABLE 4–Annual streamflow regression models based on a selection of cover type, rainfall, and leaf area index (LAI) variables, with associated model R^2, and root mean square error (Root MSE). The model coefficients (X1–X3) and standard errors (in parentheses) are shown. Selected catchments were used to test the effect of afforestation (pasture, pine subcatchments), silviculture (pine subcatchments), and land-use (all catchments).

Model	Test	X1	X2	X3	R^2	Root MSE (±mm/yr)	Intercept	X1	X2	X3
1	Afforestation	Rainfall			0.60	185	–1001 (159)	1.041 (0.10)		
2	Afforestation	Rainfall	Cover type		0.81	128	–1040 (110)	0.973 (0.07)	Pasture 268 (31) Pine 0	
3	Afforestation	Rainfall	LAI		0.91	87	–766 (76)	0.965 (0.05)	–21.5 (1.3)	
4	Silviculture	Rainfall			0.61	181	–1074 (214)	1.012 (0.14)		
5	Silviculture	Rainfall	LAI		0.92	82	–754 (101)	0.956 (0.06)	–21.21 (1.8)	
6	Land-use	Rainfall			0.63	166	–932 (112)	0.993 (0.07)		
7	Land-use	Rainfall	LAI		0.89	88	–654 (62)	0.909 (0.04)	–20.88 (1.2)	
8	Land-use	Rainfall	Cover type	LAI	0.91	81	–693 (61)	0.900 (0.04)	Indig. 95 (19) Pasture 50 (28) Pine 0	–19.7 (1.9)

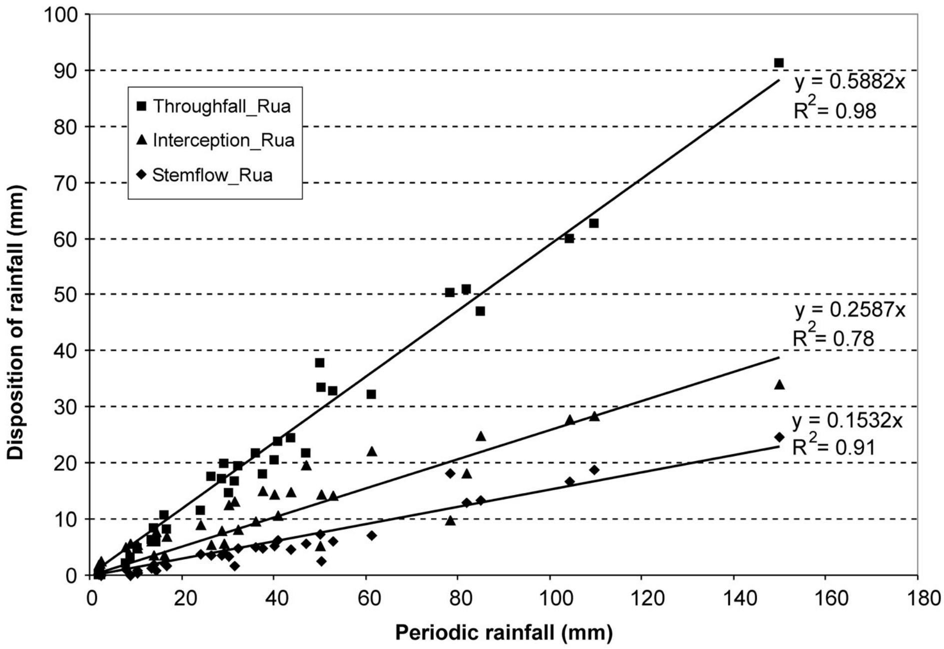

FIG. 5–Rainfall in relation to measured throughfall, stemflow, and interception (calculated by difference) for the unthinned Puruki Rua pine stand.

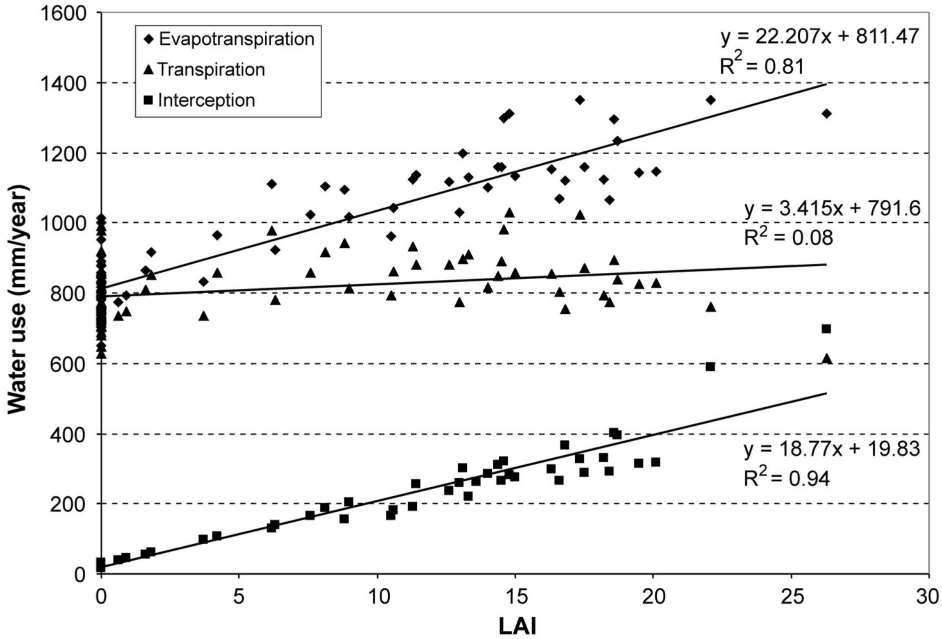

FIG. 6–Water-use in relation to leaf area index (LAI) of pine stands and pasture catchments. Pasture catchments are shown with LAI =0.

constant on an annual basis. For convenience, pasture is shown with a value of zero (Fig. 6). Based on average annual rainfall, interception by the pine stands increased linearly with leaf area index, and attained around 400 mm/year largely in parallel with evapotranspiration. Exceptionally high interception losses occurred when leaf area index peaked in a year with high rainfall (2115 mm). Transpiration was little affected by leaf area index, and averaged approximately 800 mm annually in all catchments. Transpiration was not significantly related to rainfall or interception.

DISCUSSION

In catchment studies, evapotranspiration is derived from rainfall minus average annual streamflow minus drainage losses, of which drainage losses are potentially the largest source of unknown variation. Puruki rainfall averaged 1579 mm from 1969 to 2000. Puruki Rua catchment drainage losses were assumed to be zero. Using this assumption, evapotranspiration was estimated to be approximately 800 mm prior to planting the pines, increasing to approximately 1200 mm when the pine leaf area index reached 20. The increase in evapotranspiration was due to an increase in interception loss by the pines, with transpiration remaining more or less constant with respect to leaf area index, which suggests that the increase in transpiration by the pines as the canopy developed was approximately matched by a decrease from the pasture and ground surface under the pine canopy.

Evapotranspiration, transpiration, and interception losses at Puruki Rua (1200 mm) were expected to be similar to estimates obtained by Whitehead & Kelliher (1991) who studied a similar pine stand near Rotorua where modelled evapotranspiration was 997 mm during a wet year with 1623 mm of rainfall. Our catchment-derived estimates of evapotranspiration were larger by about 200 mm annually. Our catchment-based calculations will over-estimate evapotranspiration if Rua was losing water, or alternatively under-estimate evapotranspiration if Rua was gaining water from adjacent catchments. If leaks occurred in Rua, it was considered more likely that water would be lost than gained, in which case 1200 mm of evapotranspiration is a maximum. Whitehead & Kelliher (1991) also found a significant reduction (36%) in modelled transpiration after thinning, almost in proportion to the reduction in leaf area index (42%), and modelled interception losses were much smaller (27%) than the decrease in leaf area index. At Puruki both evapotranspiration and interception varied linearly with pine leaf area index, and greater interception losses accounted for the difference in water yield between pasture and pine forest; transpiration losses were similar in all land-uses, and were not correlated to pine leaf area index or rainfall.

The hydrological impacts of afforestation of pasture with pine on flows at Purukohukohu were examined in detail by Dons (1987) for the period 1981–84; he concluded that annual pasture catchment flows averaged 2.1 and 1.6 times the flow from pine forest and indigenous forest respectively. Our equivalent flow calculations (1.5 and 1.2 times for pine and indigenous forest respectively based on Table 2) differ from Dons (1987) due partly to different assumptions about the hydrologic area. Furthermore, our analysis was based on a long monitoring period, and rainfall over his 4-year study period was about 120 mm/year lower than the long-term average for our study which was virtually identical for each land use (about 1555 mm). In addition, Dons (1987) assumed leaf area index was constant when estimating evapotranspiration, while we incorporated the effect of leaf area index variation in our analysis. The 103- to 163-mm-higher average streamflow in our results therefore equated well with Table 2 in the report by Dons (1987) after his groundwater losses were taken into account.

It was evident that afforestation of pasture with *P. radiata* reduced streamflow in proportion to the increase in pine canopy leaf area index. The increase in leaf area index from 0 to 20 with tree age resulted in increased interception losses and a gradual reduction in annual flow by up to 400 mm when leaf area index peaked, which is consistent with results from other studies (Cornish 1989; Fahey *et al.* 1997). Analysis of the throughfall/stemflow data obtained in Rua before and after thinning indicates that interception was significantly related to rainfall and leaf area index. Pruning and thinning operations temporarily reduce leaf area index, resulting in a decrease in canopy interception. Thinning effects were ephemeral, and only severe thinning outside the normally acceptable range, as in Tahi, resulted in a sustained increase in flow (approx. 100 mm) relative to other pine catchments. Hence, increases in flow arising from alternative silvicultural management regimes appear to be relatively unimportant.

Harvesting of the pine forest at Puruki increased flow above pasture values for several years, presumably because vegetation was largely absent and evapotranspiration was reduced by 120 mm. An increase in flow above pasture levels was also observed after harvesting of a small pine catchment at Nelson (Duncan 1995). Therefore, for a given rainfall, flows from pine stands can be above, equal to, or less than flows from pasture, depending on the pine forest leaf area index. Taking into account leaf area index changes over a 30-year rotation of intensively managed pine, using Model 3 (Table 4) annual flow from a site of average-to-high productivity was predicted to be 160–260 mm lower from pine forest than from pasture under similar rainfall conditions.

More tentative conclusions can be drawn regarding water yield from pine *versus* indigenous forest at Purukohukohu. Flows were less under closed canopy pine than under evergreen indigenous forest, and this is supported by Dons' (1987) 4 years of data at this site. However, the annual evapotranspiration in indigenous forest averaged 950 mm, which was approximately 100 mm less than the average under pine over a full rotation. Interception losses reported for small catchments with evergreen indigenous forest range from 300 to 350 mm (Fahey *et al*. 1997), which is less than observed in closed canopy pine but greater than the long-term average interception loss over a full rotation. Smaller gains in streamflow were observed after harvesting of deciduous hardwood forest at Hubbard Brook Experimental Forest (Hornbeck *et al*. 1997), presumably because interception losses were reduced while the trees were without leaves.

A model based on rainfall and leaf area index accounted for approximately 90% of the variation in annual flow. The coefficients of the model were almost identical regardless of which catchments were analysed selectively to test the effects of afforestation, silvicultural management, and land-use; this gave confidence in the pasture and pine catchment data and the assumptions made regarding catchment hydrologic areas. The superiority of Models 3, 5, and 7 (rainfall, leaf area index) over Models 1, 4, and 6 (rainfall) and Model 2 (rainfall, cover) emphasises the importance of leaf area index as a determinant of evapotranspiration (through its effect on interception) and flow. Either Model 3, 5, or 7 could be linked with leaf-area-based growth models to predict annual water use by *P. radiata* stands and for predicting annual runoff, given the annual rainfall, though the generality of the model should first be tested in different climatic environments.

Acceptance of generality of these models should give confidence in predictions of lower streamflows with land-use change from pasture to pine, which may be important to downstream water users in areas with low flows. However, the marked reduction in peak flows after afforestation (Dons 1987) may be a more critical consideration in areas prone to flooding than the effect of pines on average flows.

CONCLUSIONS

A comparison of streamflow from catchments under pasture, pine, and indigenous forest showed that annual flows were greatest from pasture. The only exception was recently harvested pine, where highest flows were recorded after clearfelling and replanting of the largely vegetation-free ground.

Evapotranspiration and interception both increased linearly with pine leaf area index, and accounted for the difference in water yield between pasture and pine forest. Transpiration was similar in all land-uses, and was not related to pine leaf area index.

The leaf area index of pine stands depended on tree age, silvicultural operations, and harvesting. Silvicultural operations increased water yield by reducing leaf area index, but these effects were relatively small and ephemeral. Tree age and harvesting had a large effect on leaf area index, which together with rainfall largely determined water yield.

Water yield decreased after conversion of pasture to pine, with reductions expected to range between 0 and 400 mm/year, depending on leaf area index and assuming an even-aged stand. In a normal pine forest, which has an equal area of each stand age-class, a reduction in water yield of approximately 160–260 mm/year could be expected.

Water yield from pine forest averaged around 100 mm/year less than from indigenous forest. Comparisons between pine and indigenous forest catchments at this site carry some uncertainty because the hydrologic area of the indigenous forest catchments at this site cannot be determined precisely.

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