HYDROLOGY AND SEDIMENT REGIME OF A PASTURE, NATIVE FOREST, AND PINE FOREST CATCHMENT IN THE CENTRAL NORTH ISLAND, NEW ZEALAND

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ABSTRACT

The hydrology and sediment regime of a 0.10-km^2 pasture, 0.34-km^2 pine forest, and 0.28-km^2 native forest catchment were compared. The highly permeable pumice soils of these catchments resulted in generally low annual stormflow yields (0.54-5.2% of gross rainfall) and consequently low annual sediment yields (4.0-27.0 t/km^2/yr). The pasture catchment had the highest average flows, highest peak flow rates, and greatest stormflow yields, but lowest evaporative losses. The pasture catchment also recorded the maximum instantaneous sediment concentrations and the maximum instantaneous sediment discharges. The pine forest catchment had the lowest annual average flows, lowest low flows, and lowest instantaneous sediment concentrations and discharges, but evaporative losses were similar to those from the native forest catchment. The native forest catchment had the lowest stormflow yields, lowest peak flows, and highest low flows. Some of the differences in hydrologic responses from the native forest catchment could be explained by drainage density rather than land use.

Keywords: hydrology; sediment; pasture; podocarps; afforestation; land use; **Pinus radiata.**

INTRODUCTION

The wise management of water resources requires accurate information on the relationships between land use, water yield, and water quality. Although some information is available on these relationships, in areas of highly permeable pumice soils the debate on the effects of land use on hydrology and water quality continues – particularly with reference to afforestation with *Pinus radiata* D. Don (Barry 1984). Dons (1981) has shown that afforestation of a small pasture catchment substantially reduced its annual, seasonal, and peak flows, and in another study Dons (1986) has shown that afforestation of a large central North Island catchment reduced its annual, summer, and winter mean flows. These studies did not include a native forest catchment or any water quality considerations. Dyck & Cooke (1981) compared the baseflow water quality of a pasture catchment with that of a pasture catchment converted to

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pine forest. Their study showed that nutrient losses from the pasture catchment, during baseflow, were greater than losses from the afforested catchment but the study did not compare nutrient exports during storms or compare their sediment regimes.

This study compared the hydrology and sediment regime of small pasture, pine forest, and native forest catchments located within the Purukohukohu suite of catchments.

METHODS

Site Description

The Purukohukohu suite of catchments is situated midway between Rotorua and Taupo on the central North Island volcanic plateau at 176° 13′ E, 38° 26′ S (Fig. 1). Although there have been as many as 10 study catchments at Purukohukohu, this study was confined to one pasture catchment (Purutaka), one pine forest catchment (Puruki), and one native forest catchment (Puruwai). The altitude of the catchments ranges from

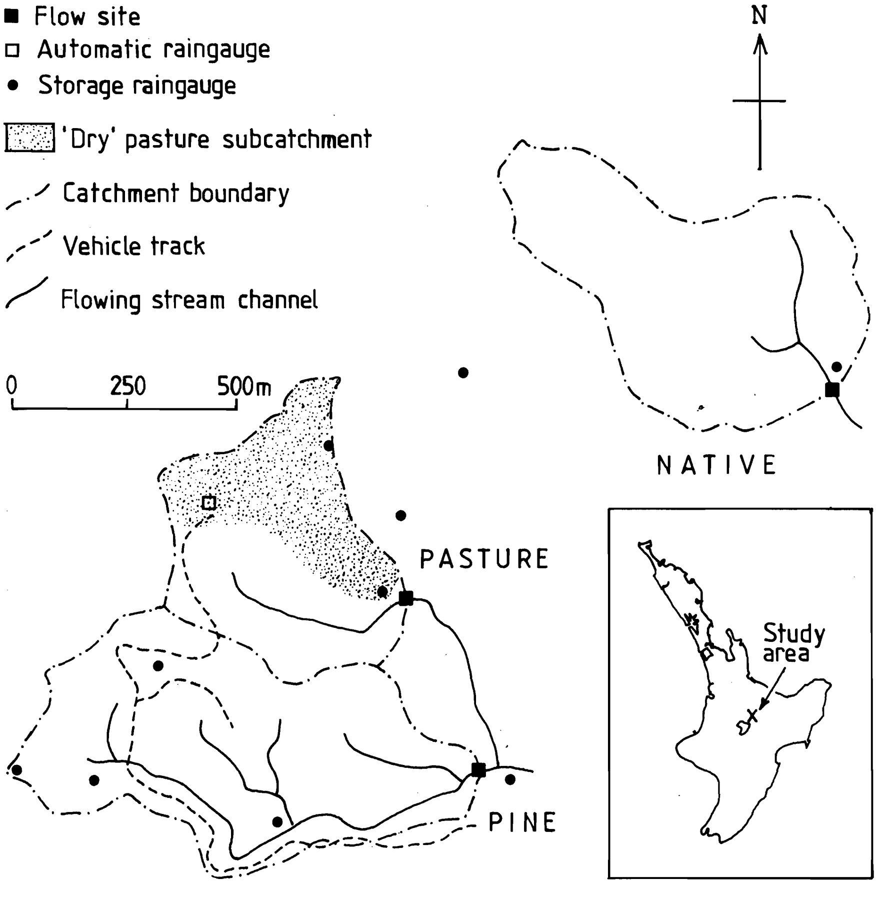

FIG. 1—Purukohukohu study area.

about 500 m to 750 m a.s.l. and the topography is moderately steep with an average slope of 17°. The geology of the study catchments is made up of a relatively impermeable base (Huka group sediments and pyroclasts) overlain by permeable uncompacted ash and pumice (Mihi Breccia and Taupo pumice alluvium). The soils, developed from volcanic ash (typic vitrandept), are porous and permeable. Average infiltration rates measured by a single 6-cm-diameter cylinder were 52 mm/h for the pasture catchment, 225 mm/h for the pine forest catchment, and 600 mm/h for the native forest catchment (R. J. Jackson pers. comm.). Rainfall averages about 1550 mm/yr with the lowest average monthly rainfall of 90 mm occurring in February and the highest average monthly rainfall of 170 mm occurring in August. On average there are nine raindays in February increasing to 19 in August. Rainfall intensities are discussed in the Results and Discussion section. Pan evaporation measured within the pasture catchment averages 720 mm/yr with a seasonal low of 10 mm for June and a seasonal high of 120 mm for January. The annual average air temperature is 11°C with a range in monthly average temperatures of 4° to 17°C.

The pre-European vegetation (podocarp/mixed hardwood forest) has been retained in the native forest catchment while both the pasture and pine forest catchments were originally developed for pasture in the 1920s. The pasture catchment is vegetated with ryegrass and clover and is used for sheep and cattle grazing. *Pinus radiata* was planted in the pine catchment in 1973. Average tree height during the study period was 13 m and the average stocking density was about 640 stems/ha. The canopy of the pine forest was closed by 1981. Some physical characteristics of the three study catchments are listed in Table 1. More detailed information has been published by Ministry of Works and Development (1971, 1973). The period of this study was from 1981 to 1984 inclusive.

TABLE 1—Physical characteristics of the study catchments

	Pasture	Pine	Native
Area (km^2)	0.10*	0.34	0.28
Channel length (km)	0.50	2.50	0.50
Average channel width (m)	4.0	3.0	2.5
Channel area (m^2)†	2000	7500	1250
$\frac{\text{Channel area}}{\text{Catchment area}}$ (%)	2.0	2.2	0.45

* Reduced from topographical area (*see* Data Analysis)
† Includes the surface saturated zone either side of the flowing channel

Instrumentation

All catchments were originally instrumented during the late 1960s and early 1970s with 0.9-m H flumes, and the pasture and pine catchment flumes were extended to 1.5 m prior to the study period. The flumes, although having theoretical ratings for the conversion of water level to flow, were checked by gauging flows to ascertain whether the theoretical ratings applied in the field. The flumes of the pasture and native forest catchments were found to have non-standard relationships between flow and water level. Once the relationships were established regular checks were made of flow *versus* water level and flume level and staff gauge level. The flumes and recorders were checked monthly to ensure reliable operation. Water levels were recorded to ± 3 mm (Herschy 1978) at 15-min intervals by Fischer and Porter digital recorders with back-up chart recorders. The sensitivity of flow measurement to an error of ± 3 mm in water level was about 5% at median flow level (Freestone 1983) although an error of ± 3 mm at low flows would cause a greater percentage error.

Rainfall was measured by nine 100-mm and one 125-mm-diameter monthly storage gauges and one automatic (OTA) tipping bucket (0.5 mm) gauge with a 6-min recorder (Fig. 1). A potentially large source of error for the storage gauges used in this study was "undercatching" due to the acceleration of air flow over the rain gauge orifice. McKerchar (1986) considered that the error due to undercatch could be as much as 10% depending on wind speed. In this study the effect of rain gauge height on the amount caught was assessed by comparing 45 monthly totals from a ground-level gauge and two automatic gauges with different heights all located at the automatic rain gauge site (Fig. 1). The heights of the orifices above the ground were 0, 0.6, and 1.3 m. The 1.3-m gauge caught on average 5.9 mm (standard error = 0.83) or 5% less than the ground-level gauge. The 0.6-m gauge caught on average 3.9 mm (standard error = 0.81) or 2% less than the ground-level gauge. The average monthly catch was about 120 mm. Because the orifices of the storage gauges used in this study were closer to the ground surface than the 0.6-m automatic gauge, the error due to undercatching was assumed to be small (<2%). The material from which a rain gauge is made also affects the amount "caught". Finkelstein (1971) showed that plastic gauges (similar to the storage gauges used in this study) caught 2% more than copper gauges owing to the extra condensation on plastic surfaces. The automatic gauge used in this study was corrected to the monthly catches of the ground-level gauge.

Suspended sediment samples were taken by flow-activated Manning 4040-S samplers, whose intakes were located 75 mm above the flume floor and to one side of the flume. The accuracy of the sediment concentrations obtained with these point automatic samplers was checked by comparing automatic samples with integrated samples taken by DH48 hand sampler. Seven comparisons yielded an average ratio of 1.02 between sediment concentrations measured by automatic point sampler and integrated hand sampler. Bed load was not sampled but assumed to be a small proportion of the total sediment transport because of the rough bed and low density of pumiceous sediments which together were assumed to induce good mixing of transported sediments. Automatic storm-period samples were augmented by 5-*l* manual baseflow samples. All samples were transported to the Water Quality Centre laboratory in Hamilton for suspended sediment determinations by standard methods (APHA 1980). Nutrient and cation determinations from these samples will be reported separately.

Data Analysis

A source of error in this study that is potentially larger than the errors in measuring flow and rainfall is the error in estimating the catchment area appropriate to the flow measurements. This error is caused by groundwater losses or gains and is a particularly difficult problem in these catchments. Firstly, most rainfall infiltrates these permeable soils because infiltration rates are high compared with the rainfall rates. Also, the basement rock is fractured which provides pathways for groundwater to flow underneath topographical boundaries. Finally, catchment surface slopes are high which indicates that water table slopes are also high and that hydraulic heads, which provide the energy for groundwater flow, are also likely to be high. For these reasons use was made of hydrological data from surrounding catchments to check and, if necessary, adjust the data from the study catchments although the true catchment areas remain unknown.

Total losses (evapotranspiration and groundwater losses) were checked by comparing ratios of rainfall to runoff of similarly vegetated catchments within the Purukohukohu suite of catchments. In all, five small catchments within the Purukohukohu suite and one large catchment downstream were used. The pasture study catchment (Purutaka) was compared with an adjacent pasture catchment (Puruhou) and with the pine forest study catchment (Puruki) before it was converted to pine forest. The pasture study catchment mean flow from 1981 to 1984 was 245 mm while the adjacent pasture catchment mean flow was 532 mm. Their catchment rainfalls were both 1432 mm and thus their respective ratios of runoff to rainfall were 0.17 and 0.37.. A similarly large discrepancy in the ratios of runoff to rainfall occurred when the pasture study catchment was compared to the pine forest study catchment before its conversion. Their respective average runoffs were 352 mm and 811 mm and their respective catchment rainfalls were 1596 mm and 1563 mm for the period 1970 to 1972 inclusive. The ratios were 0.22 for the pasture study catchment and 0.52 for the pine study catchment while in pasture. Thus, the pasture study catchment produced less than half the runoff of the two other pasture catchments. In this study the catchment area of the pasture catchment has therefore been reduced to 44% of its topographical catchment area to reflect the runoff to rainfall ratios of the two "check" pasture catchments. The reduction used was the average of the two comparisons calculated as follows:

Reduction in area of pasture study catchment $= (r1/r2+r3/r4)/2$

where

r1 = runoff to rainfall ratio for pasture study catchment (1981–84)
r2 = runoff to rainfall ratio for pasture catchment adjacent to study catchment (1981–84)
r3 = runoff to rainfall ratio for pasture study catchment (1970–72)
r4 = runoff to rainfall ratio for pine study catchment while still in pasture (1970–72).

The reduction in the catchment area of the pasture study catchment was further justified because this catchment had a large "dry" subcatchment (Purutaka No. 2) that produced small amounts of flow only during rainfall (Fig. 1). A steam vent, presumably caused by volcanic thermal activity, in the dry subcatchment indicated that its basement rock was fractured and therefore allowed a high groundwater loss. The flow of the "dry" subcatchment was monitored by a flume and chart recorder. From 1970 to 1979 flow was recorded on average for only 5 days per month while there were on average 15 days per month on which rain fell. Seventeen storms from 1970 to 1973 were analysed to compare stormflow yields from the dry subcatchment with those from the total pasture study catchment. The yields from these storms showed that in small storms the yield from the "dry" subcatchment was near zero but that in large storms the yield from the dry subcatchment approached and occasionally exceeded the yield from the total pasture study catchment. As a further check, a flow recorder was installed on the main stem of the pasture catchment about 10 m above the "confluence" of the dry subcatchment and the main stream. During 1986 the flow of the pasture study catchment was within 10% of that recorded above the confluence despite the large addition of topographic catchment area of the dry subcatchment. For this study the catchment area of the pasture study catchment was assumed to equal 0.10 km^2 for average flows or lower, with the effective catchment area increasing to its topographic area (0.23 km^2) for very large storms. The catchment areas of the native and pine study catchments were not adjusted from their topographic catchment areas because there were no large discrepancies in the ratios of runoff to catchment rainfall.

In addition to the gross discrepancy in hydrologically effective catchment area identified above, seepage of groundwater from all catchments is likely because of their elevated position and thus high potential for downward movement of groundwater. These groundwater losses were assumed to be equal for all three study catchments and were estimated as the difference between the pasture study catchment total losses (i.e., rainfall – total flow for the adjusted area) and total losses for the Mangakara catchment. The Mangakara catchment is 22 km^2, predominantly in pasture, includes the study catchments, and is monitored just upstream of its confluence with the Waikato River. Groundwater losses underneath the flow recorder from the Mangakara are likely to be small because there is little difference in water level (i.e., hydraulic head) between the Mangakara flow monitoring site and the much larger Waikato River.

Ratios were developed between the automatic rain gauge and monthly catchment mean rainfalls estimated by the Thiessen method (Chow 1964). These ratios were based on 84 monthly values using linear regressions, with zero constant, and gave correlation coefficients of greater than 0.99. These ratios were used for estimating annual and individual storm rainfalls for each study catchment. Net rainfalls, for the forested catchments, were estimated by subtracting interception loss from gross rainfall. Interception loss (26% of gross rainfall) was measured in the pine catchment (W. J. Dyck pers. comm.) and assumed to equal the native forest interception loss. Stormflow (quickflow) was estimated using the constant slope separation technique of Hewlett & Hibbert (1967). The separation slope was 0.000152 $l/s/km^2/s$. The range of individual storm responses (stormflow yield/gross rainfall) was assessed by examining 69 separate events during the study period. Only those storms where rainfall and associated stormflow could be clearly distinguished and where the pasture peak flow was greater than 50$l/s/km^2$, were used. The return period of flow events was estimated by comparing the peak flow from the pasture catchment with the annual maximum flows from the pasture catchment (1969–84) plotted on Gumbel probability paper.

Sediment discharges ($mg/s/km^2$) were estimated as the product of instantaneous water discharge ($l/s/km^2$) and suspended sediment concentration (mg/l). Analysis of variance was used to test for significant ($p<0.05$) differences in mean values between catchments. Data were normalised, where necessary, by a logarithmic transformation (base 10).

RESULTS AND DISCUSSION

Annual Water Balance

Average annual rainfalls during the 4-year study period varied between catchments by 86 mm, with the native forest catchment receiving the highest rainfalls (Table 2). The study period was drier than average with the automatic gauge receiving 120 mm less than the 1969–84 average (1567 mm). A rainfall depth-duration-frequency summary based on 15 years of data from the automatic gauge is given in Table 3. Although the average infiltration rates were greater than these rainfall intensities, infiltration excess overland flow was still possible from some localised areas of the pasture catchment with below average infiltration rates (e.g., stock tracks). Infiltration excess overland flow was unlikely from the forested catchments, especially the native forest catchment, because infiltration rates were very much greater than likely rainfall intensities beneath the forest canopy.

Total flows (Table 2) were more variable than rainfall with the pasture catchment providing 289 mm (2.1x) and 204 mm (1.6x) more flow than the pine forest and native forest catchments, respectively. Total flow from the native forest catchment was 108 mm higher than from the pine forest catchment but higher rainfalls in the native forest catchment could account for most of this difference.

TABLE 2—Estimated average annual water balance (mm) (1981–84)

	Pasture	Pine	Native
Gross rainfall	1427	1398	1484
Stormflow	74	31	8
Delayed flow	469	223	331
Total flow	543	254	339
Evapotranspiration	784	1044	1045
Groundwater loss	100	100	100

TABLE 3—Rainfall depth (mm), duration, and frequencies from automatic raingauge record (1970–84)

Return period	Duration (min)		
(yr)	30	60	120
2	21	27	34
10	26	46	64

Evaporative losses from both forested catchments were similar but 33% greater than from the pasture catchment. Estimated average evapotranspiration for the pine forest catchment of 1044 mm is supported by results from a nearby physical modelling study by D. Whitehead based on tree lysimeter data (Forest Research Institute 1987). Whitehead's study carried out 25 km from Purukohukohu showed that evapotranspiration from a forest stand of 750 stems/ha was 1028 mm, or 76% of the annual rainfall of 1347 mm. In this study evapotranspiration was 75% of gross rainfall. Both studies were based on free-draining volcanic soils. Other comparative studies between native (mixed indigenous forests) and pine (*P. radiata*) forests have also shown similar transpiration and interception rates (e.g., Pearce & Rowe 1979). Measured interception losses (26% of gross rainfall) in the pine catchment accounted for more than the difference between pasture and pine forest evaporative losses observed in this study.

Annual groundwater losses by deep seepage were estimated as 100 mm for all catchments. This was estimated by comparing the Mangakara catchment water balance with the water balance of the pasture study catchment for the period 1981–83 inclusive. The Mangakara average rainfall was 1216 mm, average runoff was 460 mm, with evaporative and groundwater losses thus equalling 756 mm. For the pasture study catchment the 1981–83 average rainfall was 1426 mm, the average runoff was 592 mm, with evaporative and groundwater losses thus equalling 834 mm. The difference between these two estimates is 78 mm which was rounded up to 100 mm because of the error involved in this estimate and because the Mangakara catchment itself may also suffer some groundwater losses. This estimate is within the two estimates of groundwater loss of 40 mm and 195 mm given by Pearce *et al.* (1982) for small (0.048- to 0.20-km^2) forested catchments with similar annual rainfall and located in the northern South Island of New Zealand.

Flow Distributions

Flow distribution curves for the three study catchments (Fig. 2) showed that the native forest catchment had a markedly different flow distribution from both the pine forest and the pasture catchments. Storm period flow rates from the native forest catchment were considerably less than from both the pine forest and pasture catchment; e.g., at the time distribution point of 0.01%, native forest flows were only 42% and 22% of pine forest and pasture flow rates, respectively. Conversely, low flows from the native forest catchment were sustained at much higher levels than from both the other catchments; e.g., at the 80% time distribution point the native forest catchment flow rate was 2.4 and 6.0 times the pasture and pine forest flow rates, respectively.

Differences in the size and location of stream channels usually carrying flow and their associated wetlands, rather than vegetation differences, could account for most of the differences in the distribution of native and pine forest flows. Total channel wetlands in the native forest catchment (as a proportion of catchment area) were only 20% of that for the pine forest catchment (Table 1). Because there was little surface runoff from either forested catchment, the proportion of the native forest catchment that contributed direct runoff was therefore about 20% of that of the pine forest catchment and so peak flows from the native forest catchment should have been considerably smaller than peak flows from the pine forest catchment despite higher native forest catchment rainfalls. Support for the much smaller stormflow generation area in the native forest catchment, than in the pine forest catchment, comes from a comparison of storm flow volumes (Table 2). The average annual storm flow generated from the native forest catchment was 26% of that generated from the pine forest catchment.

Low flows were sustained for longer in the native forest catchment than the pine forest catchment because average groundwater travel times were longer in the native forest catchment. This was because the average distance that groundwater travelled from the catchment surface to the stream channel in the native forest catchment was considerably further than in the pine forest catchment (Fig. 1) while the soil hydraulic conductivity and water slope were similar. Hydraulic conductivities were assumed similar because of the similar soil profiles (Ministry of Works and Development 1973), particularly below the A horizon, and water table slopes were assumed similar because the native and pine forest catchment hypsometric curves were similar. Higher net rainfalls in the native forest catchment would also help sustain base flows.

The independence of land use and the shape of the flow distribution curve in these porous catchments were further supported by comparing the flow distribution curves of the pine forest and pasture catchments. When the pine forest catchment was in pasture (1970–73), its specific flow distribution curve was similar to the curve for the pasture catchment (Fig. 2). Although the land use of the pine forest catchment changed between 1970–73 and 1981–84 the flow distribution curves for both catchments retained the same shape. The distribution curve for the pine forest catchment was merely displaced downward because of the decreased net rainfall, due to increased interception loss, for the pine forest catchment.

Stormflow Yields

Annual stormflow yields (Table 2) constituted only 0.54%, 2.2%, and 5.2% of gross precipitation for the native forest, pine forest, and pasture catchments, respectively. These yields are small compared to the stormflow yields from catchments in other

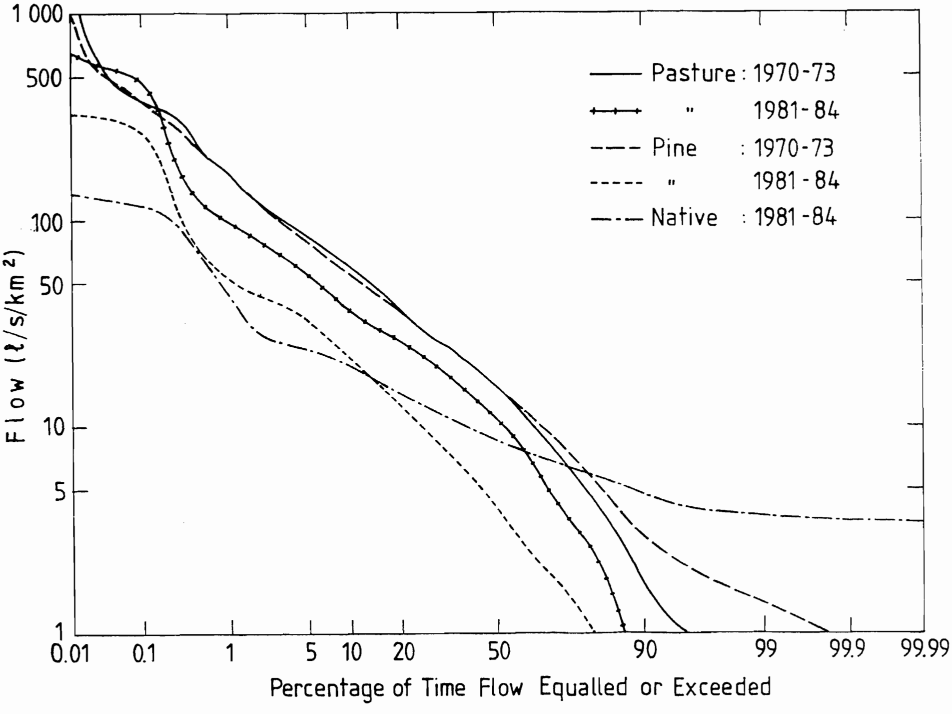

FIG 2—Flow distribution curves.

parts of New Zealand. Pearce & McKerchar (1979) who examined several catchments from throughout New Zealand found that stormflow ranged from about 7% to 40% of gross rainfall, except that the pasture study catchment in their study produced only 0.4% of gross rainfall as stormflow. This study confirms the low production of stormflow for the pasture catchment and demonstrates that catchments with other land uses in the same area also produce little stormflow on an annual basis.

The range of individual storm responses (stormflow yield/gross rainfall) was large with a minimum of near zero in the pine forest catchment and a maximum of 68% occurring in the pasture catchment (Table 4). The near-zero storm response in the pine forest catchment occurred when a small rainfall fell on to a dry catchment where flow in much of the channel had stopped. The particularly low runoff responses for most storms (i.e., 95% of the storms used for Table 4) in the native and pine forest catchments confirmed that rainfall in these catchments generally produced little surface runoff or rapid groundwater flow. Ninety-five percent of the storm responses from the native catchment can be accounted for by net rainfall on to 3.2 times the channel area which is equivalent to an extra 2.75 m of saturated soil either side of the channel. The same proportion of storms in the pine forest catchment requires 1.8 times the channel area. Storm runoff from the pine forest catchment was therefore attributed to rainfall on to the stream channel, the track which crosses the stream (Fig. 1), and perhaps some near-channel areas of low infiltration which were a legacy of its previous pasture land use. Storm runoff from 95% of the pasture catchment storms would require 4.6 times the channel area of the reduced catchment. However, as noted in the data analysis section, the normally "dry" subcatchment of the pasture study catchment contributes some stormflow during rainstorms. The proportion of rainfall actually contributing to stormflow from the "dry" subcatchment in any particular storm depends on the size, intensity, and duration of the rainfall. This is because an initial quantity of rainfall would be required to saturate the channel bottom before surface flow could commence. In the extreme, the stormflow generated by the pasture catchment could be derived equally from the total topographical catchment (area = 0.23 km^2) and thus the percentage yields in Table 4 would be reduced to 43% of the values listed. For the 95% distribution point, the pasture catchment yielded 9.3% of the gross rainfall as stormflow. This percentage would reduce to 4.0% if the total catchment contributed equally. The true percentage is likely to lie between 9.3% and 4.0%. Rainfalls in the pasture catchment probably cause some surface runoff and/or rapid groundwater flow, The available infiltration data suggest

TABLE 4—Percentage of gross rainfall yielded as stormflow for 69 study period storms

	Min	Geometric mean*	95%	Max.
Pasture	2.0	3.6	9.3	68
Pine	0.002	1.3	3.5	36
Native	0.02	0.25	1.0	12

* All geometric means significantly different at $p<0.05$

that there are areas of the pasture catchment that have infiltration rates approaching rainfall intensities (Table 3) and therefore could contribute surface runoff – especially livestock tracks or areas of exposed bedrock (R. J. Jackson pers. comm.).

Typical storm responses from the pasture, pine forest, and native forest study catchments and from a groundwater-level recorder situated near the source of one of the pine forest catchment tributaries are shown in Fig. 3. Rainfall during this storm

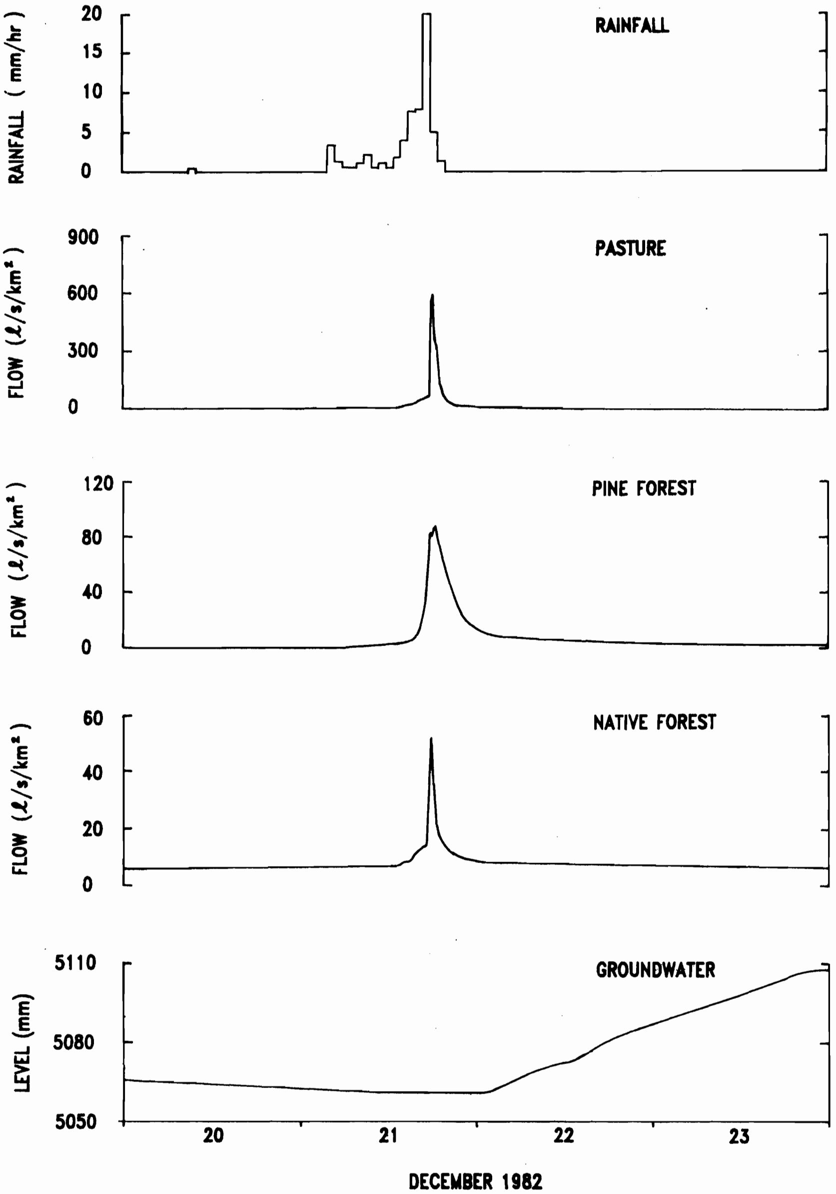

FIG. 3—Rainfall, flow and groundwater from storm of December 1982.

amounted to 69 mm of which 2.9 mm (4.2%), 1.1 mm (1.6%), and 0.2 mm (0.3%) were yielded as stormflow from the pasture, pine forest, and native forest catchments, respectively. Stormflow from the pine forest and native forest catchments could be accounted for by net rainfall (gross rainfall – interception loss) falling on to their channel areas (Table 1). Stormflow from the pasture catchment requires twice its channel area and suggests some contribution from the "dry" subcatchment and areas of low infiltration. The groundwater-level record shows little response to this rainfall apart from increasing about 46 mm during the 2 days after the rainfall, presumably due to slow seepage to the groundwater from the wetted top soil. Groundwater is assumed to contribute little to the stormflow yielded in this storm. Streamflows return close to pre-storm levels soon after the rainfall, which confirms that little was added to groundwater.

In addition to surface-derived stormflow, the potential for occasional large storm-period groundwater inputs is illustrated by the storm in Fig. 4. This storm caused the maximum responses in Table 4, which were three to eight times greater than the second-largest responses observed during the study period. Gross rainfall for the entire storm was 152 mm of which 103 mm (68%), 54 mm (36%), and 18 mm (12%) were yielded as stormflow from the pasture, pine forest, and native forest catchments, respectively. Although storm rainfall made up only 2.7% of the 4-year total rainfall, stormflow from this storm made up 35%, 44%, and 56% of the pasture, pine forest, and native forest catchments 4-year stormflow totals, respectively. The initial rainfall of 36 mm in 12 hours was followed by 56 mm in 7 hours which fell on to catchments with high baseflow and presumably with near-saturated soils and high groundwater levels. The initial fall caused relatively small peakflows but almost doubled baseflows. The second more-intense rainfall caused a rapid response (presumably surface runoff) which was followed, in all catchments, by a delayed groundwater "bulge". The pasture catchment best depicts this groundwater "bulge" starting at 1500 h on 25 October 1983. The groundwater origin of the "bulge" was confirmed by two observations. Firstly, nitrate-nitrogen (NO_3-N) concentrations of the pasture and pine forest stream water during the passage of the "bulge" (1.7 mg/*l* and 0.55 mg/*l* respectively) were much greater than typical surface runoff concentrations (C. M. Smith pers. comm.) but close to average spring-water nitrate-nitrogen concentrations (2.5 mg/*l* for pasture and 0.6 mg/*l* for pine forest) after allowing for nitrate-nitrogen removal by channel vegetation (Cooper & Cooke 1984; Cooper 1986). Furthermore, a groundwater-level recorder situated near the source of one of the pine tributaries showed a groundwater hydrograph with a shape similar to that of the pine forest stream hydrograph (Fig. 4).

Sediment Regime

Suspended sediment concentrations were distributed approximately log-normally and ranged from 0.2 to 13 000 mg/*l* (Fig. 5). The maximum concentrations from all catchments were sampled on 10 June 1983 during a 1.5-year return period storm that occurred after a 6-month period of little storm activity. This event yielded moderately high proportions of the 43-mm gross rainfall as stormflow (11%, 2.5%, and 0.5% from the pasture, pine forest, and native forest catchments, respectively) which indicated that surface runoff contributions were likely from the pasture catchment. Groundwater

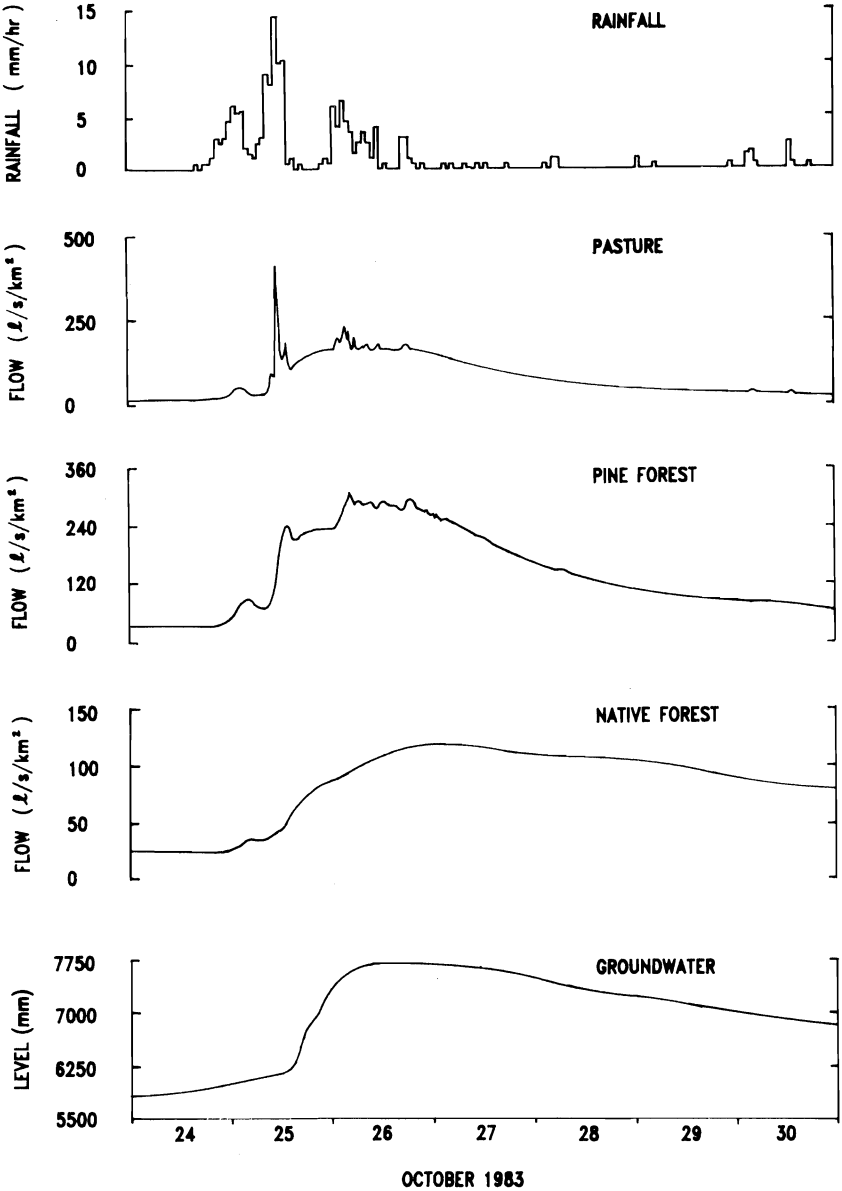

FIG. 4—Rainfall, flow and groundwater from storm of October 1983.

contributions were unlikely because the catchment soils were relatively dry before the storm. The maximum concentration sampled from the pasture catchment was an order of magnitude greater than the maxima sampled from either the native or the pine forest catchment (Table 5). Maximum concentrations from the pasture catchment during intense storms were reasonable because the pasture catchment was more susceptible to surface runoff and also more susceptible to surface disturbance by stock.

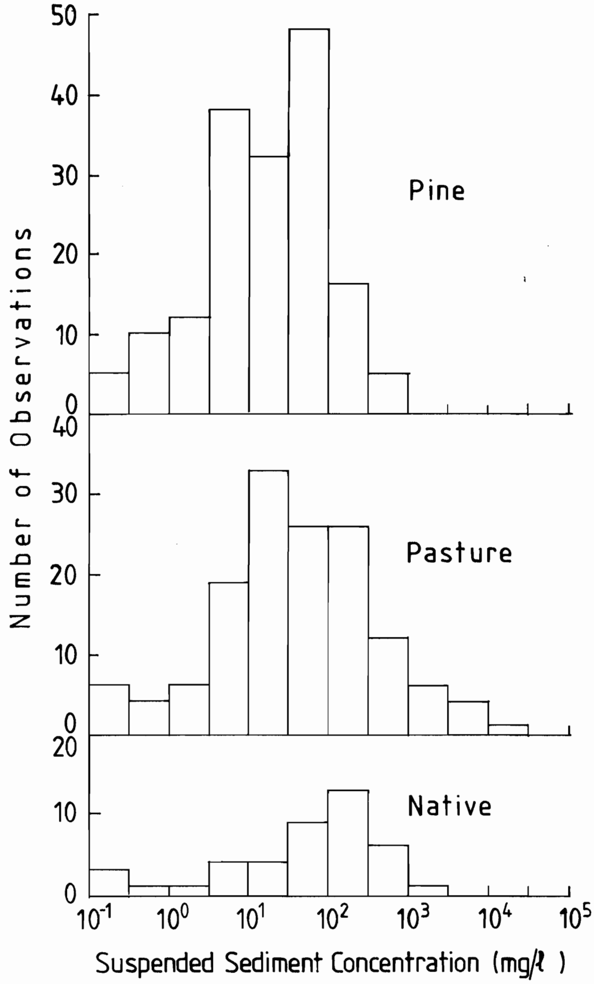

FIG. 5—Distribution of suspended sediment concentrations.

Average sediment concentrations from both the native forest and the pasture catchment were not significantly different but they were significantly higher than the average concentration from the pine forest catchment (Table 5). The source of sediments for moderate storms which produced most of the sediment samples was restricted to the stream channel and near-channel wetlands because surface runoff in these storms was unlikely in the forested catchments and required intense rainfall in the pasture catchment. Low sediment concentrations from the pine forest catchment were attributed to its channel which was heavily vegetated by grasses, rushes, and willow weed which stabilised the stream bed and trapped suspended sediments. This channel vegetation was able to grow in the pine forest catchment because of good channel lighting for at least half the channel and the exclusion of stock from the catchment. High average

TABLE 5—Distribution of suspended sediment concentrations (mg/*l*)

	n	Min.	Geometric mean*	Max.
Pasture	138	0.2	48 a	13 000
Pine	161	0.2	18 b	630
Native	37	3.2	91 b	1 230

* Means followed by same letters significantly different at $p<0.05$

concentrations from the native forest catchment were attributed to a readily erodible supply of stream sediments. These sediments lay unconsolidated in the stream channel and were not stabilised by stream vegetation – presumably because of the low light levels under the native forest canopy which was continuous over the stream channel. Although the native forest catchment had the smallest storm response, even a small increase in flow could transport the unconsolidated sediments that lay in the stream channel. The average concentration from the pasture catchment was about midway between that from the pine forest and native forest catchment. This was probably due to the net effect of highest erosive power (i.e., highest peak flows, surface runoff, and stock disturbance) modified by the stabilising effect of luxurious channel grass growth.

Sediment discharge rates also varied widely (Table 6). Again, the pasture catchment recorded the maximum value but because of the multiplicative effect of higher stormflows, the maximum sediment discharge from the pasture catchment was several orders of magnitude greater than that from either the native or the pine forest catchment. The maximum sediment discharges from the pasture catchment occurred during the storm of 10 June 1983 which also produced the maximum sediment concentrations and the maximum flows that were sampled. Although the data for this storm were not sufficiently complete to estimate a storm yield, the storm did export 545 kg from the pasture catchment during a 23-min period. These data indicated that the pasture catchment had the greatest potential for sediment export, especially during infrequent high-intensity rainfalls that occur after a dry period. Average sediment discharge rates from the pasture catchment were significantly greater than those from the native forest catchment whose average rates were in turn significantly greater than those from the pine forest catchment (Table 6).

TABLE 6—Distribution of sediment discharge rates (mg/s/km^2)

	n	Min.	Geometric mean*	Max.
Pasture	138	0.73	4640	10 350 000
Pine	161	0.27	490	34 500
Native	37	21	1730	56 200

* All means significantly different at $p<0.05$

Annual rates of sediment export were crudely estimated by applying sediment discharge – water discharge relationships (Table 7) to the continuous-flow record from each catchment from 1 January 1982 to 31 December 1984. Annual average exports from the native forest, pasture, and pine forest catchments were 27, 22, and 4.0 t/yr/km^2 respectively. These yields are comparable with the 31 t/yr/km^2 measured from the Murupara River which drains a large pumice catchment in the central North Island (Thompson & Adams 1979), but are amongst the lowest yields reported in recent reviews of New Zealand sediment export rates (Hayward 1979; Thompson & Adams 1979; Griffiths 1981; Whitehouse 1984). This reflects the high infiltration rates of pumice soils and the less-than-average rainfall of the study period. The differences between the annual exports of the study catchments reflected previously stated differences in the hydrology and physical characteristics of the catchments. The pasture catchment would probably export more sediment than the other two catchments during years of greater-than-average rainfall when storm events were more common because the pasture catchment would produce proportionally greater quantities of surface runoff and hence higher peak flows and sediment discharges.

TABLE 7—Sediment discharge – water discharge relationships*

	y	a	b	x	n	r^2
Pasture	$\log_{10}$ (SD)	–6.7	2.1	$\log_{10}$ (Q)	138	0.55
Pine	$\log_{10}$ (SD)	–1.6	0.97	$\log_{10}$ (Q)	161	0.23
Native	$\log_{10}$ (SD)	–4.5	1.8	$\log_{10}$ (Q)	37	0.45

* SD is sediment discharge (mg/s/km^2)
Q is water discharge (ml/s/km^2)
Relationship of form $y = a + b.x$

IMPLICATIONS FOR WATER AND LAND MANAGEMENT

The results of this study have some important implications for land and water managers who are considering land use changes, particularly in the central North Island of New Zealand. Three land use changes are occurring and the direction of some of the effects measured in this study can be used elsewhere in the region. The following comments are applicable only once the conversion process is completed and do not relate to the actual period of conversion when considerable catchment disturbance is possible. The conversion of native forest to pasture is likely to result in increased storm flow volumes, peak flow rates, low flows, annual average flows, and sediment yields, while evapotranspiration is likely to decrease. This study suggests, however, that sediment yields from small catchments could be reduced in small and moderate storms by allowing or encouraging grass growth in stream channels.

The conversion of native forest to pine forest would not result in large differences in hydrologic response. Differences between the hydrologic response of the native and pine forest catchments in this study can be attributed to differences in rainfall, drainage density, and the position of the drainage network within the catchment. The relative yield of sediment in small to moderate storms would depend on the channel condition. If the channel condition remained the same then the author would expect similar sediment discharges.

The effects of converting a pasture catchment to pine forest have been partially discussed by Dons (1981) using data from these catchments from 1969 to 1980. Analysis of the subsequent 4 years of data in this study confirm that peak flows, average flows, and low flows are all reduced, while evapotranspiration losses increase. This study shows that erosion and sediment yield are also likely to be less under a stable pine forest.

CONCLUSIONS

Annual pasture catchment flows, after the adjustment of catchment area, were on average 2.1 and 1.6 times those from the pine forest, and the native forest catchments respectively. Evaporative losses from the native and pine forest catchments were similar and 33% greater than from the pasture catchment. Peak flows from the catchments were ranked pasture > pine > native, with low flows ranked native > pasture > pine. Stormflow yields were small (0.54–5.2% of gross rainfall) and for most storms in the native and pine forest catchments could be accounted for by rainfall on to the stream channel and associated wetlands. Differences in the hydrological behaviour of the pine and native forest catchment could be accounted for by differences in the drainage density and channel location and not necessarily by vegetation differences. The pasture catchment showed occasional large surface runoff and groundwater flows although all three catchments exhibited the potential for large rapid groundwater flows in response to sustained rainfall on wet catchments. Sediment concentrations ranged from near zero to 13 000 mg/*l* with average values ranked native > pasture > pine and maximum values ranked pasture > native > pine. Sediment discharges also varied widely (0.27–10 350 000 mg/s/km^2) with maximum values and average values ranked pasture > native > pine. The yield of sediment from these catchments, in small to moderate storms, appeared to depend on the amount of grass growth within the channel and whether or not sediments in the stream channel were available for transport. This study indicates that management of the stream channel, in pumice catchments, to ensure good vegetation growth would reduce sediment yield and channel erosion. Annual rates of sediment export were small by New Zealand standards and were crudely estimated at 27, 22, and 4.0 t/yr/km^2 for the native forest, pasture, and pine forest catchments, respectively.

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