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HYDROLOGY AND WATER CHEMISTRY CHANGES AFTER HARVESTING SMALL, INDIGENOUS FOREST CATCHMENTS, WESTLAND, NEW ZEALAND

L. K. ROWE & B. D. FAHEY
Forest Research Institute, PO Box 31-011, Christchurch, New Zealand

ABSTRACT After a 2-to-3 year calibration period, four of six small (1.63 to 4.62 ha) catchments on the west coast of New Zealand's South Island were subjected to various harvesting treatments and then were planted in *Pinus radiata*. Streamflow yields increased after treatment up to 550 mm year^{-1}, but increases were not in the order expected from a ranking of treatment severity. After about 7 years of vegetation regrowth, streamflow seemed to stabilize at a level about 200 mm year^{-1} lower than that before treatment. The burnt catchments had the largest initial increases in streamwater electrical conductivity and cation and NO_3^- concentrations, but, apart from K^+, these returned to pre-treatment levels in about 2 years. Unburnt catchments with riparian reserves were least affected. After treatment, cation yields were highest for the catchment with the largest runoff amounts.

INTRODUCTION

The hydrological and geochemical consequences of harvesting the indigenous forest on the west coast of the South Island of New Zealand are not well known. Westland has a distinctive rainfall regime (up to 3000 mm per year with rain occurring about 25% of the time) and the forest is broad-leaved and evergreen, which makes it difficult to extrapolate results from catchment studies in other temperate forests (Hibbert, 1967; Langford, 1976; Bosch & Hewlett, 1982). In 1971, the harvesting of extensive areas of forest in Westland was proposed. This study was initiated to address concerns about the potentially detrimental effects of clearfelling and burning of indigenous forests on streamflow yield, flood hydrology, water chemistry, and aquatic habitats. Changes in streamflow yield and streamwater chemistry for up to 9 years after harvesting small experimental catchments and replanting them with *Pinus radiata* are described.

STUDY CATCHMENTS

Six small catchments (1.63 - 4.62 ha) at Maimai, in the headwaters of the Mawheraiti River, northwestern South Island, New Zealand (42°05'S, 171°48'E), have been monitored since 1974. The natural vegetation is an evergreen mixed forest dominated by podocarps and *Nothofagus* species. The catchments lie parallel to each other facing southwest. Local relief is in the range 100-150 m and slopes are short (<300 m) and steep (mainly above 25°). The area is underlain by early Pleistocene Old Man Gravel, a moderately weathered, firmly compacted conglomerate that is poorly to moderately permeable. The soils are shallow (average profile thickness 60 cm) stony podzolized yellow-brown earths (typic dystrocrepts and humults), with the combined litter and humus layer averaging 17 cm thick.

Two catchments, M6 (1.63 ha) and M15 (2.64 ha), were left in natural vegetation as controls. The other four catchments were subjected to different treatments, and are listed in order of increasing severity of treatment:

a) M13, 4.25 ha, clearfelled except for 10% riparian reserve, planted directly among the logging debris.
b) M5, 2.31 ha, clearfelled, no riparian reserve, sprayed from air with desiccant, planted directly among the logging debris.
c) M8, 3.84 ha, clearfelled except for 5% riparian reserve, burnt, planted.
d) M14, 4.62 ha, clearfelled, no riparian reserve, burnt, planted.

Logs were extracted using a downhill skyline cable system. Within 2 years of treatment, bracken (*Pteridium esculentum*) and Himalayan honeysuckle (*Leycesteria formosa*) had densely clothed the catchments.

STREAMFLOW, RAINFALL, AND WATER CHEMISTRY DATA

Reliable streamflow data for all six catchments are available from 1977 to 1987 (except for short periods during felling operations) from water-level recorders on combination V-notch weir/sediment traps. Rainfall has been recorded at two sites, Lower Maimai near catchments M5, M6 and M8, and Upper Maimai near catchments M13, M14, and M15. Between 1975 and 1987 annual rainfall at Lower Maimai ranged between 1890 and 3000 mm and averaged 2450 mm. Rainfall is evenly distributed between April and December, with January to March slightly drier. Comparison with a nearby 80-year rainfall record indicates that rainfall during the study was slightly above average, although highly variable.

Sampling for streamwater chemistry began in 1975 and stopped in 1984. For the first 2 years, water samples were collected manually during storm periods only. More intensive sampling became possible when up to four automatic samplers were installed for various periods. From mid-1979, weekly samples were collected regularly, in addition to those during storms.

RESULTS AND DISCUSSION

Water balance of the undisturbed forest

The average annual streamflow yield for the 11-year period 1977-1987 from the two indigenous forest control catchments, M6 and M15, was 54% of annual rainfall. For catchment M6, streamflow was 1320 mm and mean annual rainfall was 2435 mm at Lower Maimai; for M15 streamflow was 1260 mm and mean annual rainfall at Upper Maimai was 2300 mm. Annual interception loss for the indigenous forest in Maimai catchment M8 has been estimated as 26% of rainfall (Rowe, 1979). Permeability of the underlying gravels is variable, and loss to deep groundwater that does not appear as streamflow in these small catchments has been estimated at 100 mm year^{-1} (Pearce & Rowe, 1979). Changes in soil water and groundwater storages are assumed to have had a negligible effect on the 11-year averages.

Using these values and transpiration loss as the residual in the following water balance equation, the mean annual water balance (in mm) for the two indigenous forest catchments, M6 and M15, over the period 1977-1987 was:

$$\begin{array}{ccccccccc} \text{Rainfall} & = & \text{Streamflow} & + & \text{Interception} & + & \text{Transpiration} & + & \text{Seepage} \\ 2370 & & 1290 & & 620 & & 360 & & 100 \end{array} \qquad (1)$$

The high interception loss (620 mm) can be explained by the high total but low average intensity of the area rainfall. At Lower Maimai, 23% of clock hours (an average of 2015 hours per year) have rain of 0.1 mm or greater. If all evaporation from the wet canopy occurred during the hours of rainfall, the evaporation rate needed to satisfy interception loss would be 0.32 mm h^{-1}. As the canopy continues drying after rainfall ceases, the evaporation rate needed to satisfy interception loss is lower than this, although Pearce & Rowe (1981) showed mean wet canopy evaporation rates at Maimai of 0.46 mm h^{-1} in summer and 0.28 mm h^{-1} in winter. The transpiration estimate also is supported by the transpiration rate of 3.0-3.2 mm day^{-1} during dry days (<1.0 mm) in summer and 0.5-0.6 mm day^{-1} in winter calculated for a similar beech/hardwood forest in Nelson, 80 km north of Maimai (Benecke & Evans, 1987). For the Maimai area, an average of 208 dry days with average transpiration at 1.8 mm day^{-1} gives an annual transpiration estimate of 375 mm. This compares favorably with the residual of 360 mm in the annual water balance for catchments M6 and M15.

Effects of harvesting and regrowth on streamflow yield

Streamflow increased after harvesting, but individual catchment responses to treatment were variable and not in the order expected from the perceived severity of treatment.

To predict the change with time of extra streamflow that results from harvesting, relations of the type used by Kovner (1956) were developed:

$$\text{extra streamflow} = a + b\ \text{Log (years since harvesting)} \qquad (2)$$

This relation was modified to consider the decrease in annual streamflow with time since planting, rather than harvesting, which allows inclusion of the effects of the burning operations and rainfall term, as done by Swift & Swank (1981). The equations in Table 1 were obtained using a stepwise regression procedure.

TABLE 1 Relations between annual streamflow at Maimai catchments M5, M8, M13 and M14, annual rainfall at Lower Maimai (LM) or Upper Maimai (UM), and years since planting (Y).

$$\begin{array}{llll} M5 = & -160 - 770\ \text{Log}\ Y + 1.03\ LM & & r^2 = 0.96 \\ M8 = & -510 - 3.4\ \text{Log}\ Y + 0.89\ LM & & r^2 = 0.98 \\ M13 = & -640 - 270\ \text{Log}\ Y + 1.06\ UM & & r^2 = 0.99 \\ M14 = & -560 - 53\ \text{Log}\ Y + 0.90\ UM & & r^2 = 0.96 \end{array}$$

Estimated annual streamflow patterns after planting obtained, using the relations in Table 1, showed a good correlation with the measured streamflow, as illustrated by M5 (Fig. 1a). However, streamflow change after harvesting is masked by the highly variable annual rainfall, and the trend is clarified by plotting the differences in measured streamflow between catchment M5 and the control catchment M6 (Fig. 1b).

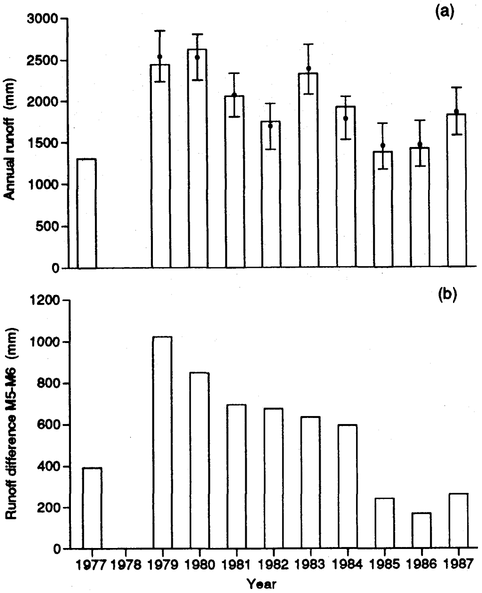

FIG. 1 Streamflow from Maimai catchment M5 (mm): a) Annual measured streamflow (histogram) and streamflow predicted from the equation in Table 1 (shown as the line with 95% confidence limits) and b) the difference between streamflow measured at catchment M5 and that measured at the control catchment M6. Note that streamflow from catchment M5 was about 400 mm greater than that from M6 during 1977 when both catchments were in undisturbed forest.

Catchment M14 was expected to have the greatest increase in streamflow after harvesting, at least in the short term, as it was subjected to the most severe treatment. However, the weir was demolished by a falling tree near the end of the harvesting operation and again by a debris avalanche about 2 years later, so that some crucial data during the period of rapidly changing streamflow yield after treatment are missing.

Catchment M5 showed the largest measured increase in streamflow; in the first year after planting, the yield was 550 mm more than that predicted for its undisturbed state. The background yields were computed from monthly streamflow regression relations for the adjacent control catchment, M6. Streamflow at M5 increased for about 8 months after harvesting because the residual vegetation became desiccated after herbicide treatment.

Although this increase is large compared to many overseas studies (for examples, see Hibbert, 1967 and Bosch & Hewlett, 1982), the interception loss, which is effectively removed after harvesting, is even larger (about 680 mm or 26% of the 2625 mm annual rainfall for 1979). This is augmented by reduced transpiration (about 350 mm) but some interception by dead vegetation and evaporation from bare soil does occur.

After the next year, when streamflow yield from M5 averaged about 45 mm month^{-1} more than that predicted if undisturbed, streamflow steadily decreased. At about 7 years after harvesting, streamflow seems to have stabilized at 15 mm month^{-1} lower than the predicted level for M5 if undisturbed.

At catchment M8, streamflow for the first year after burning and planting was about 260 mm more than that measured at M6. This was more than from catchment M13, the other catchment with a riparian reserve left unlogged, and reflected the loss of residual vegetation by burning. The decline in streamflow after harvesting did not reach pre-treatment levels until after about 7 years. Whether streamflow for M8 has now stabilized cannot be ascertained because the weir was destroyed by a debris avalanche in July 1989.

At catchment M13, pine seedlings were planted directly into the logging slash and undergrowth which was left after clearfelling. Streamflow increased by more than 200 mm in the first calendar year after harvesting. This was less than for M5 where residual vegetation was killed by herbicide application, and for M8, where the residual vegetation (except for the riparian reserve) was burnt, as much of the live understorey was retained after harvesting. Streamflow diminished to pre-harvest levels within 2 years as the residual vegetation recovered, and bracken and honeysuckle invaded the catchment.

A longer record would be needed to confirm this level of streamflow, but the trend indicates that the vegetation cover of bracken, honeysuckle, and young trees is using more water than the original forest cover, a pattern also reported after wildfires in Australia where dense eucalypt regrowth had higher water use than mature forest (Langford, 1976). In lower rainfall environments, open-grown bracken has evapotranspiration rates of over 5 mm day^{-1} and an interception loss of over 40% of rainfall (Pitman & Pitman, 1986). These rates are higher than those used to estimate the indigenous forest water balances here and supports the interpretation that the invading scrub cover could have higher water use than the original forest cover. In other studies water use by a revegetating cover of herbaceous and woody species rapidly negated any increases in streamflow yield after harvesting (Hornbeck, 1975; Baker, 1986).

Streamwater chemistry of the undisturbed forest

For the period 1975 to 1984 mean daily electrical conductivity (EC, a surrogate for instantaneous total dissolved solids concentration) was 21.5 $\mu S\ cm^{-1}$ for control catchment M6 and 23.3 $\mu S\ cm^{-1}$ for control catchment M15. The measurements for the other catchments during the pre-treatment periods all fell within this range. The quantity of dissolved material removed (TDS) annually, calculated with Mosley & Rowe's (1981) regression equation, was 145 kg ha^{-1} for each control catchment.

Mean concentrations of the cations K^+, Mg^{2+}, and Ca^{2+} for the two control catchments (M6 and M15) for the 10-year period 1975 to 1984 ranged from 0.28 to 0.68 mg l^{-1}. The means for Na^+ were 2.6 and 3.0 mg l^{-1} for M6 and M15, respectively. Nutrient concentrations for the control catchments were invariably low; total P, PO_4^{3-} and NH_4^+ were normally <0.01 mg l^{-1}, and NO_3^- averaged 0.05 mg l^{-1}. Mean annual concentrations of NO_3^- before treatment for all catchments ranged from 0.01 to 0.12 mg l^{-1}. These concentrations are less than or equal to those for other relatively undisturbed mixed evergreen forests in New Zealand (McColl *et al.*, 1977; Graynoth, 1979).

Mean annual cation yields for the period 1977-1984 from M6 and M15 were 51 and 58 kg ha^{-1}, respectively (Table 2). The estimated cation input from rainfall was 55 kg ha^{-1}, suggesting that cation inputs approximately balance cation output in the undisturbed catchments. The dominant cations in rainfall are Na^+ (59%) and K^+ (25%), reflecting the major influence that oceanic cycling has on rainfall chemistry in the Maimai area.

TABLE 2 Mean annual nitrate and cation yields, in kg ha^{-1}, for the Maimai catchments for the 8-year period, 1977-1984.

Catchment	NO_3^-	Na^+	K^+	Mg^{2+}	Ca^{2+}	Cation Total
M6	0.4	36.	3.6	4.1	7.3	51.
M15	0.5	40.	4.6	4.7	8.2	58.
M5	2.6	59.	23.0	10.3	19.0	111.
M8	2.7	43.	18.0	8.6	19.0	89.
M13	1.2	48.	17.0	7.1	13.0	85.
M14	1.2	37.	19.0	8.6	24.0	88.

Effect of treatments on streamwater chemistry

Changes in EC after treatment reflected the presence or absence of a riparian reserve and the amount of debris in the channel. Maximum mean daily EC was 95 μS cm^{-1} at M14 (no riparian reserve, burning, and logging debris in the stream channel). Maximum instantaneous EC was greater than 1000 μS cm^{-1} which occurred during the first small storm, 8 days after burning. EC was above average at M14 for 3 years after treatment. Yields of TDS in the 2 years after burning were about 3 times those for control catchment M6. At M5 (no riparian reserve, herbicide sprayed), the increase in EC was less than at M14, but more sustained, reflecting the slower decay of the dead vegetation. It took 6 years for EC to decrease to pre-treatment levels in M5. EC for M8 (riparian reserve, burning) had returned to pre-treatment levels after 2 years and TDS yields for the 2 years after burning were about twice those for M6. M13 (riparian reserve), had the smallest increase in EC. The EC for M13 decreased to levels below that of the control catchments in 2 years after treatment. A similar trend was evident in the TDS data.

The immediate post-treatment increases in mean monthly sum of concentrations for the four cations followed the expected order of response matching the severity of catchment treatment: M14 > M8 > M5 > M13.

At catchment M14, K^+ levels peaked at 183 mg l^{-1} shortly after burning in mid-February 1978. This was accompanied by a 10-fold increase in the peak concentrations of Mg^{2+} and Ca^{2+}. Levels of Na^+ were the least affected, peaking at 17 mg l^{-1}. For the other catchments the responses to treatment were similar but less pronounced. Concentrations typically returned to pre-treatment levels in 18 months for Na^+, Ca^{2+} and Mg^{2+}, but returned to background in 6 years for K^+ at catchment M5. EC and concentrations of Na^+ and sum of cations were inversely related to flow, whereas K^+ showed a weak positive relation with flow. These relations are consistent with results reported elsewhere (Johnson & Swank, 1973; Talsma & Hallam, 1982).

After treatment, catchment M8 showed the greatest increase in mean annual concentration of NO_3^-. The mean for 1981 increased to 0.56 mg l^{-1}, with a maximum of 1.65 mg l^{-1}. The NO_3^- concentration at M5 showed a similar but less pronounced increase after treatment with a maximum of 0.83 mg l^{-1}, followed by M14 with a maximum of 0.73 mg l^{-1}, and M13 with a maximum of 0.51 mg l^{-1}. Mean annual concentrations for NH_4^+ at M14 showed a slight but short-lived increase after burning, with a maximum of 1.18 mg l^{-1}.

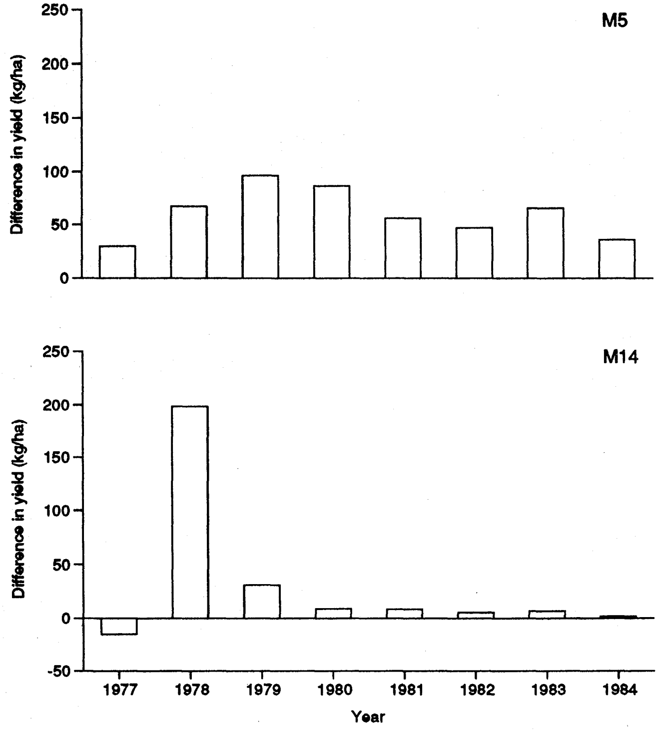

FIG. 2 Cation yields (kg ha^{-1}) for M5 (clearfelled, no riparian reserve) and M14 (clearfelled and burned, no riparian reserve) expressed as the difference between the yield from the catchment in question and that for the nearest control catchment.

The most immediate and spectacular changes in cation yields after treatment were observed in catchment M14. Immediately after burning, monthly mean output of K^+ and Ca^{2+} increased from of 0.35 and 0.70 kg ha^{-1} to 35 and 22 kg ha^{-1}, respectively. These peaks were short-lived and within 1 year yields had fallen to less than 2 kg ha^{-1} per month. This pattern was repeated but in a more subdued form at the other three catchments. On an annual basis, different land preparation techniques had a marked influence on the pattern of cation yields. In contrast to the rapid rise and fall in cation yield for M14, the increase for M5 was less spectacular but more prolonged (Fig. 2). Mean annual output from catchment M5 (111 kg ha^{-1}) for the 8-year period after treatment was considerably greater than that for the other catchments, including M14 (88 kg ha^{-1}). Because the only difference in treatment for these two catchments was the burning of M14, results suggest that this management option can cause a major initial loss in nutrients, but its impact on streamwater chemistry may be less over the long term.

Although Na^+ dominated the cation yield, percentage increases in K^+ yields were the largest, increasing by a factor of 5 for M5 and 3.5 for M14 (Table 2). The NO_3^- yields from M5 and M8 also were 5 times more than from the control catchments; yields from the other treated catchments were from 2 to 3 times more.

The largest increase in K^+ output for M5 (clearfelling, no burning, no riparian reserve) compared to M14 (clearfelled, burnt, no riparian reserve) is noteworthy, particularly since

M14 experienced much higher post-treatment K^+ concentrations. However, these high concentrations in M14 were short lived, whereas the higher than average K^+ concentrations persisted for 6 years for M5. Finally, total cation yield from the catchments, i.e M5 > M8 > M14 > M13, is inconsistent with the anticipated severity of disturbance, but it is in the same order as streamflow volumes during the same period. Thus, while high cation and nutrient concentrations are encouraged by burning and the absence of a riparian reserve, the management option that has the largest impact on runoff also will have the largest impact on cation and nutrient yields.

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