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HYDROLOGY OF MID-ALTITUDE TUSSOCK GRASSLANDS, UPPER WAIPORI CATCHMENT, OTAGO
I — EROSION, SEDIMENT YIELDS AND WATER QUALITY

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ABSTRACT

During a 4-year study period, sediment yields from two small tussock catchments underlain by schist bedrock in the East Otago uplands South Island, New Zealand, were 42.8 m^3 and 12.6 m^3 respectively. The sediment yield rates (4.9 and 1.0 $m^3\ km^{-2}yr^{-1}$) suggest that the East Otago uplands have low erosion rates. Surface erosion and mass wasting were not common on the catchments' slopes, and most sediment delivered to the streams derived from channel scouring and bank collapse during large floods. Suspended sediment concentrations ranged from less than 2 mg/*l* to 430 mg/*l* and the streamwaters remained clear (less than 15–20 mg/*l* sediment concentration) about 97 percent of the time. Stream pH averaged 6.8, stream conductivity ranged from 12.4 to 54.8 $\mu S\ cm^{-1}$ and stream temperature ranged between maxima of 16°-19°C in summer and minima of 0°-3°C in winter.

INTRODUCTION

In July 1979, a paired catchment experiment was set up in Glendhu State Forest, on the southern Lammerlaw Range, East Otago uplands, South Island, New Zealand, to study the hydrological implications of converting lightly-grazed, slightly modified, narrow-leaved snow tussock grassland to *Pinus radiata* plantation. The two experimental catchments, one treatment and one control catchment, are located in the upper Waipori river valley approximately 12 km north of Lawrence township.

One objective of the study was to determine the erosion status of the catchments under lightly modified tussock grassland and to examine the export of sediment from the catchment. A second objective was to determine the quality of the catchments' streamwater. In this paper we discuss the sediment yields from the experimental catchments and their streamwater quality during

TABLE 1: Channel widths and slopes, Glendhu experimental catchments.

	G1	G2
Mean channel slope	0.055	0.037
Mean channel slope of bedrock sections	0.081	0.072
Mean channel slope of alluvial gravel/sand sections	0.037	0.024
Mean slope of channel from weir to 300 m above weir	0.057	0.060
Mean channel width	2.30 m	1.90 m

a 4-year period both before conversion and during early conversion from tussock to pines.

PHYSICAL SETTING OF STUDY CATCHMENTS

The study catchments form part of the southern extremities of the Lammerlaw Rise, an uplifted and tilted block of quartzo-feldspathic schists belonging to the Haast schist group (McKellar, 1966). The two adjacent north-facing catchments are 218 and 310 ha in area, with rolling-to-steep topography ranging in altitude from 460 m to 670 m a.s.l. Location and topographic maps are given by Pearce *et al.* (1984)(this issue), who also describe the rainfall climate and hydrologic regime. Across-valley slope profiles indicate lower slopes are gently concave to planar, but mid and upper slopes are dominantly convex. Mean slope, based on 35 measurements of average slope from crest to valley bottom, is approximately 28°. The dendritic drainage pattern is characterised by short (< 400 m long), first-order streams which commonly rise in amphitheatre-like heads. Where streams traverse peat bogs in gully and valley bottoms, channels are often poorly defined.

Two types of channel occur in both experimental catchments (Fig. 1). The steeper channel reaches consist of a series of bedrock falls or riffles separated by bedrock-floored pools; here sediment storage is confined to the pools. The lower-gradient sections of the channel have developed in gravel, sand and silt alluvium and commonly have coarse gravel beds, often with outcrops of bedrock forming narrow ledges at irregular intervals. In meandering sections of these channels, well-developed point bars occur on the inside curves of bends. Details of channel widths and slopes are presented in Table 1. The lower reaches of both streams are deeply incised into bedrock.

Periglacial processes have been important in the genesis of the landscape (Leslie 1973, Hewitt 1982). Discontinuous mantles of colluvium are distributed over the mid and lower slopes, and have tended to smooth the slope forms by infilling ancient gullies and depressions.

Soils vary from well-drained, loessic silt loams over 1.5 m deep on slopes up to 30° (Mahinerangi hill soils and Waipori hill soils) to shallow, stony, silt loams less than 0.2 m deep on steep slopes of over 30° (Nardoo steepland

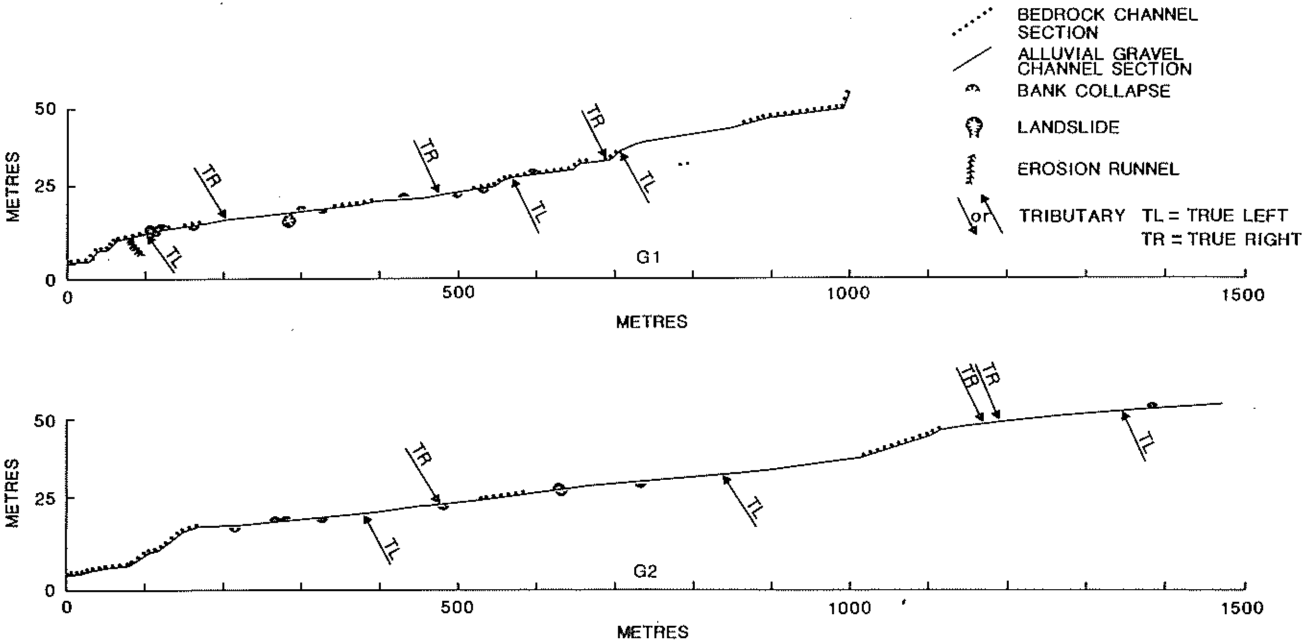

FIG. 1: Longitudinal profiles of G1 and G2 streams showing locations of alluvial and bedrock channels.

soils). On the gentle-sloping hill crests, well-defined iron pans develop in the subsoils of poorly drained silt loams (Lammerlaw silt loams). In the valley bottoms, poorly-drained peaty soils and heavily mottled silt loams occupy streamside areas and lower slope debris fans (Bungtown peats and Pioneer silt loams).

Over most of the catchment area the vegetation is dominated by swards of narrow-leaved snow tussock (*Chionochloa rigida*), often with an associated ground cover of brown top (*Agrostis tenuis*) and sweet vernal (*Anthoxanthum odoratum*). On the poorly-drained valley bottom peats, red tussock (*Chionochloa rubra*), *Juncus*, *Carex* and *Sphagnum* species are the main components of the vegetation. Occasional thickets or scattered individuals of manuka (*Leptospermum scoparium*), *Cassinia vauvilliersii* and *Hebe odora* occur on most slopes but particularly on steep rocky slopes with shallow soils (Nardoo steepland soils). Detailed descriptions of the tussock grassland communities on the Lammerlaw r[illegible]eral kilometres north of the study catchments are provided by Bulloc[illegible]

Both catchments were lightly grazed by sheep, at an average stocking rate of between 1 stock unit/2 ha and 1 stock unit/ha, until late 1982, when the treatment catchment (G2) was retired from grazing. In preparation for planting, G2 was "ripped" with a bulldozer equipped with a triangular-shaped ripping blade in December 1981. Ripping lines were spaced about 3.5 m apart and were generally located on the contours on slopes less than 20°. Ripping was not carried out on the valley bottom wetlands. Ripping generally caused little surface disturbance, but where soils were shallow, bedrock boulders were often dragged to the surface and the tussock/grass cover was often overturned, exposing the regolith. G2 was planted with *Pinus radiata* seedlings (2/0) at a rate of 1280 seedlings/ha in June 1982.

INSTRUMENTATION AND METHODS

Large, broad-crested, concrete V-notch weirs similar to the type described by Holtan *et al.* (1962) were constructed near the mouth of each catchment. Concrete-lined stilling ponds, approximately 0.6 m × 6.2 m × 6.2 m, upstream of the weirs serve as sediment traps. An automatic water sampler was established in the stilling pond close to the weir notch at the treatment catchment to extract approximately 400 ml samples at predetermined intervals. Automatic sampling of streamwater during flood flows was supplemented by manual sampling at the weir notch using plastic, wide-mouthed, 1-litre flasks. Water samples were forwarded to the Forest Research Institute laboratories in Christchurch for analyses of suspended solid concentrations by filtration methods. Electrical conductivity and pH of streamwater samples were measured at the Forest Service headquarters at Lawrence, usually within a few hours of collection. Conductivity was measured with a Metrohm E527 conductivity meter, and conductivity readings were corrected to correspond with a temperature of 25°C. pH was measured with an Orion 399A pH meter.

Temperatures of the streams at the weirs were measured with mercury thermometers during collection of water samples. Automatic submersible Ryan model J. thermographs have been installed in the weir ponds of both catchments since early 1982.

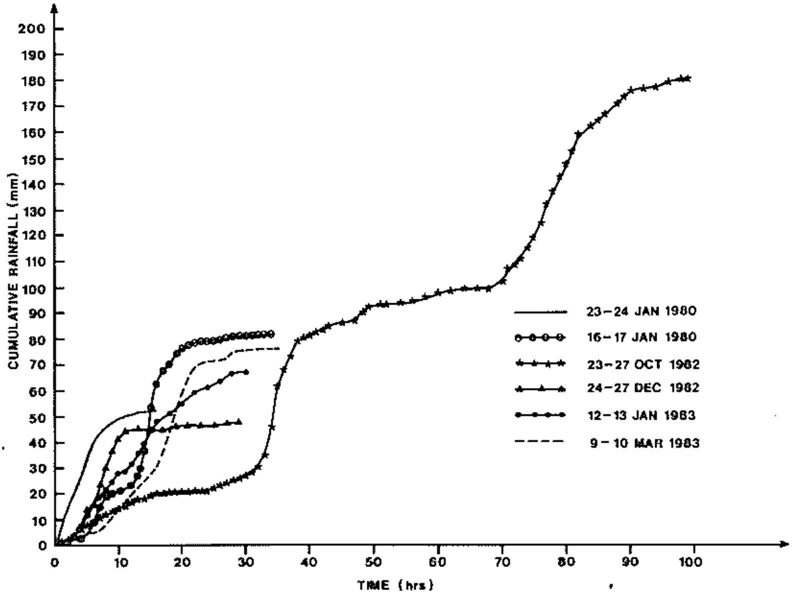

FIG. 2: Cumulative precipitation for five storms at Glendhu catchments.

On average, approximately 200 samples of water were taken each year from each catchment.

The volumes of materials collected in the sediment traps have been assessed at infrequent intervals, usually after large storms. Deposit thicknesses were surveyed using stadia rod and level methods similar to those described by Mosley (1981). The quantities of sediment passing through the traps and over the weirs were determined for individual large storms from storm water discharge and suspended sediment data.

SEDIMENT YIELDS

During 48 months of monitoring (July 1979 to July 1983), the experimental streams transported significant quantities of sediment on only six occasions when large spring, summer or autumn rain storms caused streamflows to exceed 10 *l*/sec/ha, except in one storm (12 January 1983) when peak flow in G2 reached only 9 *l*/sec/ha. Cumulative rainfalls for the five storms exceeding 10 *l*/sec/ha are shown in Fig. 2.

The quantities of suspended sediment discharged over the weirs were measured for only three of these storms (24 May 1980, 24 October 1982, 10 March 1983, Table 2). For these storms, measured suspended-sediment concentrations during the rising, peak and falling stages of the storm hydrographs were combined with stream discharge measurements, and total suspended-sediment discharges were calculated for the storm flow periods. For the storm discharges on 16 January 1980 and 12 January 1983, only limited data on suspended sediment were available for the recession part

TABLE 2: Precipitation, peak discharge and sediment yield data for six sediment-producing storms in the Glendhu experimental catchments.

DATE	PEAK DISCHARGE		PRECIPITATION			SEDIMENT					
	G1	G2				G1			G2		
	Qmax l/sec/ha	Qmax l/sec/ha	Total mm	Max./hr mm	Duration hrs	SS* m^3	BL** m^3	T*** m^3	SS* m^3	BL** m^3	T*** m^3
16. 1.80	34	30	82	14	33	6.00	12.80	18.80	3.00	3.50	6.50
24. 5.80	13	14	68	7	36	0.50	2.00	2.50	0.50	0.50	1.00
24.10.82	14	13	178	16	96	3.00	10.00	13.00	1.80	1.50	3.30
25.12.82	16	12	49	5	23	1.20	—	1.20	0.50	—	0.50
12. 1.83	12	9	67	8	27	1.00	—	1.00	0.30	—	0.30
10. 3.83	15	13	76	8	15	3.00	3.30	6.30	0.80	0.20	1.00
TOTAL YIELD FOR ALL STORMS						14.20	26.10	42.80	6.40	5.20	12.60
MEAN SEDIMENT YIELD RATE						$4.91\ m^3\ km^{-2} yr^{-1}$			$1.02\ m^3\ km^{-2} yr^{-1}$		

* SS = suspended sediment yield estimate
** BL = sediment retained in bed load trap
*** T = total sediment yield

of the storm hydrographs for either catchment. No suspended sediment data were available for the storm flows on 25 December 1982. For these three storms, estimates of suspended sediment concentrations based on the measured concentrations for similar stage heights from the monitored storm flows (24 May 1980, 24 October 1982 and 10 March 1983) were used to provide estimates of suspended-sediment discharge.

Over the 4-year study period, the control catchment, G1, yielded 42.8 m^3 of sediment and treatment catchment G2 yielded 12.6 m^3, which are equivalent to sediment yield rates of 4.9 and 1.0 m^3 km^{-2}yr^{-1} respectively (Table 2). These rates are low compared to those from hill country in undisturbed indigenous forest in North Westland (55 m^3 km^{-2}yr^{-1}) where the hills are steeper and climate wetter than at the Glendhu experiment area (O'Loughlin *et al.*, 1978). Denudation rates for the South Island mountainlands to the east of the main divide are typically hundreds of m^3 km^{-2}yr^{-1} (O'Loughlin and Pearce, 1982). Although short-term records (4 years) may not be good indicators of the long-term sediment yield rates from the Glendhu catchments, they nevertheless suggest that the landforms of the Lammerlaw Rise are stable and have low erosion rates.

During the large storm on 16 and 17 January 1980, 18.0 and 6.5 m^3 of soil and rock materials were transported to the weirs at G1 and G2 respectively. This storm produced a maximum rainfall depth of 81 mm in 24 hours, which is calculated to have a return period of about 10 years. The 6-hour and 12-hour depths and longer return periods, according to the information and procedures outlined by Tomlinson (1980). This storm caused widespread flooding and damage in Southland and Otago and was generally considered to be a storm of rare occurrence. Except for one small slump where about 10 m^3 of soil had moved 1 m downslope in a mid-slope hollow in G1, and a number of stream bank collapses, no landsliding or other forms of slope erosion resulted from the storm rainfall on the experimental catchments. The January 1980 storm caused substantial scouring along the main stream channel banks and in the streambeds. In the lower reaches of both catchments, rock pools partly filled with gravel and boulders were scoured to their schist rock floors by the flood flows. Minor bank collapses were common along the lower and middle reaches of both main streams (Fig. 1), and in G1, part of a small streamside terrace had been stripped of its cover of grasses and tussocks. Apart from these disturbances in and adjacent to the main-stream channels, the storm had little influence on the stability of the slopes, tributary gully bottoms or debris fans at the mouths of the tributary gullies.

The storm on 16–17 January 1980 accounted for 46 percent of the total sediment yield from both catchments during the 4-year study period. Approximately half of the total volume of sediment which accumulated in the sediment traps during this storm consisted of schist boulders over 0.1 m mean diameter and up to 0.9 mean diameter.

The large storm on 24–27 October 1982 dumped 178 mm of rain and snow on the Glendhu catchments and caused 13.0 m^3 and 3.3 m^3 of sediment to be transported to the G1 and G2 weir sites respectively. In G1, a large percentage of the material came from a small riparian debris slide which deposited approximately 6 m^3 of soil material directly into the main stream channel. This slide was caused by the stream under-cutting a basal slope on the concave side of a bend, resulting in failure of the shallow soil overlying the bedrock.

Surveys of the stream channels and banks showed that bank collapses and the small slide described above deposited a total of approximately 43 m^3 of soil and rock materials into the G1 stream channel during 1980, 1981, and 1982. Over the same period, bank collapses deposited approximately 17 m^3 of material in the G2 steam. The total sediment delivered to the weirs during 4 years (42.8 m^3 and 12.6 m^3) indicate that input and output of sediment were in close agreement, suggesting that the transport capacity of the streams equals or exceeds present sediment supply rates. Simple continuity equations summarise the erosion — sediment conditions in the catchments over the 4-year period.

Inflow (erosion) — Outflow (sediment yield) =Δ storage in channels
G1 43 m^3 — 42.8 m^3 = 0.2 m^3
G2 17 m^3 — 12.6 m^3 = 4.4 m^3

WATER QUALITY

Because of their importance to the flora and fauna inhabiting the streams, suspended solid concentrations, pH, electrical conductivity (which provides an index of the total dissolved ionic load) and stream water temperatures have been measured. Concentrations and outputs of the various ionic species in the experimental streams have been measured but these data are not presented here.

Suspended Solid Concentrations

Suspended-solid (sediment) concentrations ranged from less than 2 mg/*l* to 430 mg/*l* for G1 (418 samples) and from less than 2 mg/*l* to 140 mg/*l* for G2 (400 samples). Log/log plots of suspended-solid concentrations (C) vs. instantaneous stream discharge at the time of sampling (Q_i) for 1980 and 1981 produce a wide scatter (Fig. 3), a consequence of small catchment size and relatively small stream discharges enabling individual sediment inputs to influence stream-sediment concentrations significantly. Hysteresis in the behaviour of C and Q_i during storm flows also contributes to the scatter. Sediment-rating relationships for small basins and the errors caused in sediment-yield estimation have been discussed by Walling (1977), Walling and Webb (1981), and Van Sickle and Beschta (1983).

When suspended-solid concentrations exceeded 15 to 20 mg/*l*, the experimental streams became noticeably discoloured. Discoloration in G1 could be expected at specific flows exceeding approximately 0.46 *l*/sec/ha, and in G2 at specific discharges exceeding 0.48 *l*/sec/ha (Fig. 3). Such flows occur less than 3 percent of the total time according to the flow duration curves for the experimental streams.

Ripping of G2 in December 1981 did not appear to influence significantly either the concentrations of stream-suspended sediment or the total discharge of sediment. However, road construction around the true right perimeter of G2 in late 1980 caused a brief period of sediment dicharge from the road into the headwaters of a G2 tributary gully. Most of this sediment remained stored in the floor of the tributary gully until a small storm on 20 November

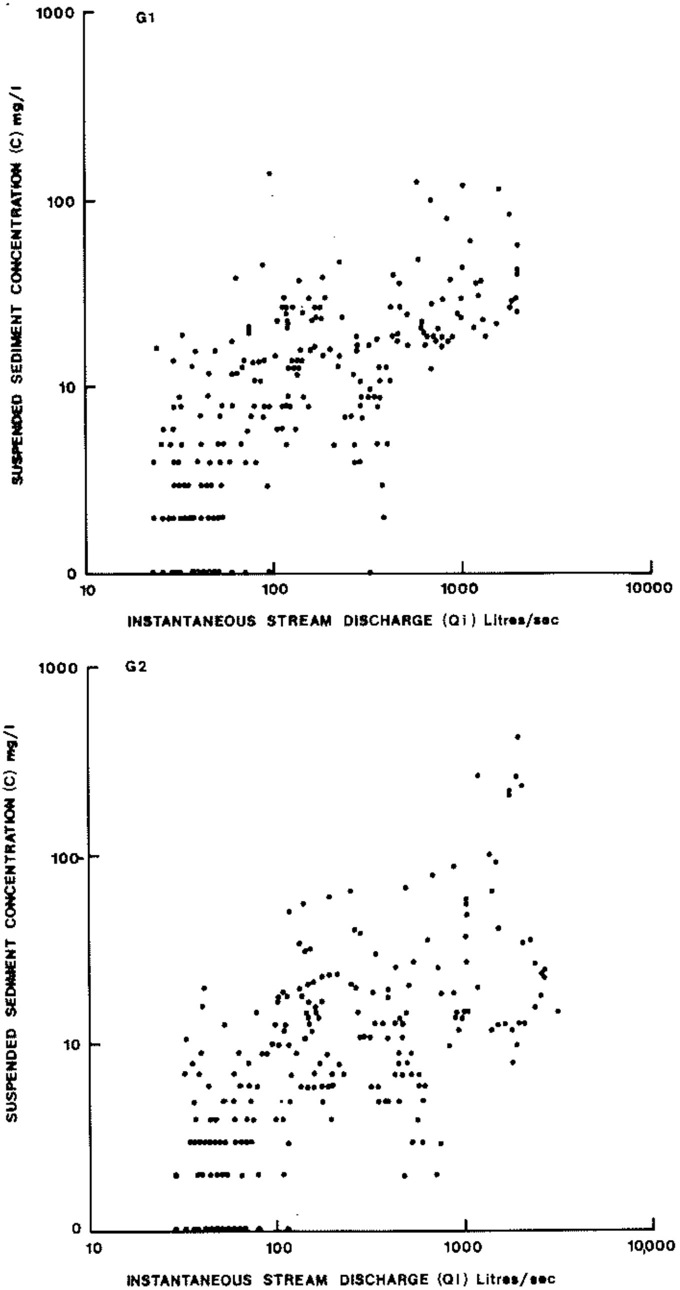

FIG. 3: Suspended sediment concentrations vs. stream discharge for G1 and G2, 1980 and 1981.

TABLE 3: Summary of pH data for Glendhu experimental catchments

Year	Max.	Min.	Mean	Std Dev.	Sample No.
G1					
1979	7.4	6.5	7.0	0.2	78
1980	7.3	5.6	6.6	0.4	97
1982	7.6	5.9	6.8	0.4	136
G2					
1979	7.4	6.4	7.0	0.2	77
1980	7.3	5.7	6.6	0.4	97
1982	7.5	5.6	6.8	0.4	137

1980, when sediment from the gully head found its way into the main stream, causing marked discoloration and the highest suspended sediment concentration measured so far (433 mg/*l*).

pH

pH data for both streams are summarised in Table 3 and the trends in pH over the 4-year study period are shown in Figures 4 and 5. Mean pH for individual storms, for monthly periods and for years were not significantly different between streams. Streamwater pH ranged from 7.6 to 5.9 (mean 6.8) for G1 and G2 respectively. A depression in pH values occurred in both experimental streams between December 1980 and January 1982. The mean annual pH for 1981 was approximately 1 pH unit lower than the values for 1980 and 1982, and it is suspected that this may be related to malfunctioning of the pH probe rather than a real increase in stream acidity. Repeated sampling through storm flow periods indicated that pH was not markedly influenced by changing discharge during individual storms (Fig. 6). The pH fluctuations in the Glendhu experimental streams lie well within the range of pH values not directly toxic to fish (pH 5 to 9, NWASCO 1981).

Conductivity

Electrical conductivity ranged between 12.4 and 54.8 μS cm^{-1} for G1 and G2 respectively. Mean annual conductivities showed little variation between years and between catchments over the 4 years of study (Table 4). There is a consistent reduction in conductivity with increasing stream discharge during individual storms (Figs 4, 5, and 6). Mean conductivity during 1979–1983 for both catchments during stormflows over 0.5 *l*/sec/ha was 29.0 μS cm^{-1} compared to 39.3 μS cm^{-1} for flows less than 0.5 *l*/sec/ha. The relationships between conductivity (SC) and discharge (Q_i) are given by the following regression equations:

G1 SC = 37.71 (±1.02) – 0.02 (±0.0001) Q_i [N = 455, F = 237.5, R^2 = 0.34]
G2 SC = 37.69 (±0.64) – 0.01 (±0.0001) Q_i [N = 456, F = 629.9, R^2 = 0.58]

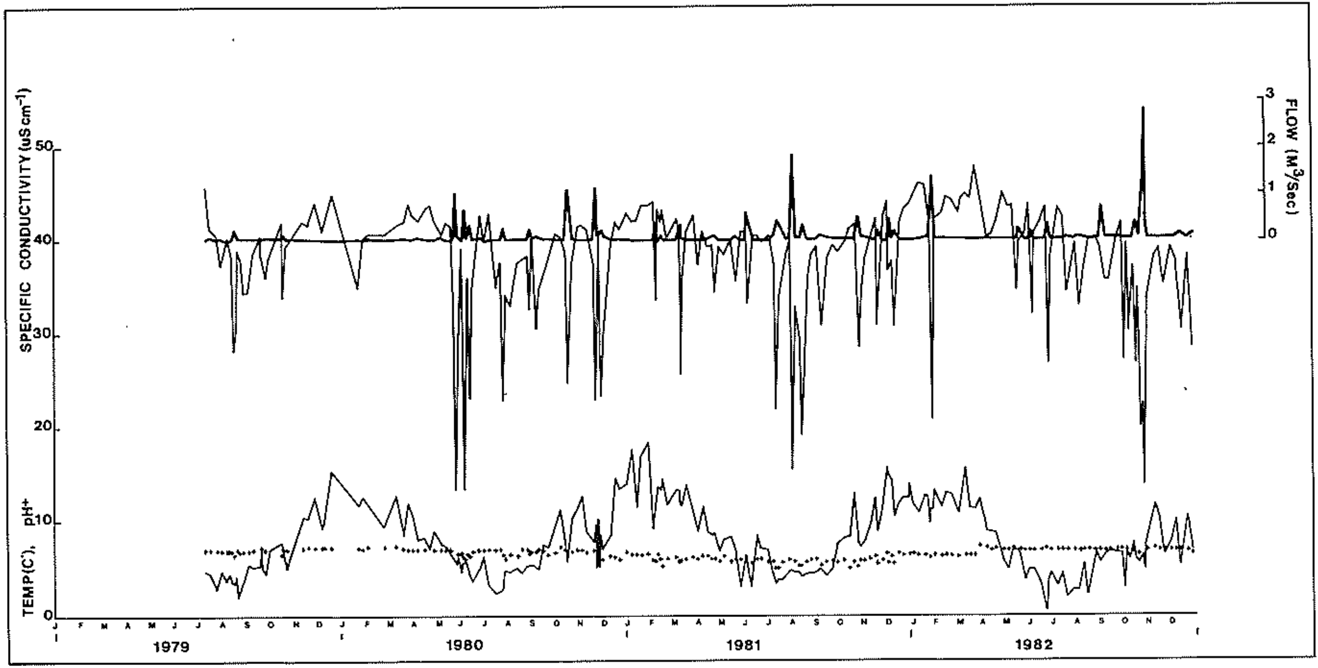

FIG. 4: Changes in stream discharge, specific conductivity, pH, and temperature 1979–1982 for G1. Plots are based on water sample data collected at irregular intervals and do not represent a complete record of changes during the study period.

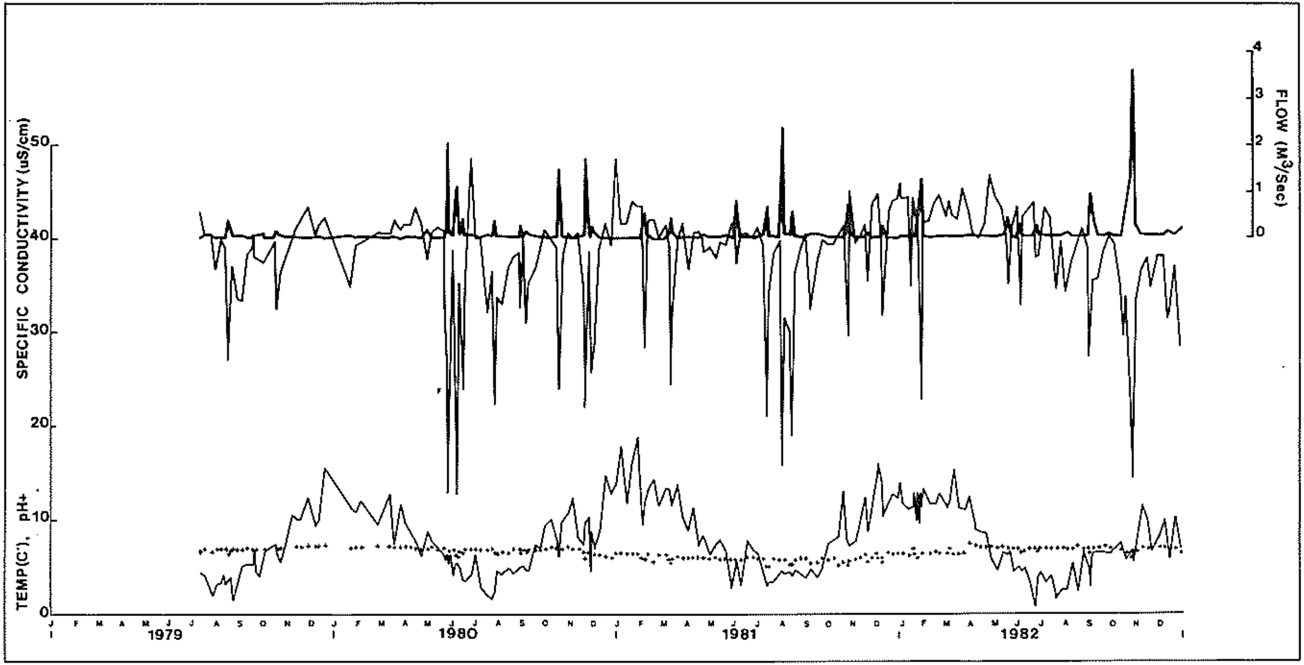

FIG. 5: Changes in stream discharge, specific conductivity, pH, and temperature 1979–1982 for G2. Plots are based on water sample data collected at irregular intervals and do not represent a complete record of changes during the study period.

TABLE 4: Summary of electrical conductivity data for Glendhu experimental catchment

Year	Max.	Min.	Mean	Std Dev.	Sample No.
G1					
1979	54.8	25.3	36.7	5.8	78
1980	44.0	12.7	31.1	9.4	87
1981	46.4	14.4	33.3	8.8	139
1982	48.0	12.4	33.5	7.9	136
G2					
1979	47.5	23.7	36.3	5.5	77
1980	43.6	12.4	30.7	9.3	97
1981	46.2	14.4	33.9	9.3	141
1982	46.8	12.6	32.7	8.4	137

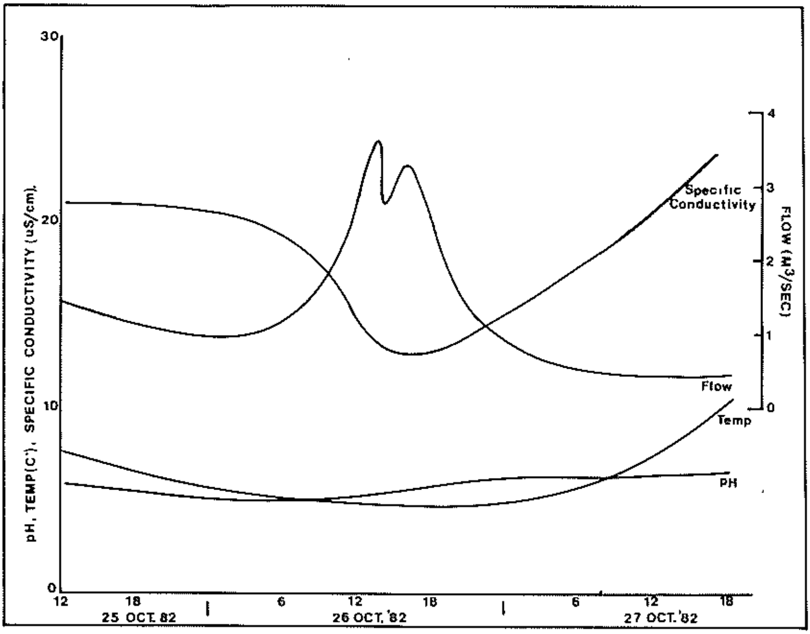

FIG. 6: Changes in stream conductivity, pH and temperature in catchment G2 during passage of a storm in October 1982.

The relatively low conductivities of the Glendhu streams imply that total dissolved ionic loads in the streamwaters are low.

Temperature

Steam temperatures ranged between 16°C to 19°C (January/February/March) and 0°C to 3°C (June/July/August). Mean annual stream temperatures approximated 7.5°C in both catchments. Since curve analysis of the temperature data presented in Figures 5 and 6 provided equations of the following form —

$$T = a \sin (bx + c) + \overline{T}$$

where T = predicted stream temperature °C on day x
a = amplitude of the sine surve °C
b = radians/day
c = phase coefficient of sine curve in degrees
$\overline{T}$ = mean annual temperature °C
x = number of days since 1 January

Similar sine curve analyses have been used by Ward (1963) and Johnson (1971) for studying annual variations in stream tempatures. The best fitting sine curves have correlation coefficients of over 0.99 and are highly significant.

G1 $T = 4.5 \sin (0.017\,x + 1.14) + 8.5$
G2 $T = 4.7 \sin (0.017\,x + 1.16) + 8.4$

Diurnal stream temperature ranges varied from 0.1°C on overcast winter days to over 4°C on fine summer days.

Compared to intact forested catchments in North Westland (Maimai experimental catchments) and Nelson (Big Bush experimental catchments), the annual and diurnal variations in stream temperatures are greater in the essentially unshaded, north-facing Glendhu catchments. However, maximum stream temperatures at Glendhu do not attain those in recently clearfelled and burnt forest catchments at Maimai, where mid-afternoon summer stream temperatures often exceed 20°C despite the south aspects of these catchments (unpublished FRI data). The larger heat storage capacity of the Glendhu streams, which maintain discharges exceeding 0.1 *l*/sec/ha throughout most of the summer, compared to the smaller Maimai streams probably accounts for the lower summer maximum temperatures in the Glendhu streams.

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