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Sediment yields from a forested and a pasture catchment, coastal Hawke's Bay, North Island, New Zealand

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Abstract

This study compares the suspended sediment load from two catchments, one in pasture (7.95 km^2) and the other in a mature exotic plantation forest (3.45 km^2) for a 29-month period (January 1995–May 1997) before harvesting. Both catchments are underlain by gently dipping Tertiary sediments capped with gravels, volcanic ash, and loess. The mean annual rainfall is 1300 mm, but the annual variability is large. Streamflow is measured with broad-crested weirs, and suspended sediment concentrations are monitored with automatic water samplers. The sediment yield response to nine storms was monitored in both catchments and when the calculated suspended sediment yields were summed, the catchment in pasture generated almost 2.5 times the amount of sediment per unit area compared with the one in forest. Initially, sediment rating curves based on log–transformed concentration and instantaneous flow data were used in conjunction with flow duration curves to estimate annual suspended sediment yields, but the scatter in the plots was unacceptably high. Instead, the relationship between peak discharge and storm suspended sediment load for both catchments was used to estimate the total yields. The total suspended sediment yield for the forested catchment (January 1995–May 1997) was estimated at 32.7 (± 3.0) t /km^2, and for the catchment in pasture at 104.4 (± 8.3) t/km^2, which is roughly three times the former. Between a quarter and a third of the total suspended sediment was contributed by one storm. Bedload made up less than 1% of the total sediment yield.

Introduction

The Hawke's Bay region of the east coast of New Zealand's North Island is underlain by fine-grained, weakly indurated Tertiary marine sediments. Much of the land was cleared of indigenous forest and scrub and converted to pasture before the turn of the century (Guthrie-Smith, 1969). Page and Trustrum (1997) used evidence from sediment cores recovered from Lake Tutira in northern Hawke's Bay to deduce historic rates of sedimentation. They found that rates under pasture were 8–17 times higher than those under indigenous forest, and concluded that the conversion of indigenous forest, initially to a fern-scrub combination and more recently to pasture, has increased landsliding and hillslope channel erosion, as well as sheet and tunnel gully erosion.

Numerous plantation forests have been established over the years on the soft rock hill country of coastal Hawke's Bay, many of which will soon be ready for harvesting. Concern has been expressed that harvesting these forests may cause a renewed phase of erosion. We know little about long-term sediment yields from catchments that have been planted and harvested, compared with those that have remained in pasture over the same period.

In 1993 a catchment research project was established to compare the relative impacts of forest harvesting and pasture farming on sediment yield and stream water quality in the steep hill country of coastal Hawke's Bay, so that "best management practices" and policies can be developed to sustain soil and water resources while maximising production. This paper compares the sediment yield from a catchment in pasture with that of an adjacent one with a mature exotic forest cover.

Field area

The catchments chosen for the study are the Tamingimingi (7.95 km^2) and the Pakuratahi (3.45 km^2) located 18 km north-west of Napier (Fig. 1). They are representative of the coastal hill country between Napier and Wairoa formed on unstable Tertiary rocks and overlain by a thin cover of loess and volcanic ash. The catchments are steep. For example, 49% of the slopes in the Pakuratahi exceed 20°, and in the Tamingimingi 23% exceed 20° (Fransen, pers. comm.). Local relief is likewise considerable (20–350 m).

Lithologically the area comprises a gently dipping (5–10°) sequence of Pliocene-Pleistocene strata (Haywick *et al.*, 1991). Four main rock units underlie the two catchments (from oldest to youngest): the Te Ngaru Formation (a silty mudstone), the Waipataki Formation (a calcareous sandy limestone), the Devil's Elbow Formation (a silty mudstone), and the Kaiwaka Formation (a coarse-grained shelly sandstone interbedded with limestone). Coarse-grained units form prominent scarps while their fine-grained counterparts form the gentler slopes between the scarps. Springs located at the basal contact of limestone units in the Kaiwaka Formation serve as important sources of streamflow, and can maintain base flow for long periods. On upper slopes and ridge-tops the Kaiwaka Formation is overlain by greywacke alluvium (the Ohakean Gravels) with a mantle of ash and loess.

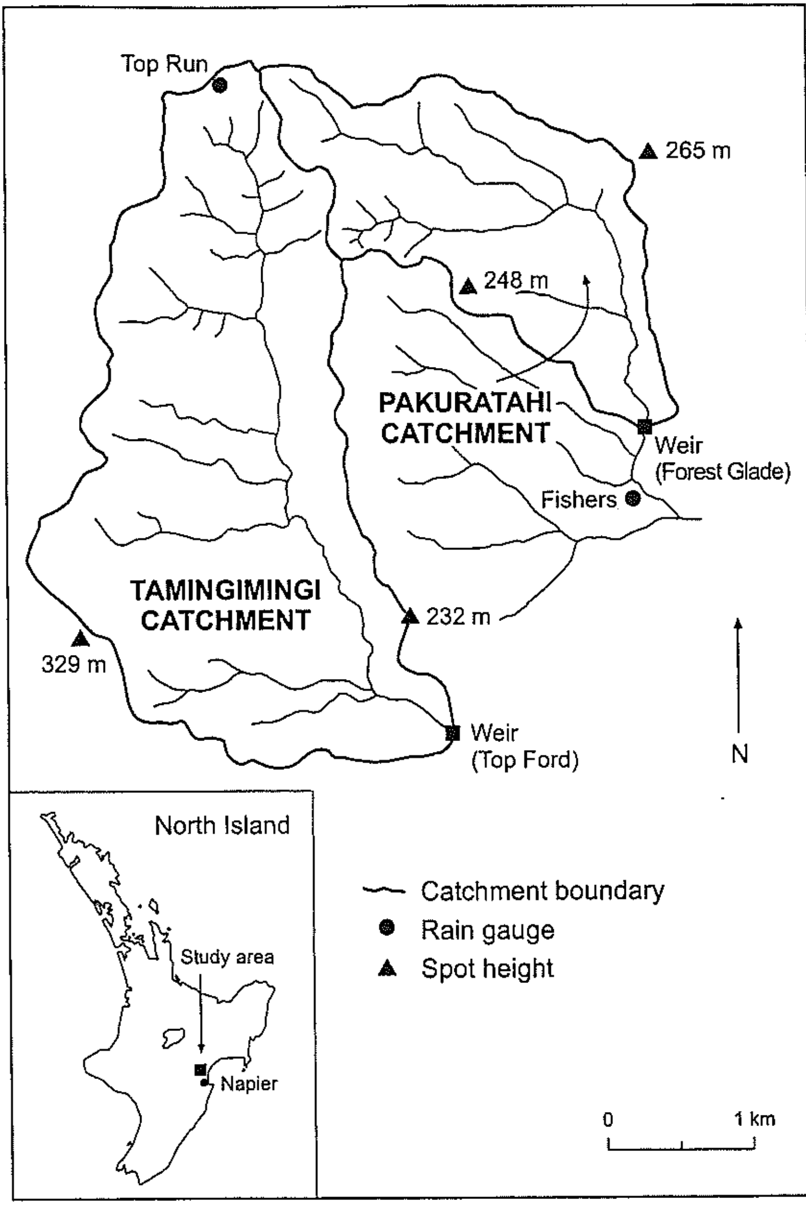

Figure 1 – Location map of study area showing the Pakuratahi and Tamingimingi catchments.

The Kaiwaka Formation is areally dominant in both catchments, outcropping over 64% of the Tamingimingi, and 50% of the Pakuratahi (Fransen and Brownlie, 1996). Ohakean Gravels occupy 35% of the Pakuratahi catchment, but only 5% of the Tamingimingi. Large-scale (0.10–1.00 km^2) bedrock landslides in both catchments pre-date ash believed to have been deposited 3500 years ago.

Pallic soils (Hewitt, 1998) are common on the coastal hill country north of Napier. They exhibit greyish weakly structured top soils and yellowish subsoils. Some profiles display a thick massive horizon at approximately 45 cm depth (New Zealand Soil Bureau, 1954), and are referred to as Duric Pallic (Hewitt, 1998). Pohlen *et al.* (1947) show Crownthorpe sandy loams to be the most common soil in the Tamingimingi catchment, with Matapiro sandy loams restricted to the interfluves. Both soils may have hard pans, which can impede drainage. Seepages may occur on lower slopes. In the steeper Pakuratahi catchment, Tangoio silty loams predominate, with isolated patches of Matapiro sandy loams. These soils are all prone to surface erosion and mass movement.

The Hawke's Bay region experiences warm summers with frequent strong drying winds from the north-west. Winter temperatures are moderate. The mean annual air temperature for Tangoio, 5 km north of the catchments, is 13.3°C (February 18.0°C and July 8.4°C) (New Zealand Meteorological Service, 1983). The mean annual rainfall (1951–1980) at Tangoio is 1501 mm, of which 54% falls in the winter half year of April to September (New Zealand Meteorological Service, 1983). The mean annual rainfall for Napier (1900–1980) is 824 mm. Annual rainfall variability is high. At Tangoio for example, the lowest recorded annual total is 966 mm, and the highest is 2496 mm. The 5-year return period totals for 1 h and 24 h are 26 and 184 mm respectively (Tomlinson, 1980). Droughts are common in spring and summer.

The rainfall regime during the period of the study included a dry year (1995), a wet year (1997), and one close to the average (1996). The catchment mean annual rainfall during this period, based on two rain gauges (one at the head of the catchments and the other at the base), was 1300 mm.

The Tamingimingi has been intensively grazed since the 1900s, but the steeper and more difficult terrain of the Pakuratahi was allowed to revert to scrub. The Pakuratahi was planted in *Pinus radiata* in 1971–72. Road clearance and landing construction in preparation for harvesting began in the lower reaches of the Pakuratahi catchment in mid-1997. This activity coincided with two large storms in June and July which caused a series of roadside slope failures. Thus, for the purposes of this study the pre-harvest period is taken to be from January 1995 to May 1997.

Methods and instrumentation

Data collection

A Unidata Star logger-tipping bucket automatic rain gauge was installed in each of the catchments in 1994. One of these (Fishers) is located 400 m downstream from the Pakuratahi weir at an elevation of 60 m above sea level, and the other (Top Run) is located at the head of the Tamingimingi catchment at an elevation of 360 m (Fig. 1).

Streamflow is monitored at Crump-type weirs. Pakuratahi (Forest Glade, NZMS V20: 438997) was constructed in September 1993, and Tamingimingi (Top Ford, NZMS V20: 424977) in September 1994. Water levels are measured with Stevens A71 float-operated chart recorders. Both were coupled to a float-operated shaft encoder in February 1995. Stage heights are recorded with Campbell CR10 data loggers. Although they can be read to a resolution of ±1 mm, actual stage heights are recorded only if the current reading changes by ±4 mm from the previous one. The rating of flow with stage height at the Pakuratahi weir is based on 38 gaugings between 1993 and 1997. Of these 61% lie within ±8% of the rating curve. The standard deviation for the curve is 10.3%. For the Tamingimingi, 21 gaugings were used to establish the rating, and 86% of these lie within ±8%. The standard deviation is 5.7%. Storm quickflow was separated from delayed flow using the procedure outlined by Hewlett and Hibbert (1967). The hydrographs indicated that a separation line with a slope of 0.0055 L/s/ha/hr was appropriate for both catchments.

A 24-bottle Sigma water sampler with a CR10 logger attached was installed initially at the Pakuratahi in February 1994 to sample suspended sediment, but did not produce reliable results until early in 1995. A second Sigma water sampler was installed just above the Tamingimingi weir in February 1995. Both were set to trigger at predetermined stage heights on the rising and falling limb of the storm hydrograph, and to collect samples at intervals of 30 to 60 minutes. Occasional adjustments were made to the trigger levels during the course of the study. Samples were vacuum-filtered and oven dried to determine suspended sediment concentrations. Sediment load for a given period (e.g., a storm) is measured in t, and sediment yield in t/km^2 per unit time.

Bedload was not sampled. However, in August 1996 paving stones were laid in a checkerboard pattern immediately behind the weir in both catchments to serve as a base level on which to measure depth of sediment accumulation. A total of four cross sections were installed along a 6–m reach immediately upstream of the Pakuratahi weir, and 11 cross sections covering a 42–m long reach were installed upstream of the Tamingimingi weir. Changes in the profile of these cross sections were used to establish sediment storage and removal. Sediment depths were measured in April 1997. The cross sections were surveyed at the same time.

Analytical procedures

Suspended sediment yields for selected storms were calculated by multiplying the flow for a given interval during the storm by the average suspended sediment concentration for the same interval, and summing these over the duration of the storm. Only those storms with a strong positive relationship between suspended sediment concentration and instantaneous discharge were chosen for analysis.

The conventional approach for estimating longer term (e.g., annual) suspended sediment yields involves the construction of a sediment rating curve. This relies on the relationship between suspended sediment concentration and flow, which, if strong enough, can be used in conjunction with flow duration or flow time series data to estimate total suspended yields. In this instance the data points exhibited considerable scatter, a situation normally attributed to hysteresis. To reduce the arithmetical impact of this scatter, and to make the data homoscedastic, suspended sediment concentrations and their associated instantaneous flows were log transformed and a linear regression model fitted to the data.

The sediment rating curve technique does not reliably estimate suspended sediment yields if hysteresis–loop ratings show inconsistencies in shape, position, and phase (Hicks, 1988; Hicks and Harmsworth, 1989). As an alternative, the long-term average suspended sediment yield can be estimated using the storm yield rating method which exploits the relationship between storm peak flow and suspended sediment yield to estimate the yield for all storms in a given interval (Basher *et al.*, 1997; Hicks, 1990).

In this study the storm suspended sediment load and peak flow data for both catchments were log transformed and a least-squares regression model used to establish the relationship between the two parameters. Storms for the period January 1995–May 1997 were extracted from the database as discrete quickflow events, the peak flows identified, and individual suspended sediment yields calculated from the regression equation. These were summed to estimate total yields associated with all quickflow events for both catchments. The 95% confidence intervals for the annual yields were calculated following the procedure outlined by Basher *et al.* (1997). An attempt was made to estimate the amount of sediment associated with delayed flow between storms based on suspended sediment concentrations sampled during low flow periods and on storm recession limbs. However, they showed considerable scatter when related to the corresponding instantaneous discharge, and have not been included in the analyses to estimate total suspended sediment loads.

Table 1 – Suspended sediment yields and associated peak discharges for storms recorded at the Pakuratahi and Tamingimingi weirs between January 1995 and May 1997.

	Pakuratahi		Tamingimingi	
Date	**Yield (t)**	**Pk.Q (l/s)**	**Yield (t)**	**Pk.Q (l/s)**
5/4/95	6.2	535	*	*
1/5/95	0.4	204	*	*
18/6/95	0.5	218	*	*
5/7/95	1.1	253	12.1	1050
15/7/95	0.2	206	8.1	1310
3/8/95	*	*	4.3	1070
18/9/95	*	*	0.1	191
1/11/95	0.2	210	2.0	736
16/1/96	0.2	220	*	*
26/1/96	*	*	0.1	271
9/2/96	4.6	680	*	*
28/2/96	0.1	202	*	*
3/3/96	0.2	121	*	*
31/3/96	*	*	236.0	6548
23/6/96	8.9	785	42.8	3204
4/7/96	0.6	354	13.4	2055
10/8/96	2.3	537	*	*
30/12/96	7.5	850	70.1	3655
19/2/97	0.4	419	0.2	415
11/3/97	3.4	650	12.8	1764
23/3/97	1.0	518	*	*
27/5/97	4.3	509	6.0	973

* no data available

Results and discussion

Suspended sediment yields for individual storms

From January 1995 to May 1997, 18 storms were sampled in the Pakuratahi catchment for suspended sediment concentrations, and 13 storms were sampled in the Tamingimingi catchment (Table 1). In the Pakuratahi, the storm sediment loads ranged from 0.1 to 8.9 t, and in the Tamingimingi, from 0.1 to 236 t. Nine storms were monitored in both catchments concurrently (Table 2). Specific yields per storm from the Tamingimingi catchment normally exceeded those from the Pakuratahi, but there was substantial variation in the relative specific yields for the two catchments from storm to storm. However, when summed over the period, the amount of sediment per unit area from the Tamingimingi was almost 2.5 times that from the Pakuratahi.

Table 2 – Suspended sediment yields for storms monitored concurrently at the Pakuratahi and Tamingimingi catchments between January 1995 and May 1997.

Date	Pakuratahi (t/km^2)	Tamingimingi (t/km^2)
5/7/95	0.28	1.60
15/7/95	0.05	1.02
1/11/95	0.05	0.25
23/6/96	2.58	5.38
4/7/96	0.17	1.68
30/12/96	2.17	8.82
19/2/97	0.11	0.03
11/3/97	1.00	1.61
27/5/97	1.25	0.76
Total	7.66	21.15

Suspended sediment yields based on flow duration

A total of 330 water samples were collected at the Pakuratahi weir, and 316 at the Tamingimingi weir. The former had suspended sediment concentrations that ranged from 0.7 to 7700 mg/l, and the latter from 0.2 to 6400 mg/l. These were matched with their respective instantaneous discharge readings and both sets converted to a log–log scale to generate a sediment rating relationship for each catchment (Fig. 2). The r^2 values for linear regression fits to the log-transformed data were 0.613 for the Pakuratahi, and 0.666 for the Tamingimingi. The spread in the data around these regression lines was substantial in both cases, especially in the low flow range. In the Pakuratahi, for example, it exceeded two orders of magnitude for flows up to about 80 l/s, and up to two orders of magnitude at the Tamingimingi for flows between 100 and 500 l/s.

Most of the 18 storms monitored for suspended sediment concentrations at the Pakuratahi catchment between January 1995 and May 1997 showed either a clockwise hysteresis or little difference between the trends on the rising and falling limbs. Data from the Tamingimingi catchment revealed that, out of the 13 storms monitored for suspended sediment concentrations, 7 showed clockwise hysteresis, 3 showed anticlockwise behaviour, and 3 showed little difference in concentration on either the rising or the falling limb. The latter two categories tended to be associated with comparatively small events. The degree of hysteresis observed in the storm data is thought to explain much of the scatter observed in the sediment rating curve for both catchments.

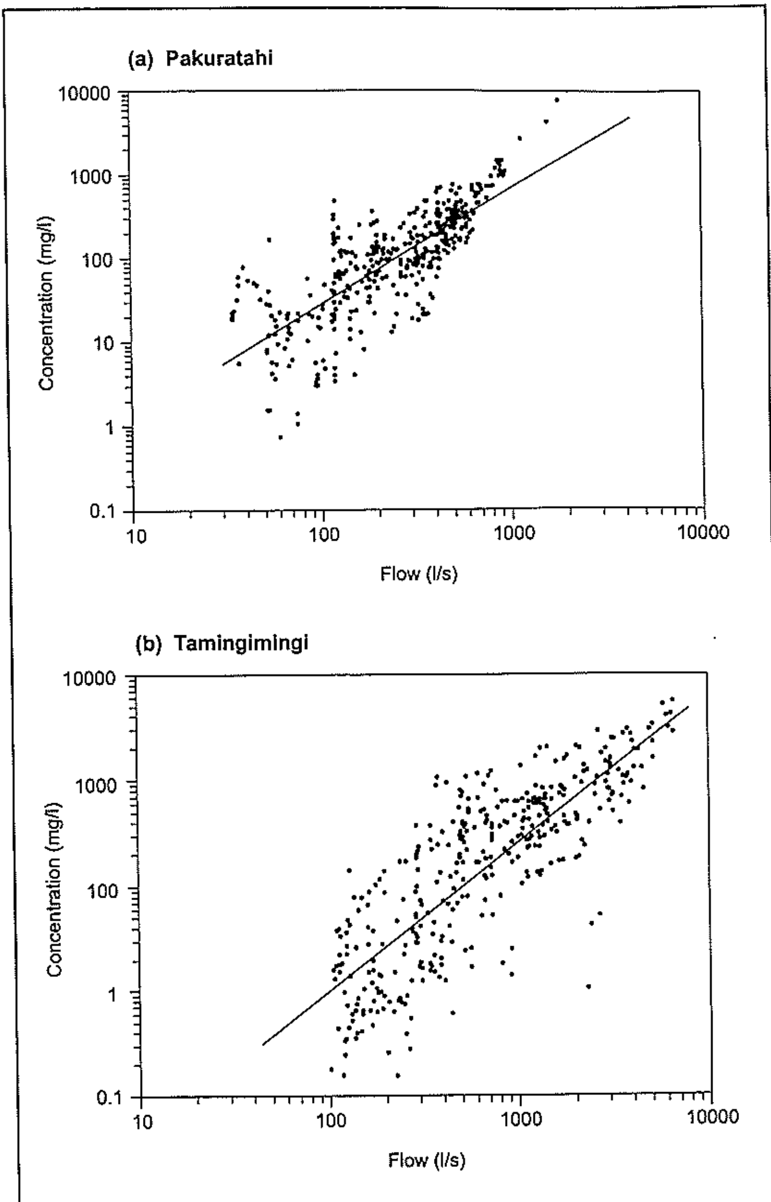

Figure 2 – Suspended sediment concentrations plotted against instantaneous discharge for (a) the Pakuratahi catchment, and (b) the Tamingimingi catchment, with lines of best fit derived from regression analysis.

Table 3 – Suspended sediment load and yield for the Pakuratahi and Tamingimingi catchments for the period January 1995 to May 1997, derived from the relationship between storm loads and associated peak discharges. The figures in brackets are the 95% confidence limits calculated from the procedure described by Basher *et al.* (1997). Catchment flow data are also provided.

	Pakuratahi			Tamingimingi		
Year	**Sed. flow (t)**	**Sed. yield (t/km^2)**	**Flow (mm)**	**Sed. flow (t)**	**Sed. yield (t/km^2)**	**Flow (mm)**
1995	22.2 (± 2.0)	6.4 (±0.6)	270.9	206.1 (±14.3)	25.9 (±1.8)	282.8
1996	63.7 (±5.7)	18.5 (±1.7)	386.7	517.5 (±39.8)	65.0 (±5.6)	428.6
1997 (Jan–May)	26.9 (±2.4)	7.8 (±0.7)	145.8	107.2 (±7.5)	13.5 (±0.9)	238.5
Total		32.7 (±3.0)	803.4		104.4 (±8.3)	949.9

The regression equations derived from the log-transformed data were used to estimate the annual sediment yields, but the calculated error limits were exceptionally large. There is an indication that the Tamingimingi catchment yielded more than double the suspended sediment per unit area compared with the Pakuratahi. However, it is the variability in the relationship between suspended sediment concentration and instantaneous flow that is possibly the most noteworthy feature of this analysis.

Total flow over the period of record for the Tamingimingi catchment was also higher than that from the Pakuratahi, but the difference (146.5 mm) was only 15% of the total flow for the former (949.9 mm) (Table 3). This is substantially less than that reported in the New Zealand literature for experimental catchment studies comparing annual flows from pasture catchments and adjacent ones in forest. Normally, for example, flow from catchments in mature forest is 30–50% lower than that from comparable ones in pasture or tussock grassland (Duncan, 1995; Fahey and Jackson, 1997). The reason or reasons for the small difference in flow between the two catchments is not readily apparent. It is possible that flow from the Pakuratahi is augmented by extra groundwater entering its upper reaches from areas outside its boundaries.

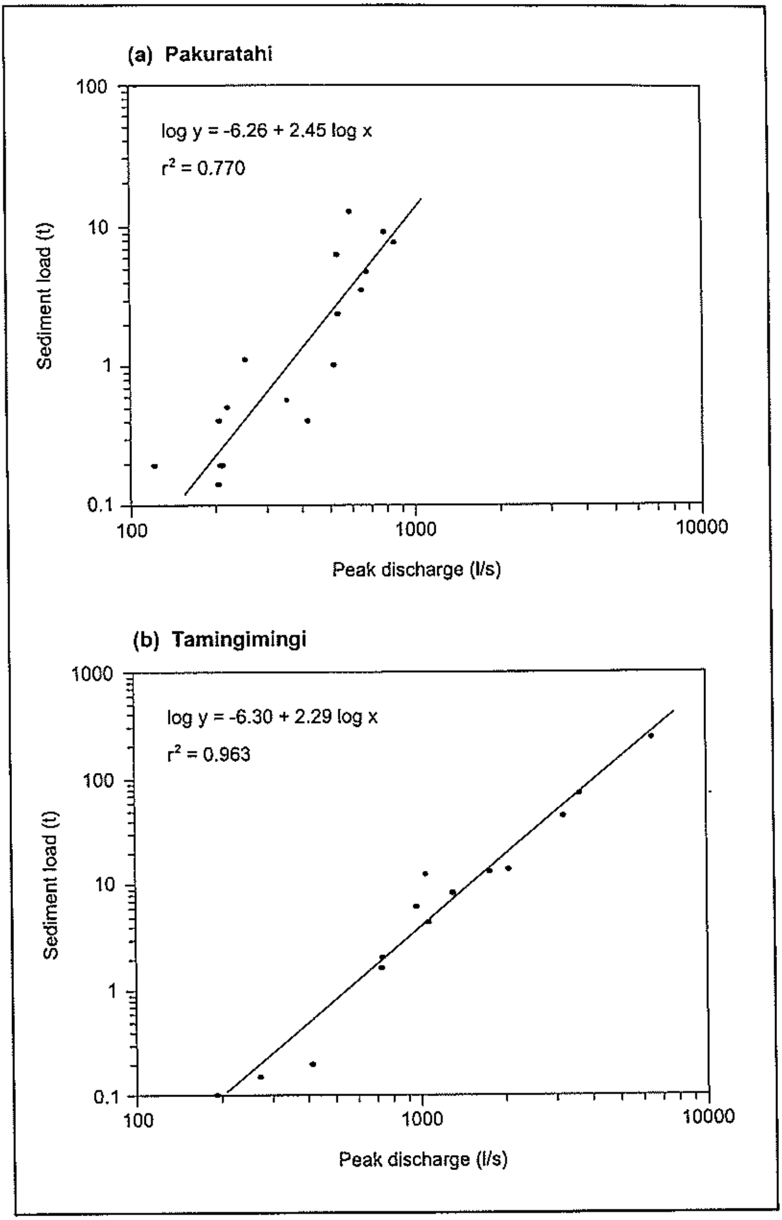

Figure 3 – Relationship between storm-derived suspended sediment yields and instantaneous peak discharges for (a) the Pakuratahi catchment and (b) the Tamingimingi catchment showing lines of best fit derived from regression analysis.

Suspended sediment yields based on peak discharge

Storm-related suspended sediment yields for the two catchments were calculated from the relationship between peak discharge and measured storm suspended sediment loads (Fig. 3). Table 3 shows that between January 1995 and May 1997, the Tamingimingi generated 104.4 (±8.3) t/km^2, which is three times the amount estimated to have come from the Pakuratahi in the same period (32.7 (±3.0) t/km^2). One storm on 31 March 1996 produced 33% and 23% of these amounts from the Tamingimingi and the Pakuratahi, respectively. The average annual sediment loss for 1995–1996 was 45.5 (±3.7) t/km^2 for the Tamingimingi and 12.4 (±1.2) t/km^2 for the Pakuratahi.

Bedload accumulation

Between August 1996 and April 1997 sediment accumulation immediately behind the Pakuratahi and Tamingimingi weirs was 0.39 m^3, and 0.45 m^3 respectively. Assuming an average bulk density of 1600 kg/m^3, these values convert to 0.2 t/km^2 and 0.1 t/km^2 respectively. This is less than 1% of the total suspended sediment yield for the same period in the two catchments. Although minor scouring of the stream bed had occurred at both sites, overall, bed levels behind the respective weirs became adjusted in response to sediment accumulation. Some bedload over-topped both weirs but this was negligible compared with the amounts that built up behind them. For the length of the stream reach monitored by the cross sections there was a total net gain of 0.9 m^3 of sediment above the Pakuratahi weir, and 1.8 m^3 above the Tamingimingi weir. These convert to 0.4 t/km^2 for both catchments or approximately 0.5 t/km^2 per year.

Comparisons with other studies

Dons (1987) compared the sediment regimes of three small catchments in pumice terrain in the central North Island, one in pasture (0.10 km^2), one in pines (0.34 km^2), and one in native forest (0.28 km^2). For the 3-year period 1982–84 the average annual sediment yield for the pine catchment was 4 t/km^2/yr, and for the pasture catchment it was 22 t/km^2/yr, a 5-fold difference. Dons (1987) regarded these yields to be low compared with those noted elsewhere in New Zealand (e.g., Thompson and Adams, 1979; Griffiths, 1981), reflecting the high rates of infiltration in pumice soils. Nevertheless, in keeping with the results of the present study, they do indicate that suspended sediment yields from catchments in pasture are normally higher than those from comparable areas with an exotic forest canopy.

Hicks (1988) presents some preliminary results on suspended sediment yields from 13 small paired catchments (in pasture and mature exotic forest) in Northland, Rotorua, Nelson, and Otago. Over the period 1980–84, one of the Northland pasture catchments (Kokopu) yielded 6 times more sediment per unit area than its forested counterpart (Topuni). Furthermore, when the storm magnitude was plotted against storm sediment yield for all basins, those in pasture yielded 6–8 times more sediment than those in forest. Further analysis of the same data set by Hicks (1990) showed that for a given event, catchments in pasture mobilised on average 2.7 times more suspended sediment than catchments in plantation forestry.

Conclusions

In the steep soft rock terrain of coastal Hawke's Bay, any given storm may generate up to 2.5 times the amount of suspended sediment from pasture catchments compared with those in exotic forest. Because of hysteresis, the scatter in the relationship between suspended sediment concentration and instantaneous discharge is such that the sediment rating/flow duration approach cannot be used to reliably estimate longer term sediment yields. However, the storm rating method suggests that annual suspended sediment yields from catchments in pasture may be higher by a factor of three compared with their counterparts in a mature exotic forest cover. Bedload is a very minor component of the total amount of sediment leaving the catchment. Taken collectively, the results suggest that suspended sediment yields from pasture catchments in coastal Hawke's Bay may be 2–3 times those from similar catchments in plantation forests. The difference noted here in suspended sediment yields between the Tamingimingi and the Pakuratahi catchments is similar to the figures reported in the literature for other New Zealand locations where yields from pastoral and forested land have been compared.

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References

Basher, L.R.; Hicks, D.M.; Handyside, B.; Ross, C.W. 1997: Erosion and sediment transport from market gardening lands at Pukekohe, Auckland, New Zealand. *Journal of Hydrology (NZ) 36:* 73–95.

Dons, A. 1987: Hydrology and sediment regime of a pasture, native, and pine forest catchment in the central North Island, New Zealand. *New Zealand Journal of Forestry 17:* 161–178.

Duncan, M.J. 1995: Hydrological impacts of converting pasture and gorse to pine plantation, and forest harvesting, Nelson, New Zealand. *Journal of Hydrology (NZ) 34:* 15–41.

Fahey, B.D.; Jackson, R.J. 1997: Hydrological impacts of converting native forests and grasslands to pine plantations, South Island, New Zealand. *Agricultural and Forest Meteorology 84:* 69–92.

Fransen, P.J.B; Brownlie, R. 1996: Historical slip erosion in catchments under pasture, pine plantations, scrub, and indigenous forest: a comparison from Cyclone Bola. *New Zealand Forestry 40 (4):* 29–33.

Griffiths, G.A. 1981: Some suspended sediment yields from South Island catchments, New Zealand. *Water Resources Bulletin 17:* 662–671.

Guthrie-Smith, H. 1969: *Tutira. The story of a New Zealand sheep station.* 4th edition, A.H. & A.W. Reed, Wellington.

Haywick, D.W.; Lowe, D.A.; Beu, A.G; Henderson, R.A.; Carter, R.M. 1991: Pliocene–Pleistocene (Nukumuruan) lithostratigraphy of the Tangoio block, and origin of sedimentary cyclicity, central Hawke's Bay, New Zealand. *New Zealand Journal of Geology and Geophysics 34:* 213–225.

Hewlett, J.D.; Hibbert, A.R. 1967: Factors affecting the response of small watersheds to precipitation in humid areas. *In*: Sopper, W.E.; Lull, H.W. (*eds.*), International Symposium on Forest Hydrology, Proceedings of a National Science Foundation Advanced Science Seminar. Pergamon Press, New York, pp. 275–290.

Hewitt, A. 1998: New Zealand soil classification. 2nd edition. *Landcare Research Science Series 1.* Manaaki Whenua Press, Lincoln, New Zealand.

Hicks, D.M. 1988: Differences in suspended sediment yield from basins established in pasture and in exotic forest. In: Proceedings of the New Zealand Hydrological Society Symposium, Dunedin, August 1988, 5 p.

Hicks, D.M 1990: Suspended sediment yields from pasture and exotic forest basins. *In*: Proceedings of the New Zealand Hydrological Society Symposium, Taupo, November 1990, 4 p.

Hicks, D.M.; Harmsworth, G.R. 1989: Changes in sediment yield regime during logging at Glenburvie Forest, Northland, New Zealand. Hydrology and Water Resources Symposium, 1989, Christchurch, New Zealand. pp. 424–428.

New Zealand Meteorological Service 1983: Summary of climatological observations to 1980. *New Zealand Meteorological Service Miscellaneous Publication* 177: 172 p.

New Zealand Soil Bureau 1954: General survey of the soils of North Island, New Zealand. New Zealand Department of Scientific and Industrial Research, Soil Bureau Bulletin 5.

Page, M.J.; Trustrum, N.A. 1997: A late Holocene lake sediment record of the erosion response to land use change in a steepland catchment, New Zealand. *Zeitschrift fur Geomorphologie (N.F.) 41:* 369–392.

Pohlen, I.J; Harris, C.S.; Gibbs, H.S.; Raeside, J.D. 1947: Soils and some related agricultural aspects of mid Hawke's Bay. DSIR Bulletin 94, Cliff Press, New Zealand.

Thompson, S.M.; Adams, J. 1979: Suspended load in some major rivers of New Zealand. *In*: Murray, D.L.; Ackroyd, P. (*eds.*). *Physical Hydrology–the New Zealand Experience.* New Zealand Hydrological Society, pp. 213-228.

Tomlinson, A.I. 1980: The frequency of high intensity rainfalls in New Zealand. New Zealand Ministry of Works and Development, Water and Soil Division, *Water and Soil Technical Publication 19*, 36 p.

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