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Sediment yield following plantation forest harvesting, Coromandel Peninsula, North Island, New Zealand

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Abstract

The suspended sediment yield following logging of a 36-ha plantation forest catchment on the Coromandel Peninsula was determined over a 30-month period (October 2000 to March 2003), as part of a wider investigation of sediment generation and delivery to streams. Streamflow was measured with a capacitance probe water-level recorder, and *in situ* turbidity and suspended sediment concentrations were monitored with a Greenspan turbidity probe and automated pump water sampler, respectively. Rainfall was measured at three locations in the catchment, using 0.1-mm resolution tipping-bucket raingauges. A regression relationship was determined from a relationship between the concentrations of water samples collected in the stage-triggered autosampler and the simultaneous turbidity probe trace ($r^2 = 0.85$). This relationship was used to calculate the suspended sediment yield for all flow events using a combined sedigraph and hydrograph approach. Total suspended sediment yield for the catchment for the whole period was 73.2 t. On an annual basis this ranged between 59 and 116 t km^{-2}. Two storms with annual to 2-year return periods in April 2001 and February 2002 contributed 37% of the total sediment yield. Most landslides occurred during the April 2001 event. Suspended sediment yields determined from this study are in the range of those of previous forest harvesting studies in New Zealand.

Introduction

A unique combination of weathered volcanic soils and steep slopes, together with a climate characterised by frequent and damaging high intensity rainfalls, predisposes hillsides on the Coromandel Peninsula to erosion (Salter *et al.*, 1983; Pearce and Hodgkiss, 1987; Marden and Rowan, 1995 a,b; Marden *et al.*, 2002). The region's streams have a high incidence of flood flows and the potential to deliver significant volumes of sediment to coastal estuaries. The return period for a rainfall event of 133 mm in 24 hours is estimated to be only 2 years (New Zealand Meteorological Service, 1980); this was recently revised to 127 mm in 24 hours for the same return period (National Institute of Water and Atmospheric Research, 2003).

On-site activities related to forestry, such as road construction and harvesting, together with the off-site effects of localised flooding and sediment input into estuaries downstream had been concerns of local residents, regional authorities, recreationists and forest owners well before logging began of forests on the Coromandel Peninsula in the late 1980s and early 1990s (Coker, 1988). In addition, questions of the effects of logging on in-stream values such as invertebrate habitat (Harding *et al.*, 2000) and fish populations (Rowe *et al.*, 2002) have also been raised.

Within a logged area, sediment can be generated both as a consequence of practices during harvesting (e.g., scalping during hauler-logging) and processes after harvesting (e.g., erosion through raindrop impact, sheetwash erosion, rilling and storm-initiated landslides). Sediment can also be generated during the pre-logging phase of road and landing construction (Mosley, 1980; Fahey and Coker, 1989; Fransen *et al.*, 2001; Fahey and Marden, 2000).

Sediment generation from these processes have not previously been quantified for logging of exotic forest in a weathered volcanic terrain in New Zealand. In addition, few studies in New Zealand have attempted to quantify the relative contribution of sediment generated by these processes to stream channels and, hence to stream sediment yield.

This paper presents catchment scale (36 ha) post-harvest sediment yield results, which are part of a wider investigation of sediment generation rates, yields and delivery ratios following clear-fell logging at Whangapoua Forest, vegetation recovery after logging, and sediment delivery from various sources to the stream channels.

The results presented here do not cover the pre-harvesting period, including road or landing construction, nor are they compared against a control catchment.

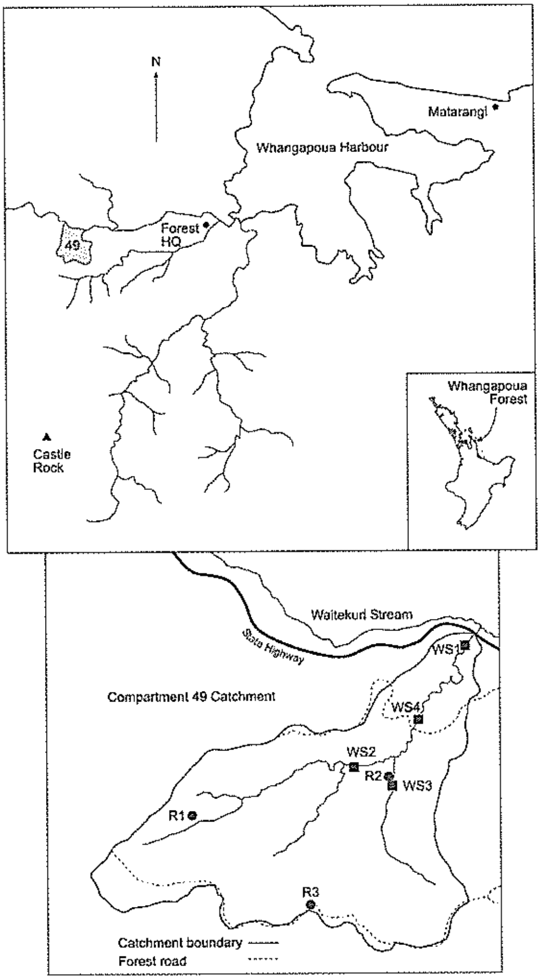

Figure 1 – Location map of study area showing Compartment 49.

Field area

The study catchment comprises Compartment 49 and part of Compartment 11 in Whangapoua Forest, near Te Rerenga, on the Coromandel Peninsula (Fig. 1). The catchment is 36 ha in area and drains into the Waitekuri Stream, which in turn flows into Whangapoua Harbour. The catchment is typical of most catchments within the Whangapoua plantation forest—it is steep and underlain by weathered volcanic soils. The slopes are short and may approach 40° in places.

The basement volcanic rocks in the area consist of hydrothermally altered Whangapoua and Matarangi andesites (Skinner, 1976). The soils are highly variable and strongly related to parent materials, altitude, and slope steepness. The soils developed from deeply weathered andesite are of medium to low fertility and are prone to erosion, particularly during extreme rainfalls.

The soils are described as Waitekere and Rangiuru hill soils (McGraw and Bell, 1975). They occur on moderately steep to steep terrain; they are similar in structure to soils on rolling hill country but are thinner due to erosion. Generally the soils consist of silt loams or brown clay with a friable, strongly developed structure, underlain by yellow-brown clay (McGraw and Bell, 1975).

The closest long-term rainfall records are for Whitianga, 13 kms to the southeast. Here the average annual rainfall is 1729 mm, with a distinct March to June 'wet season' (Coker, 1988). Environment Waikato has operated an automatic raingauge since 1992 on Castle Rock, a few kilometres south of the study area (P. Mora pers. comm.) (Figs. 1 and 2). This gauge recorded a maximum storm rainfall for a 24-hour duration of 206 mm in early April 2001.

Several episodes of extreme rainfall and significant erosion have occurred in and around Whangapoua forest in the last 40 years or so (Marden and Rowan, 1995a, b; C.L. O'Loughlin pers. comm.). During a storm that caused significant landslides and flooding in March 1995, maximum 24-hour intensities of 100–150 mm were recorded from raingauges within 50 km of the forest, but local observations indicated that most rain fell in 6 hours and that 150–200 mm rainfall for the duration of the storm was a better estimate (Marden and Rowan, 1995a). This event magnitude had an estimated return period of 20–50 years. However, a lack of historical rainfall records for the general area, particularly for higher elevations, make it impossible to calculate accurate return periods for storms in this region (Quinn *et al.*, 1995).

The catchment was planted in 1973 and is exclusively in *Pinus radiata*. Some areas where plantings failed, such as on former landslide scars or in the wetland near the catchment outlet, had a poor tree cover and were colonised with other species, including native and exotic weeds. In addition, remnants of native riparian vegetation remained along the main stem of the stream at the lowest elevations.

During 1998–99, in preparation for harvesting, trees adjacent to existing and newly constructed roads were removed (a technique know as 'day-lighting') and landings were constructed. The effects of this phase of operation on sediment generation and sediment yield were not assessed. Clear-fell logging was carried out sporadically throughout the catchment between October 2000 and March 2001. Most of the catchment was harvested with cable yarders, but a small proportion, particularly on the flatter areas closest to the state highway, was harvested with ground-based machinery. After harvesting the area was replanted, following aerial dessication to control the regeneration of pine and weeds, oversowing of grass and legumes, and spot spraying. Hauler pads were decommissioned; slash on the edge of the landing was pulled up and burned. Some attention to runoff control from landings was also evident. Roads were re-metalled, particularly those used for operations in other parts of the forest. At the end of the period reported here, the new trees were nearly 2 years old.

Methods

Three tipping bucket raingauges (Texas Instruments 0.1-mm tip) fitted with Trutrac data loggers were installed. Two gauges were at higher elevations near the catchment boundary (R1 – installed 28 November 2000 and R3 – installed 11 April 2001), while the third was located centrally at lower elevation (R2 – installed 17 January 2001) (Fig. 1). The raingauges were removed in September 2003. The record from raingauge R1 has been used as the principle record for comparison with flow and sediment yields.

Streamflow was measured at a site close to the point where the catchment drains into the Waitekuri Stream (WS1), about 30 m upstream of the culvert under State Highway 25 (Fig. 1). The site is an open channel, and stream stage was measured with a Trutrac capacitance probe that has a resolution of

± 5 mm. Data were stored in a data logger every 10 min. The WS1 site was established on 30 August 2000, several months prior to logging. The catchment area above the site is 36 ha. The stream at this point is about 1 m wide and 15–20 cm deep. The bed consisted of cobble- to boulder-sized material with finer sediment in some places. The stream is incised between steep banks 2 m in height, with a small floodplain on the true right bank about 40 cm above the water level. Data collection began in October 2000, once initial instrument and flow triggering levels were established. Tree logging operations were completed by March 2001. Flow continued to be measured up to September 2003. A rating curve of flow with stage height for WS1 was established using 10 stream gaugings made between August 2000 and January 2003. The gauging reach is a straight uniform reach immediately upstream of the flow recorder and water sampler intake. While the rating had an r^2 value of 0.97, no gaugings were carried out at the upper end of the range of stages recorded during this period. The number of stream gaugings is low and no gaugings were made at high flows because routine visits did not coincide with periods of high flow and a drive of over 7 hours was required for a field party to reach the site.

A 24-bottle ISCO water sampler, controlled by a data logger, was used to sample suspended sediment at the water-level recording site. The sampler was set to sample above predetermined stage heights at intervals of 30 and 60 min on the rising and falling limb of the hydrograph respectively. Water samples (0.5 L) were collected at the time of each site visit and turbidity (NTU) was determined using a Hach turbidimeter (Model 2100P) to take manual readings of water in the sample bottles after the sample bottle had been shaken by hand. Selected samples were then transported to the laboratory, and stored in the refrigerator in the dark until they were vacuum-filtered and oven dried to determine suspended sediment concentrations (e.g., Davies-Colley and Smith, 2001).

In addition, water clarity was measured at two sites, WS1 (installed 13 March 2001) and WS4 (installed 11 April 2002, largely as a backup for WS1), using *in situ* turbidity probes (Greenspan Model TS 300: Range 0–1000 NTU). Readings were taken at 15-min intervals and recorded in the probe's logger. The WS4 probe was removed on 14 January 2003 and the WS1 probe in September 2003 when the experiment ended. A period of data from WS1 was lost because of instrument malfunction between November 2002 and April 2003 and data from WS4 was used to 'patch' the record. The WS1 probe was calibrated approximately annually in the laboratory with formazin standards by the instrument supplier (NIWA). A temporary replacement probe was installed while calibration took place. Instrument drift between calibrations reached a maximum of 11% of full scale, compared to the normally acceptable limits of 3%.

The use of turbidity probes for estimating sediment yield has become common in many studies (e.g., Lewis and Eads, 1998). Data from battery-powered turbidity probes that automatically collect high-frequency turbidity (water clarity) data is potentially a much better predictor of suspended sediment concentration in rivers than discharge records (Lewis and Eads, 1998). With sensors calibrated to give a linear response to formazine standards, turbidity and sediment concentration should have a linear correlation of close to unity for a given size and composition of suspended sediment particles (Foster *et al.*, 1992; Gippel, 1995). For events of limited duration, a few (less than 10) data pairs spanning the range of concentrations should be sufficient to reliably establish the relationship between suspended sediment concentration and turbidity (Lewis, 1996). Air bubbles or scraps of debris momentarily passing in front of the optics, however, can cause high-frequency noise in the data. Biological fouling of the optics can be a problem, so each turbidity probe was fitted with a spray pump nozzle that was activated every 30 min to spray high-pressure stream water across the face of the sensor to limit the build up of algal material. During each site visit (every 3–4 weeks) the sensor was also cleaned by wiping the lens with a soft cloth.

The relationship between suspended sediment concentration and turbidity will vary over time with changes in sediment sources, organic loading, or sensor calibration (Gippel, 1995). However, if the relationship between turbidity and suspended sediment concentration is roughly linear, load estimates will be nearly unbiased (Lewis and Eads, 1998). In waters with a limited range of particle characteristics, the mutual correlation of visual clarity, turbidity, and suspended sediment concentrations may be high: in those cases suspended sediment concentration may be predicted from the optical variables with reasonable precision (Davies-Colley and Smith, 2001). Where suspended sediment concentration is the concern and where estimates of suspended matter yield are required, such as in this study, then such correlations may be very useful (Davies-Colley and Smith, 2001).

High-frequency noise in the turbidity data was 'filtered' using a hydrological data management programme, HYDSYS (Version 8.6.0, HYDSYS Pty Ltd). Instrument malfunction or low batteries caused several instances of lost data during the study.

The conventional approach for estimating suspended sediment yields involves the construction of a sediment rating curve, although this approach is widely known to be relatively inaccurate (e.g., Walling, 1977). This method 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 sediment yields. In small streams, with catchment areas of less than a few square kilometres, the instantaneous sediment concentration for a given discharge can vary greatly, with concentrations responding to random injections of sediment from erosion sites (Hicks and Griffiths, 1992). In these cases, the instantaneous rating is rarely adequate. However, good relationships can often be found between storm sediment yield, measured accurately for a sample of storms using an autosampler, and some index of storm magnitude such as peak discharge, runoff volume, rainfall, or rain erosivity (Hicks, 1990). In this study, we use a combination of the sedigraph approach (flow and corresponding sediment concentration) and the storm yield rating method (Basher *et al.*, 1997; Hicks, 1990), which exploits the relationship between storm peak flow and suspended sediment yield for all storms in a given interval. The storm data on suspended sediment load and peak flow were log transformed and a linear regression model was used to estimate sediment yields for periods when continuous turbidity probe data were unavailable at both the start (October 2000 to March 2001) and end (December 2002 to March 2003) of the measurement periods.

Results and discussion

Rainfall

From October 2000 to March 2003, the most significant rainfalls in terms of amount and intensity were on 2 April 2001, 21 February 2002 and 9 January 2003 (Table 1). These three rainfalls exceeded 100 mm in 24 hours (return periods of 1-2 years, National Institute of Water and Atmospheric Research (2003)). For comparison, daily totals for raingauge R1 and for Castle Rock are shown in Figure 2. Raingauge R1 is used here, as it had the longest record. When all three rain gauges were recording, no significant

Table 1 – Intensity-duration details for the largest rainfalls measured by the R1 raingauge

Duration	Date	Start Time (hours)	Amount (mm)	Intensity (mm h^{-1})
6 min	21 Feb 2002	0958	8.2	82.0
10 min	21 Feb 2002	0958	8.2	49.2
20 min	21 Feb 2002	0958	15.2	45.6
30 min	21 Feb 2002	0848	21.0	42.0
1 h	21 Feb 2002	0848	33.1	33.1
2 h	21 Feb 2002	0828	57.9	28.9
3 h	21 Feb 2002	0718	69.3	23.1
4 h	21 Feb 2002	0718	74.3	18.6
6 h	21 Feb 2002	0708	82.3	13.7
12 h	21 Feb 2002	0228	98.7	8.2
18 h	02 Apr 2001	0808	116.3	6.5
24 h	02 Apr 2001	0258	124.4	5.2
48 h	08 Jan 2003	1208	146.6	3.1
72 h	08 Jan 2003	0158	162.6	2.3

differences in rainfalls existed between them. Only one event (21 February 2002) exceeded an intensity of 25 mm h^{-1} over a duration of one hour, a threshold that typically triggers landslides on hillslopes (Caine, 1980). Four other events exceeded one-hour duration intensities of 15 mm/h: 3 April 2001, 13 April 2001, 2 March 2003 and 28 March 2003. The event in February 2002 had the most intense short-duration rainfalls, while

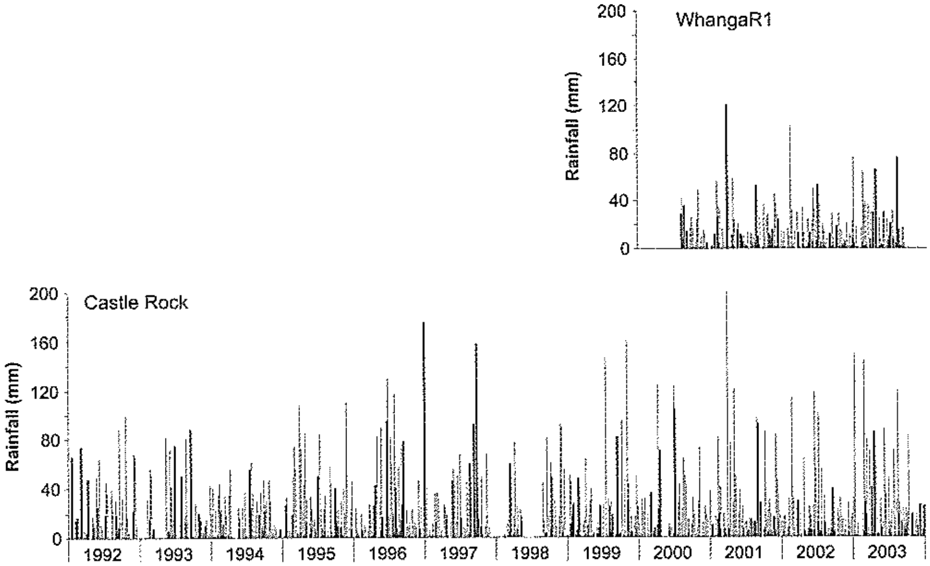

Figure 2 – Daily rainfall from Castle Rock raingauge and from WhangaR1 raingauge showing period overlap.

the greatest longer-duration totals occurred in the April 2001 and January 2003 events (Table 1).

These rainfalls are typical for this area and are comparable to previous rainfalls known to cause varying degrees of erosion (Marden and Rowan, 1995a). Although the February 2002 rainfalls had the greatest intensities, it was the earlier event in April 2001 that produced most of the landslides observed during the course of the study (Phillips *et al.*, 2002). This event was the most significant in terms of erosion or sediment generation during the study period. The exact causes of this are unknown, though we speculate that it relates to changes in landslide thresholds for certain parts of the slope during the 25 years or so of the forest rotation.

Flow

Runoff was 28 mm in October-December 2000, 279 mm in 2001, 203 mm in 2002, and 448 in January-September 2003. Runoff as a percentage of rainfall varied from 7 to 28% (7% in 2000, 15% in 2001, 14% in 2002, and 28% in 2003). The greatest stage height measured at WS1 was 0.7 m at 0944 hours on 21 February 2002, with the second highest of 0.66 m at 2256 hours on 2 April 2001. On two other occasions in the period October 2000 to March 2003 the stream stage reached 0.5 m. There were 27 rainfalls in which the stage exceeded 0.2 m. Most events with a stage height greater than 0.2 m had durations of only a few hours. The three biggest events had durations of 5–10 h. Events at the scale of the study catchment tend to be 'flashy' in this region, as the soils are relatively thin and the slopes are steep. The rapid response of the catchment was one of the reasons that stream gaugings were not carried out at the higher stages, as the field party was over 7 hours' drive away, by which time most events were over.

Suspended sediment yields

A total of 363 water samples were collected at WS1: of those, 94 were sent to the laboratory for determination of suspended-sediment concentrations. Sample selection was based on turbidity readings made on each sample with a portable turbidimeter to provide a range of data pairs of turbidity and suspended-sediment concentration and to keep costs down. Hysteresis effects between the rising and falling stages of the hydrograph were not assessed, largely due to a lack of complete sample sets across a range of event sizes, particularly on the falling limb of the hydrograph. The laboratory-derived suspended-sediment concentrations were matched to their instantaneous discharge readings and converted to a log-log scale to generate a sediment rating relationship (Fig. 3). The r^2 value for the linear fit to the log-transformed data was 0.58. The relationship was Log (SSC mg L^{-1}) = 1.657 (Log flow L s^{-1})*0.453, where SSC is

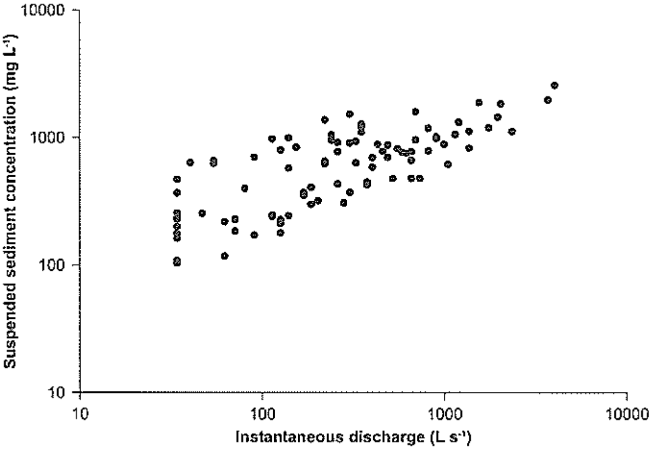

Figure 3 – Relationship between instantaneous discharge (L s^{-1}) and sediment concentration (mg L^{-1}).

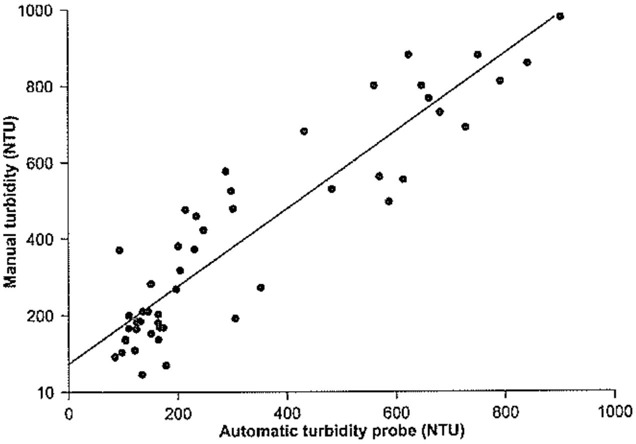

Figure 4 – Relationship between manual reading of turbidity from water samples and the corresponding continuous turbidity probe measurement.

suspended sediment concentration. Because of the low r^2 value this relationship was not used to calculate sediment yields and is provided for information only.

For each water sample sent to the laboratory, a relationship was also derived for the manual reading of the turbidity of the water sample and the corresponding continuous turbidity probe measurement made at the time of sampling. This was done in part to check against the automatic turbidity probe and in part to provide data when there were gaps in the automatic turbidity probe record. From the 94 water samples, 54 were used to derive the relationship in Figure 4 (r^2 = 0.86). Forty pairs had to be dropped, as the values for these water samples exceeded the ranges of both the portable turbidimeter and the *in situ* automatic probe (maximum 1000 NTU).

A linear or near linear regression was fitted to the suspended-sediment concentration – turbidity pairs, excluding those samples that had an NTU reading of greater than 1000 ($r^2 = 0.85$, suspended-sediment concentration $= 1.602\ (\mathrm{NTU})^{0.9787}$; slope = 1.03, S.E. 0.058, $t_{52} = 17.71$, $p < 0.0001$) (Fig. 5). Where there was a continuous turbidity probe record, this relationship was then used, together with the corresponding flow, to estimate the sediment load (i.e., sedigraph – hydrograph approach).

During several storms in the earlier part of the monitoring period, the turbidity exceeded the range of the instrument (1000 NTU). While there was a high degree of scatter in the stage-turbidity data, there appeared to be a rough trend of lower values for the same flow later in the study period.

Suspended sediment yields for individual storms

From October 2000 to July 2002, 15 storms with flows greater than 0.1 $m^3\ s^{-1}$ were sampled to determine suspended-sediment concentrations at the catchment outlet.

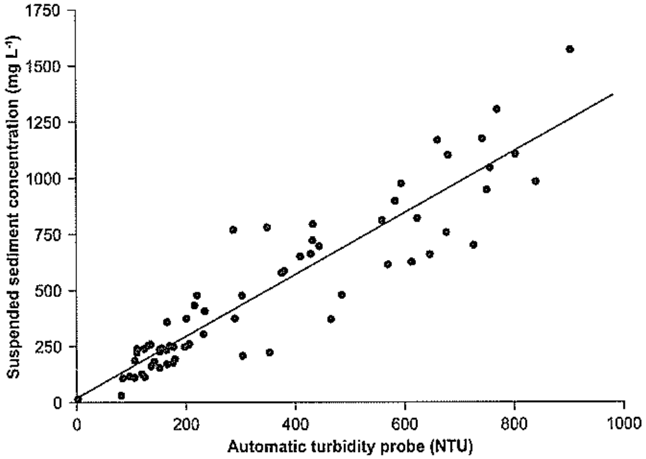

Figure 5 – Relationship between automatic turbidity probe (NTU) and suspended sediment concentration (SSC) (mg L^{-1}) derived from water samples taken at the same time.

Storm sediment loads are reported in tonne (t) and sediment yield in tonnes per square kilometre (t km^{-2}). Suspended sediment yields were determined from the product of flow and suspended-sediment concentration (from the relationship in Figure 5; i.e., turbidity determined from the turbidity probe and corrected to give the concentration in milligrams per litre). Bedload was not sampled. The storm loads ranged from 0.1 to 17 t (Table 2).

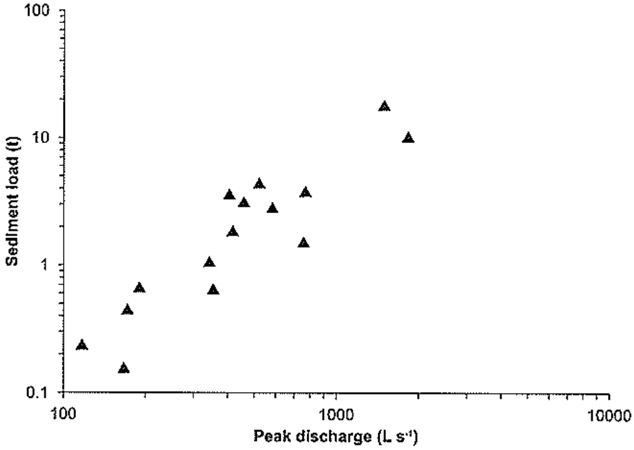

Figure 6 – Relationship between storm peak discharge (Ls^{-1}) and sediment load (t).

Using the relationship between peak discharge and measured storm suspended-sediment loads (Fig. 6, Sediment load (t) = 0.00294 (Peak discharge (L/s)$^{1.1287}$), storm-related suspended sediment yields were calculated for the periods October 2000 to March 2001 and for December 2002 to March 2003, when both continuous turbidity data and/or suspended-sediment concentration data were not available.

For the largest storms, the method routinely used for calculating sediment yield probably underestimates the actual yield. This is largely because the method used to calculate sediment yield was based on a relationship that could not take into account the very high suspended sediment concentrations that were actually measured, i.e., those greater

Table 2 – Storm sediment loads together with peak discharge and maximum hourly rainfall intensity.

Start date (hours)	Time (hours)	End date	Time (hours)	Sediment load (t)	Peak discharge (L s^{-1})	Maximum hourly rainfall intensity (mm h^{-1})
2 Apr 2001	0315	5 Apr 2001	1800	17.1	1488	16
21 Feb 2001	0015	22 Feb 2002	2030	9.8	1825	31.9
12 Apr 2001	1445	13 Apr 2001	2100	8.6	756	15.3
18 Jun 2002	2200	25 Jun 2002	2200	4.1	520	10.2
2 May 2001	0630	4 May 2001	0615	3.9	769	10.3
28 Aug 2001	0900	1 Sep 2001	0000	3.3	405	7.6
11 Jul 2002	0830	14 Jul 2002	1200	2.9	458	12.2
22 Jul 2002	2000	25 Jul 2002	1600	1.9	582	14.2
1 Dec 2001	0130	4 Dec 2001	0800	1.7	417	8.7
30 Jun 2002	0400	4 Jul 2002	0700	1.0	344	11.5
28 Jun 2002	0930	30 Jun 2002	0400	0.6	190	6.1
9 Oct 2001	0400	12 Oct 2001	1000	0.6	355	17.6
21 May 2002	0630	23 May 2002	0015	0.4	172	10.9
15 Sep 2001	1600	17 Sep 2001	1700	0.2	117	9.2
28 Oct 2001	0030	30 Oct 2001	0830	0.1	167	8.1

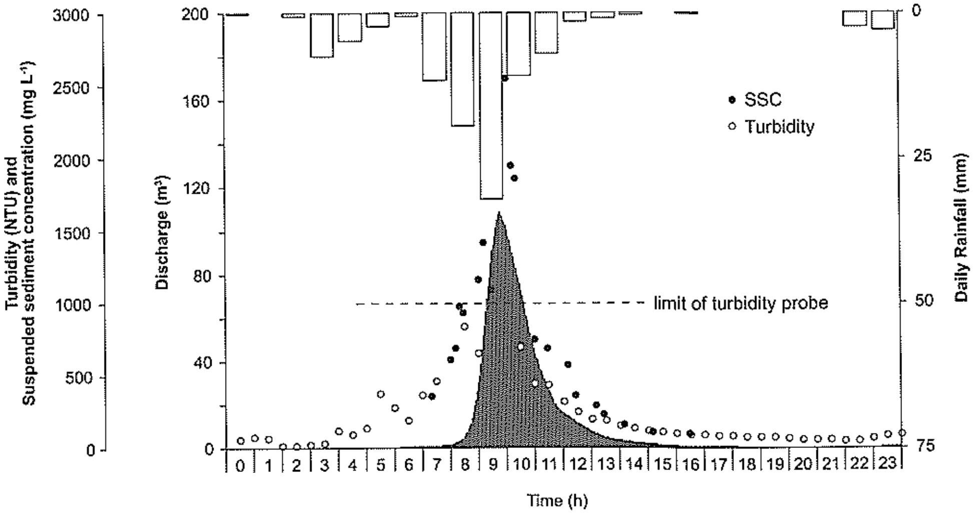

Figure 7 – Event on 21 February 2002 showing, 1-h rainfall (mm), 1-min discharge (m^3) and NTU from the automatic turbidity probe (open circles – max reading 1000 NTU) and the suspended sediment concentration SSC (solid circles) for collected samples.

than the maximum range of the manual and automatic turbidity probe used in this study (1000 NTU). In addition, the estimates of flow at the highest stages are also likely to contain errors, as stream gaugings were not carried out during these larger events. This is illustrated for one storm on 21 February 2002 (the largest in the record), where both the rising and falling limbs of the whole storm were sampled and where suspended-sediment concentrations reached close to 2000 mg L^{-1} near the peak of the event (Fig. 7).

In this case, if we take the suspended-sediment concentration of the sample for the time period in which it was taken and multiply it by its corresponding flow volume and sum these over the event where we have suspended-sediment concentration data, then we get a value of 17 t, compared with 9.8 t (see Table 2). However, similar calculations for other moderate to large events, or parts of events, show a much closer correspondence in values, in comparison with this one storm (Table 3). This suggests that the method

Table 3 – Selected storm (or part storm) sediment yields calculated using regression relationship in Figure 5 and from actual suspended-sediment concentration values derived from auto samples and flow (manual).

Start date	Time (hours)	End date	Time (hours)	Sediment load (t)	Sediment load manual (t)
2 Apr 2001	1600	2 Apr 2001	2400	16.3	20.9
12 Apr 2001	2100	13 Apr 2001	0500	9.3	8.8
2 May 2001	1700	2 May 2001	0615	3.0	3.8
21 Feb 2001	0700	21 Feb 2002	1800	9.8	17.4
20 Jun 2002	1300	20 Jun 2002	1500	0.6	0.7

used to calculate sediment yield is reasonably reliable in all but the largest events.

While the largest flow event (21 February 2002) produced 17 t sediment in 12 h, the storm was of much shorter duration and produced a lower runoff volume (13 000 m^3) than the storm in April 2001, which was of longer duration and had a runoff volume of 21 000 m^3 and a sediment load of 17 t.

Annual suspended-sediment yields

The total suspended-sediment yield for the period of measurement October 2000 to March 2003 was 73.2 t km^{-2}. Annual sediment yields ranged from 59 to 116 t km^{-2} a^{-1} for years 2002 and 2001 respectively (Table 4).

In both 2001 and 2002 the largest events made significant contributions to the total sediment yield, indicating the importance of events of this magnitude (1–2-year return period) to the annual sediment load. No large-magnitude events occurred during this study, but it is likely that an event with a return period of 10 years or greater would have produced an even greater proportion of the annual sediment yield, as a larger number of landslides would probably be triggered by such an event (Marden and Rowan, 1995a, b; Quinn *et al.*, 1995).

Table 4 – Annual sediment yields and storm numbers.

	2000 (Oct–Dec)	2001	2002	2003 (Jan–Mar)
Number of storms greater than stage height (0.25 m)	1	11	11	6
Number of storms greater than stage height (0.4 m)	0	4	5	3
Sediment yield (t)	1.5 (3 months)	41	21.3	9.4 (3 months)
Sediment yield (t km^{-2})	4.4 (3 months)	116	59	26 (3 months)

Comparisons with other studies

Several studies have been conducted in New Zealand to assess the effects of forest logging on stream sediment yields. Of these, some included a pre- and post-harvest assessment of sediment yield, while for others, including those carried out for consent compliance, the effects of harvesting on stream biota and water clarity were monitored. However, data from the latter studies have generally not been converted to suspended sediment concentrations or sediment yields. Of those published studies, only a few have monitored both stream flow and suspended-sediment concentration or water clarity for more than a few months after harvesting and, as one might expect, the sediment yields vary according to the geology and climate of the study area (Table 5). Our study did not have an extended period of monitoring before logging commenced, nor did we compare results against a control catchment.

Of those studies listed in Table 5, the Glenbervie and the Pakuratahi catchments are closest to Whangapoua in both the type and practice of forestry. In addition, the

Table 5 – Sediment yields from harvesting studies in New Zealand.

Location	**Geology**	**Post-harvest annual sediment yield ($t\ km^{-2}\ year^{-1}$)**	**Reference**
Maimai	Old Man Gravels	80–450[a]	O'Loughlin *et al.*, 1980
Pakuratahi	Tertiary mudstone	18–112[b]	Fahey et al. 2003
Glenbervie		46	Hicks and Harmsworth 1989
Pokororo[c]	Weathered granite	21	Hewitt 2001a, 2002
Little Pokororo[c]	Weathered granite	45	Hewitt 2001a, 2002
Apahi[c]	Weathered granite	27–148	Hewitt 2001a, 2002
Greenhill[c]	Weathered granite	60	Hewitt 2000, 20001b
Whangapoua	Weathered volcanics	59–116	This study

[a] Data reported in $m^3\ km^{-2}\ year^{-1}$ – conversion at $1.7\ t\ m^{-3}$

[b] Data reported in $t\ km^{-2}$ for various periods and phases of harvesting and converted here to annual yields by dividing by the period in years

[c] Only part of catchment logged

Whangapoua study catchment is midway in size between those of the studies of 'clear-cut' catchments listed in Table 5. Several other studies (e.g., Hewitt, 2000, 2001b) have involved monitoring only partial cuts within the catchment, making it difficult to separate out the exact effects of the logging.

In a weathered granite catchment at Greenhill (Table 5), suspended sediment yield was $32.9\ t\ km^{-2}\ year^{-1}$ during the pre-harvest phase, $7.5\ t\ km^{-2}\ year^{-1}$ during road building, $81.5\ t\ km^{-2}\ year^{-1}$ during harvesting and $60\ t\ km^{-2}\ year^{-1}$ during the post-harvest phase (Hewitt, 2000, 2001b). The reasons for the low sediment yield during the roading phase include low rainfall at this time, the location of tracks and landing pads along ridges, limited soil exposure at any time, and rapid reversion to scrub.

In a mudstone catchment near Napier the sediment yield from a logged catchment was compared to the yield from an adjacent catchment in pasture (Fahey *et al.*, 2003; Eyles 2004). Suspended sediment yields for each period were as follows: pre-harvesting (29 months) $44\ t\ km^{-2}$; road construction phase (2 months) $45\ t\ km^{-2}$; $179\ t\ km^{-2}$ in the logging phase (16 months); and $348\ t\ km^{-2}$ for the post harvest period (42 months). Over the whole logging and post-logging period of 66 months the total suspended sediment yield was $617\ t\ km^{-2}$, or an estimated average annualised yield of $112\ t\ km^{-2} year^{-1}$. While the post-harvest storm-based suspended sediment yields of the harvested catchment were substantially higher than those from an adjacent pasture catchment in the early part of the recovery period, over the whole post-harvest period the yields were similar, indicating that storm yields from the harvested catchment were beginning to return to pre-harvesting levels.

Unlike the Pakuratahi study (Fahey *et al.*, 2003), this study did not include the road-daylighting, road upgrading and landing construction phase of harvesting. Any generated sediment that reached the streams during this phase, and did not pass out of the system prior to the beginning of measurements in August 2000, was likely to be held in temporary storage in the stream. It could then be remobilised by later events and contribute to the measured sediment yield. Indeed, we observed such sediment accumulations in parts of the streambed 6–9 month before our measurement programme began. This was also observed in 1999 by Kevin Collier (NIWA pers. comm.). This remobilised sediment obviously contributes to the sediment yield measured at the catchment outlet, but it was not possible to differentiate between sediment generated from just the logging phase and that from these earlier activities.

Sources of error

Annual sediment yield estimates determined in this study have associated errors typical of other similar studies. The main source of error is likely to arise from the determination of flow. While the section of the stream bed at WS1 remained relatively stable for the duration of the study, the stream rating curve largely relied on flow gaugings carried out at low to moderate flows and did not include any gaugings at higher recorded stages. Estimates of flow at these stages were obtained by a linear extrapolation of the rating from the lower stage gaugings. Similarly, the other main source of error was the wide scatter in the relationships between suspended-sediment concentration and turbidity, and storm suspended-sediment yield and peak discharge. These all combine to produce uncertainty in the estimates of suspended sediment yield. A detailed error analysis was not carried out, largely due to the mix of approaches for calculating sediment yield and the lack of gaugings at moderate to high flows over the period of study. The estimates of sediment yield are however, within a similar order of magnitude of those reported in previous studies. In Fahey *et al.*'s 2003 study they found a large confidence interval for estimated sediment yield in the harvested catchment (Pakuratahi) and concluded that the sediment response to storms was erratic early in the post-harvesting recovery period and suggested that this would remain so until canopy closure.

Conclusions

Post-logging peak suspended-sediment concentrations reached around 2000 mg L^{-1} but were typically between 100 to 1000 mg L^{-1} for most storms. The turbidity exceeded the range of the instrument (1000 NTU) in several storms in the earlier part of the monitoring period. As one might expect, turbidity tended to be lower for the same flow later in the study period, i.e., for a given flow, the water was more turbid and contained more sediment in the 12-month period following harvesting compared to the later period of monitoring. This indicates a reduction in sediment supply from slopes as bare areas are re-vegetated (Marden and Rowan, 1997) and/or a reduction in mobilisation of stored sediment within the channel.

No extreme rainfalls coincided with the post-harvesting monitoring period of this study. An event the size of the annual or slightly greater return period contributed the greatest proportion of the total sediment yield. The first storm of this magnitude in April 2001 caused a significant number of landslides in the cutover, while the second of a similar magnitude but of higher intensity in February 2002 caused fewer landslides but produced a greater sediment yield. The April 2001 event was the most significant in terms of erosion or sediment generation during the study period. The exact causes of this are unknown, though we speculate that it relates to changes in landslide thresholds for certain parts of the slope during the 25 years or so of the forest rotation.

Data from this study has shown that the post-harvest sediment yields are of a similar order of magnitude to those reported in previous studies conducted elsewhere in New Zealand in catchments with differing bedrock and climate regimes. These yields fall into the 10^1 to low 10^2 order of magnitude values of tonnes per square kilometre per year. Similarly, we observed that elevated storm sediment yields in the immediate post-logging period tended to return to the lower yields more typical of mature forest within a few years following logging, as have been reported elsewhere (e.g., Fahey *et al.*, 2003).

While we had no control catchment, nor did we monitor any significant pre-harvest period, we believe our study confirms the view that harvesting may result in elevated sediment yields. In the absence of any high-magnitude, low-frequency rainfalls during the 3-year period following harvesting, our results are remarkably similar in magnitude to those of earlier studies. They also confirm that, in the absence of extreme events, those the size of the annual or slightly greater event tend to provide most of the sediment yield.

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