IN THE MATTER	**of the Resource Management Act 1991**
AND	
IN THE MATTER	of the Proposed Waikato Regional Plan Change 1 – Waikato and Waipa River Catchments ("Proposed Plan or PC1")
AND	
IN THE MATTER	**of submissions and further submissions by Hancock Forest Management (NZ) Limited and New Zealand Forest Owners Association Inc**

SUPPLEMENTARY EVIDENCE OF SALLY STRANG ON BEHALF OF HANCOCK FOREST MANAGEMENT (NZ) LIMITED AND NZ FOREST OWNERS ASSOCIATION (NZFOA) IN RESPONSE TO PANEL QUESTIONS

20 AUGUST 2019

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vbc VULCAN BUILDING CHAMBERS

CONTENTS

1. INTRODUCTION..2
2. SEDIMENT SAMPLING METHODOLGY PAKURATAHI-TAMINGIMINGI PAIRED CATCHMENT STUDY..2
3. GRAPH UNITS (FIGURE 5) 3

1. INTRODUCTION

1.1 My full name is Sally Barker Strang.

1.2 My experience and qualifications are set out in paragraphs 2.2 – 2.10 of my statement of evidence dated 15 February 2019.

1.3 At the Block 3 hearing on 8 August 2019 the Hearings Panel requested further information in relation to:

- The method of sampling used to calculate sediment yields in the Pakuratahi-Tamingimingi paired catchment study quoted in section 5 of my evidence;
- The correct units of measurement for the second graph (Figure 5) on page 8 of my evidence.

2. SEDIMENT SAMPLING METHODOLGY PAKURATAHI-TAMINGIMINGI PAIRED CATCHMENT STUDY

2.1 The graphs used in section 5 of my evidence were taken from Chapter 5 of the book '*Pakuratahi-Tamingimingi Land Use Study*'. Chapter 5 was written by Barry Fahey and Mike Marden, and in turn references two Journal of Hydrology papers, prepared by the same authors on the same topic of sediment yields from the Pakuratahi study.

2.2 The methodology they used is summarized in Chapter 5 of the book, which is attached as Attachment 1 (refer page 51 methodology).

2.3 The methodology is described in more detail in two NZ Journal of Hydrology papers that are referenced in the above Chapter, one of which is attached at Attachment 2 (refer page 29 of the paper).

2.4 In summary the sampling methodology was based on:

- Installation of weirs in both catchments to calculate flows;
- Water levels that were measured using flow-operated chart recorders;

- Rainfall that was measured using logger tipping bucket automatic rain gauges;
- Suspended sediment that was measured using automatic samplers set to trigger at a predetermined water level (to activate during storm events) and set to collect samples at intervals of between 20 and 90 minutes to obtain samples through the event until the water level dropped below the given water depth;
- Samples that were oven dried to determine suspended solids concentrations.

3. GRAPH UNITS (FIGURE 5)

3.1 As noted above, the full Chapter from which the graphs were taken is now attached.

3.2 As was reported verbally at the time, the units for the second graph are tonnes/km^2 with the graph showing the values for each year over the given period.

Sally Strang

Chapter 5

Forestry Effects on Sediment Yield and Erosion

Barry Fahey and Mike Marden

Introduction

This chapter compares sediment yield from the Pakuratahi catchment (3.45 km^2) in mature forest, that was subsequently harvested and replanted, with that monitored over the same period in the adjacent Tamingimingi catchment (7.95 km^2) left in pasture. The broader question of whether land in pasture or forestry can be expected to generate more sediment in the longer term, is also considered. In addition, the relative contribution of the various sediment generating processes to sediment yield are assessed, together with the degree of site disturbance, and subsequent vegetation recovery. Forest management practices (roading, harvesting, over-sowing, and replanting) are described in full in Chapter 3. Sediment yields are compared from the two catchments for 11 years (January 1995–December 2005), which includes a pre-harvesting period, a harvesting period, and a post-harvesting period. Details on sediment yield from the two catchments before, and shortly after harvesting are also provided in Fahey and Marden (2000) and Fahey, et. al (2002) respectively.

For the preparation of this report, the data set from both catchments for the 11 year period of record was completely re-analysed. In the light of this exercise, some sediment yield totals that appear here differ slightly from those listed in Fahey and Marden (2000) and Fahey et al., (2002). However, these adjustments have made no difference to the ratios and comparisons quoted here and in earlier reports and publications.

Methods

Rainfall was measured with two tipping bucket rain gauges, one installed near the Pakuratahi weir (Fisher's), and the other at the head of the Tamingimingi catchment (Top Run). Stream water levels were monitored with float-operated shaft encoders at Crump-type weirs, and recorded with Campbell CR10 data loggers.

Two 24-bottle automatic water samplers, controlled by a CR10 logger, were used to sample suspended sediment. They were set to sample above predetermined stage heights equivalent to 15 l/s/km^2 at both catchments at intervals of between 30 and 90 minutes on the rising and falling limb of the storm hydrograph. Sampling ceased when the hydrograph fell below the same stage heights. Instantaneous flows below 15 l/s/km^2 at both catchments were almost always in the base flow range, and thus not regarded as capable of generating significant amounts of suspended sediment. Occasional adjustments were made to the trigger levels during the course of the study. If, because of storm size or duration, all bottles were filled before the end of an event, the relationship established between flow and sediment concentration on the falling limb for other storms, was used to complete the record. Data from turbidity probes installed at both weirs were also used to fill in gaps in the sediment concentration record for some storms between 1999 and 2003. Samples (0.5 l) were vacuum-filtered and oven dried to determine suspended sediment concentrations. Storm sediment loads were estimated in tonnes, and sediment yield in tonnes per square kilometer.

Suspended sediment yields for sampled storms were determined from the product of flow and the average suspended sediment concentrations calculated for the chosen interval. These were

summed over the duration of the storm. Between January 1995 and December 2005, 50 storms were sampled for suspended sediment concentrations at the Pakuratahi weir, and 30 at the Tamingimingi weir. The numbers differ because of spatial variability in rainfall events, and occasional equipment malfunctions. A total of 27 storms were monitored and sampled concurrently in both catchments. Storm suspended sediment loads and associated peak flows for both catchments were log transformed and a least-squares regression model was used to establish the relationship between the two parameters (Hicks, 1990; Basher et al., 1997).

For the Pakuratahi catchment, all events between January 1995 and December 2005 with peak flows ≥20 l/s/km^2 were identified, and the list subdivided into the intervals assigned to the various forest rotation periods. The use of the ≥ 20 l/s/km^2 threshold ensured that all medium-and-larger-sized storms were included in the calculations. The regression equations derived from the relationship between suspended sediment yields and peak discharge for each of these periods were used to estimate the suspended sediment yields for those storms with no suspended sediment concentration data. In cases where storms displayed more than one peak, a single event was considered to have occurred if there was less than 6 hours between individual peaks. The biggest peak was used in the regression procedure. If there was more than 6 hours between peaks, they were considered as separate events. These data were summed and added to those derived from sampled events to provide total yields for each interval. These totals were then compared with those for the Tamingimingi (based on events ≥ 20 l/s/km^2), calculated for the same intervals using the regression equation for that catchment.

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 and July 1998. The cross sections were surveyed at the same time, and in March and November 1999, and January 2000.

Fransen (1998) assessed slip erosion associated with two major pre-harvest storms in the winter of 1997, one in early June and the other in early July. Both caused severe slip erosion in coastal Hawke's Bay. The examination of slip damage focused on the upper reaches of both catchments, specifically above three of the stream sites chosen for assessing channel responses (T1, P1, and P2) (Fig. 1). The areas above sites T1 and P1 covered 119 ha and 117 ha of the Tamingimingi and Pakuratahi catchments respectively. In the latter catchment, half was in mature pine trees and just over a third in 8–year old pines. Measurements were made of the dimensions of fresh scars, tree root-plate features, and runout distance. Slopes adjacent to site P3 just up-stream from the Pakuratahi weir were also surveyed to determine slip-derived sediment inputs to the stream channel. In addition, 10 transects were established at each of the three sites to measure changes in channel profiles. through the harvesting and post-harvesting period (see Chapter 7).

A site-disturbance survey method, based on McMahon (1995) was used to identify the extent of potential sediment source areas across the harvested areas. A plot-based assessment of the rate of ground cover vegetation recovery, for a 24-month period following harvesting, was also used as a measure of the persistence of those disturbance classes likely to generate most sediment. For the post-harvesting recovery period the effect of site-preparation practices, including desiccation and over-sowing, on vegetation recovery and sediment generation was recorded. Finally, sediment fences were constructed across four zero order drainage basins each between 1-to-2 ha to measure the amount of sediment generated from disturbed sites and its potential to reach a stream channel (Fig.1). Slope-derived sediment volume was converted to t/km^2 using a bulk density of 1820 kg/m^3. Sediment accumulation totals were measured at 6-weekly intervals for a 12-month period

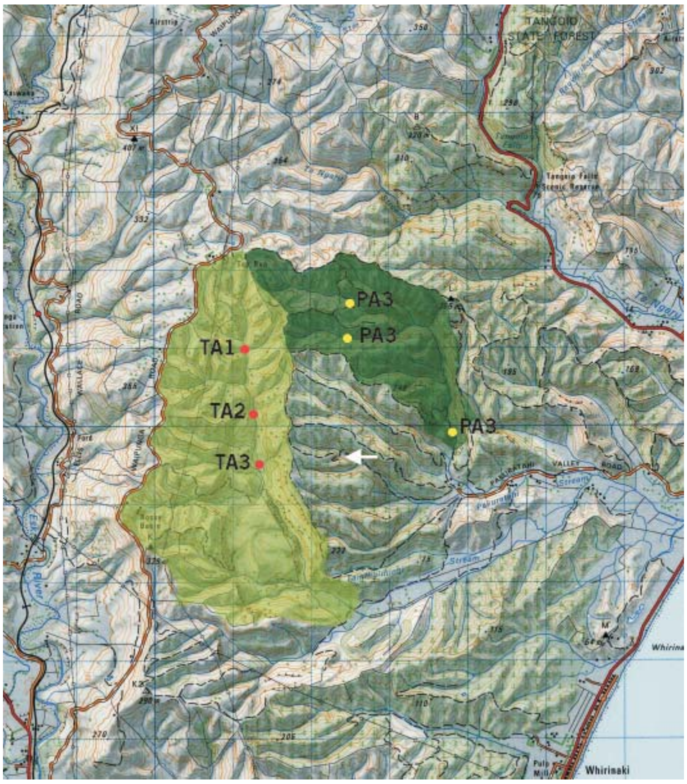

Figure 1. Sites for assessing channel responses. Areas above T1 in the upper reaches of the Tamingimingi catchment and P1 in the upper reaches of the Pakuratahi catchment were those used for assessing sediment sources and slip damage. The arrow identifies the location of the plots used in the Pakuratahi catchment for assessing site disturbance and vegetation recovery, and slope wash. The map scale is approximately 1:70,000.

commencing immediately after the completion of harvesting and concurrent with harvesting activities on slopes upstream of the Pakuratahi weir.

Fransen (1996) produced a GIS-based erosion risk model for the two catchments, incorporating local geology, soils, landforms, slope, and aspect, and historical slip distribution. Risk ratings were assigned by assessing the percentage area of slips within sub-classes of each landscape feature, which produced five erosion risk categories: very high, high, moderate, low and very low. The total area of all slips was 234 ha. Most slips identified were triggered by the 1938 Anzac storm, and Cyclone Bola in 1988.

Sediment yield periods

The first activity that might increase sediment production in the Pakuratahi catchment was the extension of the road just upstream of the weir in July 1997. Extensive road upgrading began in 1998 together with the construction of new landings. In addition, half of the planted area in the catchment was harvested that year, mostly by skyline hauler. In 1999, 1.5 km of new road was constructed, and the rest of the tree crop was removed (Fig.2). The harvesting operation was virtually complete by October. Thus three main periods (one with two phases) can be identified to help explain any trends in sediment yield: a pre-harvesting period (January 1995–June 1997) described in detail by Fahey and Marden (2000); a harvesting period comprising an initial preparation phase of road and landing construction in the second half of 1997, and a 2-year logging phase extending through 1998 and 1999; and finally a post-harvesting period associated with over-sowing and replanting commencing in 2000 (Fig.3).

Figure 2. View of the headwaters of the Pakuratahi catchment after harvesting by skyline hauler, March 1999.

Figure 3. View of the Pakuratahi catchment 200 m upstream from the weir showing continuous cover of grass after over-sowing, March 2000. The area was harvested in July 1999.

Results

Pre-harvesting period sediment yields

Nine events were sampled concurrently in both catchments. On average the Tamingimingi (in pasture) yielded 3 times more sediment per unit area than the Pakuratahi catchment (in mature pines) (Table 1).

Period	Date	Pakuratahi Yield (t/km^2)	Tamingimingi Yield (t/km^2)	Ratio Pak:Tam
Pre-harvesting (Jan. 1995 to June 1997)	5/7/95	0.46	1.6	1:3.5
	15/7/95	0.28	1.02	1:3.6
	1/11/95	0.09	0.25	1:2.8
	23/6/96	2.41	5.56	1:2.3
	4/7/96	0.17	1.71	1:10.1
	30/12/96	2.70	8.83	1:3.3
	19/2/97	0.20	0.05	1:0.3
	11/3/97	1.00	1.61	1:1.6
	27/5/97	1.16	0.76	1:1.8
	Total	7.5	21.4	1:2.9

Table 1. Suspended sediment yields for storms sampled concurrently at the Pakuratahi (forested) and Tamingimingi (pasture) catchments, and the ratio of the Pakuratahi to the Tamingimingi yields during the pre-harvesting period.

When the calculated sediment yields for non-sampled storms over 20 l/s/km^2 were added to the sampled storms, the Tamingimingi catchment is estimated to have generated 3.7 times more sediment (153.3 t/km^2) than Pakuratahi catchment (41.8 t/km^2) (Fig 4).

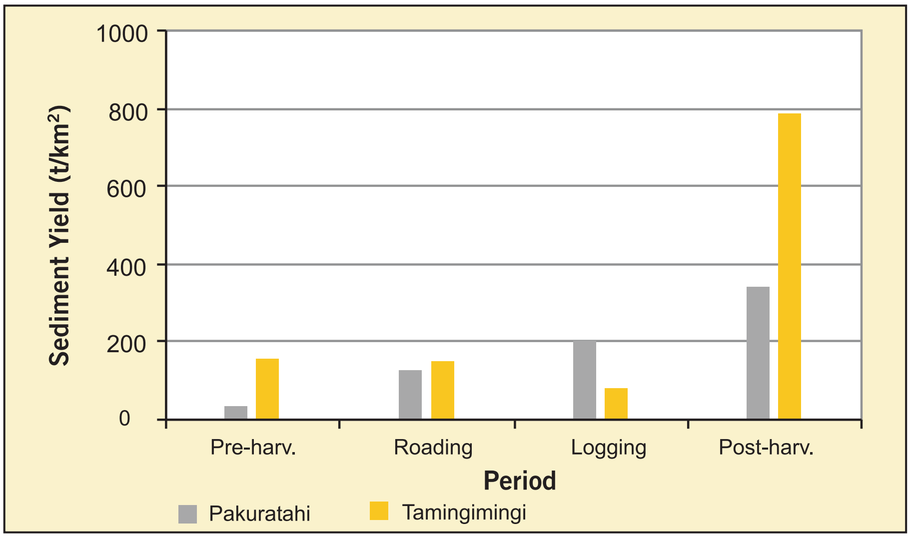

Figure 4. Suspended sediment yields for the pre-harvest period (Jan 1995 to Jun 1997), the road construction phase (Jul to Dec 1997), the logging phase (Jan 1997 to Dec 1999), and the post-harvesting period (Jan 2000 to Dec 2005).

Harvesting period sediment yields

Table 2 shows no evidence of additional sediment being mobilised on a storm-by-storm basis in the Pakuratahi catchment during the initial road and landing construction phase (July to December 1997). Total storm specific yields from the Tamingimingi catchment remained just under 3 times higher than those from the Pakuratahi.

However, when all unsampled storms exceeding 20 l/s/km^2 were included using the regression procedure, specific yield from the Pakuratahi catchment was 125.4 t/km^2 compared with 148 t/km^2 for the Tamingimingi (pasture) catchment (Fig 4), suggesting that additional sediment derived from road construction and logging may have entered the Pakuratahi catchment during this period.

Period	Date	Pakuratahi Yield (t/km^2)	Tamingimingi Yield (t/km^2)	Ratio Pak:Tam
Initial road construction phase	22/8/97	1.8	3.0	1:1.7
(July to Dec. 1997)	24/9/97	1.8	7.0	1:3.9
	14/10/97	1.3	2.4	1:1.8
	Total	4.9	12.4	1:2.5
Logging phase	15/7/98	14.7	12.0	1:0.8
(Jan. 1998 to Dec. 1999)	26/7/98	13.8	10.5	1:0.8
	17/1/99	4.4	0.5	1:0.1
	14/3/99	9.8	6.9	1:0.7
	15/3/99	11.3	2.4	1:0.2
	2/5/99	2.3	0.6	1:0.3
	5/6/99	23.0	15.0	1:0.7
	28/11/99	2.7	1.0	1:0.4
	Total	84.9	48.9	1:0.6

Table 2. Suspended sediment yields for storms sampled concurrently at the Pakuratahi (forested) and Tamingimingi (pasture) catchments, and the ratio of the Pakuratahi to the Tamingimingi yields during the harvesting period.

During the logging phase (January 1998 to December 1999) the 8 concurrently monitored storms produced a total of 85 t/km^2 at the Pakuratahi catchment (in pines) but only 49 t/km^2 at the Tamingimingi (in pasture) (Table 2). Adding the non-sampled storms to this list using the regression procedure produced estimated suspended sediment yields of 204 t/km^2 and 80 t/km^2 for the Pakuratahi and Tamingimingi respectively (Fig 4), suggesting that sediment yield associated with roading and logging had increased to the point that it was now over 2½ times that associated with pasture. Over the entire harvesting period (roading plus logging), the Pakuratahi is estimated to have yielded 330 t/km^2, and the Tamingimingi, 229 t/km^2, which amounts to a 1.4-fold increase from the former catchment.

To ensure that higher sediment yields during the road construction and logging phases were not the result of a greater number of high magnitude storms through the period, a comparison was made of the mean and maximum peak flows for each interval. It showed that the record of high magnitude ($\geq$100 l/s/km^2) runoff events in the pre-harvesting, harvesting, and post-harvesting periods at the Tamingimingi (remaining in pasture) was similar. This confirms that any observed changes in storm sediment yields in the Pakuratahi catchment during the harvesting period can safely be attributed to land-use effects rather than to any change in the magnitude and frequency of storm events.

Post-harvesting period sediment yields

In the first year of the post-harvesting recovery period (2000) storm-based suspended sediment yields were, for the most part, similar from both catchments (Table 3). However, when the non-sampled storms were added for that year the Pakuratahi is estimated to have produced 228 t/km^2 but the Tamingimingi only 139 t/km^2 (Table 4 and Fig.5).

Between 2003 and 2005 however, suspended sediment yields for individual storms monitored in the Tamingimingi (in pasture) were all substantially higher that those measured concurrently in the

Pakuratahi (harvested and replanted) (Table 3). Adding in all the non-sampled storms ≥20 l/s/km^2 over these three years the Tamingimingi yielded 503 t/km^2, whereas the Pakuratahi yielded only 93 t/km^2 (Table 4).

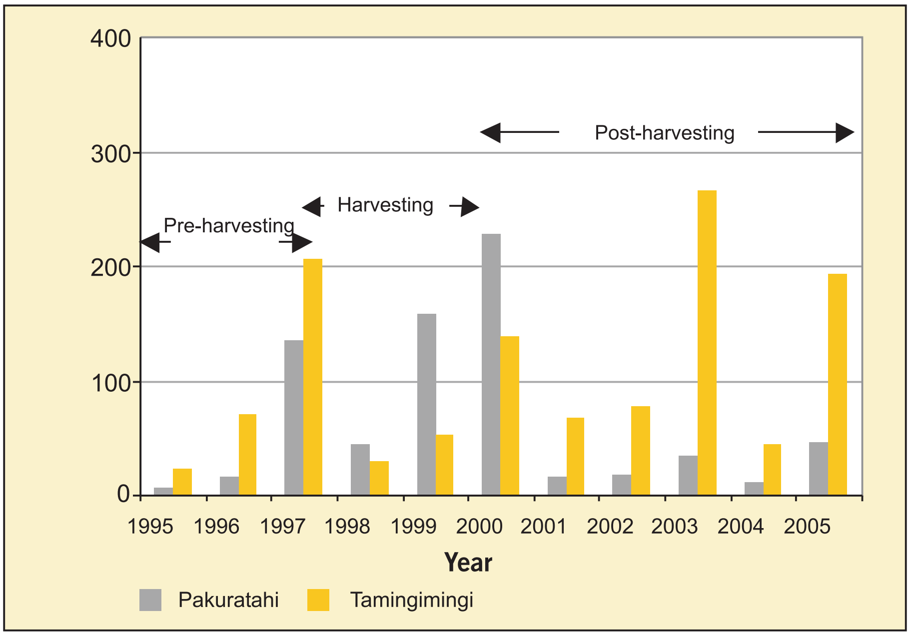

Table 3. Suspended sediment yields for storms sampled concurrently at the Pakuratahi (forested) and Tamingimingi (pasture) catchments, and the ratio of the Pakuratahi to the Tamingimingi yields during the post-harvesting period.

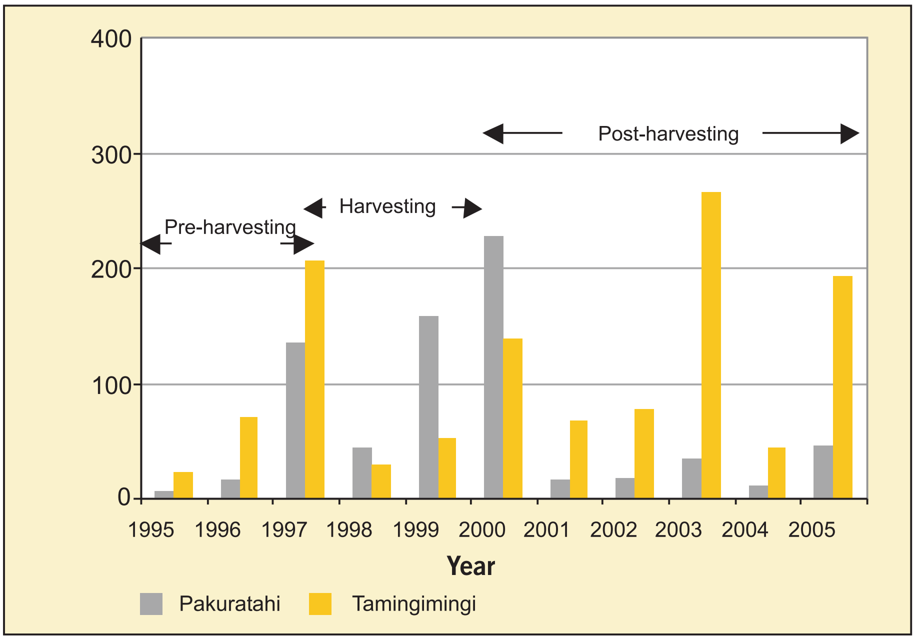

Figure 5. Annual suspended sediment yield for the Pakuratahi and Tamingimingi catchments from 1995 to 2005.

Yearly comparisons

Between 1995 and 1997, corresponding approximately with the pre-harvesting period, the annual suspended sediment yields for the Tamingimingi were 2–4 times higher than those for the Pakuratahi (Table 4 and Fig. 4). By the second year of the harvesting period (1999), the situation was just the reverse, with the yield for the Pakuratahi about 3 times that of the Tamingimingi. In

the first year of the post-harvesting (recovery) period (2000), the suspended sediment yield for the Pakuratahi was still almost twice that from the Tamingimingi, but in 2001 it had declined to the point that the Tamingimingi was generating 4 times as much, a situation not seen since 1995, suggesting that sediment yields had returned to pre-harvest levels. This situation was repeated each year between 2002 and 2005 (Table 4 and Fig.5).

Figure 5 and Table 4 show sediment yields for 2003 to be much higher than in the previous two years of the post-harvesting period, especially for the Tamingimingi. It is estimated to have yielded 265 t/km^2 from the 26 storms that exceeded 20 l/s/km^2 (160 l/s). Six of these had peak discharges that were over 600 l/s/km^2 (5000 l/s). In contrast, there was only one event in each of the two preceding years with peak discharges exceeding 5000 l/s.

The total suspended sediment yields for both catchments over the 11-year period were 713 t/km^2 for the Pakuratahi, and 1168 t/km^2 for the Tamingimingi.

Bedload estimates

Between August 1996 and April 1997 (pre-harvesting) 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 for bedload material, 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. On a unit area basis, these convert to 0.4 t/km^2 for both catchments or approximately 0.5 t/km^2 per year.

Bedload measurements for the Tamingimingi ceased in July 1998 by which time the length of the channel monitored by cross section measurement had aggraded to the level of the weirs. Thus the trend has been one of increasing stream bed aggradation throughout the length of the monitored channel reach. The information on bedload collected upstream and downstream of the Pakuratahi weir up until 2000 (when measurements ceased) is inconclusive and thus difficult to interpret, but collectively it suggests that bedload is a very minor component of the total load, compared with material carried in suspension. This situation is common in most New Zealand rivers (Griffiths and Glasby, 1985).

Erosion

In the first 7 months of 1997 stream scour occurred in the Tamingimingi catchment, and the upper reaches of the Pakuratahi, accompanied by stream infilling in the vicinity of the lower Pakuratahi site. Bank erosion was observed along all channels in both catchments as slumps or bank collapses and intermittent lateral scour. The density of slips was highest in the area of mature forest (131/km^2) falling to 13/km^2 under 8-year old pines. In the Tamingimingi under pasture, slip density was 54 /km^2. In the area just above the Pakuratahi weir, 70% of the volume of material mobilised by slips came from sidecast associated with an access road constructed in 1982. Runouts extended downslope for up to 120 m. Fewer land slips entered the channel from the Tamingimingi compared with the Pakuratahi. Fransen (1998) suggested that the unexpected result of more slip erosion under mature forest compared with pasture could be due to a combination of factors, including inherent differences in slope stability, variations in rainfall and catchment wetness, and vegetation characteristics.

Fransen's (1996) GIS-based erosion risk model showed that very high risk areas occupied 6% of the Pakuratahi, and 2% of the Tamingimingi catchments. They are defined by Ohakean Gravels

with Recent Tephric and Orthic Soils on upper ridges and on east or west-facing slopes of 20º to 25º. High risk areas covered 8% and 10% of the Tamingimingi and Pakuratahi catchments respectively, and are associated with Ohakean Gravels and the Kaiwaka Formation, and Recent Tephra and Orthic soils on steep slopes and upper ridges. Moderate levels of slip erosion occupied 14% of both catchments on slopes between 15º and 25º. Finally, low and very low risk areas occupied 77% of the Tamingimingi and 70% of the Pakuratahi.

	Pakuratahi (forested)			Tamingimingi (pasture)			Ratio
Year	**Flow (mm)**	**Events (≥20l/s/km²)**	**Sed. yield (t/km²)**	**Flow (mm)**	**Events (≥20l/s/km²)**	**Sed. yield (t/km²)**	**Pak:Tam**
1995	271	15	7.0	283	16	22.5	1:3.2
1996	387	25	17.0	429	21	71.0	1:4.1
1997	484	22	136.2	526	22	207.2	1:1.5
1998	313	12	44.8	271	12	29.0	1:0.6
1999	443	14	158.9	373	16	52.4	1:0.3
2000	416	18	227.7	369	15	138.6	1:0.6
2001	391	17	16.1	325	18	68.0	1:4.3
2002	448	13	19.3	35	18	77.2	1:4.1
2003	519	25	34.3	462	26	265.4	1:7.7
2004	410	14	11.2	354	18	44.1	1:4.0
2005	544	10	47.0	515	13	193.0	1:4.1
Means	400			381			
Totals		133	713		133	1168	1:1.6

Table 4. Annual water yield (mm), storm events (≥20 l/s/km^2), and suspended sediment (t/km^2) yields for the Pakuratahi (forested) and Tamingimingi (pasture) catchments for the period 1995–2005.

Site disturbance, vegetation recovery, and slope wash

Over 90% of the 23 ha of logged-setting surveyed in the Pakuratahi catchment sustained only minimal ground-surface disturbance or remained undisturbed. Sites of deep-disturbance, associated with hauler-logging, occupied just 9% of the logged setting. This is at the low end of the range of values found for similarly logged settings elsewhere in New Zealand (McMahon, 1995; Marden and Rowan, 1997; Marden, et al., 2006).

As a consequence of harvesting, groundcover vegetation at the site of the study plots was effectively reduced to 1% on sites of deep-disturbance (Fig. 6) and to 7% on sites of shallow-disturbance. After the completion of harvesting (August 1998), vegetation recovery was fastest on the less disturbed sites and slowest on sites where disturbance had been more extensive and to a greater depth. Within 6 months of the completion of harvesting (March 1999) groundcover vegetation occupied ~95% of the former sites but just 77% of the latter sites. Following the application of desiccant (April 1999), a normal forest practice to reduce competition between young pine seedlings and the regenerating groundcover, this groundcover was effectively killed across all sites. The desiccant had its greatest effect on deep-disturbance sites where the weed-dominated groundcover was burnt-off to re-expose the bare ground beneath and where sediment generation by slopewash processes increased. In contrast, on sites of shallow-disturbance the grass dominated groundcover remained in situ and, though dead, it continued to afford protection against sediment generation. Within 2-years of over-sowing harvested areas with exotic grass species, a practice designed to encourage the re-establishment of a low-stature groundcover that will reduce sediment generation and its movement off-slope, groundcover re-occupied ~80% of sites of deep-disturbance (Fig.7), and 97% of shallow-disturbance sites.

Slopewash processes on sites of deep-disturbance (9% of logged setting) in the first year after logging are estimated to have delivered sediment to the stream at a rate of 2.4 t/km^2. Logging over the planted area (3.13 km^2) was completed in August 1998, and is estimated to have yielded 7.5 t/km^2, which is only 1% of the total suspended load of the Pakuratahi (713 t) for the 11–year period of record (Table 4).

Figure 6. View taken soon after harvesting in October 1998 of a plot established in an area of deep disturbance (for location see Figure 1).

Figure 7. View of same deep disturbance plots as shown in Figure 6, two years after harvesting in September 2000.

Comparisons with other studies

O'Loughlin et al., (1980) compared the sediment yields from two of the Maimai experimental catchments near Reefton immediately after harvesting, one by skidder (M9) and one by hauler (M7) with an adjacent control (M6). Sediment yield rates were 264, 47, and 33 m^3/km^2/yr respectively. These figures are not considered typical of the longer term as the measurement period

was drier than usual with fewer large storms. Hicks and Harmsworth (1989) monitored changes in suspended sediment yield from the harvesting phase of a section of Glenbervie Forest in Northland. They found that landing construction and road upgrading before harvesting caused storm yields to rise to 300 t/km^2 representing an increase of 40 times over yields from similar storms before harvesting.

The 2–3-fold increase in suspended sediment yields estimated for the Pakuratahi catchment following harvesting is low compared with that noted by Hicks and Harmsworth (1989) at Glenbervie Forest in Northland. This may be a reflection of the weather conditions during the critical harvesting period, differences in harvesting methods, or both.

Fransen (1998) identified the principal sources of sediment during the harvesting and post-harvesting periods, in order of importance, as: sidecast from old roadlines, shallow landslides and channel bed scouring (Fig. 8). Most of the post-harvest reduction in sediment yield from Pakuratahi can be attributed to a lessening of forest-related activites such as reduced traffic flows, roading works and reduced runoff from revegetated landings and areas of roadside fill. In addition, the contribution to sediment yield by runoff from these sites will further diminish in response to improved on-slope sediment filtering by groundcover vegetation as it continues to spread, and as grass swards thicken.

Figure 8. Potential sources of sediment from road cut banks, and sidecast, in the middle reaches of the Pakuratahi catchment.

Conclusions

The data show that pasture catchments in coastal Hawke's Bay can yield 3–4 times more suspended sediment than those catchments in mature plantation forests in the pre-harvesting period. During the logging phase of the harvesting period, the situation can be reversed, with the amount of sediment being 2–3 times that generated from comparable pasture catchments. For the first year after harvesting, suspended sediment yields will exceed those from comparable catchments in pasture, but with the adoption of appropriate management practices such as rapid replanting and over-sowing, sediment yields from harvested areas should be back to pre-harvest levels within 2–3 years. The main sources of sediment are from cutbank and sidecast failures, shallow landslides,

and channel beds and banks. Slopewash on cutovers is not an important sediment generating process. The data also confirm that, in the absence of a Bola-type event at or shortly after harvesting, total suspended sediment yields over a full forest rotation in this type of terrain will be substantially less than those from catchments in pasture.

Acknowledgements

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Attachment 2

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Sediment yields from plantation forestry and pastoral farming, coastal Hawke's Bay, North Island, New Zealand

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Abstract

Suspended sediment yields have been monitored since 1995 in two catchments in the erodible hill country of coastal Hawke's Bay, one in pasture (the Tamingimingi, 7.95 km^2), and the other initially in mature *Pinus radiata* plantation forest (the Pakuratahi, 3.45 km^2). The latter was harvested by skyline hauler (85%) and skidder (15%) between December 1997 and October 1999. Post-harvesting preparation in early 2000 included over sowing with grass and legumes, and ripping of hauler pads before replanting. Suspended sediment yields were calculated for 50 events at the Pakuratahi and 30 at the Tamingimingi. The relationship between storm sediment yields and corresponding peak flows was used to estimate yields for all unsampled storms exceeding 20 L/s/km^2 in both catchments. Data for the sampled storms and those calculated for the unsampled ones were then summed to estimate annual suspended sediment yields and totals for given periods during the forest rotation. During the pre-harvesting period (January 1995 to June 1997) total suspended sediment yield for the pasture catchment was 3 times higher than for the catchment in mature pines. In the logging phase of the harvesting period (January 1998 to December 1999) the situation was reversed, with the total yield for the harvested catchment twice that of the one in pasture. Despite the removal of the vegetation cover during harvesting, slope disturbance was minimal, with the increase in yields thought to have come predominantly from road sidecast, landslides, and channel bed scouring. Yields from the harvested catchment declined markedly after over sowing and replanting, and in 2001 were substantially less than those from the pasture catchment. This reduction is attributed as much to a decline in forest-related activities as it is to a steadily increasing grass cover across all disturbed sites. Over the 7 years of record (1995–2001) the catchment originally planted in pines and subsequently harvested has yielded only 20% more suspended sediment than the one in pasture. This suggests that, with average weather conditions during and immediately after harvesting, sediment yields from catchments in plantation forestry over a full forest rotation in this type of terrain should be less than from catchments left in pasture.

Key words

plantation forestry, sediment yield, harvesting impacts

Introduction

Plantation forestry is a common activity in the soft-rock hill country of the east coast of the North Island, New Zealand. Many of these forests are approaching maturity, and concerns have been expressed that harvesting might trigger a phase of erosion similar in scale to that accompanying the removal of the original forest cover in the late 19th and early 20th centuries. In 1993, an experimental catchment project involving the Hawke's Bay Regional Council, local forestry companies, and government science providers, was established near Napier to assess short- and long-term changes in sediment yield and water quality in response to forestry operations in the area. A broader, and more fundamental question to be considered was whether land in pasture or forestry could be expected to yield more sediment in the longer term, i.e., over the length of a forest rotation (20–30 years).

As a first step in addressing these issues, the programme compared sediment yields from two catchments, one in pasture (the Tamingimingi) and the other in mature exotic plantation forest (the Pakuratahi) for the pre-harvesting period (January 1995 to May 1997) (Fahey and Marden, 2000). Between 1997 and 1999 the forested catchment was harvested. This paper assesses the sediment yield response to harvesting and subsequent over sowing and replanting, during the period June 1997 to December 2001. Furthermore, in order to assess the relative contribution of different sediment-generating processes to sediment yield, particularly during the post-harvesting recovery period, we have drawn on the findings of research in progress on slopewash, and those of Fransen (1998), who documented road-related, landslide and channel scour sources of sediment delivered to streams in the Pakuratahi during the winter of 1997.

Field area

The two catchments are located 18 km northwest of Napier (Fig.1). The Tamingimingi ($7.95\ km^2$) has been intensively grazed since the 1900s and is currently in improved pasture. The Pakuratahi ($3.45\ km^2$) was planted in *Pinus radiata* in 1971–1972. In the latter half of 1997 road clearance and landing construction began in preparation for harvesting, which took place through 1998 and 1999.

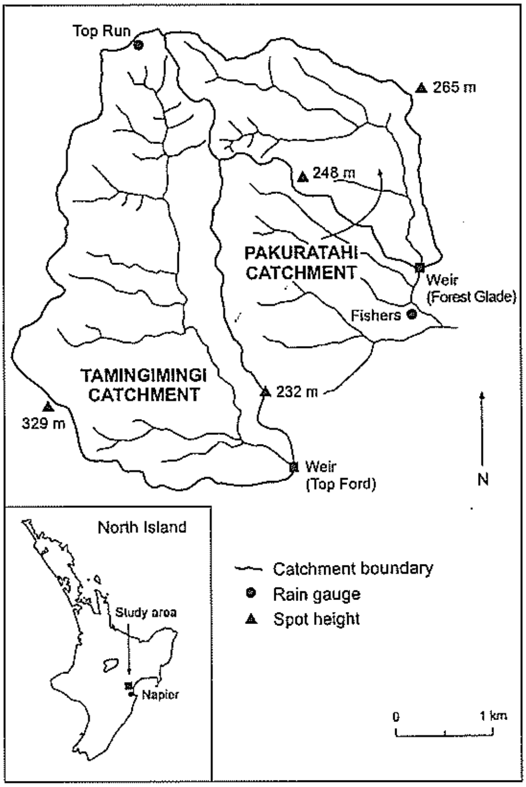

Figure 1 – Location map of study area showing the Pakuratahi and Tamingimingi catchments.

The catchments are underlain by gently dipping Tertiary sediments capped with gravels, volcanic ash and loess (Haywick *et al.*, 1991). The dominant soils are Pallic and Duric Pallic soils (Hewitt, 1998). Both may have hard pans that impede drainage, and are prone to surface erosion and mass movement. The climate is characterised by warm summers, and moderate winters. In 1980 the long-term mean annual rainfall at Tangoio 5 km to the north was 1501 mm (New

Zealand Meteorological Service, 1983), with high rainfall variability from month to month and year to year. Additional details on the geology, soils, and climate of the field area are given in Fahey and Marden (2000).

Methods

Rainfall was measured with two tipping-bucket rain gauges, one installed near the Pakuratahi weir (Fishers), and the other at the head of the Tamingimingi catchment (Top Run). Stream water levels were monitored with float-operated shaft encoders at Crump-type weirs, and recorded with Campbell CR10 data loggers. Details on weir ratings and accuracy of records can be found in Fahey and Marden (2000). Instrument malfunctions between January and May 2001 at the Tamingimingi weir required that the flow record for this period be estimated by comparison with the flow record from the Pakuratahi weir. This was achieved by comparing peak flows and low flows before and after the missing data period at the Tamingimingi, and visually adjusting the Pakuratahi flow on-screen with a time-series data management system (HYDSYS), to simulate the Tamingimingi record.

Two 24-bottle Sigma water samplers, controlled by a CR10 logger, were used to sample suspended sediment. They were set to sample above predetermined stage heights equivalent to 50 L/s (15 L/s/km^2) for the Pakuratahi and 120 L/s (15 L/s/km^2) for the Tamingimingi at intervals of either 30 or 90 minutes on the rising and falling limb of the storm hydrograph. Sampling ceased when the hydrograph fell below the predetermined stage heights. Instantaneous flows below 15 L/s/km^2 at both catchments were almost always in the base flow range, and thus not regarded as capable of generating significant amounts of suspended sediment. If, because of storm size or duration, all bottles were filled before the end of an event, the relationship established between flow and sediment concentration on the falling limb for other storms was used to complete the record. Samples (0.5 L) were vacuum-filtered and oven-dried to determine suspended sediment concentrations. Storm sediment loads were measured in tonnes, and sediment yield in tonnes per square kilometre.

Suspended sediment yields for sampled storms were determined from the product of flow and the average suspended sediment concentrations calculated for the chosen interval. These were summed over the duration of the storm. Between January 1995 and December 2001, 50 storms were sampled for suspended sediment concentrations at the Pakuratahi weir, and 30 at the Tamingimingi weir. The numbers differ because of spatial variability in rainfall, and occasional equipment malfunctions. A total of 27 were monitored and sampled concurrently in both catchments.

Storm suspended sediment loads and associated peak flows for both catchments were log transformed and a least-squares regression model was used to establish the relationship between the two parameters (Hicks, 1990; Basher *et al.*, 1997). The procedure described by Basher *et al.* (1997) was used to calculate the 95% confidence intervals associated with the different stages of the forest rotation, and to calculate annual yields.

For the Pakuratahi catchment, all events between January 1995 and December 2001 with peak flows ≥ 20 L/s/km^2 were identified, and the list subdivided into the intervals assigned to the various forest rotation periods (pre-harvesting, road construction and crop removal phases, and post-harvesting). The use of the ≥ 20 L/s/km^2 threshold ensured that all medium-and larger-sized storms were included in the calculations. The regression equations (Table 1) derived from the relationship between suspended sediment

Table 1 – Rating-curve regression equations derived from the log-log relationship between peak storm discharge (PQ) and suspended sediment yields (SSY), where log SSY = a + b log PQ is used to estimate suspended sediment yields for storms with no suspended sediment concentration data. The number of data pairs is given by n, and r^2 is the coefficient of determination.

Catchment	Period	a	b	n	r^2
Pakuratahi (forested)	Pre-harvesting	–6.00	2.33	18	0.779
	Road construction phase	–4.56	1.95	5	0.950
	Logging phase	–4.01	1.78	11	0.858
	Post-harvesting	–5.13	2.07	13	0.942
Tamingimingi (pasture)	Jan. 1995 to Dec. 2001	–4.71	1.84	28	0.914

yields and peak discharge for each of these periods were used to estimate the suspended sediment yields for those storms with no suspended sediment concentration data. In cases where storms displayed more than one peak, a single event was considered to have occurred if there was less than 6 hours between individual peaks. The biggest peak was used in the regression procedure. If there was more than 6 hours between peaks, they were regarded as separate events. These data were summed and added to those derived from sampled events to provide total yields for each interval. These totals were then compared with those for the Tamingimingi (based on events ≥ 20 L/s/km²), calculated for the same intervals, using the regression equation for that catchment listed in Table 1.

We also identify here the methods used by others working on on-site, process-based studies on sediment sources in the two catchments. Their findings help explain relationships between sediment yield and land use, before and after harvesting in the Pakuratahi catchment. First, a site-disturbance survey method, based on McMahon (1995), was undertaken to identify the extent of potential sediment source areas across the logged setting. Secondly, a plot-based assessment of the rate of revegetation by ground cover for a 24-month period following harvesting, was used as a measure of the persistence of those areas likely to generate most sediment. For the post-harvesting recovery period the effect of site-preparation practices, including desiccation and over sowing, on vegetation recovery and sediment generation was recorded. Thirdly, to measure the amount of sediment generated from disturbed sites and its potential to reach a stream channel, sediment fences were constructed across four zero-order drainage basins each between 1 to 2 ha. The fences were positioned at the point where drainage from these basins entered a permanent stream channel, the assumption being that any sediment trapped behind these fences was destined to reach the main channel. So as not to influence the sediment yield figures measured at Pakuratahi weir the sediment fences were located in a sub-catchment downstream of the weir (Fig. 1).

Sediment accumulation behind each fence was measured using the "erosion bridge" method of Ranger and Frank (1978). Sediment volume was converted to t/km² using a bulk density of 1820 kg/m³. Data were collected at 6-weekly intervals for a 12-month period commencing immediately after the completion of harvesting and concurrent with harvesting activities on slopes upstream of the weir.

Harvesting procedures

The tree crop in the Pakuratahi catchment was harvested by Pan Pac Forest Products, Napier (Gilmore, 1999; unpublished report). Approximately 8 km of the existing road network required upgrading. This began in 1998 and was largely complete in early 1999.

New road construction began in July 1997 with the extension of a road on the true right bank just upstream from the weir. Approximately 2 km of new road were added in 1998, and 1.5 km in 1999. A total of 52 hauler pads were used. Of these, 25 were new, 20 were upgraded from thinning sites, and the remaining 7 did not require upgrading. Slash was kept to a minimum on all landings and away from the perimeters where possible.

Two main sites were established outside the catchments where the logs were processed and cut to customer specifications. The separation of yarding activities from log processing meant that hauler sites within the catchment could be smaller than the standard 50 × 50 m area. Approximately 15% of the catchment was harvested using an excavator and rubber-wheeled skidder, mostly on ridge tops and crests. The rest was skyline-logged using a BE70 and a BE85 yarder; their tower height meant more lift, less soil disturbance, and higher payloads.

Harvesting began in late December 1997 and by December 1998 141 ha, or approximately half of the area, had been clearfelled. The remaining 50% was logged by October 1999. The post-harvesting preparation comprised aerial desiccation to control the regeneration of pine and blackberry, over sowing with grass and legumes, replanting, and spot spraying. Many of the hauler pads were ripped with a bulldozer for replanting. At the end of the period reported here trees were 2 years old.

In summary, the first activity that might increase sediment production in the catchment was the extension of the road just upstream of the weir in July 1997. Extensive road upgrading began in 1998, together with the construction of new landings. In addition, half of the planted area in the catchment was harvested that year, mostly by skyline hauler. In 1999, 1.5 km of new road were constructed, and the rest of the tree crop was removed. The harvesting operation was largely complete by October. Thus three main periods (one with two phases) can be identified to help explain any trends in sediment yield: a pre-harvesting period (January 1995–June 1997) described in detail by Fahey and Marden (2000); a harvesting period comprising an initial preparation phase of road and landing construction in the second half of 1997, and a 2-year logging phase extending through 1998 and 1999; and finally a post-harvesting period associated with over sowing and replanting commencing in 2000.

Results and discussion

Pre-harvesting period sediment yields

Nine events sampled concurrently in both basins yielded 3 times more sediment from the Tamingimingi catchment (in pasture) per unit area than from the Pakuratahi (in mature pines) (Table 2). Similarly, when the regression equation from Table 1 was used to calculate sediment yields for non-sampled storms over 20 L/s/km^2, and these were added to the sampled storms, the pasture catchment is estimated to have generated 3 times more sediment than the one in mature pines (Fig. 2). The confidence intervals are sufficiently small to suggest that the difference between the two totals is significant. Further details of the comparison between concurrent event-based suspended sediment yields from the two catchments for the pre-harvesting period are provided in Fahey and Marden (2000).

Harvesting period sediment yields

Table 2 shows that during the initial road and landing construction phase (July to December 1997) there is no evidence of additional sediment being mobilised during storms in the forested catchment. Indeed,

Table 2 – Suspended sediment yields for storms monitored concurrently at the Pakuratahi (forested) and Tamingimingi (pasture) catchments, and the ratio of the Pakuratahi to the Tamingimingi yields (July 1995 to July 2000)

Period	Date	Pakuratahi Yield (t/km^2)	Tamingimingi Yield (t/km^2)	Ratio Pak:Tam
Pre-harvesting (Jan. 1995 to June 1997)	5/7/95	0.28	1.6	
	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	8.83	
	19/2/97	0.11	0.05	
	11/3/97	1.00	1.61	
	27/5/97	1.25	0.76	
	Total	7.6	21.2	1:2.80
Road construction phase (July to Dec. 1997)	22/8/97	2.3	3.0	
	24/9/97	1.3	9.3	
	15/10/97	1.3	9.7	
	Total	4.9	22.0	1:4.50
Logging phase (Jan. 1998 to Dec. 1999)	15/7/98	14.7	12.0	
	26/7/98	13.8	6.9	
	21/11/98	0.8	0.1	
	26/11/98	1.6	0.1	
	17/1/99	4.4	0.5	
	14/3/99	9.8	5.2	
	15/3/99	11.3	2.4	
	2/5/99	2.3	0.6	
	5/6/99	23.0	15.0	
	28/11/99	2.7	1.0	
	Total	84.4	43.8	1:0.52
Post-harvesting (Jan. 2000 to Dec. 2001)	8/1/00	101.0	96.2	
	9/4/00	60.2	17.7	
	27/6/00	0.14	0.1	
	3/7/00	15.4	15.0	
	27/7/01	0.10	0.05	
	Total	176.84	129.05	1:0.73

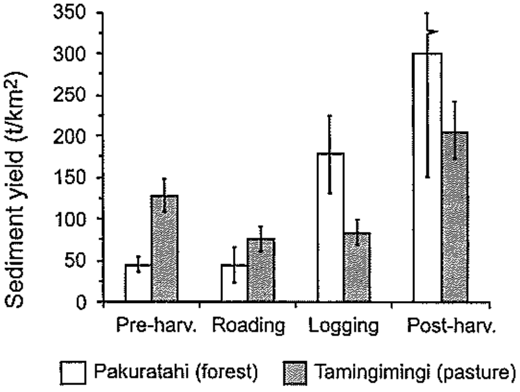

Figure 2 – Suspended sediment yields for the pre-harvesting, harvesting (road construction and logging phases), and post-harvesting periods. These were derived by combining the measured amounts with those calculated from the regression equations in Table 1. The 95% confidence intervals are shown on the bars.

specific yields from the pasture catchment were 4–5 times more than from the catchment in pines, which was a higher ratio than that observed during the pre-harvesting period. However, when all unsampled storms exceeding 20 L/s/km^2 were included using the regression equation in Table 1, specific yield from the pasture catchment was only about 1.5 times higher (Fig. 2), suggesting additional sediment may have entered the Pakuratahi catchment during this period.

During the logging phase (January 1998 to December 1999) the 10 concurrently monitored storms produced a total of 84 t/km^2 at the Pakuratahi catchment (in pines) but only 44 t/km^2 at the Tamingimingi (in pasture). Adding the non-sampled storms to this list using the regression equation in Table 1 produced estimated suspended sediment yields of 179 (±46) t/km^2 and 82 (±14) t/km^2 for the Pakuratahi and Tamingimingi respectively (Fig. 2).

Post-harvesting period sediment yields

Early in the post-harvesting recovery period, storm-based suspended sediment yields from the Pakuratahi remained substantially higher than those from the Tamingimingi (Table 2). During the storm of 9 April 2000, for example, the Pakuratahi yielded 3.5 times more sediment than the Tamingimingi. However, totals for the five storms over the whole post-harvesting period were similar (177 t/km^2 for the Pakuratahi, and 129 t/km^2 for the Tamingimingi), suggesting that the yields from the Pakuratahi are beginning to return to pre-harvesting levels. Adding yields from all unsampled storms $\geq$ 20 L/s/km^2, calculated using the regression equation from Table 1, shows the suspended sediment yield for the Pakuratahi (299 ±147 t/km^2) to still exceed that for the Tamingimingi (205 ±35 t/km^2) (Fig. 2). The large confidence interval for the Pakuratahi compared with the Tamingimingi suggests that the sediment response to storms is erratic early in the post-harvesting recovery period and will remain so until canopy closure.

Comparison of peak flows

To ensure that the higher sediment yields measured during the road construction and logging phases were not the result of a greater number of high-magnitude storms during that period, a comparison was made of the mean and maximum peak flows for each interval (Table 3). In the pre-harvesting period the mean peak discharge for large events ($\geq$100 L/s/km^2) at the Pakuratahi (211 L/s/km^2) was substantially lower than that calculated for the same period for the Tamingimingi (295 L/s/km^2). The maximum peak discharge for the Pakuratahi was 674 L/s/km^2, compared with 1030 L/s/km^2 for the Tamingimingi. By contrast, in the 2-year harvesting period the mean peak discharge for events over 100 L/s/km^2 at the Pakuratahi (385 L/s/km^2) exceeded that for the Tamingimingi (339 L/s/km^2). The

Table 3 – Mean and maximum peak flows ≥ 100 L/s/km² recorded at the Pakuratahi (forested) and Tamingimingi (pasture) catchments during the pre-harvesting, harvesting, and post-harvesting periods.

Period	Pre-harvesting		Harvesting		Post-harvesting	
Catchment	Mean	Max	Mean	Max	Mean	Max
Pakuratahi (forested)	211	674	385	943	407	2072
Tamingimingi (pasture)	295	1030	339	693	365	1224

maximum peak discharge for the Pakuratahi was 943 L/s/km², and that for the Tamingimingi was 693 L/s/km². Likewise, the mean peak discharge for the post-harvesting period at the Pakuratahi (407 L/s/km²) was higher than that at the Tamingimingi (365 L/s/km²) (Table 3). The same was true for the maximum peak discharge (2072 and 1224 L/s/km² respectively). These were recorded on the same day but very early in the post-harvesting period (8 January 2000). Overall however, the record of runoff events ≥ 100 L/s/km² in the pre-harvesting, harvesting, and post-harvesting periods at the Tamingimingi was similar, suggesting that the observed increases in storm sediment yields in the Pakuratahi catchment during the harvesting period are related to land use rather than to any increase in the magnitude and frequency of storm events.

Yearly comparisons

Rainfall: The mean annual catchment rainfall (based on data from Fishers and Top Run) for the period 1995–2001 was 1131 mm (Table 4). The harvesting period (1998–1999) was comparatively dry. The 850 mm recorded in 1998 was by far the driest between 1995 and 2001. However, the average annual number of runoff events ≥ 20 L/s/km² recorded at the Tamingimingi weir in the pre-harvesting period (1995–1997) was 27, whereas the average number recorded between 1998 and 1999 was 29.

Annual flow: Table 4 shows that between 1995 and 1997, the average annual flow for the Tamingimingi was about 8% higher than that for the Pakuratahi, but with the progressive removal of the forest canopy from the Pakuratahi catchment through the harvesting period (1998–1999), the average annual flow was 15% higher than from the Tamingimingi. In the post-harvesting period, the average annual flow for the Pakuratahi remained 14% higher than for the Tamingimingi.

Suspended sediment yields: In the 3 years from 1995 to 1997 that correspond approximately with the pre-harvesting period, the annual suspended sediment yields for the Tamingimingi were 2–5 times higher than those for the Pakuratahi. By the second year of the harvesting period (1999), the situation had reversed, with the yield for the Pakuratahi about 3 times that of the Tamingimingi. In the first year of the post-harvesting (recovery) period (2000), the suspended sediment yield for the Pakuratahi was still twice that from the Tamingimingi, but in 2001 that from the Pakuratahi had declined to the point where the Tamingimingi was generating almost 4 times as much, a situation not seen since 1995. The total suspended sediment yields for both catchments over the 7-year period were similar (568 t/km² for the Pakuratahi, and 489 t/km² for the Tamingimingi).

Site disturbance and vegetation recovery

Overall, 92% of the 22.6 ha of logged area surveyed in the Pakuratahi catchment sustained minimal ground-surface dis-

Table 4 – Catchment rainfall and annual flows for the Pakuratahi (forested) and Tamingimingi (pasture) catchments for the period 1995–2001. Annual suspended sediment yields were calculated by adding the measured storm totals to those calculated using the regression equations listed in Table 1. The figures in brackets are the 95% confidence limits.

		Pakuratahi (forested)			Tamingimingi (pasture)			Ratio
Year	Rainfall 1	Flow (mm)	Events (≥ 20L/s/km²)	Sed. Yield (t/km²)	Flow (mm)	Events (≥ 20L/s/km²)	Sed. Yield (t/km²)	Pak:Tam
1995	1130	271	15	5.1 (±1.3)	283	16	25.2 (±4.6)	1:4.9
1996	1299	387	25	21.8 (±5.0)	429	21	66.8 (±12.0)	1:3.1
1997	1463	484	22	62.3 (±14.4)	526	22	110.3 (±19.8)	1:1.8
1998	850	313	12	37.8 (±9.5)	271	12	34.0 (±6.1)	1:0.9
1999	1116	443	14	140.9 (±35.2)	373	16	47.4 (±8.5)	1:0.3
2000	949	416	18	282.4 (±121.5)	369	15	141.6 (±25.5)	1:0.5
2001	1167	391	17	17.1 (±8.4)	325	18	63.0 (±11.3)	1:3.7
Means	1131	386			368			1:0.8
Totals			123	568		120	489	

turbance or remained undisturbed. These are not considered to be important areas of sediment generation. Sites with deep disturbance, largely attributable to hauler-logging at the time of harvesting, occupied just 9% of the logged area. The extent of sites with deep disturbance attributable to hauler-logging at the Pakuratahi is at the low end of the range of values (9-15%) found for similarly logged areas in New Zealand (McMahon, 1995; Marden and Rowan, 1997) and North American forests (Dyrness, 1965; Garrison and Rummell, 1951; Wooldridge,1960).

Harvesting effectively reduced groundcover vegetation to zero on sites with deep disturbance and to <10% on sites with shallow disturbance. Post-harvesting vegetation recovery was fastest on the less disturbed sites, but vegetation covered about 80% of sites in both disturbance classes within 6 months of the completion of harvesting. Within 5 months of germination the over sown species had re-occupied 75% of sites with shallow disturbance, but were slower to re-colonise deep-disturbance sites, covering just 58%. Revegetation of sites in both disturbance classes steadily increased thereafter and within 2 years of the completion of logging the groundcover vegetation occupied 80% of deep-disturbance sites and 97% of shallow-disturbance sites.

Sediment mobility and vegetation relationships

Results from a previous study indicate that within 2 years of the completion of harvesting there can be up to an 83% reduction in on-slope sediment generation and mobility, due to the combined effects of diminished slopewash generated per unit area of disturbed ground and a decrease in contributing area through time. The latter is a consequence of site re-colonisation by groundcover vegetation (Marden and Rowan, 1997). From sites of ground disturbance (9% of the logged area) slopewash processes in the first year after logging potentially delivered sediment to the stream at a rate of 2.4 t/km^2. In the first year of the logging period (January to December 1998, (Gilmore, 1999)), 1.41 km^2 were logged, during which a total of 3.4 t of sediment were delivered to streams. Logging over the planted area (3.13 km^2) was completed in October 1999, and is estimated to have yielded 7.5 t of sediment, which is just over 1% of the 7-year total suspended sediment load (568 t/km^2) that left the Pakuratahi catchment (Table 4).

Slopewash-transported sediment, derived from sites disturbed during harvesting, is therefore a minor contributor of sediment to streams and hence to stream sediment yield. We therefore agree with Fransen (1998), who identified the principal sources of sediment during this post-harvesting period as, in decreasing order of importance, sidecast from old roadlines, shallow landslides and channel bed scouring.

Comparisons with other studies

Few studies have been conducted in New Zealand to assess the effects of forest harvesting on stream sediment yields. O'Loughlin *et al.* (1980) compared the sediment yields from two of the Maimai experimental catchments near Reefton immediately after harvesting, one by skidder (M9) and one by hauler (M7), with an adjacent control (M6). Sediment yield rates were 264, 47, and 33 m^3/km^2/yr respectively. These figures are not considered typical of the longer term, as the measurement period was drier than usual with fewer large storms. Hicks and Harmsworth (1989) monitored changes in suspended sediment yield during the harvesting phase of a section of Glenbervie Forest in Northland. They found that landing construction and road upgrading before harvesting caused storm yields to rise to 300 t/km^2, representing an increase of 40 times over yields from similar storms before harvesting.

Thus, the 2–3-fold increase in suspended sediment yields estimated for the Pakuratahi catchment following harvesting is low compared with that noted by Hicks and Harmsworth (1989) at Glenbervie Forest in Northland. This may be a reflection of the weather conditions during the critical harvesting period, differences in harvesting methods, or both.

Conclusions

Data from the Pakuratahi and Tamingimingi catchments have shown that pasture catchments in coastal Hawke's Bay can yield 3 times more suspended sediment than those in mature plantation forests. During the logging phase of the harvesting period, the situation can be reversed. Here for example, the catchment that had been clearfelled generated twice the amount of sediment compared with the one in pasture. Coincidental with the post-harvesting period a series of moderate-sized storms caused roadline scouring, landslide failure and channel bed scouring (Fransen 1998). These are the likely sources of increased stream sediment yield in the Pakuratahi. Ground disturbance during hauler-logging undoubtedly contributed to the increase in suspended sediment yield. However, site disturbance in the logged area was minor and the relative contribution of slopewash-derived sediment originating from disturbed sites on successively logged areas was therefore small.

Early in the post-harvesting period,

suspended sediment yields from the Pakuratahi were still above those of the Tamingimingi, but in 2001 they were marginally lower, showing that they are returning to pre-harvesting levels. The combined effects of decreased erosion rate per unit area of disturbed ground and a significant decrease in contributing area through time had effectively halted sediment generation and its mobility to streams, by slopewash processes, within a year of the completion of harvesting. The latter was a consequence of rapid site re-colonisation by over sown groundcover vegetation. However, since harvesting began, slopewash processes on disturbed sites contributed just 1% of the 7-year total suspended sediment load recorded at the Pakuratahi catchment weir.

We conclude therefore that slopewash was the least important of the sediment-generation processes during the harvesting and post-harvesting periods and concur with Fransen (1998) that the principal sources of sediment during these periods were, in order of importance, sidecast from old roadlines, shallow landslides and channel bed scouring. Most of the post-harvest reduction in sediment yield from Pakuratahi can be attributed to a lessening of forest-related activites such as reduced traffic flows, roading works and reduced runoff from revegetated landings and areas of roadside fill. In addition, the contribution to sediment yield by runoff from these sites will further diminish in response to improved on-slope sediment filtering by groundcover vegetation as it continues to spread, and as grass swards thicken.

The similarity in total suspended sediment yields for the two catchments over the 7 years of record suggests that, in the absence of any high-magnitude, low-frequency events during harvesting, total sediment yields over the length of a normal forest rotation (20–30 years) from erodible sediments in coastal Hawke's Bay hill country will be higher from catchments in pasture compared with those in pines.

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