Chapter 5

Forestry Effects on Sediment Yield and Erosion

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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

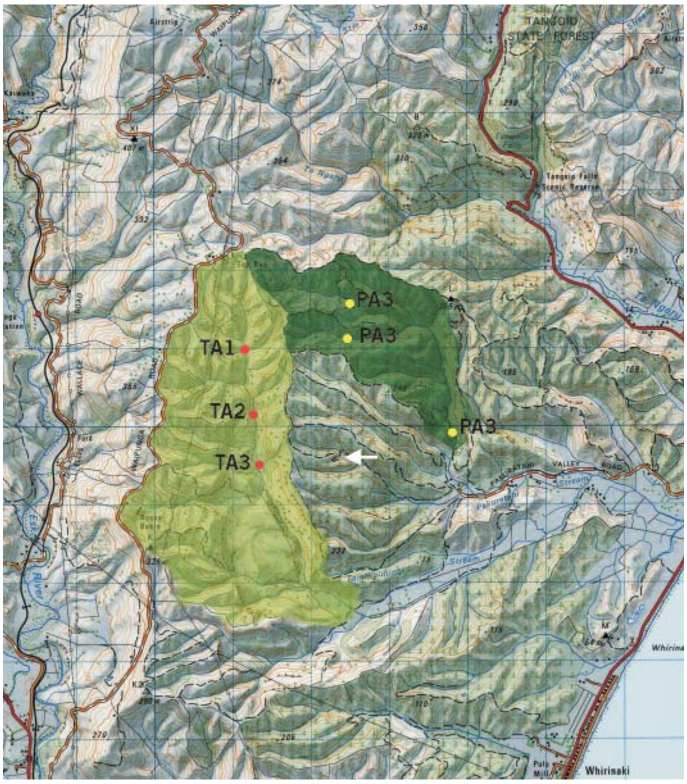

Figure 1. Sites for assessing channel responses. Areas above T1 in the upper reaches of the Tamingimingi catchment and P1 in the upper reaches of the Pakuratahi catchment were those used for assessing sediment sources and slip damage. The arrow identifies the location of the plots used in the Pakuratahi 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).

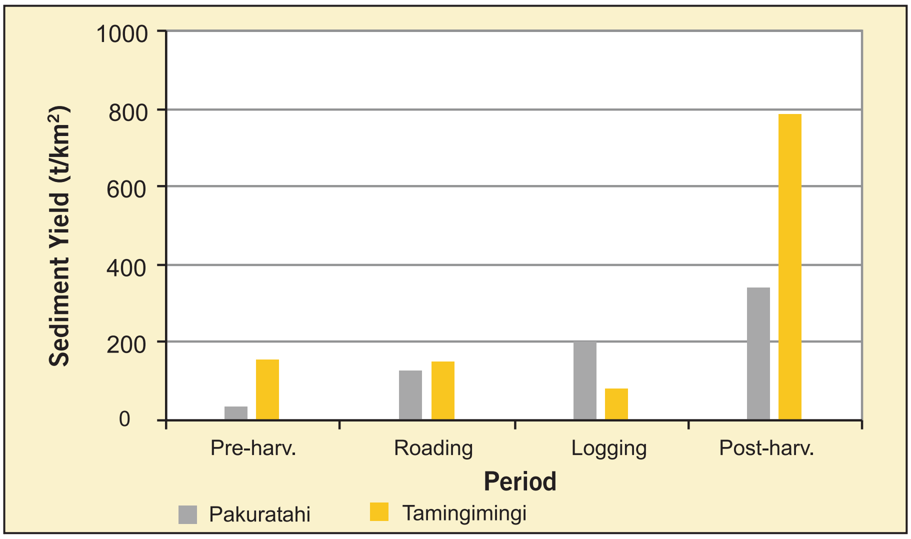

Figure 4. Suspended sediment yields for the pre-harvest period (Jan 1995 to Jun 1997), the road construction phase (Jul to Dec 1997), the logging phase (Jan 1997 to Dec 1999), and the post-harvesting period (Jan 2000 to Dec 2005).

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 (July to Dec. 1997)	22/8/97	1.8	3.0	1:1.7
	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 (≥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).

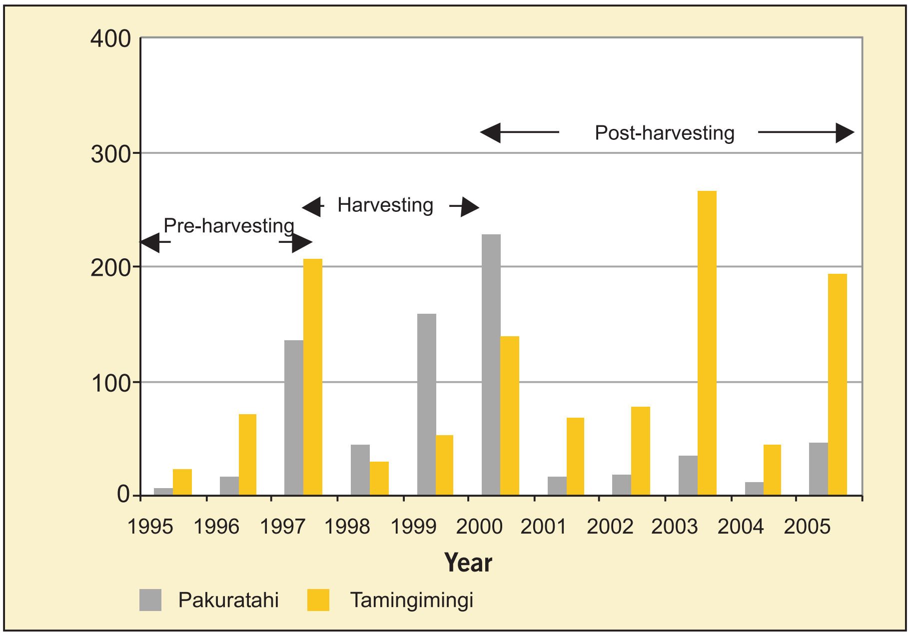

Table 3. Suspended sediment yields for storms sampled concurrently at the Pakuratahi (forested) and Tamingimingi (pasture) catchments, and the ratio of the Pakuratahi to the Tamingimingi yields during the post-harvesting period.

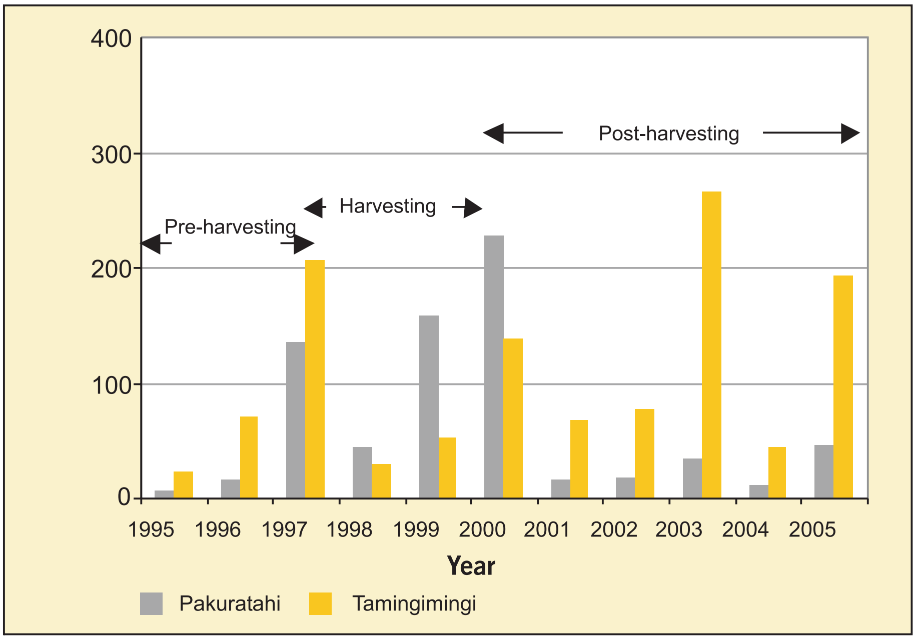

Figure 5. Annual suspended sediment yield for the Pakuratahi and Tamingimingi catchments from 1995 to 2005.

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.

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