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Sediment production from Cyclone Bola landslides, Waipaoa catchment

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Abstract

A method for assessing sediment production from landslides was applied in the Waipaoa catchment to quantify landsliding which occurred during Cyclone Bola in 1988, and to assess the contribution landslides made to the suspended sediment load of the Waipaoa River during the storm. Relationships between storm rainfall and landslide frequency, defined for different landslide-prone terrains, were used with a geographic information system containing data on the distribution of landslide terrain, vegetation and storm rainfall, to estimate landslide density in the Waipaoa catchment. Field measurements of landslide dimensions and air-photo-based estimates of sediment delivery allowed calculation of total sediment generation and delivery to streams during the storm. Comparison of calculated sediment input for the portion of the Waipaoa catchment upstream of the Kanakanaia gauging station with estimates of the total sediment load during the storm indicate that shallow landslides contributed 48% of the storm's sediment load at that site. Calculated inputs from the remainder of the catchment suggest that shallow landslides were responsible for approximately 64% of the sediment load at the mouth of the catchment.

While landsliding is the major erosion process during large magnitude rainstorms, landslides contribute only about 10% to 19% of the long-term suspended sediment yield. Landsliding is of lower relative importance over the long term primarily because other erosion processes, such as gully, sheet wash and streambank erosion, produce significant sediment during the frequent storms that are too small to generate landslides.

Introduction

Shallow landsliding was the most visible signature left by Cyclone Bola on hillslopes in the soft-rock hill country of the east coast of the North

Island, New Zealand. The storm, which occurred in March 1988, was the largest on record, with a return period estimated to be of the order of 100 years (Hicks *et al.*, in press), although a recent review of flood data suggests the return period may be less than 100 years (D. Peacock, pers. comm.). Studies at Lake Tutira, northern Hawke's Bay, indicate that such major cyclones represent a dominant geomorphic event in these landscapes (Page *et al.*, 1994a). The Cyclone Bola sediment yield for the Waipaoa River on the east coast of the North Island (Fig. 1) has been estimated to exceed 40 million tonnes (Foster and Carter, 1997), or about three to four times the average annual sediment yield.

Following Cyclone Bola, landslide density was observed to vary widely over relatively short distances, reflecting differences in inherent erosion potential and local differences in storm character. In addition, other erosion processes occur in the Waipaoa catchment. What then was the contribution of landsliding to the storm's sediment yield? In this paper we calculate landslide-related sediment production from Cyclone Bola in the Waipaoa catchment by applying relationships between storm rainfall and landslide density to storm rainfall zones within the catchment. These relationships have been developed for different land systems in the area, to calculate the annual average sediment production from landslides for a sediment budget for the Waipaoa catchment (Reid and Page, in press). The budget, which will identify the relative contribution of the various erosion processes, is part of a larger study to evaluate the cumulative environmental effects of land-use change in the area (Trustrum, *et al.*, 1999).

The catchment embodies many of the land use and floodplain management issues common to catchments with high sediment production and transport (Taylor (comp.),1970; Williams, 1980; Water and Soil Directorate, 1987). The frequency and severity of shallow landsliding is of concern because of the on-site effects on pasture productivity and the off-site contribution to river sediment loads. Productivity decreases at the site of landsliding through the removal and burial of topsoil. In addition, the district has frequent dry periods during the summer, so the loss of potential soil moisture storage leads to reductions in pasture growth. Landsliding also damages fences, farm tracks, and stock ponds, as well as causing stock losses. All these increase the cost of farming. Downstream issues include degradation of water quality and aquatic ecosystems, flooding and siltation on the fertile, productive Gisborne Plains, and siltation of the harbour and coastal fisheries habitat.

Information about the importance of major storms as producers and deliverers of sediment is essential for planning strategies for soil conservation work, and flood control schemes, and for sustainable land use in general. Such information will assist better targeting of landslide susceptible areas and the development of the most effective "area for benefit" restoration and reforestation strategies.

Study area

The headwaters of the Waipaoa catchment (approximately 20%) is part of the East Coast Allochthon (Moore, 1988) and is underlain by Cretaceous argillites and greywackes, while most of the catchment is underlain by Miocene-Pliocene mudstones and sandstones. The 2205 km^2 catchment is in a tectonically active zone, with uplift of the order of 3 mm/yr (Pillans, 1986).

Rainfall in the Gisborne district is highly variable, and is greatly influenced by relief (Hessell, 1980). Major rainstorms, which cause widespread landsliding and flooding, are either tropical cyclones or sub-tropical depressions from the north, or southerly depressions. Storms that are confined to small areas but with extremely severe local effects are more common. There is a marked seasonal distribution of rainstorms, with most occurring in autumn (March-May). Periods of low rainfall and accompanying drought are also comparatively common. Rainfall records in the district were begun in 1890 at Gisborne Harbour.

Cyclone Bola affected much of the North Island, but the heaviest rainfalls and worst damage occurred on the east coast between East Cape and Napier. Between 6–9 March rainfall in the Waipaoa catchment varied from 300 mm at Gisborne to 900 mm in the northeast of the catchment. Although these figures make this storm the largest on record, large storms have caused catchment-wide landsliding on ten occasions since 1920 (Hicks, 1995).

Land systems

About 85% of the Waipaoa catchment is hill country, with a diversity of landforms, erosion processes and erosion rates. To aid catchment analysis and sediment budgeting, the catchment has been divided into land systems. The land systems and their spatial distribution were derived from the New Zealand Land Resource Inventory (Fletcher, 1988; National Water and Soil Conservation Organisation, 1979), a GIS-based land resource data base which records rock type, soil, slope, erosion and vegetation, and uses the land use capability system of land classification. Land use capability units were grouped on the basis of rock type to create the land systems. Each land system has a unique combination of rock type, landforms, erosion processes and sediment-supplying capacity, drainage density and channel morphology, and each has been given a local name, based on a typical area, to identify it (Harmsworth *et al.*, 1994; Page, 1994). Sixteen land systems have been defined, six of which are susceptible to landslide erosion (Fig. 1). Shallow landslides on these land systems are planar failures that mobilise only the soil profile and the uppermost surface of weathered bedrock. The landslide sediment moves as a highly mobile debris flow, leaving a veener of mud (the debris tail) on the hillslope surface over which it flows. Debris flows that do not reach channels terminate where they run out of sediment or where a decrease in slope gradient allows deposition. At the time of Cyclone Bola, 89% of these land systems were in pasture, with only 3% in exotic forest.

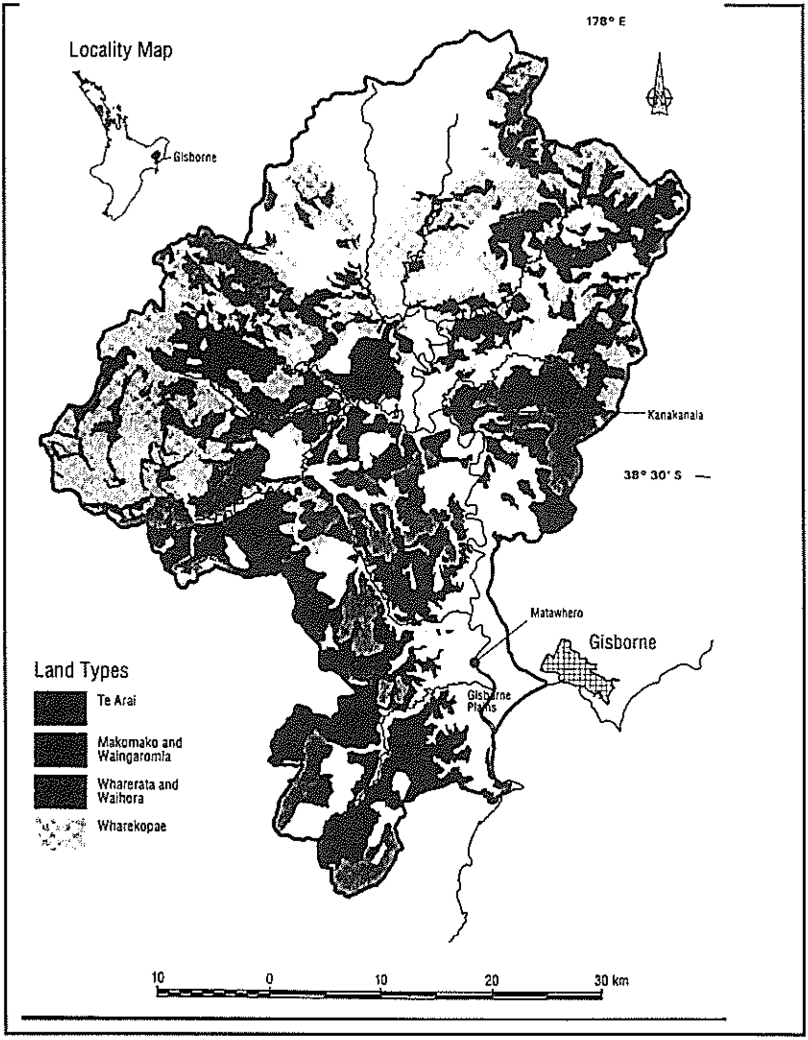

FIGURE 1 – Location of Waipaoa catchment and extent of landslide-prone land types.

Te Arai

The Te Arai land system comprises 51 320 ha (23%) of the catchment. It is the major landslide-prone land system, both in terms of area and sediment-supplying capacity. The bedrock is very weak to weak mudstone of Miocene-Pliocene age that weathers readily and on exposure exhibits a closely spaced fracture pattern or surface frittering. Thin, patchy tephra is present on stable sites, but has been eroded from most slopes. Soil depth is highly variable, ranging from more than 100 cm on ridges and rare stable slopes to 0–30 cm on recently eroded slopes. The hills have broken irregular surfaces formed by landslides, narrow shallow earthflows and some linear gullies (Fig. 2). Slopes are between 20 and 40°. Streams are narrow and often incising, and have a drainage density of about 3.8 km/km^2.

At the time of Cyclone Bola pastoral farming was the major land use (96%), with the remainder of the area in exotic forest (2%) and indigenous forest and scrub (2%). Annual rainfall ranges from 1000 mm near the coast and adjacent to the Gisborne Plains, to 2000 mm in higher altitude inland locations.

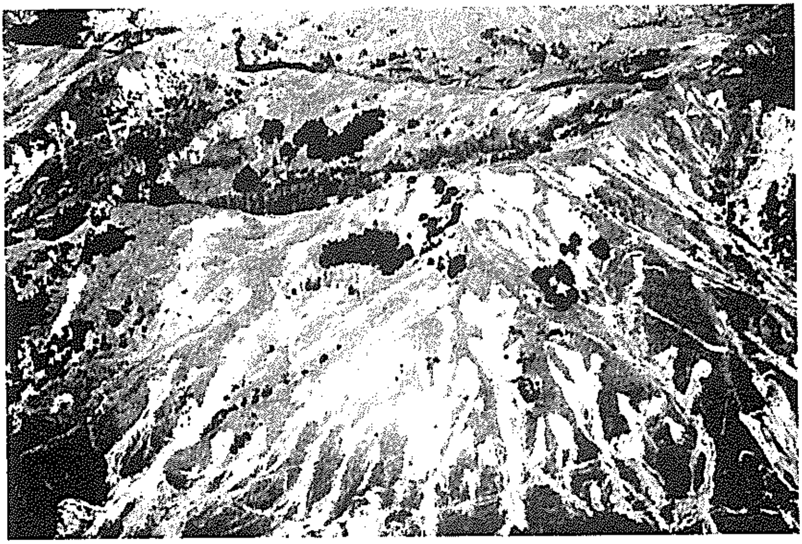

FIGURE 2 – Te Arai land type showing typical hillslope morphology and Cyclone Bola landslides.

Wharerata

The Wharerata land system comprises 27 770 ha (12.5%) of the catchment, mainly in the west and south. The bedrock is Miocene-Pliocene massive sandstone, or thickly bedded sandstone alternating with thin mudstone. Thin tephra may be present on uneroded sites, especially in the west. Soil depths are more than 80 cm on stable sites and 0–20 cm on recently eroded sites. The hillslopes are moderately steep to steep (25–45°). Slopes are often planar, and lead directly into channels at their base. The land system includes steep scarp slopes of cuestas, mainly in the west of the catchment. Stream channels are stable and incised.

In 1988 land use was 75% pastoral farming, 5% exotic forestry, 10% indigenous forest and 10% scrub and fern. Although much of the land system has an annual rainfall between 1400 and 2000 mm, rainfall is lower in areas near the Gisborne Plains.

Waihora

This land system is confined to the Waihora and Mangaoae catchments, where it occupies 7 760 ha (3.5% of Waipaoa catchment). Steep to very steep hillslopes with narrow ridge crests have formed from Pliocene, massive to poorly bedded siltstone. Slopes are long (150–350 m), planar, and lead directly into streams, where minor channel incision may occur. Soil depths are up to 100 cm on uneroded sites.

Land use was 76% pastoral farming, 6% exotic forest, 16% kanuka/manuka scrub, and 2% indigenous forest at the time of Cyclone Bola. Annual rainfall ranges from 1200 to 1600 mm.

Makomako

Hill slopes in this land system are moderately steep to very steep, similar in form to those of the Waihora land system, and lead directly into streams. The bedrock is of Miocene-Pliocene age and consists of alternating beds of thick, frittered or massive mudstone and thin sandstone. In areas of severe landsliding and gullying, exposed bedrock is slow to revegetate. Soil depths are more than 80 cm on stable sites and 0–20 cm on recently eroded sites.

The Makomako land system occupies 6% of the Waipaoa catchment (13 770 ha), mainly in the west and north east, where annual rainfall ranges from 1100 to 1700 mm. In 1988, pasture occupied 84% of the area, and exotic forest 6%, with the remainder in scrub and indigenous forest.

Waingaromia

This land system comprises moderately steep hillslopes and long dip slopes broken by gullies, deep-seated earthflows and slumps. The bedrock is Miocene-Pliocene mudstone, similar to that of the Te Arai land system, that has been crushed and sheared. On steeper areas less affected by gully and earthflow erosion, landsliding is common. This land system occurs mainly in the upper Waingaromia catchment and totals 2 890 ha (1.5% of Waipaoa catchment).

Land use in 1988 was 89% pastoral farming and 10% exotic forestry, with 1% scrub. Annual rainfall ranges from 1300 to 1800 mm.

Wharekopae

Strongly rolling to moderately steep hills, dip slopes and plateaux mantled with tephra characterise the Wharekopae land system. The tephra overlies massive and bedded mudstones and sandstones of Miocene-Pliocene age. The land system occupies 44 970 ha or 20.5% of the Waipaoa catchment, mainly in the north and west. Soil depths are more than 100 cm. Slopes are short (50–100 m) and planar-concave, with stable stream courses.

At the time of Cyclone Bola, 92% of the land system was in pasture, 2% in exotic forest, and 6% in indigenous forest and scrub. Rainfall ranges from 1200–2000 mm per year.

Methods

Reid and Page (in press) defined relationships between storm rainfall and areal landslide frequency for each of the land systems discussed above. Data from aerial-photo surveys of landslide distribution after Cyclone Bola had been used to define the relationships, so those relationships are expected to be well-suited for calculating the overall effects of the storm on landslide distribution and rate.

The relationships were based on counts of landslides in twenty representative 1–15 km^2 subcatchments of the Waipaoa catchment. The available aerial photography provided data for pre-Bola storms of 100 to 350 mm, and Cyclone Bola itself provided a sample of landslides for storm intensities ranging between 350 and 800 mm across the basin. The resulting relationships for the Te Arai and Wharekopae land systems were both significantly different from those of other land systems. The relationships for Wharerata and Waihora land systems are not significantly different from one another, so data were combined to construct a relationship applicable to both. Similarily, data from Makomako and Waingaromia land systems were combined.

Landslide scars from Cyclone Bola were still visible in the field in 1996. Scar length, width and depth were measured for 95 landslides in four of the land systems to determine average scar volumes (Table 1), for calculating storm sediment production from landsliding (Reid and Page, in press). Landslides with surface areas between 920 m^2 and 1150 m^2, and those larger than 1150 m^2 were counted in representative subcatchments to define further the cumulative frequency distributions for the largest slides. Volumes are approximately log-normally distributed, so an average volume for each land system was calculated by plotting the cumulative frequency distribution for volumes measured in that land system and extrapolating each relationship to estimate the frequencies of the largest slides. The proportion of slides in each volume interval was then multiplied by the average volume in that interval and the results summed to calculate the mean landslide volume for the land system. Data on landslide density and sediment generation for the twenty representative subcatchments are given in Table 2.

TABLE 1 - Summary of landslide measurements

Land system		**Te Arai**	**Wharerata**	**Waihora**	**Wharekopae**
		n=22	n=21	n=31	n=21
Slope angle (°)	range	22-40	24-39	11-43	20-40
	mean	32.8	31.4	30.0	30.8
Scar length (m)	range	4-59	11-61	5.4-120	5.8-28
	mean	18.95	31.52	20.23	14.69
Scar width (m)	range	3.5-27.5	9-37	3.7-60	2.1-18
	mean	14.45	19.47	11.06	9.04
Scar depth (m)	range	0.3-2.0	0.3-1.5	0.34-1.11	0.24-1.55
	mean	0.76	0.83	0.75	0.75
Volume (m^3)	range	10-3068	143-1236	14-5544	5-872
	mean	210	450	140	130

Because rainfall during Cyclone Bola varied widely over short distances, the distribution of storm rainfall throughout the catchment was needed to estimate landsliding rates. Two methods were used. First, a map of storm isohyets at 100 mm intervals was created using rainfall records from 32 rain gauges distributed widely in and around the Waipaoa catchment (Fig. 3). However, such detailed rainfall information is rarely available in other areas, so a second method was employed using data from a smaller number of sites. Eight storm magnitude-frequency regimes had previously been defined for different areas in the catchment by Reid and Page (in press), using data from four sites with records of 70 years or longer, and from nine sites with shorter records. Each of these areas was now assigned a rainfall value for Cyclone Bola, measured at the rain gauge used to define that regime (Fig. 4). In essence, the simplifying assumption was made that the rainfall distribution during a single storm would be influenced by the same factors influencing the long-term average distribution of storms.

Landslide densities were then calculated by applying the relationships shown in Figure 5 to each rainfall zone, as defined first by the isohyetal

TABLE 2 – Rainfall and sediment generation data for representative subcatchments

Land system	Bola rainfall (mm)	Landslide density (number/ha)	Sediment generation (m^3/ha)
Te Arai			
Taurau Valley	c.350	1.10	231
Puha	c.380	1.59	335
Ngatapa	c.500	2.26	475
Cheviot Hills	487	2.36	495
Waitahoata Station	c.400	2.38	500
Gentle Annie	c.450	2.41	506
Mangakiore Station	606	3.22	677
Wharerata			
Waikura River	409	0.50	224
Waingake	606	0.62	278
Waimata River #2	601+	0.70	315
Ngatapa	c.500	0.92	414
Waimata River #1	654	1.14	513
Waihora			
Ahioteatua	654	1.21	170
Wharekopae			
Te Kowhai	431	0.35	46
Parakanapa	641	0.39	50
Wharekopae	478	0.49	63
Tutamoe	706	0.55	72
Makomako			
Parakanapa	631	0.98	206
Tauwhareparae	c.800	2.61	548
Waingaromia			
Huanui	675	1.85	388

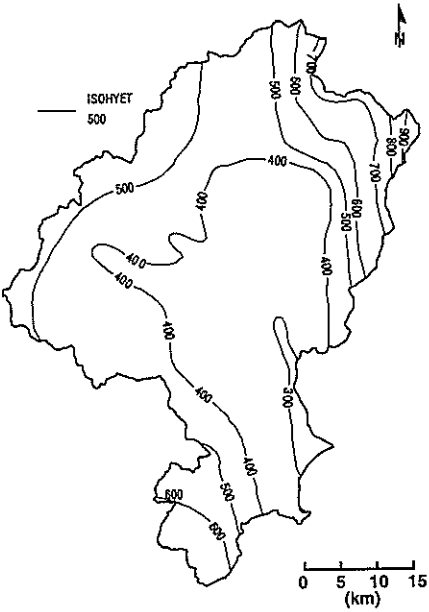

FIGURE 3 – Cyclone Bola rainfall isohyets (in mm)

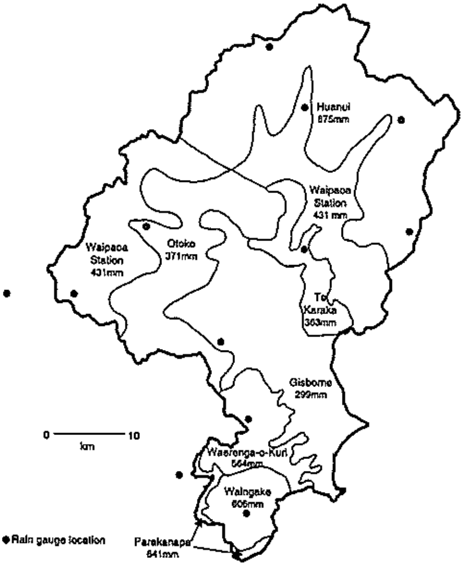

FIGURE 4 – Map of storm rainfall intensity zones for Cyclone Bola (derived from storm magnitude-frequency regimes, Reid and Page in press)

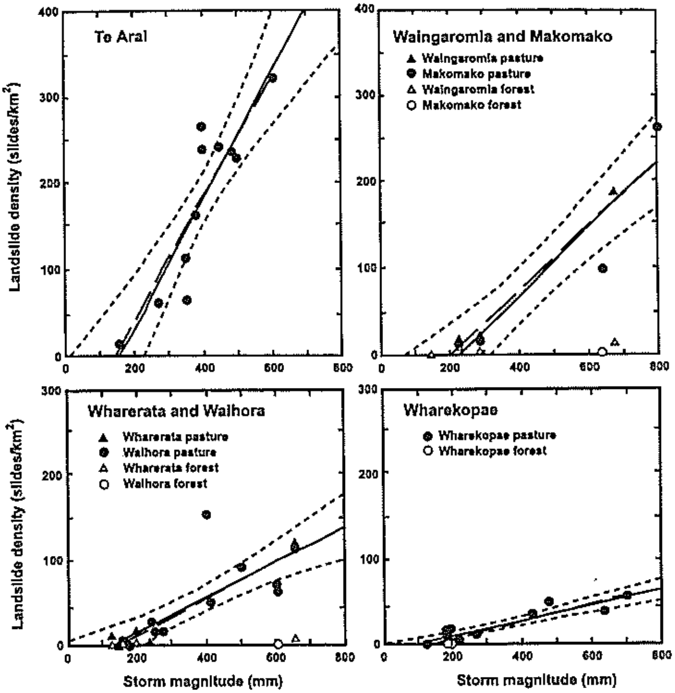

FIGURE 5 – Relationship between storm rainfall and landslide density for landslide-prone land systems (after Reid and Page in press).

map and then by the map of magnitude-frequency regimes. Each calculated density was then multiplied by the area of the corresponding land system within that rainfall zone to calculate the number of landslides generated. To convert to volume of sediment generated, the number of landslides was multiplied by the average landslide volume.

A number of studies indicate that the relationship between rainfall and landsliding is more complex than a simple correlation between storm rainfall and landslide number. Magnitude-frequency-effectiveness relationships will come into play (Pearce, 1986), for example, as each subcatchment will have its own unique chronology of storms. The size and timing of these storms will mean each subcatchment is at a different stage in the process of regolith stripping and soil formation, and so during subsequent storms each will have a different triggering threshold for landslides. The raising of this threshold is termed "event resistance" (Crozier, 1986), and has been recorded by Page *et al.* (1994a, 1994b) and demonstrated by Crozier and Preston (1998). Eyles (1979) demonstrated the need to consider antecedent rainfall in an evaluation of conditions producing landslides in Wellington.

Despite these complications, the relationship has been shown to be useful for estimating long-term average landslide frequencies (Reid, 1998; Reid and Page, in press). The reason that the simplistic method adopted here provides a useful relationship seems to be that large storms produce large effects, irrespective of antecedent conditions, and that there is a correlation between high intensity storms and wet periods. The technique does provide data at a suitable level of accuracy for constructing large-scale sediment budgets, and given the assumptions and uncertainties inherent in predicting and modelling future trends.

Sediment generation from landslides

Results calculated using the storm isohyet data indicate that, for areas in pasture, sediment generation from landslides averaged 421 m^3/ha for the Te Arai land system. Rates decreased in the following order: Waingaromia 373 m^3/ha, Wharerata 332 m^3/ha, Makomako 218 m^3/ha, Waihora 99 m^3/ha, and Wharekopae 48 m^3/ha.

To calculate the total volume of sediment generated in Cyclone Bola, adjustments were made for areas in forest and scrub, and for areas with soil conservation plantings. The percentage area of forest and scrub in 1988 in each storm rainfall zone within each land system was calculated by overlaying a vegetation map derived from a Landsat Thematic Mapper image taken in January 1993 (Dymond *et al.*, 1996), on the land systems and rainfall maps. Percentages were then modified according to the area of exotic forest in 1988 that was more than 8 years old and thus effective in reducing landslides (P. Fantham, pers. comm.). Based on landslide counts under forest and scrub in this study, and studies by Phillips *et al.* (1990), Hicks (1991), Marden and Rowan (1994), De Rose (1996), and Page and Trustrum (1997), areas in forest or scrub were assigned a tenfold reduction in sediment generation. This gave a reduction in sediment generation of 3.6×10^6 m^3 due to the presence of forest and scrub.

The percentage of each land system with soil conservation plantings in 1988 was estimated by Regional Council staff with extensive local knowledge (P. Fantham, pers. comm.). Hicks (1992), in a study in the Waihora catchment following Cyclone Bola, found that soil conservation plantings in pasture had reduced mass movement by 22%. Plantings were either open or close planting of trees on slopes, or pair planting of trees along streams and in gullies. Both adequate and inadequate levels of treatment were represented, as defined by a combination of the extent and spacing of planting, and the health and age of trees. The levels of treatment were considered representative of measures in the district. Land with soil conservation plantings was thus assigned a 22% reduction in sediment generation. From these figures a reduction in sediment generation of 0.9 x 10^6 m^3 was calculated for the Waipaoa catchment.

On this basis, the total sediment generated during Cyclone Bola was 32.8 x10^6 m^3 (Table 3). Had the entire catchment been in pasture, sediment generation would have been 37.3 x10^6 m^3. The combined effect of forest/scrub and soil conservation plantings therefore was to reduce sediment generation by 12%. With the increase in afforestation that has occurred on landslide-prone land since 1988, if Cyclone Bola struck today the reduction would be 27%.

TABLE 3 – Summary of sediment generated from landslides in Waipaoa catchment during Cyclone Bola - derived using storm isohyet data

Land system	area (ha)	% pasture *	sediment generation (m^3)**	% of total
Te Arai	51,320	96	20,053,000	61
Wharerata	27,770	75	6,809,000	21
Waihora	7,760	76	577,000	2
Wharekopae	44,970	92	1,978,000	6
Makomako	13,770	84	2,493,000	7
Waingaromia	2,890	89	948,000	3
Total	148,480		32,858,000	100

* as at 1988 (excludes indigenous forest, scrub and exotic forest >8 years old)

** adjusted for forest, scrub and soil conservation plantings

TABLE 4 – Summary of sediment generated from landslides in Waipaoa catchment during Cyclone Bola - derived using storm magnitude-frequency regimes

Land system	area (ha)	% pasture*	sediment generation (m^3)**	% of total
Te Arai	51,320	96	22,277,000	64
Wharerata	27,770	75	6,514,000	19
Waihora	7,760	76	777,000	2
Wharekopae	44,970	92	2,053,000	6
Makomako	13,770	84	2,355,000	7
Waingaromia	2,890	89	831,000	2
Total	148,480		34,807,000	100

* as at 1988 (excludes indigenous forest, scrub and exotic forest >8 years old)

** adjusted for forest, scrub and soil conservation plantings

The above exercise was repeated using the storm rainfalls derived from the map of magnitude-frequency regimes. Results were similar, with 34.8 x 10^6 m^3 of sediment generated under the actual vegetation cover (Table 4). The relatively close agreement indicates that little information is lost through use of the less precise approximation of rainfall distribution, and also suggests that storm magnitude-frequency regimes may be a useful basis for extrapolation of rainfall data.

Because landslide scar depths were measured several years after the slides had occurred, the calculated landslide volumes represent the combined effects of landsliding and subsequent surface erosion. Sediment may be removed from landslide scars by sheet erosion both during the initiating storm and in any subsequent storms until surface sealing and revegetation of the scar has occurred. Megahan (1974) found that surface erosion rates decrease exponentially after initial exposure of an erodible surface. Field estimates suggest that for Te Arai land system, about two thirds of the area of landslide scars were revegetated after seven years, and that the debris tails were revegetated within two years. Given an estimate of a maximum of 5 mm of sediment removed by sheet erosion (Page *et al.*, 1994a; Lehre, 1982), this process would account for only 0.5% of scar volume. Thus the effect on landslide sediment volumes would not be significant. From field measurements of percentage area and depth of rills on recent scars, rilling accounts for a further 3% of scar volume. Rill erosion of landslide scars during Cyclone Bola could be expected to increase the volume of sediment generated by about 2-3%.

Sediment delivery

A proportion of the sediment mobilised by landslides is redeposited downslope of scars as debris tails. The proportion that is delivered to streams during a storm will depend on the location of landslides relative to the stream channel network, scar size, and the nature of the terrain over which the debris flows. Sediment delivery is likely to increase with increasing storm rainfall as the stream channel network extends upslope, increasing connectivity with landslides. By using aerial photographs to classify debris tail distribution, and measuring debris tail thickness, Reid and Page (in press) have estimated sediment delivery to streams to be approximately 50% for landslides in a Te Arai subcatchment with approximately 600 mm rainfall during Cyclone Bola. Given that rainfall in Cyclone Bola ranged from 300 mm to 900 mm, a sediment delivery ratio of 0.50 has been adopted in this study. A mean value of 0.50 is similar to delivery ratios for each land system derived from a computer simulation model by Dymond *et al.*, (in press). They reported sediment delivery ratios of 0.42 ± .08 (Te Arai), 0.50 ± .10 (Waihora), 0.36 ± .08 (Waingaromia), 0.44 ± .10 (Makomako), 0.54 ± .10 (Wharerata), and 0.20 ± .05 (Wharekopae).

Relative importance of landslides

In a storm like Cyclone Bola, landslides are the most obvious source of sediment. The preceding calculations enable an estimate of their real importance to be made, not only for the storm concerned, but also in relation to cumulative landsliding from smaller storms.

To identify the importance of landsliding during Cyclone Bola, the measured suspended sediment load at Kanakanaia was compared with the estimated contribution from landsliding of 19.9 x 10^6 m^3 for the 1582 km^2 (72%) of the catchment above the gauging site. Assuming a sediment delivery ratio of 0.5 and an average soil bulk density of 1250 kg/m^3 (Malcolm McLeod, unpublished data), landslides contributed 12.4 x 10^6 tonnes or 48% of the Cyclone Bola suspended sediment load of 25.9 x 10^6 tonnes (Hicks *et al.*, in press). Contributions from the six landslide-prone land types were as follows: Te Arai 22%, Wharerata 12%, Makomako 6%, Wharekopae 5%, Waingaromia 2%, and Waihora 1%.

Most of the area of the Waipaoa catchment that is not susceptible to landsliding is located upstream of Kanakanaia, so the proportional landslide contribution in the remainder of the catchment is higher than suggested by the results for Kanakanaia. No measure of suspended sediment yield was made for the whole Waipaoa catchment, and the figure of 40 x 10^6 tonnes quoted by Foster and Carter (1997) is now considered an over-estimate. A figure of 32 x 10^6 tonnes has been derived by adding together the above Kanakanaia figure of 25.9 x 10^6 tonnes, the Te Arai catchment yield of 2.8 x 10^6 tonnes (Hicks *et al.* in press), and 3.3 x 10^6 tonnes from the remaining catchments for which there were no suspended sediment yield data. The figure of 3.3 x 10^6 tonnes is an estimate derived by adjusting the Te Arai figure according to catchment area, percent landslide terrain, and storm rainfall. The contribution of landslides to this total Waipaoa catchment suspended sediment load of 32 x 10^6 tonnes increased to an estimated 20.5 x 10^6 tonnes or 64%. Land system contributions were as follows: Te Arai 39%, Wharerata 13%, Makomako 5%, Wharekopae 4%, Waingaromia 2%, and Waihora 1%. The remaining 36% of the sediment load was derived from gully, sheetwash and rill, streambank, earthflow, and tunnel gully erosion, and bedrock failures.

There has been some uncertainty about the magnitude of the Cyclone Bola flood, and a recent review of the Waipaoa River floods for the Gisborne District Council recommend revising the Bola peak discharge down from 5300 cumecs to 4000 cumecs (±10%) (D. Peacock, pers. comm.). This would reduce the suspended sediment yield at Kanakanaia to 20.9 x 10^6 tonnes, increasing the landslide contribution at Kanakanaia from 48% to 59%, and increasing the landslide contribution to the total Waipaoa catchment yield from 64% to 76%. However, given the numerous other erosion processes operating in the Waipaoa catchment, the authors feel that landslide contributions are likely to be nearer to 48% at Kanakanaia, and to 64% for the whole catchment.

In the Tutira catchment, 90 km south of the Waipaoa catchment, a sediment budget for Cyclone Bola indicated that landslides contributed 89% of the total sediment generated (Page *et al.*, 1994a), and a similar percentage of delivered sediment. The Tutira catchment has 63% landslide-prone terrain, similar to the amount in the Waipaoa catchment, and a Bola rainfall of 753 mm. However in the Tutira catchment, gully and earthflow erosion are insignificant, whereas 20% of the Waipaoa catchment is occupied by gully and earthflow terrain.

Shallow landslides thus accounted for a major portion of Cyclone Bola's sediment yield on the East Coast. However, the overall significance of landsliding during large storms can be evaluated only by comparison with long-term average rates of sediment input. Reid and Page (in press), using the same technique and an analysis of storm magnitude-frequency history, calculated that landslides are responsible for 10% to 19% of the long-term average suspended sediment yield at Kanakanaia. Similarly, for the entire Waipaoa catchment, landslides contribute 2.4 x 10^6 tonnes or 16% of the estimated mean annual suspended sediment load of 15.2 x 10^6 tonnes, (derived by combining the mean annual yield of 14.4 x 10^6 tonnes at Matawhero (Reid and Page, in press) and the yield of 0.8 x 10^6 tonnes for the Te Arai catchment, below Matawhero (Hicks *et al.*, in press)). Therefore, although landslides are amongst the most visible sources of sediment in the Waipaoa catchment, and landslide-prone land systems occupy 69% of the catchment, they make only a moderate contribution to the long-term average sediment yield. Reid and Page (in press) also found that about 50% of the catchment's landslides occur during storms with return periods of less than 7 years, and 75% during storms with return periods of less than 25 years. Cyclone Bola has a nominal return period of about 100 years. Landslides during Cyclone Bola would contribute approximately 1% of the expected suspended sediment yield over a 100 year period. Storms such as Cyclone Bola, although they have a major impact on the landscape and its management, occur infrequently enough that their effects are outweighed by the cumulative effects of low magnitude, frequent events.

The basis for these findings lies in the nature of sediment generation, storage, conveyance, and deposition. First, about 50% of landslide sediment is retained on the landscape, and only a portion of this volume reaches channels during smaller, subsequent storms by other processes. Second, although some other processes may have lower rates of sediment generation, several, such as gullying and streambank erosion, supply sediment directly to the channel system; they therefore have a disproportionate influence on sediment yield. Third, significant landsliding occurs only when rainfall exceeds a threshold value of approximately 200 mm, which occurs on average only once every 2–4 years, whereas gullies, riverbeds and stream banks have constantly bare surfaces which supply sediment whenever it rains. That these other chronic sources of sediment are important over the long term is also demonstrated by suspended sediment data, which indicate that 50% of the suspended sediment load is transported by events with return periods of one year or less (too small to generate landslides), and 86% by events with return periods of less than 10 years (Trustrum *et al.,* 1999).

Conclusions

Major rainstorms such as Cyclone Bola cause severe and widespread erosion. Often the most dramatic impact on the landscape is provided by landslides, leading to the perception that they are the most important source of sediment. The damage done during such events can also bring into question the value of soil conservation measures: if conservation works are so obviously overpowered by the forces of a major storm, is there any point in installing them? Results of this study show that landslides produced about two-thirds of the Cyclone Bola suspended sediment yield in the Waipaoa catchment. However, analysis of long-term landsliding rates by Reid and Page (in press), using the same technique, indicates that landslides are responsible for only 10% to 19% of long-term suspended sediment yields, and that the Cyclone Bola contribution was equivalent to only about 1% of the yield expected in 100 years. Clearly the long-term benefits of soil conservation works and other protection measures should not be based on their performance in extreme events. Indeed, conservation works capable of modifying landslide rates during storms with recurrence intervals shorter than 10 years will be capable of influencing more than half of the potential landslide-derived sediment.

The relationship between rainfall and landsliding is acknowledged as being more complex than a simple correlation between storm rainfall and landslide number, and such a correlation therefore should not be applied at the hillslope scale. However, at the large catchment scale there is an averaging effect on the variability exhibited by local conditions, and in large magnitude events the effects are less influenced by antecedent conditions. The technique outlined here is a reconnaissance-level one which allows rapid assessment of large areas, where high precision is not required.

In addition to identifying the importance of major storms as producers and deliverers of landslide sediment, the technique applied in this study provides information about the susceptibility of land types and the effect of forest and soil conservation plantings; information necessary for effective land use and floodplain management. Such pragmatic approaches to environmental problem solving are required at a time when both funders and communities expect increasingly issue-driven research that delivers tangible benefits.

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