Gully erosion and sediment load: Waipaoa, Waiapu and Uawa rivers, eastern North Island, New Zealand

MICHAEL MARDEN[1], HARLEY BETTS[2], GREGORY ARNOLD[2] & RANDOLPH HAMBLING[3]

1 *Landcare Research, PO Box 445, Gisborne 4040, New Zealand*
mardenm@landcareresearch.co.nz

2 *Landcare Research, Private Bag 11-052, Palmerston North 4442, New Zealand*

3 *Ministry of Agriculture and Forestry, PO Box 2122, Gisborne 4040, New Zealand*

Abstract The onset of gully erosion following deforestation was mapped for the three largest and heaviest sediment-laden rivers within the East Coast Region, North Island, New Zealand. Gullies were then re-mapped after a ~40-year reforestation period (~1957–1997) and sediment production from gullies was calculated from these data bases using a degradation rate based on DEMs of gullies at differing stages of development in each of two different geologic/tectonic terrains. At the end of the measurement period the total composite gully area for the Waipaoa, Waiapu and Uawa catchments was 5%, 33% and 39% greater than before reforestation, and for the study period, gullies in both terrains collectively contributed the equivalent of 43%, 49% and 54% of the average annual suspended sediment yield from just 0.8%, 2.4% and 1.7% of hill country areas in these respective river systems. A potentially significant reduction in sediment production and yield at catchment-scale could be achieved through a more targeted approach to reforestation, particularly of gullies in the most highly erodible and unstable pastoral hill country areas of Waiapu catchment.

Key words gullies; sediment production and yield; reforestation; eastern New Zealand

INTRODUCTION

Sediment yields from the Waipaoa (2205 km^2), Waiapu (1749 km^2) and Uawa (557 km^2) drainage basins are very high by global standards, and globally, similarly small mountain drainage basins comprise a major component of continental margin systems. Their production and discharge of sediment are typically episodic and potentially have a substantial impact on margin stratigraphy because of the large supply. The East Coast steepland basins are the three heaviest, sediment-laden rivers in New Zealand and together generate ~55 Mt of suspended sediment annually (Hicks & Shankar, 2003). This amounts to ~0.3% of the total global suspended sediment input to the ocean (from ~0.003% of Earth's total land area).

The anthropogenic impact on the sediment load (or equivalent suspended sediment yield) in these basins is considered to be significant and has been in response to the influence of vegetation clearance and land-use change (Page *et al.*, 2001; Gomez *et al.*, 2003; Marden *et al.*, 2005).

Gullies are purported to be the largest sediment sources and contributors to the sediment load of rivers draining these basins (Page *et al.*, 2001; Marden *et al.*, 2005). However, this has yet to be substantiated at the basin-scale.

The region consists of two contrasting geologic/tectonic terrains, and until now the number and size distribution of gullies, and hence sediment production from them relative to these terrains, were unknown. Previous studies have estimated the volume of sediment removed from gullies on the basis of elevation differences using high-resolution digital elevation models (DEMs) constructed from sequential aerial photography. These data were then used to derive a relationship between gully area and sediment production for a sample of gullies within Cretaceous terrain (De Rose *et al.*, 1998) and Tertiary terrain (Betts & De Rose, 1999), respectively. However, in deriving these relationships, the full complement of gully sizes present in both terrains, particularly the medium to large gullies (5–15 ha), of which there are many throughout the East Coast region, were not well represented and these relationships may not therefore be appropriate for calculating the volume of gully-derived sediment produced from the respective terrains.

In this paper we combine data derived from DEM analyses in the two previous studies with that from DEMs constructed for 11 medium to large gullies and derive a new degradation model for gullies in each of the two contrasting geologic/tectonic terrains. We use this model to: (i) calculate the volume of sediment excavated from individual gullies; (ii) assess the relative amounts and rates of sediment production from each terrain; and (iii) calculate the equivalent contribution of gully-derived sediment to the average annual suspended sediment yield of the Waipaoa, Waiapu and Uawa rivers. In addition, we explore the influence reforestation has had on sediment production and compare the proportional contribution of gully-derived material from forested and pastoral areas, by terrain, to the sediment load and average annual suspended sediment yield of these basins over a ~40-year reforestation period.

Background

A combination of factors predisposes the East Coast Region to gully erosion. These include tectonic influences (e.g. earthquakes, uplift rates), geologic influences (rock type, degree of faulting and crushing), a dynamic climate influenced by tropical cyclones, and the recent clearance of vegetation from steep slopes. The East Coast is positioned on the circum-Pacific mobile belt at the boundary of the converging Pacific and Indian–Australian lithospheric plates, which results in high rates of tectonic uplift (1–7 mm/year) and frequent large magnitude earthquakes (Smith & Berryman, 1986). The region can be subdivided into two geologic terrains based on lithology, age and style of deformation. In this paper we adopt the terms "Cretaceous terrain" and "Tertiary terrain", respectively (Fig. 1). The inland, Cretaceous terrain comprises variably indurated,

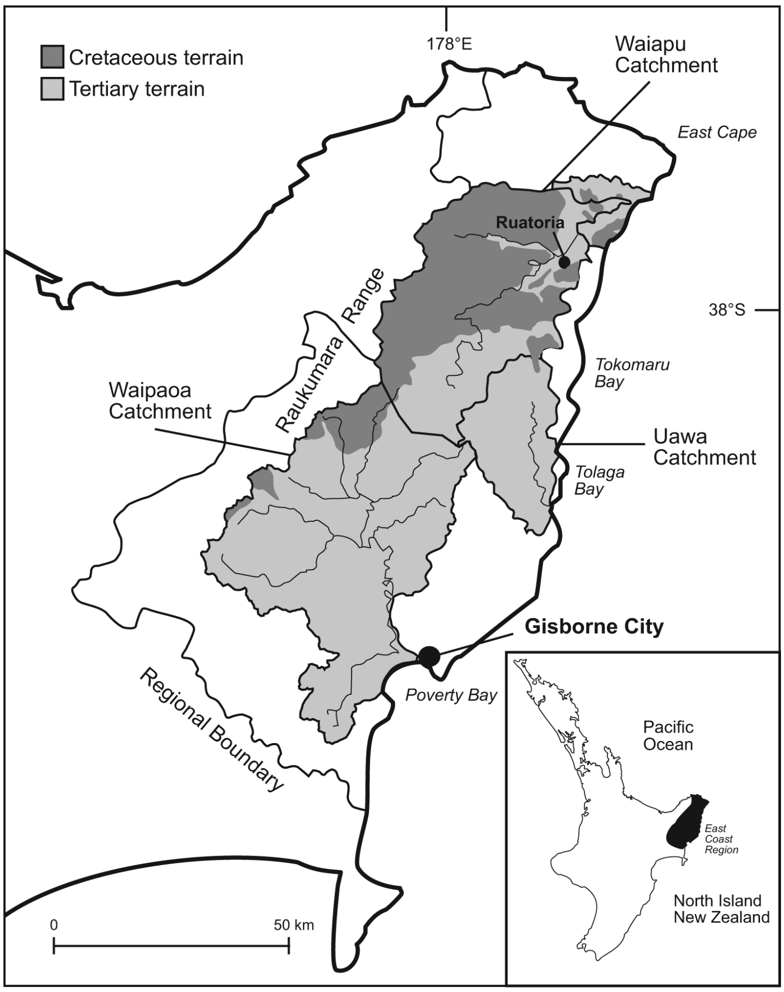

Fig. 1 Location map showing the extent of Cretaceous and Tertiary terrains within the Waipaoa, Waiapu and Uawa catchments, East Coast Region, North Island, New Zealand.

extensively sheared, alternating siliceous mudstone and sandstone of Late Cretaceous to Palaeocene age comprising part of the East Coast Allochthon (Mazengarb & Speden, 2000). Eastward of this allochthon lies the autochthonous Tertiary terrain comprising tectonically less-deformed, bedded to massive, sandstones and mudstones of Early to Middle Miocene age. In places, the two terrains are separated by areas of melange consisting essentially of Cretaceous-aged rocks. The melange formed during the emplacement of the allochthon in Early Miocene time and on the basis of its age and structural style has been included as part of the Cretaceous terrain.

The forest clearance history is similar for all three catchments. At around the turn of the 19th century (~1880–1920) there was rapid removal of extensive areas of indigenous forest for conversion to pasture. This was followed by a period of geomorphic slope adjustment in response to the removal of this forest (Hill, 1895; Henderson & Ongley, 1920), the most noticeable being the initiation of gully erosion. Gully erosion was precipitated by changing soil moisture conditions and the subsequent loss of root strength that lowered the threshold for their development (O'Loughlin, 1974a,b). The chronology of the early stages of gully development is obscure. Based on written accounts of the presence of gully erosion in upper catchment areas it is likely that gully initiation occurred within a decade or two following deforestation (Allsop, 1973; Gage & Black, 1979) and is supported by observations of increased channel aggradation (Kennedy, 1912; Laing-Meason, 1914), attributable predominantly to gully erosion (Gage & Black, 1979). Furthermore, the earliest available aerial photography (~1939–1957) shows gully erosion to be absent from remaining steepland areas of indigenous forest, suggesting it was also minimal in forested areas cleared for pastoral use in the late 1880s to early 1920s. Once initiated, gullies rapidly became entrenched, with steep sides showing evidence of repeated slumping. Together with associated mass movement processes, gullying is unique in that its magnitude is greater than in any other region of New Zealand and it is one of the most spectacular examples of its kind to be found anywhere in the world (NWASCO, 1970).

Initial, on-farm attempts to control gully erosion with fascines and check dams were effective only for the smaller and linear-shaped gullies, but were largely ineffective for the larger and amphitheatre-shaped gullies. Increasing costs associated with on-farm gully stabilisation for the protection of downstream infrastructure and utilities led to the Government purchasing large tracts of eroding farmland in the headwater reaches of the Waipaoa, Uawa and Waiapu catchments for reforestation. Reforestation commenced in 1961, and on completion in 1985 in excess of 40 000 ha of exotic forest had been established in the East Coast Region. The principal tree species include radiata pine (*Pinus radiata*), Douglas fir (*Pseudotsuga menziesii*), and assorted minor species. Additional plantings, predominantly of *Populus* (Poplar) and *Salix* (willow) species, were undertaken within gully systems to stabilise side slopes and reduce channel scour (Dolman, 1982). These early attempts at reforestation for erosion control have proved to be a practical, inexpensive and successful treatment option for much of the severely eroding hill country in this region (Phillips *et al.*, 1991; Marden & Rowan, 1993; Marden, 2004; Marden *et al.*, 2005). Beginning in the 1980s, a second wave of forest plantings followed extensive damage sustained to large tracts of pastoral hill country during successive storms in 1980, 1982 and Cyclone Bola in 1988. Region-wide, by 1997, a total of ~135 000 ha of eroding hill country has been replanted in exotic forest since the 1960s.

The regional climate is warm temperate maritime, with warm moist summers and cool wet winters. Rainfall gradients increase from south to north and from the coast to inland areas. Mean annual rainfall for coastal areas in the south (Gisborne City) is 1200 mm, while that in the north (Ruatoria Township) is 1600 mm. Inland areas in the south of the region receive ~2500 mm, while areas in the north and near the main divide of the Raukumara Range receive 4000 mm (Hessell, 1980). The region's climate is strongly influenced by the El Nino/Southern Oscillation (ENSO), with an increase in major rainfall events during La Nina conditions and severe and prolonged droughts during El Nino years. Tropical cyclones during the summer months (November–March) have on occasion accelerated erosion; the last was in 1988 (Cyclone Bola) during which 300–900 mm of rain fell in a 5-day period. Since the turn of the 20th century and as at 1995 there had been 29 extreme rainfall events where the discharge rates for the Waipaoa River exceeded 1500 $m^3 s^{-1}$, and during which evidence of widespread hillslope failure was often documented. Analysis of storm frequency and associated flooding in the Waipaoa catchment suggested there was a 29% chance of a major event every year, and a greater than 99% chance one would occur every 10 years (Kelliher *et al*., 1995). Erosion-generating storms and associated flooding in the Uawa and Waiapu catchments are more frequent and in the Waiapu catchment have a recurrence interval of between 2.6 years in the headwaters and 3.6 years near the coast (Hicks, 1995). This volatile climate contributes to high erosion rates (Water and Soil Directorate, 1987).

METHODS

Region-wide mapping of gullies

The region-wide distribution of actively eroding gullies was mapped for the two time periods for which aerial photographic coverage was available for the entire region. The earlier coverage was based on aerial photography flown between 1939 and 1957, but primarily 1957, and we refer to this as the 1957 coverage. This captures the extent of gully development following clearance of the indigenous forest (~1880s–1920s) up until the commencement of reforestation for erosion control in 1961 (i.e. the pre-reforestation period). A later mapped coverage, based on aerial photography flown in 1997, captures the status of gully erosion after ~40 years of reforestation effort (i.e. the reforestation period).

After Betts & De Rose (1999), gullies were defined as areas of actively eroding bare ground that were contiguous with the channels that drained them. Incipient gullies (non-active) were not mapped because the emphasis here was on identifying only those gullies considered to be active sediment sources. Gullies were identified stereoscopically from aerial photography. The planimetric area of individual gullies, but excluding adjacent areas of broken ground attributable to mass-movement, was scribed directly onto non-orthorectified photographic prints. This linework was then digitised and orthocorrected using MAPVIEW. The area of individual gullies and differences in area between 1957 and 1997 were determined in GIS.

Construction of gully DEMs

Following De Rose *et al*. (1998) and Betts & De Rose (1999), we acquired 14-micron scans of aerial photography for 11 gullies selected on the basis of their size and the availability of historic sequential aerial photography. The latest photography (flown in 2004–2005) for which triangulation data were available was orthorectified to a resolution equivalent to that of the original imagery and was used to fix ground control points (GCP) for earlier photographic coverage. The software used was ERDAS OrthoBase, part of the Leica Photogrammetric Suite v. 9.1.

Raster DEMs were generated from each set of photography. The first date of photography represented the earliest available (1939–1949), the second represented the latest available before reforestation (1957–1964) and the most recent coverage was taken after forestry had become well established (1997–2005). Following DEM construction, the scanned images were orthorectified to provide planimetrically correct base maps from which gully areas could be accurately measured. Gullies were delineated on-screen using the orthorectified imagery. Each orthophoto was generated at a minimum pixel resolution of 2.0 m with error estimates ranging from 0.61 m to 9.60 m (90% confidence interval).

For the range of gully sizes analysed (0.07–60.5 ha), changes in gully depth were derived by subtracting the DEM representing the end of a measurement period from the DEM representing the beginning of a measurement period. The values in the "difference image" within each gully boundary was then averaged and divided by the duration of the measurement period (in years) to derive an average annual increase in depth (m/year). Multiplying this by the gully area gives the degradation rate (m^3/year) for each gully (Fig. 2).

Relationship between annual change in gully depth and area

Sixty-six DEMs from 37 gullies located at 6 sites were used to estimate the rate of increase in gully depth, 45 observations in Tertiary, and 21 observations in Cretaceous terrain. Correlation

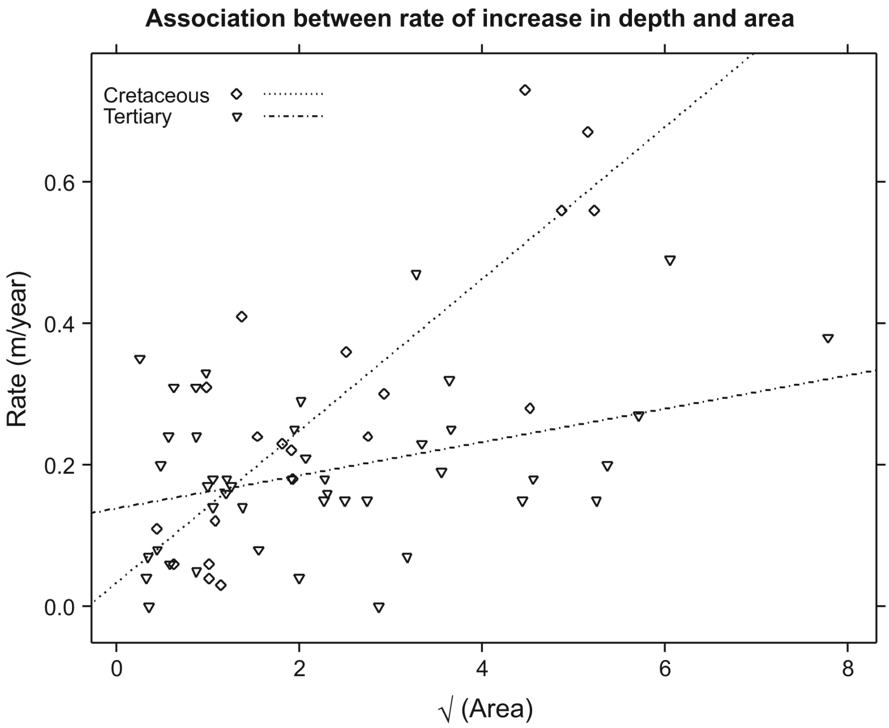

Fig. 2 Relationship between rate of increase in gully depth (m/year) and the square root of gully area for individual gullies located in Cretaceous (n = 21 observations) and Tertiary (n = 45 observations) terrains.

between observations of the same gully at different times and of different gullies at the same site were accommodated by fitting the model:

$$\text{Rate}_{ijk} = a_G + b_G \text{ sqrt } (\text{Area}_{ijk}) + s_i + g_{ij} + e_{ijk}$$

where e_{ijk} are random differences between time periods at one gully, g_{ij} are random differences amongst gullies at the same site, and s_i are random differences between sites. The data indicated the constant a_G and slope b_G differed between geologies and so separate lines were fitted for each (Fig. 2). Analysis used the *nlme* package (Pinheiro *et al.*, 2008) within the statistical computing language *R* (R Development Core Team, 2008).

Sediment production

All calculations, irrespective of land cover, assume that gullies produced sediment at a rate proportional to their area and that area changed linearly between 1957 and 1997. Sediment volume was calculated for individual gullies by terrain type (Tertiary and Cretaceous), for periods 1957 and 1997 and for the Waipaoa, Waiapu and Uawa catchments (Tables 1 and 2). To calculate sediment production from 850 individual gullies that did not exist in 1957 but were present in 1997 (i.e. exact date of initiation unknown) we assumed, on the basis of their small size as at 1997, that they had been sites of active sediment generation for no longer than half the duration of the 1957 to 1997 measurement period (i.e. ~20 years). Similarly, for the calculations for 2345 individual gullies present in 1957 but "closed" by 1997 (predominantly due to reforestation but exact date of closure unknown), we assumed these gullies had generated sediment for no longer than half the duration of this 40-year measurement period (Table 3). These assumptions are based on previous research showing that for the majority of gully sizes represented, reforestation effectively closes them down within 20 years of planting (Marden *et al.*, 2005). There were 832 gullies that remained active throughout the 1957–1997 period, mostly in areas of pastoral hill country and from which sediment was generated throughout the 40-year measurement period.

Table 1 Combined gully area as at 1957 and 1997 and percent increase/decrease for the period. Figures in parentheses are percent of the total composite gully area within each catchment.

Catchment	Waipaoa Gully area (km²)			Waiapu Gully area (km²)			Uawa Gully area (km²)		
	1957	1997	% inc/dec	1957	1997	% inc/dec	1957	1997	% inc/dec
Cretaceous terrain	7.77 (54%)	3.13 (21%)	–60	19.35 (73%)	27.12 (69%)	+29	0.25 (5%)	0.30 (4%)	+17
Tertiary terrain	6.61 (46%)	12.06 (79%)	+45	7.09 (27%)	12.09 (31%)	+41	4.89 (95%)	8.14 (96%)	+40
Totals	14.38	15.19	+5	26.44	39.20	+33	5.14	8.44	+39

Table 2 Total (Mt) and annual sediment production (Mt/year) from gullies in Cretaceous and Tertiary terrains for the period 1957–1997 and their equivalent contribution to the average annual suspended sediment yield (ssy) (Mt/year) of the Waipaoa, Waiapu and Uawa rivers. Figures in parentheses are percentages.

Catchment	Waipaoa	Waiapu	Uawa
Sediment production from gullies in Tertiary terrain	148 (58)	162 (24)	104 (96)
Sediment production from gullies in Cretaceous terrain	106 (42)	514 (76)	4 (4)
Total sediment production from all gullies combined	254 (100)	676 (100)	108 (100)
Average annual suspended sediment yield	15	35	5
Annual sediment production and % equivalent of ssy from gullies in Tertiary terrain	3.7 (25)	4 (12)	2.6 (52)
Annual sediment production and % equivalent of ssy from gullies in Cretaceous terrain	2.7 (18)	13 (37)	0.1 (2)
Total annual sediment production & % equivalent of ssy from all gullies combined	6.4 (43)	17 (49)	2.7 (54)

Table 3 Comparative total sediment production (Mt/year) and annual rates (t/km²/year) for gullies reforested with exotic pines during the period 1957 to 1997 *vs* gullies remaining in pasture, by terrain. Calculations are based on the area of each terrain remaining in pasture and for reforested areas, on the area of each terrain planted in exotic forest by the end of the measurement period. Note: Catchment totals are based on total catchment area. Sediment production from gullies in areas of indigenous forest and scrub reversion has not been included.

Catchment	Waipaoa		Waiapu		Uawa	
Sediment production	#Mt/year	t/km²/year	Mt/year	t/km²/year	Mt/year	t/km²/year
Reforested gullies-Tertiary terrain	1.85	5331	0.75	5319	1.15	5227
Reforested gullies-Cretaceous terrain	1.95	18 224	2.5	12 143	0.1	62 500
Total for reforested gullies	3.8	8370	3.3	9402	1.25	5656
Gullies remaining in pasture for 1957–1997 – Tertiary terrain	1.6	1303	2.25	9259	0.9	5294
Gullies remaining in pasture for 1957–1997 – Cretaceous terrain	0.85	16 667	5.85	14 772	0.05	41 667
Total for pastured gullies	2.45	1916	8.1	12 857	0.9	5257
Catchment totals	6.25	2834	11.4	6518	2.2	3860

assumptions behind calculation are explained under methods.

We adopt the annual suspended sediment yields of Hicks & Shankar (2003) for the Waipaoa (15 Mt/year), Waiapu (35 Mt/year) and Uawa (5 Mt/year) as being representative of the reforestation period (post-1960) and calculate sediment production from gullies as a proportional (%) equivalent of the annual suspended sediment yield of these rivers. The mass (Mt) of material supplied by gully erosion was computed using a dry bulk density of 2000 kg/m³ (Phillips, 1988; cf.

De Rose *et al*., 1998; Marden *et al*., 2005). The estimates represent an upper bound because no account is taken of deposition in feeder channels and on fans, or of the proportion of coarse sediment (gravel) generated by gully erosion (Gomez *et al*., 2003).

RESULTS

Relationship between rate of increase in gully depth and gully area

Within the Tertiary terrain there was no evidence ($p = 0.4$) that the rate of increase in gully depth varied with gully area (Fig. 2).

$$\text{Rate} = 0.1963 + 0.0117 \sqrt{\text{Area}} \qquad \text{se} = 0.118 \qquad \text{\% Variance explained} = 19\%$$

The rate was therefore taken to be a constant 0.242 m/year (se = 0.131) regardless of area. However, within the Cretaceous terrain there was strong evidence of a relationship ($p = 0.002$):

$$\text{Rate} = 0.0558 + 0.09526 \sqrt{\text{Area}} \qquad \text{se} = 0.123 \qquad \text{\% Variance explained} = 61\%$$

which was therefore used to estimate total degradation.

Gully distribution, sediment production and contribution to yield

Waipaoa catchment Cretaceous terrain (173 km^2) occupies 8% of catchment area and Tertiary terrain (1710 km^2) 78% (Fig. 1). In 1997 there were 447 active gullies with a combined area of 15.19 km^2, of which 21% (3.13 km^2) was located in Cretaceous terrain and 79% (12.06 km^2) occurred in areas underlain by Tertiary terrain (Table 1). Total sediment production from gullies for the period 1957–1997 was 254 Mt at an annual rate of 6.4 Mt/year (2880 t/km^2/year), of which gullies in Tertiary terrain generated 58%. Gullies in both terrains combined produced the equivalent of 43% of the average annual suspended sediment yield of the Waipaoa River (Table 2) from just 0.8% of the combined hill country terrains.

Waiapu catchment Cretaceous terrain (1158 km^2) underlies 60% of catchment area and Tertiary terrain (504 km^2) 29%. In 1997 there were 976 active gullies with a combined area of 39.20 km^2 of which 69% (27.12 km^2) is located in Cretaceous terrain and 31% (12.09 km^2) occurs in areas underlain by Tertiary terrain (Table 1). Total sediment production from gullies for the period 1957–1997 was 676 Mt, at an annual rate of 17 Mt/year (9548 t/km^2/year) of which gullies in Cretaceous terrain generated 76%. Gullies in both terrains combined produced the equivalent of 49% of the average annual suspended sediment yield of the Waiapu River (Table 2) from just 2.4% of the combined hill country terrains.

Uawa catchment Cretaceous terrain (3 km^2) outcrops only in the extreme northeast of this catchment and makes up just 0.5% of the total catchment area. Tertiary terrain (482 km^2) occupies 86% (Fig. 1). In 1997 there were 290 currently active gullies with a combined area of 8.44 km^2, of which 4% (0.30 km^2) is located in Cretaceous terrain and 96% (8.14 km^2) occurs in areas underlain by Tertiary terrain (Table 1). Total sediment production from gullies for the period 1957–1997 was 108 Mt, at an annual rate of 2.7 Mt/year (4847 t/km^2/year), of which gullies in Tertiary terrain generated 96%. Gullies in both terrains combined produced the equivalent to 54% of the average annual suspended sediment yield of the Uawa River (Table 2) from just 1.7% of the combined hill country terrains.

Trends in gully erosion

During 1957–1997, the composite area of active gullies in areas of Cretaceous terrain in the Waipaoa catchment decreased by 60% but increased by 29% and 17% in the Waiapu and Uawa catchments, respectively (Table 1). By comparison, in areas of Tertiary terrain the composite gully area increased by 45%, 41% and 40% within the Waipaoa, Waiapu and Uawa catchments, respectively. Thus after ~40 years of reforestation effort, during which ~135 000 ha of some of the most severely eroding land across all three catchments was reforested, the total composite area of actively eroding gullies was greater (as at 1997) than before reforestation for erosion control began by 5% in the Waipaoa, by 33% in the Waiapu and by 39% in the Uawa catchments (Table 1).

Overall, for 1957–1997, the rate of sediment production (calculated using total catchment area) from all gullies irrespective of land cover in the Waiapu catchment (9548 t/km^2/year) was ~3.5 times greater than in the Waipaoa catchment (2880 t/km^2/year) and twice that in the Uawa catchment (4847 t/km^2/year).

DISCUSSION

Gully erosion in the headwater reaches of the Waipaoa, Waiapu and Uawa catchments was initiated within a few decades of the clearance of indigenous forest for pasture. Gullies developed fastest and were most widespread in areas of Cretaceous terrain where structurally weak and fault-crushed bedrock coincide with high rainfall regimes in headwater reaches of each of these catchments. This combination of factors predisposes these areas to gully erosion and associated mass movement processes, the mechanism by which many gullies increase in size. In contrast, gully development in the generally lower rainfall areas of Tertiary terrain was predominantly by fluvial processes and gullies typically maintain a linear shape, contrasting with the predominance of amphitheatre-shaped gullies found in areas of Cretaceous terrain.

An increase in gully depth with gully size is commensurate with greater runoff rates and enhanced runoff concentrations within gully systems. However, for gullies developed within Tertiary terrain the relationship between the rate a gully deepens and its area is weak. With the exception of a few amphitheatre-shaped gullies associated with mélange or fault crush-zones, structural and bedrock controls determine the rate and mode of gully expansion, which is predominantly by fluvial processes. These gullies therefore deepen with little corresponding increase in gully area, and thus typically maintain a linear shape. In contrast, gullies associated with structurally weak materials typically found in areas of Cretaceous terrain increase in size more by mass movement than by fluvial processes and increasingly become amphitheatre-shaped (De Rose *et al.*, 1998; Betts & De Rose, 1999; Marden *et al.*, 2005). For such gullies, the rate of increase in depth increases with size (area) and thus this relationship is stronger. Betts & De Rose (1999) also noted such a relationship between degradation rates and the square root of gully area and similarly found that for linear gullies this relationship was not as strong as for amphitheatre-shaped gullies. They concluded nonetheless that such relationships are significant for assessing the contribution of sediment derived from gullies to the sediment budget of a catchment.

The most significant period for gully development occurred in the 1940s–1960s under a pastoral regime and was exacerbated by major floods in 1938 and 1948, followed by a succession of heavy rainfall events in the late 1950s and early 1960s. Gully erosion peaked in the 1970s, a decade after the introduction of reforestation and about the time early gully plantings achieved canopy closure and gullies began to stabilise (Marden *et al.*, 2005). The early history of gully development and its influence on the contribution of gully-derived sediment to the sediment load of the Waipaoa River over a period of one rotation of *Pinus radiata* has previously been documented (Marden *et al.*, 2005). From this and other research it is apparent that in the absence of a forest cover not all gullies form at the same time or develop at the same rate, and furthermore the timing of gully-closure in response to reforestation is highly variable and largely a function of gully size at the time of planting (Marden *et al.*, 2005). Accordingly, sediment production rates also vary considerably through time (De Rose *et al.*, 1998; Betts & De Rose 1999; Marden *et al.*, 2005).

Reforestation has had the greatest influence in closing-down gullies within Waipaoa catchment where Cretaceous terrain occupies just 8% of catchment area. Here, numerous gullies were replanted during the early stages (1961–1985) of the reforestation programme and resulted in a ~64% reduction in gully area within one rotation length (~27 years) of *Pinus radiata*, the preferred species for erosion control in New Zealand (Marden *et al.*, 2005). Nonetheless, the few but large gullies that remained active throughout the 40-year duration of the reforestation period contributed the equivalent of 18% of the average annual suspended sediment yield of the Waipaoa River (Table 2). By comparison, in the Waiapu catchment where Cretaceous terrain occupies 60% of the catchment area, reforestation also commenced in the early 1960s, but planting was at a slower rate than in the Waipaoa catchment and consequently a lesser proportion of this terrain in Waiapu catchment was reforested. As a result fewer gullies were planted at this time. The majority of the 976 gullies present in this terrain are therefore found in areas of pastoral hill country and since most were not treated over the past 40 years, their combined area has increased by 29% to 27.12 km^2. In addition, many of these gullies occur within zones of melange where this tectonically weakened material is prone to mass movement, and once gullies have formed they readily enlarge into amphitheatre-shaped features. Thus for gullies in areas of pastoral hill country within Cretaceous terrain, sediment production rates are high, especially so if significant gully development occurs within zones of melange. In the Waiapu catchment Cretaceous gullies produced 76% of the catchment's total sediment production at a rate of 14 772 $t/km^2/ha$ (Table 3); equivalent to 37% of the average annual suspended sediment yield of the Waiapu River (Table 2). Similarly, in the Waipaoa catchment, high sediment production rates were associated with pastoral hill country areas in Cretaceous terrain (16 667 $t/km^2/year$) much of which was derived from gullies associated with melange. Although the extent of Cretaceous terrain in the Uawa catchment is small (0.5% of catchment area), the rate of sediment production from a small composite gully area (0.30 km^2) was exceedingly high (62 500 $t/km^2/year$), with most sediment being produced when these gullies were associated with a pastoral regime. In addition, given that these gullies were not planted in forest until 1982–1989, sediment production rates would likely have remained high on account of several major storm events in the mid- to late-1980s, at a time when the gully plantings would have been too young to provide effective stabilisation. However, further reductions in sediment production will accrue with increasing age of the forest plantings associated with gullies in Cretaceous terrain.

Irrespective of land use, gullies in areas of Cretaceous terrain collectively contributed the equivalent of ~18% of the average annual suspended sediment load of the Waipaoa, 37% of Waiapu, and 2% of the Uawa rivers (Table 2).

The timing of reforestation in areas of Tertiary terrain largely reflects the history of successive storm events in the 1980s. While most of this new forest was targeted at erosion prone land, these planted areas included few gullies. The greatest proportion of a catchment planted at this time was in the Uawa catchment (~80% of catchment currently in forest/scrub reversion). Here, young plantings were established on storm-damaged hill country after heavy rainfall events in the early 1980s and further areas were reforested following Cyclone Bola (1988). For the measurement period, the rates of sediment production from forested gullies in Tertiary terrain were similar for all three catchments (~5000 $t/km^2/year$), and were 60% less (in Waipaoa), 56% less (in Waiapu) and 97% less (in Uawa) than that generated from forested gullies in Cretaceous terrain (Table 3). This reflects the generally slower rates of increase in gully size (area) and the likelihood that gully closure following planting occurs sooner for the typically smaller and linear shaped gullies associated with Tertiary terrain. Accordingly, sediment production rates would likely decline earlier and quicker than for the more active, larger and difficult-to-treat gullies associated with the Cretaceous terrain.

Since Cyclone Bola (1988), the area planted in exotic forest has more than doubled. While a substantial proportion of the most vulnerable gully-prone areas has already been reforested and a significant reduction in gully-derived sediment has occurred in response to reforestation (De Rose *et al*., 1998; Marden *et al*., 2005), the contribution to the sediment yield from reforested areas remains high because gullies in these areas were already too big and active at the time of planting for such plantings to be effective. In addition, 57% of the gullies present in 1957 in the Waipaoa, 80% in the Waiapu, and 40% in the Uawa catchments had not been treated by 1997, and in the interim, untreated gullies individually increased in size, and together with the initiation of 850 new gullies, their combined area increased by 5%, 33% and 39% in the respective catchments (Table 1). Significant areas of pastoral Tertiary hill country in each of the Waipaoa, Waiapu and Uawa catchments are also prone to gully erosion. Traditionally considered to be viable pastoral land, many gullies present in the 1950s were never treated, and in this unprotected landscape many new gullies were initiated as a result of storm events in the early to late 1980s. As a consequence, the composite gully area within pastoral areas of Tertiary terrain in each of the three major catchments increased by ~40% during the 1957–1997 period (Table 1). The rate of sediment production from such gullies was greatest in the Waiapu catchment (9259 t/km^2/year), ~7 times higher than from gullies in similar terrain within the Waipaoa catchment (1303 t/km^2/year) and approx. twice that from gullies in the Uawa catchment (5294 t/km^2/year) and is mostly a reflection of the large proportion of gully-prone pastoral hill country within this catchment and its location within a higher rainfall regime than in either the Waipaoa or Uawa catchments.

Irrespective of land use, gullies in areas of Tertiary terrain collectively contributed the equivalent of ~25% of the average annual suspended sediment load of the Waipaoa, 12% of the Waiapu, and 52% of the Uawa rivers (Table 2).

Overall, for both forested and pastoral hill country, the annual rate of sediment production from gullies was greater in areas of Cretaceous terrain than in Tertiary terrain and with the exception of Waiapu catchment annual sediment production rates from reforested areas continue to remain greater than that (e.g. in the Waipaoa) or equivalent to that (e.g. in the Uawa) generated from pastoral hill country. Across both terrains and land uses, the annual rate of sediment generation for the measurement period was greater for Waiapu catchment (6518 t/km^2/year) than for Uawa (3860 t/km^2/year) and Waipaoa (2834 t/km^2/year) (Table 3). For the 40-year reforestation period gullies in forested and pastoral areas of both terrains combined contributed the equivalent of 43%, 49% and 54% of the average annual suspended sediment load of the Waipaoa, Waiapu and Uawa rivers (Table 2), from just 0.8%, 2.4% and 1.7% of hill country areas in these respective river systems. Gullies therefore continue to be the single largest source of sediment, and until sediment production from them is halted, suspended sediment yields will remain high.

CONCLUSIONS

Gully erosion in the headwater reaches of the Waipaoa, Waiapu and Uawa catchments was initiated within a few decades of the clearance of indigenous forest for pasture. Gullies developed fastest and were most widespread in areas of Cretaceous terrain where structurally weak and fault-crushed bedrock coincides with high rainfall regimes in headwater reaches of each of the respective catchments. This combination of factors predisposes these areas to gully erosion and associated mass movement processes, the mechanism by which many gullies increase in size. In contrast, gully development in areas of Tertiary terrain was predominantly by fluvial processes and gullies typically maintain a linear shape, contrasting with the predominance of amphitheatre-shaped gullies found in areas of Cretaceous terrain. Accordingly, the rate of sediment production from gullies in areas of Cretaceous terrain was significantly higher than for areas of Tertiary terrain.

Reforestation has been the most successful mechanism employed to stabilise actively eroding gullies and is equally effective in reducing sediment production from them. Its influence has been greatest where areas of Cretaceous terrain were reforested earliest and where plantings encompassed substantial areas of gully-prone land within the headwaters of these drainage basins. Region-wide, and since the 1960s, ~135 000 ha of forest has been established for erosion control, despite which the composite gully area within each of the three major catchments is currently greater than before planting started over four decades ago. Gully erosion has been and remains the most significant sediment-producing process in these river systems.

Of the three major river systems, the greatest potential for achieving a significant reduction in sediment production and yield, at the catchment-scale, is in the Waiapu catchment. Here, through the targeting of a relatively small proportion of the total catchment area, more specifically the gullies themselves, it would in the long term be possible to reduce sediment production. This will require a more targeted approach to the replanting options available for gullies (reforestation, reversion or pole planting) than has been achieved in the past, and in particular the targeting of those gullies located in the more highly erodible and unstable pastoral hill country areas in both the Cretaceous and Tertiary terrains. Reforestation is the most practical and effective means of controlling gully erosion and for all but the largest gullies it is achievable within one forest rotation (approx. 24 years). However, to achieve effective control of these gullies, particularly of the medium to large ones, the area treated would require the inclusion of adjacent areas of associated mass movement and therefore would likely incorporate part of or their entire watershed. To reduce the supply of material at source will require a genuine attempt to treat a significant number of gullies within a short time frame and even then it will take several decades before the beneficial influences of gully stabilisation will be reflected in a reduction in sediment yield. In addition, sediment yield will remain at current levels until sediment already stored in the heavily aggraded riverbeds has been excavated. Until this process is underway it will not be possible, in the short term (decadal time frame), to achieve other potential environmental co-benefits such as improved water clarity and quality, a reduction in channel aggradation or flood risk or cost savings associated with bridge replacement and repairs to flood damaged roads.

Acknowledgements This work was supported by the Foundation for Research Science and Technology, contract number CO9X0706. We are indebted to the Gisborne District Council and in particular to the staff of the Soil Conservation Section for providing access to their collection of aerial photography. The assistance of the Ministry of Agriculture and Forestry (East Coast Forestry Project, Gisborne Office) in providing GIS and financial support is gratefully acknowledged. Nic Faville assisted with the figures, Anne Austin edited the initial text, and Mandy Cains formatted the draft manuscript.

REFERENCES

Allsop, F. (1973) *The Story of Mangatu*. Government Printer, Wellington, New Zealand.

Betts, H. D. & De Rose, R. C. (1999) Digital elevation models as a tool for monitoring and measuring gully erosion. *J. Appl. Earth Obser. Geoinform.* **1**(2)*,* 91–101.

De Rose, R. C., Gomez, B., Marden, M. & Trustrum, N. A. (1998) Gully erosion in Mangatu Forest, New Zealand, estimated from digital elevation models. *Earth Surf. Processes Landf.* **23,** 1045–1053.

Dolman, K. (1982) *Gully Revegetation on the East Coast-with a Focus on Acacia*. New Zealand Forest Service, Gisborne, New Zealand.

Gage, M. & Black, D. (1979) Slope-stability and geological investigations at Mangatu State Forest*. New Zealand Forest Service Technical Paper no. 66.* New Zealand Forest Service, Wellington, New Zealand*.*

Gomez, B., Banbury, K., Marden, M., Trustrum, N. A., Peacock, D. H. & Hosking, P. J. (2003) Gully erosion and sediment production: Te Weraroa Stream, New Zealand*. Water Resour. Res.* **39**(7), 1187, doi: 10.1029/2002WR001342.

Henderson, J. & Ongley, M. (1920) The geology of the Gisborne and Whatatutu subdivisions, Raukumara Division. *Bull* **21** (new series). Geological Survey Branch, Department of Mines, New Zealand.

Hessell, J. W. D. (1980) The climate and weather of the Gisborne Region*. New Zealand Meteorological Service Miscellaneous Publication* **115**(8).

Hicks, D. L. (1995) A way to estimate the frequency of rainfall-induced mass movements (note). *J. Hydrol. (NZ),* **33** (1), 59–67.

Hicks, D. M. & Shankar, U. (2003) Sediment from New Zealand Rivers. NIWA Chart, Miscellaneous Series no. 79. National Institute of Water and atmospheric Research, Wellington, New Zealand.

Hill, H. (1895) Denudation as a factor of geological time. *Trans. Proc. New Zealand Institute* **28,** 666–680.

Kelliher, F. M., Marden, M., Watson, A. J., & Arulchelvam, I. M. (1995) Estimating the risk of landsliding using historical extreme river flood data. *J. Hydrol. NZ.* **33,** 123–129.

Kennedy, C. D. (1912) *Flood Prevention Report: Poverty Bay River District*. Gisborne Herald, New Zealand.

Laing-Meason, G. (1914) *Prevention of Floods: The Waipaoa River Trouble.* Poverty Bay River Board report on flood prevention. Gisborne Times, 17 July 1914, p. 11.

Marden, M. (2004) Future-proofing erosion-prone hill country against soil degradation and loss during large storm events: have past lessons been heeded? *NZ J. For.* **49**, 11–16.

Marden, M. & Rowan, D. (1993) Protective value of vegetation on Tertiary terrain before and during Cyclone Bola, East Coast, North Island, New Zealand. *NZ J. For. Sci.* **23**(3), 255–263.

Marden, M., Arnold, G., Gomez, B. & Rowan, D. (2005) Pre- and post-reforestation gully development in Mangatu Forest, east coast, North Island, New Zealand. *River Res. Appl.* **21,** 1–15.

Mazengarb, C. & Speden, I. G. (2000) Geology of the Raukumara area. *Institute of Geological and Nuclear Sciences 1:250 000 geological map 6.* Institute of Geological and Nuclear Sciences, Lower Hutt, New Zealand. 1 sheet + 60 p.

NWASCO. (1970) Wise landuse and community development. Report of the technical committee of enquiry into the problems of the Poverty Bay-East Coast District of New Zealand. National Water and Soil Conservation Organisation. Water and Soil Division, Minisrty of Works, Wellington, New Zealand.

O'Loughlin, C. L. (1974a) The effect of timber removal on the stability of forest soils. *J. Hydrol. (NZ)* **13**, 121–134.

O'Loughlin, C. L. (1974b) A study of tree root strength deterioration following clearfelling. *Can. J. For. Res.* **4,** 107–113.

Page, M., Harmsworth, G., Trustrum, N. A., Kasai, M., & Marutani, T. (2001) Waiapu River. In: *Source-to-Sink Sedimentary Cascades in Pacific Rim Geo-Systems* (ed. by T. Marutani, G. J. Brierley, N. Trustrum & M. J. Page), 102–111. Matsumoto Sabo Work Office, Ministry of Land, Infrastructure and Transport, Motomachi, Matsumoto, Japan.

Phillips, C. J. (1988) Rheological investigations of debris flow materials. PhD thesis, Lincoln College, New Zealand.

Phillips, C. J., Marden, M. & Pearce, A. J. (1991) Effectiveness of reforestation in prevention and control of landsliding during large cyclonic storms. In: *Proc. 19th Int. Union of Forestry Research Organisations*, 358–361 (Montreal).

Pinheiro, J., Bates, D., Debroy, S., Sarkar, D. & the R Core Team (2008) nlme: Linear and Nonlinear Mixed Effects Models. R package version 3.1–88.

R Development Core Team (2008) R: A language and environment for statistical computing. R Foundation for Statistical Computing. Vienna, Austria. ISBN 3-90051-07-0. URL http://www.R-project.org.

Smith, W. D. & Berryman, K. R. (1986) Revised estimates of earthquake hazard in New Zealand. *Bull. New Zealand National Soc. Earthquake Engng* **16**(4), 259–272.

Water and Soil Directorate (1987) East Coast Project Rev*iew*. Water and Soil Directorate, Ministry of Works and Development, Wellington, New Zealand.