WATER RESOURCES RESEARCH, VOL. 39, NO. 7, 1187, doi:10.1029/2002WR001342, 2003

Gully erosion and sediment production: Te Weraroa Stream, New Zealand

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Received 27 March 2002; revised 10 December 2002; accepted 10 April 2003; published 23 July 2003.

[1] We derive a sediment budget for Te Weraroa Stream, New Zealand, the principal drainage in a small (29 km^2) steepland catchment where gully erosion, triggered by conversion to pasture early in the twentieth century, was ameliorated by reforestation that commenced in 1962. Estimates of sediment production were made using the change in gully area observed in sequential aerial photographs. Channel storage was assessed from stream cross-section surveys. At its peak, gully erosion affected ~6% of the total catchment area. The amount of sediment contributed from gullies declined by 62% as the forest became established, but of the 28.7 Mt of sediment generated by gully erosion between 1950 and 1988, 48% was stored in the channel along the lower 8 km of Te Weraroa Stream. Even if the amount of sediment generated by gully erosion continues to decline, it likely will be many decades before the gravel is released from storage. *INDEX TERMS:* 1815 Hydrology: Erosion and sedimentation; 1824 Hydrology: Geomorphology (1625); 1878 Hydrology: Water/energy interactions; *KEYWORDS:* channel storage, gully erosion, sediment production

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

1. Introduction

[2] Concern over accelerated erosion induced by human activity has generated a substantial literature on gully development [*Harvey et al.*, 1985], but there is a dearth of quantitative information on the contribution gully erosion makes to sediment production and downstream sedimentation. The latter effect is important because, though most sediment generated by gullies is eventually removed, storage induces a significant lag time between production and output which, in turn, makes it difficult to quantify the effect of past land use change on channel conditions and confounds attempts to estimate future adjustments [*Marutani et al.*, 1999; *Clark and Wilcock*, 2000]. Sediment production by gully erosion has been evaluated using sequential aerial photography and elevation differences derived from high-resolution digital elevation models [*Seginer*, 1966; *DeRose et al.*, 1998], and changes in channel storage assessed from cross-section surveys [*Osborn and Simanton*, 1989]. It remains that these components of the fluvial sediment budget rarely have been integrated, and reach-scale storage rarely is quantified in sediment budget studies [*Wathern et al.*, 1997]. Thus a sediment delivery ratio typically is used to account for differences between the amount of sediment generated by gully erosion and sediment production at a basin outlet [*Reid and Dunne*, 1996; *Kasai et al.*, 2001]. Quantitative insights into the processes that operate in low-order steepland channels and field observations that permit the contributions to changes in bed elevation to be assessed directly also are rare, though they are a necessary prerequisite to validating conceptual and simulation models of sediment transport and storage [*Benda and Dunne*, 1997; *Miller and Benda*, 2001].

[3] In this paper we use chronological changes in channel cross section and gully area, as documented by survey data and sequential aerial photography, to derive a sediment budget for Te Weraroa Stream. Te Weraroa Stream is a low-order channel in the headwaters of the Waipaoa River Basin, New Zealand, that was severely impacted by gully erosion following a brief, but pervasive, period of deforestation in the colonial period. The gravel generated by gully erosion caused aggradation, and our analysis is facilitated by an unusually comprehensive data set that permits us to quantify spatial and temporal variability in the patterns of sediment supply to and storage within 12 reaches along an 8 km long section of Te Weraroa Stream. These data, in conjunction with information gained from repeat aerial photography, permit us to elaborate the approach of previous studies of sediment production, storage and output from headwater catchments impacted by gully erosion. Moreover, because the rapid initial change in land use was mirrored by a comprehensive program of reforestation, beginning in 1962 and largely completed by 1965, the response of Te Weraroa Stream to changing watershed conditions in the period since 1947 can be clearly discerned. Thus our data provide a perspective on aggradation that compliments knowledge of the pattern of bed level changes associated with discrete natural events, such as landslides, or mining operations and timber harvesting observed in other steep-

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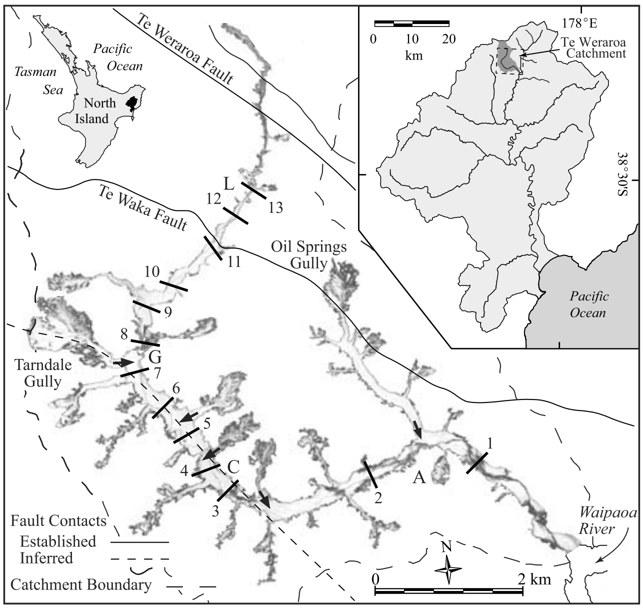

Figure 1. Location map showing the disposition of gullies along Te Weraroa Stream (derived from 1960 aerial photography) and the sites of surveyed cross sections. Reaches are designated by letters, and arrows indicate gullies that were active in 1988. Fault contacts are after *Black* [1980].

land channels [*James*, 1991; *Madej and Ozaki*, 1996; *Miller and Benda*, 2001; *Lisle et al.*, 2001].

2. Study Area

[4] Gully erosion is widespread throughout New Zealand's North Island, affecting some 10% of the land area [*Eyles*, 1985]. Some of the most spectacular examples of gully erosion occur in the headwaters of the Waipaoa River Basin [*Gage and Black*, 1979; *Pearce et al.*, 1981]. Gully erosion provides the dominant source of sediment to Te Weraroa Stream, an ungauged, headwater tributary of the Waipaoa River (Figure 1). The braided stream channel occupies the entire valley floor (Figure 2) and, though there are a plethora of lateral sediment inputs, there is an essentially continuous pattern of fining along the lower 8 km of the channel. The median grain size of the surficial bed material declines from 11 mm in the reach upstream from the point where the feeder channel from the Tarndale gully complex enters Te Weraroa Stream, in reach G, to 6.8 mm in reach A (Figure 1) [*Banbury*, 1996]. Bedrock in the catchment is sheared and friable, and consequently the coarse bed material breaks down relatively rapidly. However, there are numerous angular and sub-angular particles in the channel, suggesting that the residual sediment experienced a minimal amount of fluvial transport prior to deposition. In 1948, 77% of the 29 km^2 catchment was in pasture, and 13% was covered by beech-podocarp forest or scrub and bracken [*Allsop*, 1973]. The remaining 10% of the catchment either was impacted by erosion or aggradation.

[5] Gullies developed in the catchment after the native beach, podocarp and mixed hardwood forest was replaced by pasture over a ~20 yr period, beginning in 1894. Most gullies are associated with the Whangai (or Mangatu) Formation (calcareous mudstone (argillite) [*Black*, 1980; *Mazengarb and Speden*, 2000]), and occur south of the Matakonekone fault bock, which is bounded by the Te Waka and Te Weraroa faults (Figure 1). The more stable terrain to the north is underlain by the Tikihore Formation (alternating fine-medium-grained sandstone and carbonaceous mudstone [*Black*, 1980]). The more indurated, intensively folded sandstone is, in general, more coherent than the finer-grained argillite, but the major fold and fault structures, and topography also affect the susceptibility of the relatively homogeneous Whangai and Tikihore rocks to mechanical disintegration under the influence of water [*Gage and Black*, 1979]. For example, a major north-west trending fold structure influences the form of the junction of Te Weraroa Stream and the Waipaoa River (Figure 1), and the orientation of many gullies along Te Weraroa Stream may have been influenced by a major joint pattern [*Black*, 1980; *Gage and Black*, 1979]. The large (Tarndale and Oil Springs) gully complexes occur in association with zones of extensive crushing along the major faults and argillite rocks that are especially susceptible to acid sulphate weathering [*Pearce et al.*, 1981].

[6] The planimetric surface area of gullies along Te Weraroa Stream varies from <0.01 to ~0.2 km^2, and the drainage basins that support them range from a few thousand square meters to 0.5 km^2 in area. The smaller, linear gullies occupy topographically convergent areas in otherwise unchanneled zero-order basins, but the larger, amphitheater-like gully complexes have absorbed virtually their entire drainage basin [*De Rose et al.*, 1998]. Gully development was precipitated by changing soil moisture conditions following the removal of the native forest cover and the subsequent loss of root strength which lowered the threshold for erosion [*O'Loughlin*, 1974]. The chronology of the early stages of gully formation in the early part of the twentieth century is obscure, but anecdotal evidence suggests that the largest feature, the Tarndale gully complex (Figure 2), was initiated in the winter of 1915 on the site of an extant mass movement that occurred under the native forest cover. Many other gullies appear to have been initiated during the winters

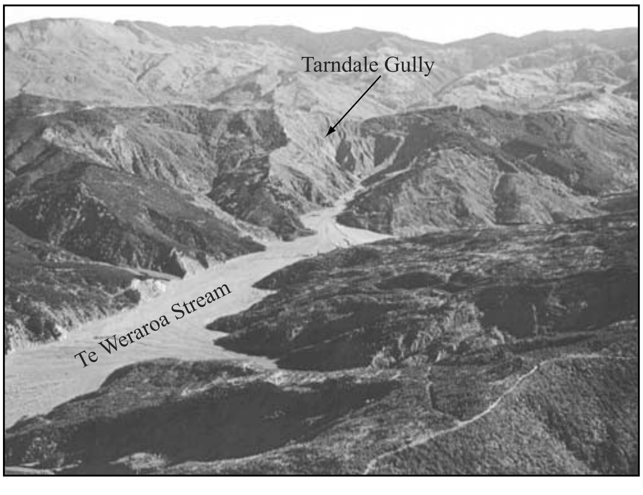

Figure 2. Te Weraroa Stream and the Tarndale gully complex (J. H. Johns, 1972).

Table 1. Cross-Section Characteristics[a]

	Cross Section												
	1	**2**	**3**	4	5	**6**	7	8	9	**10**	**11**	12	13
Distance Upstream (m)	**1433**	**3103**	**4632**	4992	5390	**5859**	6237	6639	7007	**7423**	**7970**	830 8	8676
Representative Width (m, as determined in 1948–1950)	**80.2**	**112**	**135**	93.3	174	**187**	123	25.0[b] (96.0)	146	**77.4**	**76.8**	30.5	32.3

[a] Cross sections resurveyed after 1980 are indicated in bold.
[b] Aggradation overtopped debris toe at base of slope in 1973.

of 1916, 1917 and 1918, and by the late 1920s aggradation had begun to have a noticeable effect on river channels [*Gage and Black*, 1979]. For example, between 1896 and 1940, as the valley was infilled the width of Te Weraroa Stream at the confluence with the Waipaoa River increased by 600%.

[7] Initial attempts to control gully erosion in Te Weraroa catchment using fascines and check dams were largely ineffective. Eventually, most gullies were stabilized after a program of exotic reforestation, that encompassed 80% of the catchment, was implemented in 1962 [*Allsop*, 1973]. The principal tree species involved were *Pinus radiata*, *Pseudotsuga menziesii* and *Pinus nigra*, and the majority of planting was completed by 1965. The amelioration of gully erosion was accomplished through a combination of reduced runoff (mature *Pinus radiata* stands have the potential to reduce runoff by between 25 and 30%), and a shortened period of soil moisture surplus [*Pearce et al.*, 1987]. However, erosion in the large Tarndale and Oil Springs gully complexes, where the bare head- and sidewalls extend from the channel to the ridge top (Figure 2), was too far advanced to be mitigated by afforestation, and these features have remained active [*DeRose et al.*, 1998; *Marutani et al.*, 1999].

3. Database and Sediment Budget

[8] A systematic survey of the Waipaoa river system, including five sites along Te Weraroa Stream, was performed in 1947 by the then Poverty Bay Catchment Board. Cross-section surveys subsequently were made at 13 locations along Te Weraroa Stream, beginning 1433 m upstream from the confluence with the Waipaoa River (Figure 1 and Table 1). Concern about the amount of coarse sediment contributed by gully erosion in the headwaters was a motivating factor for these surveys. Thus although the precise location of each cross section was influenced by the stability of the adjacent hillslopes, they are positioned at more or less regularly spaced, ~400 m (0.25 mile) or ~1600 m (1 mile) intervals upstream and downstream from the confluence with the feeder channel from the Tarndale gully complex, which is the major sediment source in the catchment (Figure 1). Most cross sections were resurveyed annually between 1950 and 1975, and in 1980 (by the East Cape Catchment Board and subsequently by the Gisborne District Council). Thereafter, periodic resurveys were conducted at only six locations. All the resurveys were undertaken between permanent benchmarks located near the ends of each cross section using a level and stadia rod or electronic distance meter, and measurement points along the survey line were determined by breaks in slope on bar surfaces above and below the waterline. *Banbury* [1996] provided a graphical summary of the complete data set.

[9] After the survey data were reduced to a common datum (elevation above sea level), the mean bed level at each site was determined as the weighted mean of the elevation within a representative portion of the cross section, the active bed as determined in the period 1948–1950 (Table 1 and Figure 3). The change in cross-section area between consecutive surveys was computed on the basis of the elevation difference across the entire active bed, and the volume of sediment stored within the intervening reach was determined as the mean of the upstream and downstream cross-section areas times the reach length [cf. *Griffiths*, 1979].

[10] The first aerial photographs of Te Weraroa Stream catchment were obtained in 1939. *DeRose et al.* [1998] estimated the volume of sediment removed from 11 gullies along Te Weraroa Stream and the neighboring Mangatu River on the basis of the elevation differences between high-resolution digital elevation models constructed from aerial photographs obtained in 1939, 1958, and 1992. These data were used to derive relationships between gully area and degradation rate [*Betts and DeRose*, 1999]. We used a

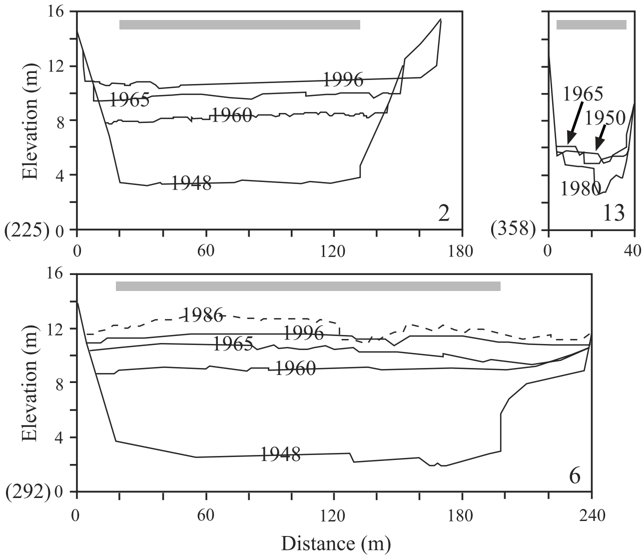

Figure 3. Summary of changes in bed elevation recorded at cross sections 2, 6, and 13 (see Figure 1 for locations). The numbers in parentheses indicate elevation above sea level, and the shaded horizontal bars delimit the representative portion of each cross section (the active bed in the period 1948–1950, Table 1) that was used to determine the mean bed elevation.

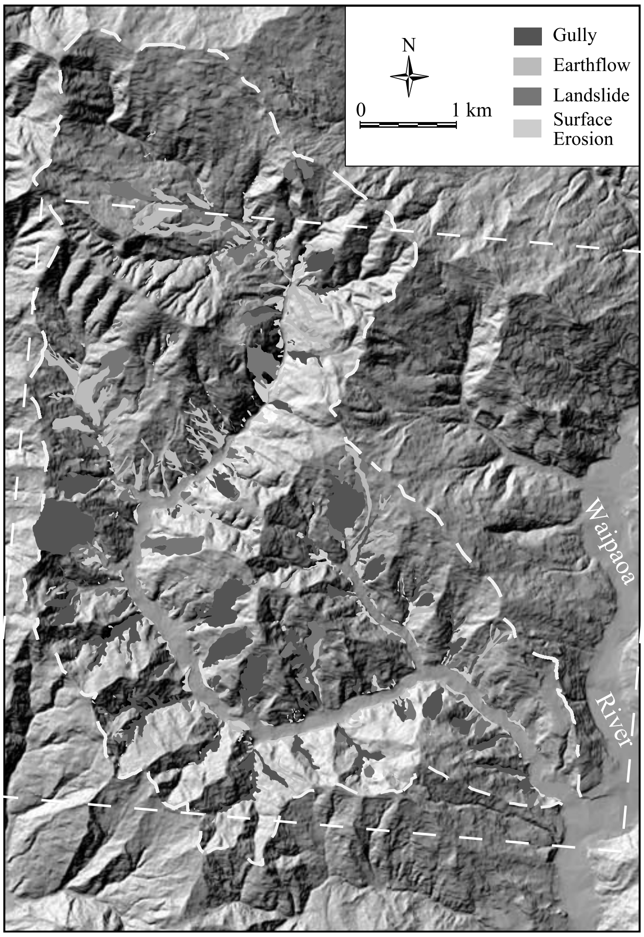

Figure 4. Digital shaded relief image (2 m DEM) showing the location and maximum extent of gullies and other sediment sources in Te Weraroa catchment activated by deforestation and mapped from aerial photographs obtained in 1939, 1960, 1969/1972, and 1988. Area of catchment shown in Figure 1 is delimited by dashed line. See color verison of this figure at back of this issue.

regression equation ($r^2 = 0.996$) that can be applied to both linear and amphitheater-shaped gullies at all stages of development to estimate the volume of sediment produced by each gully along Te Weraroa Stream:

$$y = 460 + 2750x + 160x^2 \qquad (1)$$

where y is sediment production (m^3 yr^{-1}) and x is gully area (ha), determined on the basis of linear interpolation between measurements made from aerial photographs taken in 1939, 1960, 1969/1972, and 1988. Using the available photographs we also mapped the area of the catchment affected by other erosion processes (Figure 4).

[11] Retrospective analyses of existing data sources invariably encounter inconsistencies introduced by the use of nonsynchronous data sets; thus we computed a sediment budget for three complementary time periods (1950–1960, 1960–1970, and 1970–1988). The mass of sediment in the channel and mass of material supplied by gully erosion were computed using dry bulk densities of 1840 and 2000 kg m^{-3}, respectively [cf. *De Rose et al.*, 1998]. Sediment transfer to the adjacent reach downstream was approximated as the difference between the amounts of sediment supplied to and stored within a reach. For the decades 1950–1960 and 1960–1970 the sediment budget was computed on a reach-by-reach basis, but we used a reduced data set to compute the budget for the period 1970–1988, because resurveys were performed at only six of the original 13 locations after 1980 (Table 1).

[12] Sediment generated by processes other than gully erosion and/or stored in feeder channels and fans exerts an influence on the sediment budget. Over timescales of a decade or more a negligible amount of sediment is added to storage in the narrow feeder channels downstream from gullies [*Marutani et al.*, 1999; *Kasai et al.*, 2001], but storage on fans accounts for ~15% of the sediment produced by some gullies [*DeRose et al.*, 1998]. Sediment produced by shallow landslides, earth flows and surface (sheet) erosion, which have affected ~9% of the catchment area (Figure 4), as well as by bank erosion, offsets these losses to storage. Surface erosion and earth flows produce predominantly fine material. Shallow translational and, more common, rotational landslides, in combination with bank erosion, generate greater amounts of coarse sediment, because material from these failures, which typically comprises both colluvium and weathered bedrock, often has a direct connection to channels. We estimate the total amount of sediment involved is ~10% of the 28.7 Mt of sediment generated by gully erosion between 1950 and 1988.

[13] We are not able to calculate precisely the errors associated with the sediment budget, which is impacted by sediment that is generated by processes other than gully erosion and/or stored in feeder channels, and the effect of variations in the width of the stream channel and changes in the rate of gully development with time that induce nonstationarity in the relationship between erosion rate and gully area. However, these factors, in combination with the conversion from volume to mass, likely induce errors of ±10% in our first-order estimates of sediment production and storage along Te Weraroa Stream.

4. Sediment Production, Storage, and Output

[14] Since 1939, the number of active gullies in the catchment has declined steadily and in 1988 only five gullies, including the Tarndale and Oil Springs gully complexes, were still active (Figure 1). The initial (pre-1960) reduction was a response to the encroachment of bracken and native species on smaller gullies, but active gully area, and hence sediment production, did not begin to decline until the 1960s in response to the program of wholesale reforestation (Figure 5). Once the forest cover matured the rate of deposition slowed appreciably, and after 1970 there was only a small net increase in the volume of sediment stored along Te Weraroa Stream (Figure 6). As the number of active gullies declined the relative importance of the Tarndale gully complex to sediment production increased. Except in the decade from 1960 to 1970, when the contribution from Oil Springs gully was greater, the Tarndale gully was the largest individual sediment source in the catchment, accounting for 14, 20 and 62% (1.5, 0.65, and 2.2 Mt) of all sediment generated by gully erosion in the periods from 1948 to 1960, 1960 to 1970 and 1970 to 1988, respectively (Figure 5). However, it remains that, even at its

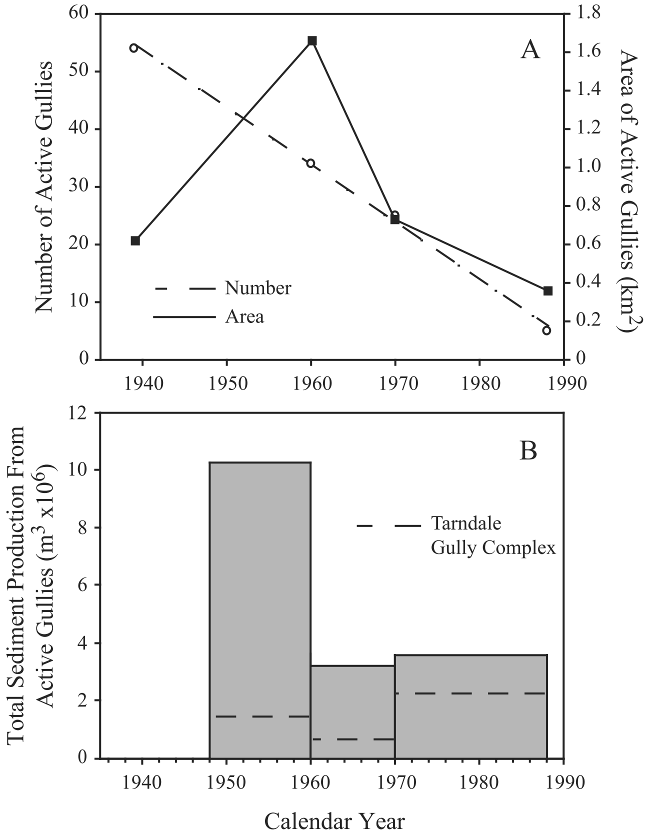

Figure 5. Number, area, and total sediment production (during indicated time interval) from active gullies as determined from aerial photographs obtained in 1939, 1960, 1969/1972, and 1988.

peak (*ca*. 1960) gully erosion only affected ∼6% of the total catchment area.

[15] Aggradation in Te Weraroa Stream occurred in response to overloading by sediment inputs to the middle reaches and was downstream-driven [cf. *Soni et al.*, 1980]. The sediment deposit formed by the excess gravel thins in the downstream direction (Figure 6). (By contrast, aggradation that is up-stream driven, often occurs in response to a change in base level at the downstream end of a reach and forms a wedge of sediment that thins upstream from the control point.) All reaches of the stream downstream from cross section 13 have aggraded, but the depth of aggradation is greatest in the middle reaches, between about 4000 and 7000 m upstream from the confluence (Figures 6 and 7). Because of the contrasting stability of the terrain underlain by Whangai and Tikihore formations [*Gage and Black*, 1979], comparatively little sediment is generated upstream from the point where the feeder channel from the Tarndale gully complex emerges onto a fan and enters Te Weraroa Stream in reach G (Figures 1, 2, and 7). Storage in the channel upstream from this point is, in large part, controlled by the fan, which constricts the channel and interferes with sediment transfer downstream. The most active period of fan growth occurred prior to reforestation [*De Rose et al.*, 1998], and little or no sediment has accumulated in the upper reaches of Te Weraroa Stream since 1960.

[16] An indication of the ability of the stream to disperse the material supplied to it can be gained by comparing sediment production and output (Figure 8). In the period from 1950 to 1960, the amount of sediment exported from reach A was ∼50% (0.81 Mt yr^{-1}) of the total amount of sediment generated by gully erosion. This decreased to 35% (0.21 Mt yr^{-1}) in the succeeding decade, and increased to 76% (0.27 Mt yr^{-1}) in the period from 1970 to 1988. The decline in the proportion of sediment generated by gully erosion that was exported from the catchment between 1960 and 1970 probably was a consequence of increased production from the Oil Springs gully complex. In the preceding decade 79% (12.8 Mt) of the sediment was generated by gullies elsewhere in the catchment, whereas for the period in question the gullies upstream accounted for 63% (3.8 Mt) of total sediment production. Evidence that the increased production from the Oil Springs gully complex affected sediment transfers through the lower reaches of the channel is provided by the relatively small decline (0.15 and 0.41 Mt) in the amount of sediment stored in reaches A and B (Figure 7). The dramatic increase in the proportion of sediment generated by gully erosion that was exported from

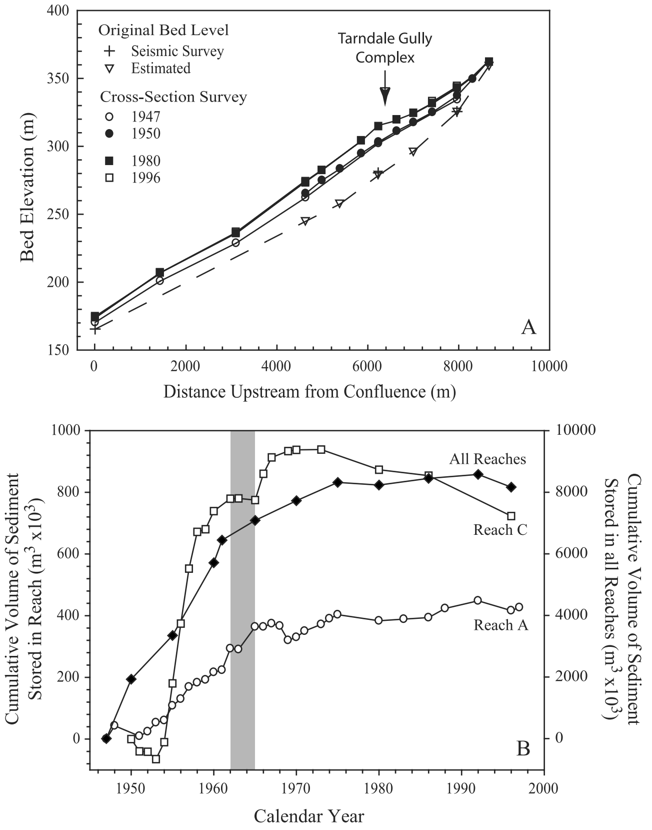

Figure 6. (a) Change in bed elevation along Te Weraroa Stream. The elevation of the channel prior to deforestation was estimated on the basis of the extrapolation of hillslope profiles and seismic survey data which indicate the depth to bedrock. Mean bed elevations between 1947 and 1996 were determined from cross-section surveys. The elevation at 0 m is that of the Waipaoa River bed immediately upstream from the confluence. (b) Cumulative volume of sediment stored in Te Weraroa Stream (1947–1997). The period of reforestation is indicated by shading.

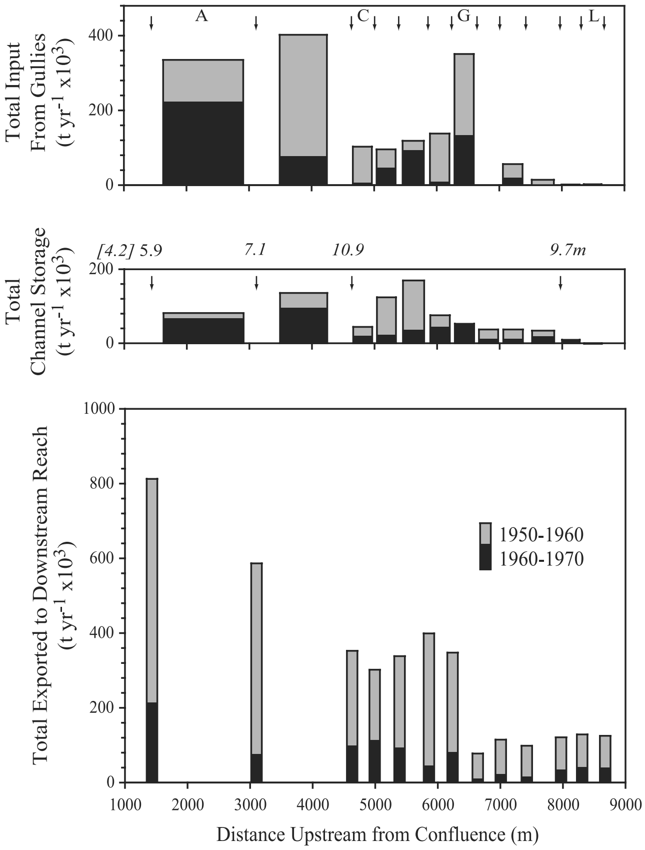

Figure 7. Sediment budget for Te Weraroa Stream. Arrows indicate cross-section locations, reaches are designated by letters, and numbers in italics give the total amount of aggradation at indicated locations, including the confluence with the Waipaoa River (bracketed), in the period 1947–1996.

reach A in the period from 1970 to 1988, noted above, also reflects the reestablishment of the Tarndale gully complex as the dominant sediment source (Figure 5), as well as the caliber of the sediment it generates (~60% is <2 mm in diameter [*Phillips*, 1988]). Despite the amount of material involved (a total of 0.125 Mt yr^{-1}, as estimated in this study), most of this sediment is removed in suspension and does not contribute to channel storage. The total amount of sediment contributed from gullies declined by 62% (from 1.6 to 0.6 Mt yr^{-1}) as the forest became established (Figure 8), and of the 28.7 Mt of sediment generated by gully erosion between 1950 and 1988, 48% (13.7 Mt) was retained in (channel) storage along Te Weraroa Stream (a much smaller proportion (~10%) is retained in storage along the lower order feeder channels immediately downstream from gullies [*Marutani et al.*, 1999; *Kasai et al.*, 2001]).

[17] Channel storage is the main impediment to sediment routing in Te Weraroa Stream, but the recovery time of the channel system will be determined by the rate that the sediment sources grow or diminish in response to land use change, the available stream power, and rate at which the response (measured as a variation in sediment supply) is translated downstream. Changes in the composition of the bed material that occur during recovery will also affect the rate of degradation, as will the behavior of the Waipaoa River. In some rivers degradation is episodic, with periods of rapid incision separated by periods of relative stability [*James*, 1991; *Miller and Benda*, 2001]. In other rivers, there is an exponential decrease in recovery rate with time [*Nakamura et al.*, 1995], but *Marutani et al.* [1999] argued that for the feeder channels downstream of gullies in the upper Waipaoa River basin the cross-section survey data supported a constant recovery rate. On this basis, assuming the amount of sediment generated by gully erosion continues to decline and is not offset by the scouring of first order (feeder channels) [*Marutani et al.*, 1999; *Kasai et al.*, 2001], if the recent (post-1992) decrease in the volume of sediment stored along Te Weraroa Stream is sustained we estimate that it will take ~90 yr for the bed to degrade to its 1947 level. However, ~60% of the total increase in bed elevation along Te Weraroa Stream was accomplished prior to 1947, when the cross-section surveys began (Figure 6). Thus the sediment that has accumulated along Te Weraroa Stream likely will remain in storage for countless decades to come.

[18] Considering the amount of material involved the response of Te Weraroa Stream, first to an increase and then to a decrease in sediment production, was rapid. However, the transition to a degrading mode has been much more protracted. Experience suggests the lag that storage introduces between sediment production and yield, which depends on the extent and magnitude of the perturbation to the catchment environment, endures for decades or centuries if the disturbance is temporally persistent or broadly disseminated over the landscape [*Roberts and Church*, 1986; *Knighton*, 1989; *Nakamura et al.*, 1995; *Jacobson*, 1995; *Jacobson and Gran*, 1999; *Liébault et al.*, 1989]. In this respect the situation in Te Weraroa Stream contrasts with that in other steepland channels where large, spatially and temporally discrete influxes of gravel have been observed to generate sediment waves that rapidly (over a period of about a decade) disperse or propagate downstream [*Madej and Ozaki*, 1996; *Miller and Benda*, 2001]. Instead, it is similar to the situation encountered in headwater tributaries to the Drôme River, southeastern

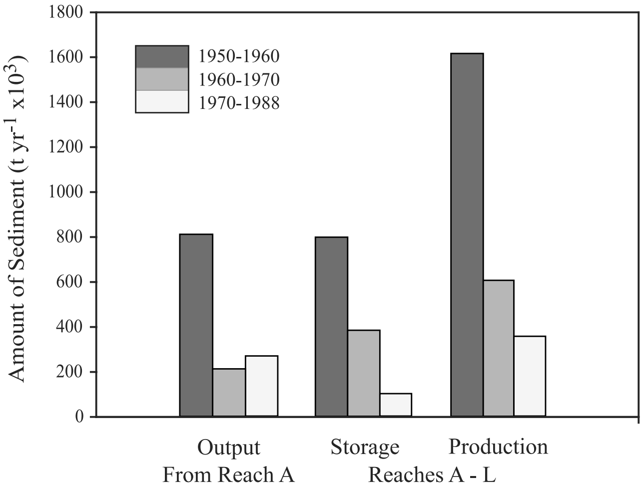

Figure 8. Sediment production, storage, and output (approximated as the difference between the amounts of sediment supplied to and stored within reach A), for specified time periods.

France [*Liébault et al.*, 1989], where degradation lagged the change in land use (reforestation between 1860 and 1920) by many decades.

5. Conclusion

[19] Gully erosion in the Te Weraroa catchment was initiated in the first quarter of the twentieth century after the native forest was cleared, and ameliorated by a program of reforestation that commenced in 1962. At its peak during the late 1950s and early 1960s, gully erosion affected ~6% of the total catchment area and, between 1970 and 1988, a single source, the 0.2 km^2 Tarndale gully complex (Figures 2 and 5), generated 62% of the sediment. We estimate that 48% of the 28.7 Mt of sediment generated by gully erosion between 1950 and 1988 was stored in the channel of Te Weraroa Stream. In the ensuing decade, the amount of sediment contributed from gullies declined by 62% as the forest became established. The rate of aggradation slowed as the supply of sediment waned (Figure 6), and in the period from 1970 to 1988 only 24% of the sediment generated by gully erosion went into storage, compared to 50% in the decade prior to reforestation (Figure 8). There has been little degradation to date and, even if the amount of sediment generated by gully erosion continues to decline, it likely will take many decades for the gravel stored along the lower reaches of Te Weraroa Stream to be released from storage.

[20] **Acknowledgments.** This paper is a contribution to Manaaki Whenua-Landcare Research's Waipaoa Catchment Study. We are grateful to the New Zealand Foundation for Research, Science and Technology (contract C09X0013), and the National Science Foundation (grant SBR-9807195) for their support of our work. We are especially indebted to Brian Currie and the Gisborne District Council, East Cape Catchment Board, and Poverty Bay Catchment Board survey crews who were responsible for periodically updating the cross-section data. We also thank the reviewers and AE for their comments.

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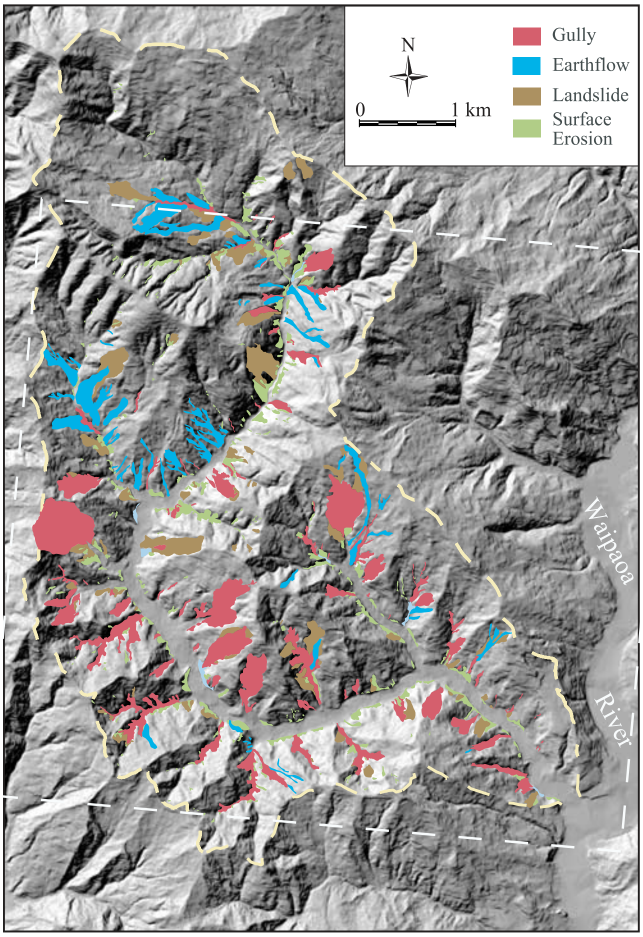

Figure 4. Digital shaded relief image (2 m DEM) showing the location and maximum extent of gullies and other sediment sources in Te Weraroa catchment activated by deforestation and mapped from aerial photographs obtained in 1939, 1960, 1969/1972, and 1988. Area of catchment shown in Figure 1 is delimited by dashed line.