A R T I C L E I N F O

1. Introduction

Understanding mechanisms of sediment generation, storage and flux to the ocean is a key goal of the MARGINS Source to Sink Programme. Estimating the flux of fluvial sediments discharged to the ocean from small, steep, catchments located in tectonically active margins has proven to be difficult (Milliman and Syvitski, 1992; Walling and Fang, 2003). Equally challenging is to understand factors that influence different erosion processes operating in steepland catchments and which largely dictate temporal and spatial variability in the supply of sediment to fluvial systems and ultimately to the ocean. Gully erosion can contribute a significant proportion of sediment to fluvial systems in steepland catchments (De Rose et al., 1998; Hicks et al., 2000; Kasai et al., 2001; Marden et al., 2005; Page et al., 2008). Sediment supplied from gullies tends to be more persistent than that delivered by influx from shallow landsliding in these environments because established gullies are activated by small, frequent rainstorms, whilst landsliding is activated during less frequent, high magnitude events (Hicks et al., 2000). At the head of the catchment sediment cascade, gully erosion may be enhanced by mass movement processes and the two mechanisms of sediment delivery may combine. Whilst smaller gullies tend to be linear features in zones of topographic convergence in otherwise unchannelled, zero-order basins (De Rose et al., 1998), larger features develop an amphitheatre-like form in conjunction with mass movements. These mechanisms give rise to fluvio-mass movement gully complexes (sensu Betts et al., 2003), where sediment is generated both by fluvial incision and mass movement, with the latter being dominant in terms of sediment volumes produced (De Rose et al., 1998; Betts et al., 2003). In these systems, mass movements tend to comprise debris flows and deep seated and shallow sliding, which may be (re) activated by gullying within the complex as part of intrinsic feedback mechanisms (e.g. slope undercutting), as well as high magnitude rainstorms. In the steepland East Coast Region of New Zealand's North Island, more than half of the sediment load of the Waipaoa and Waiapu Rivers is derived from these complexes (Marden et al., 2005; Page et al., 2008). The suspended sediment discharge of the Waipaoa River is contingent upon gully erosion as a whole, which is the dominant process of sediment delivery to this river (Gomez et al., 2003a). Annual average suspended sediment yields are among the highest recorded in the world (Walling and Webb, 1996; Hicks et al., 2000). The current sediment yield of the Waipaoa is 15 million tonnes per annum, with a mean specific yield of 6750 t $km^{-2}yr^{-1}$ (Hicks et al., 2000). De Rose et al. (1998) suggest that ~3% of this figure is derived from a single gully-mass movement complex known locally as Tarndale Slip. The significance of the Tarndale gully complex to the Waipaoa sediment cascade has increased as other gully complexes have been shut down by reforestation since the 1960s (Gomez et al., 2003b; Marden et al., 2005). The significance of gully erosion and contribution from the Tarndale gully complex in the Te Weraroa Stream (a principal headwater tributary of the Waipaoa) can be further appreciated in recognising that whilst gully erosion in this sub-catchment affected ~6%

of catchment area at its peak, in the period 1970–1988 62% of all sediment in this catchment was generated from the Tarndale complex (Gomez et al., 2003b).

The Tarndale gully complex is buffered from the channel system by a small (~11 ha) depositional fan. These fans are typical of large gully complexes in the region (De Rose et al., 1998; Betts et al., 2003) and sediment is supplied directly to them by both fluvial and slope processes operating in the contributing gully complex. The cutting or filling of these fans may respectively amplify or modulate sediment supplied to the stream system from contributing gully complexes. The extent of buffering is therefore temporally variable and requires assessment to better understand sediment delivery processes in this upper component of the sediment cascade. Page et al. (2001) identified the need to improve understanding of the drivers of sediment production, transport and deposition, their interaction and spatial controls on sediment fluxes. This paper therefore seeks to extend that understanding at a key location within the upper Waipaoa sediment cascade by addressing the temporal variability of stream channel buffering via assessment of cutting and filling of the Tarndale Fan over decadal and seasonal timescales. In terms of addressing source to sink, this component of the sediment cascade is highly significant, given the contribution of gully erosion to the sediment yielded to the ocean from the Waipaoa catchment (cf. Gomez et al., 2003a). This implies that a large proportion of sediment deposited on the shelf is sourced by gully complexes such as Tarndale. This paper focuses on quantifying those mechanisms and volumes of sediment involved over a 33 month period from December 2004 to August 2007. We do so by examining in detail the cutting and filling of the Tarndale Fan in the headwaters of the Waipaoa catchment as it responds to sediment delivered from a major gully complex. This extends our understanding of sediment production, storage and transfer in a significant gully-fan system in the Waipaoa by increasing the temporal and spatial resolution of investigation. To date research has tended to be decadal or at best annual. Here a seasonal approach enhances the temporal resolution of the processes responsible for sediment generation, storage and transfer. Furthermore, in adopting a high-resolution survey approach we are able to provide a higher spatial resolution of fan aggradation and incision than has been allowed to date using cross-section surveys or photogrammetry. As such, this paper will provide new insights into fan behaviour and the role of these fans in sediment transfer within the Waipaoa catchment as a whole.

2. Study site

2.1. Location

The Tarndale gully complex and fan are located in Te Weraroa Stream, an ungauged headwater tributary in the 2200 km^2 Waipaoa River basin (Fig. 1). The catchment surrounding the Tarndale gully

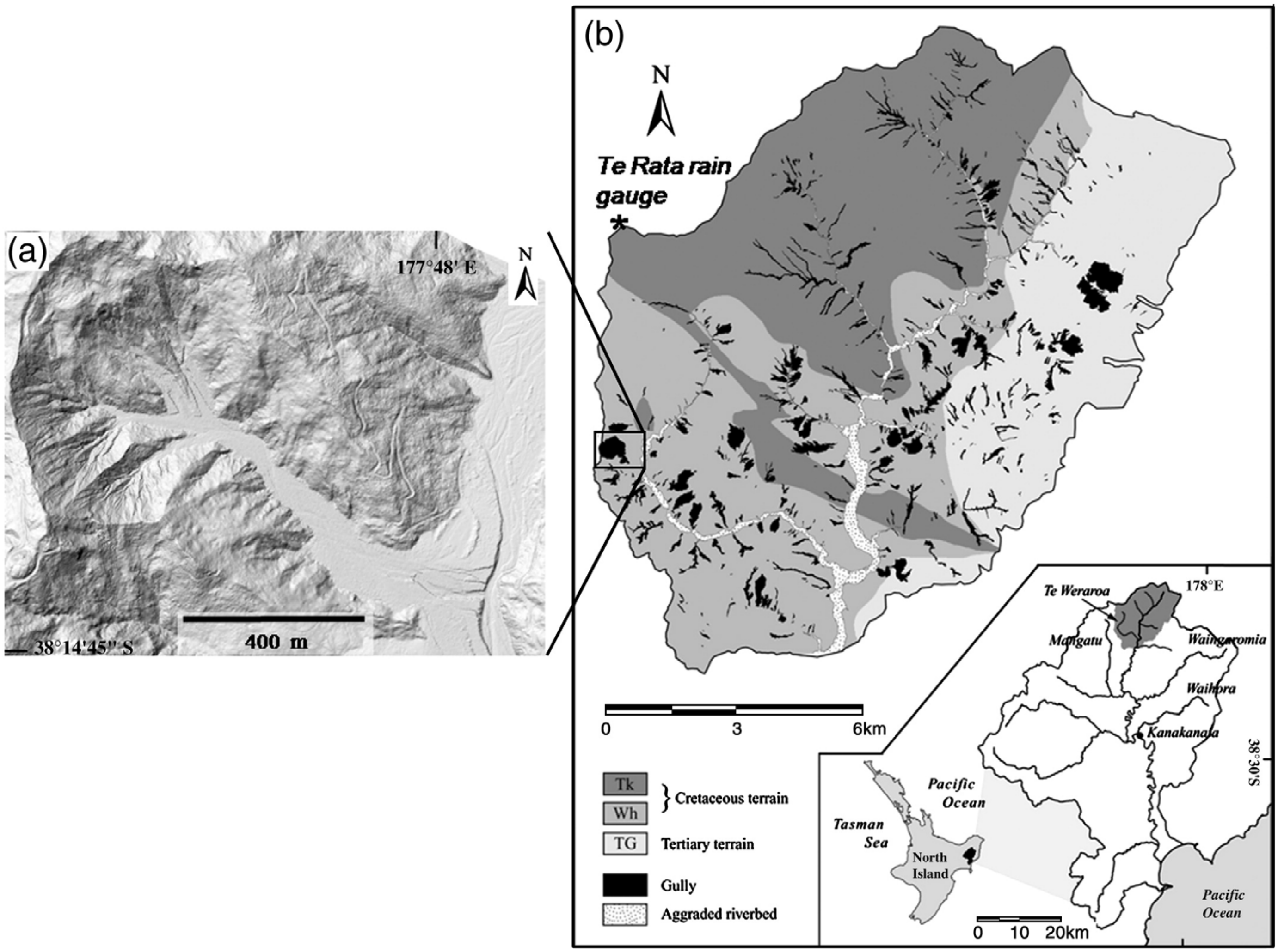

Fig. 1. Location map of Tarndale gully and fan in the context of the upper Waipaoa catchment: (a) LiDAR derived digital elevation model of the gully-fan complex (LiDAR data© Gisborne District Council, courtesy Dave Peacock), (b) upper Waipaoa catchment showing major lithologies and gullies (after Marden et al., 2005).

complex (Fig. 1) at its highest elevation is 580 m. Valley side slopes are c. 800 m long, with an average slope angle of 25°. The fan extends from the base of the headwall (elevation 420 m) to its junction with Te Weraroa Stream (elevation 320 m), a distance of ~1 km. At its upstream end the fan system comprises four tributaries each draining a different part of the ~20 ha (De Rose et al. 1998), amphitheatre-shaped, gully complex headwall and converging to form a single feature (Fig. 1).

2.2. Geology

The gully-fan complex at Tarndale is underlain by variably indurated, sheared and crushed, well bedded, light and dark grey siliceous mudstone alternating with thin sandstone, and poorly bedded, pale grey calcareous mudstone of Late Cretaceous to Palaeocene age (Black, 1980; Mazengarb et al., 1991). In the vicinity of Tarndale extensive crushing associated with major faults and an extant slump (Black, 1980; Mazengarb et al., 1991), together with argillites that are especially susceptible to acid sulphate weathering (Pearce et al., 1981), have predisposed lithologies of the Whangai Formation (Fig. 1) to mechanical disintegration under the influence of water (Marden et al., 2005). These conditions generate a highly erodible substrate with potential for high rates of sediment delivery from the gully complex to the fan. Furthermore, rapid mechanical disintegration produces an abundance of fine grained material; the D_{50} of surface material on the upper fan is 1.4 mm (Gomez et al., 2001) and 60% is finer than 2 mm (Phillips, 1988).

2.3. Climate

Climate is humid temperate, but the area is subjected to periodic high intensity cyclonic storms. There is a 29% chance that an extreme rainfall event will occur every decade (Kelliher et al., 1995). Since 1900 there have been 33 extreme rainfall events, when the discharge of the Waipaoa River (at Kanakanaia, cf. Fig. 1) exceeded 1500 m^3s^{-1}, and there is concommitant evidence of widespread and accelerated gully erosion (Cowie, 1957; Phillips et al., 1990; Kelliher et al., 1995). The largest recorded cyclonic storm (Cyclone Bola) occurred in March 1988, and generated 500 to 700 mm of rain in a 5-day period. Rainfall figures from rain gauge sites near the study site (Fig. 1) show that August has the highest monthly rainfall with a maximum of 284 mm (Gage and Black 1979). At 200 m average annual rainfall is ~1339 mm, increasing to 2500 mm at elevations of 800 m (Pearce et al.,1981). Monthly flood occurrence, precipitation and rain days all show a pronounced late-winter maximum. Flooding is also associated with prolonged periods of wet weather and not simply with exceptional rainfall intensities.

2.4. Gully-fan morphology

Along the longitudinal profile of the Tarndale gully-fan system, three morphologically distinct zones can be distinguished. Bergstrom (1982) suggests distinct breaks in valley morphology generally mark boundaries between headwater, transitional, and lower braided zones. Drainage from the headwall scarp is confined to steep and narrow rills which progressively widen and deepen in a downslope direction. At the base of the headwall scarp, slope decreases abruptly at the nexus with the fan (Fig. 2). Excessive sediment accumulation in the reach of the central fan immediately downstream of its junction with the lowermost tributary (upper mid-fan) results in over-steepening and widening. Between this point and the junction of the fan with Te Weraroa Stream channels are braided. For much of its length the fan consists of an active zone, swept by channels, incised within 'older' aggradational terrace/fan alluvium. The latter spans the total width of valley floor and represents the maximum elevation of valley-floor infilling attained in this gully-fan system. This stable and currently elevated surface exists today as discontinuous remnants flanking the channel along much of its length (Fig. 3).

The current fan morphology dates to the 1960s. In May 1960 sediment emanating from the Tarndale gully-mass movement complex completely destroyed fascines emplaced to mitigate sediment supply to the Te Weraroa Stream (Marden et al., 2005) and buried existing benchmarks established to measure changes in bed level across the valley floor. With the destruction of the fascines it is likely a phase of channel incision began with the development of a nick-point at this site, which propagated upstream to the base of the gully headwall. This process created a narrower active fan incised below the level of the former fan surface with remnants of the latter being temporarily preserved along either side of the valley. More recently, and as a result of a major storm event in 1980 (Cyclone Bernie), sediment deposition across the width of the fan and subsequent channel incision culminated in the formation of a new and extensive terrace flanking much of the 1 km length of Tarndale Fan. This elevated surface is here referred to as the 'inactive fan' (Fig. 3). In 1983 a new network of benchmarks on this elevated surface was established and channel cross-section measurements commenced. These data contribute to the 20 year record of fan behaviour reported in this paper. Early planform surveys of the downstream end of the fan show that at times of excessive sediment influx the channel was only shallowly incised and frequently changed its position across much of the fan-width. In contrast the contemporary active channel deeply incises the fan surface (Fig. 2a). The fan terminates at its junction with Te Weraroa Stream (Figs. 2c and 3) where deposition in the past has splayed upstream and downstream of this confluence and on occasion has completely blocked Te Weraroa Stream to form a temporary lake. Sediment discharged from the Tarndale gully complex has, over the years, deflected Te Weraroa Stream against its true left bank (Figs. 2c and 3) where the valley slope above has become destabilised and continues to fail as a large rotational slump. The morphological development of the fan over the last 20 years provides a context for a more detailed appraisal of cutting and filling of the fan between 2004 and 2007.

3. Methodology and results

3.1. Cross-section surveys

The past 20 years of fan behaviour has been established by cross-sectional survey of the fan, carried out (by MM) between benchmarks installed in 1983 (Fig. 3). Survey data were collected using a Sokkhisha Total Station (electronic distance measurement (EDM) precision $\pm(5+5\ \text{ppm}\times D)$ mm, angular resolution 1 s). Biannual surveys within this period permitted identification of seasonal cut and fill cycles, where surveys were completed in May (end of summer) and November (end of winter). The volume of scour and fill, and the net change in sediment storage was determined as the mean of the upstream and downstream cross-section area times the length of each reach (cf. Griffiths, 1979). Changes in cross-section area between consecutive surveys were based on changes in elevation across the width of the active portion of the fan.

The end point method calculates the volume as per Eq. (1).

$$V = \left[\frac{A_1 + A_2}{2}\right] \times L \tag{1}$$

where A_1 = area of cross section at downstream end of reach (m^2) A_2 = area of cross-section at upstream end of reach (m^2)L = distance between the sections (m)

Net volumetric changes are shown in Fig. 4. These demonstrate a degree of seasonality where seasonal surveys were completed. Generally the winter period is dominated by infilling of the fan, whilst

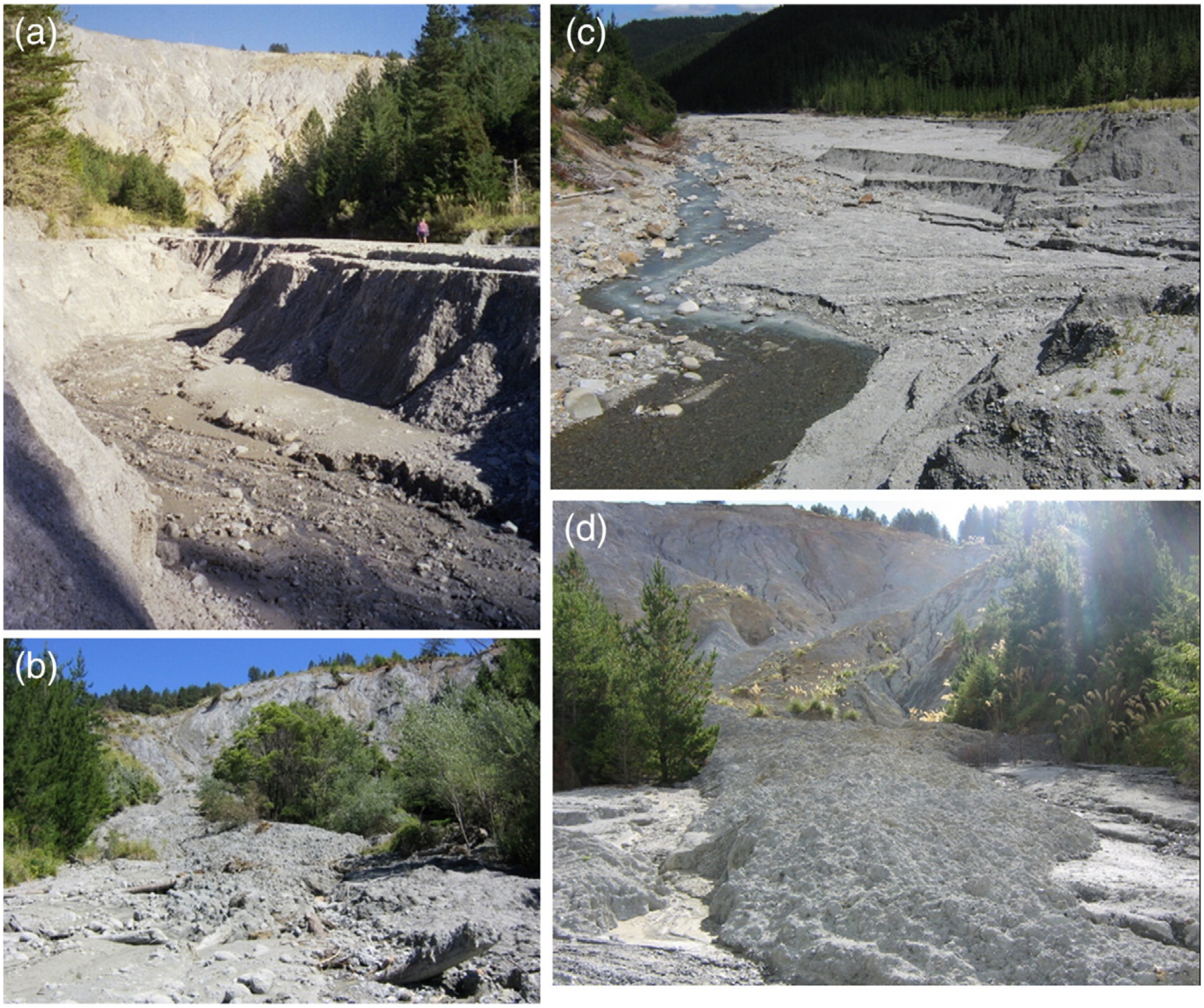

Fig. 2. Photographs of cutting and filling on the Tarndale Fan 2004–2007. Locations of these photos are given in Fig. 5, where both spatial and temporal context are provided. (a) 3 m deep channels incised in the upper Tarndale fan (April 2005, cf. Fig. 5(a), photo I.C. Fuller). (b) direct delivery of sediment to the upper fan by landsliding attributed to the Labour Weekend storm, 22–24 October 2005 (cf. Fig. 5(c), photo I.C. Fuller). Note the dry and hardened surface, photo taken December 2005. (c) formation of a new fan building into the Te Weraroa Stream (November 2006, cf. Fig. 5(f), photo I.C. Fuller). Note the delivery of fines to the Te Weraroa Stream in the colour change at the confluence. (d) up to 5 m deep infilling by single debris flow (April 2007, cf. Fig. 5(g), photo I.C. Fuller).

the summer period is dominated by incision. These cross-sections are at a relatively coarse spatial and temporal resolution and it is evident that a seasonal cutting and filling may be an oversimplification. To further assess fan behaviour a more intensive approach to survey was adopted from 2004 using a Real Time Kinematic differential Global Positioning System (RTK-dGPS) to generate topographic data for subsequent analysis using digital elevation models (DEMs).

3.2. Digital elevation models

DEMs derived from aerial photos have been used previously to assess gully erosion (Betts and DeRose, 1999), although necessarily these are at a lower resolution than is feasible using detailed GPS data. Between December 2004 and August 2007, the entire active fan surface was surveyed nine times using RTK-dGPS. A Trimble® R8 GPS receiver was set up in transmit mode to act as a base station and a second R8 receiver was used as a Rover unit, to deploy RTK-dGPS survey. This setup permits rapid data acquisition using 1 s occupation time per observation and real time coordinate calculation using on-the-fly algorithms (Stewart and Rizos, 2002). The minimum acceptable vertical accuracy of observations was set at 0.05 m. Average vertical accuracy was 0.02 m. Points were surveyed to a precision of 0.001 m. The base station was set up some distance away from the active fan itself, preventing any multipath errors (Kennedy, 2002).

DEMs were constructed using Surfer® GIS. These DEMs are based on 1 m grids (Fuller et al., 2003); however as survey data are not collected on a grid basis they were interpolated to create a digital elevation surface. Data interpolation (DEM generation) in this study uses Triangulation with Linear Interpolation (TLI). TLI is a grid-based version of a triangulated irregular network (TIN). It is constructed of contiguous triangular facets, irregularly sized and spaced (Tsai, 1993; Lee, 1991). TLI is based upon optimal Delaunay triangulation. All grid nodes within a given triangle are defined by the triangular surface and because the original data are used to define the triangles, the data are honoured very closely (although not exactly) (Surfer, 2002). TLI does not extrapolate z values beyond the range of data. TLI is regarded as being most effective when the data are distributed evenly throughout the study area, but sparse data points can manufacture obvious (and unrepresentative) triangular faces (Surfer, 2002).

3.2.1. DEM validity

DEM accuracy is assessed using an approach recommended by Fisher and Tate (2006), which derives the error standard deviation (S)

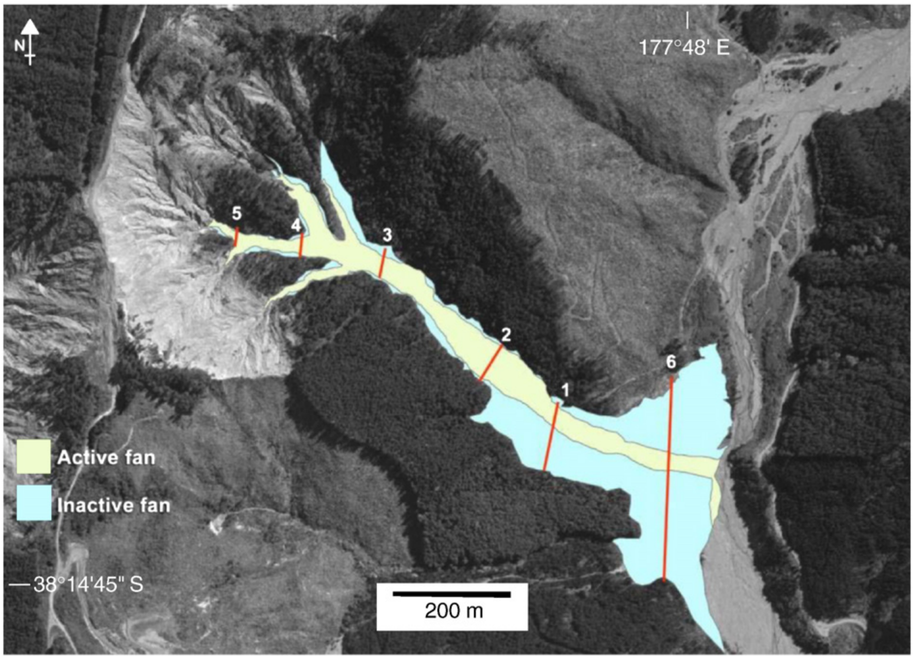

Fig. 3. Cross-section locations overlaying an orthophoto of the Tarndale gully-fan, with active and inactive portions of the fan highlighted.

(Eq. (2)), and also permits estimation of bias using the Mean Error, which may be positive or negative (Table 1).

$$S = \sqrt{\frac{\sum[(z_{\mathrm{DEM}} - z_{\mathrm{ref}}) - ME]^2}{n-1}} \tag{2}$$

where z_{DEM} is the measurement of elevation from the DEM, z_{ref} is the higher accuracy measurement of elevation for a sample of n points. ME is the mean error (Eq. (3)).

$$ME = \frac{\sum(z_{\mathrm{DEM}} - z_{\mathrm{ref}})}{n} \tag{3}$$

Each survey point was used as a z_{ref} value, to provide an estimation of error derived from the entire DEM. However, it should be noted that this method of error estimation is dependent upon the surveyed points; error at interpolated points is not assessed, as independent data are not available. Whilst survey points could have been thinned to provide quasi-independent data to check interpolation, as surface sampling was designed to provide the best possible data for interpolation, this would inevitably reduce the quality of the DEM and still not provide a rigorous measure of accuracy. This approach therefore does not necessarily provide an unbiased measure of overall DEM quality, but research elsewhere indicates this approach is fit for purpose (Fuller and Hutchinson, 2007). The errors (S) and bias (ME) for each surface are indicated in Table 1. Generally the ME indicates a consistent underestimation of the surface, with the exception of the first survey in December 2004. That this was slightly positively biased (i.e. interpolated surface lying above the date points), and the subsequent surface slightly negatively biased suggests that when comparing these two consecutive surveys, volumetric estimates will be biased towards scour.

3.2.2. DEM differencing and sediment transfer estimation

Elevation changes between successive DEMs may be used to derive sediment gains and losses based on morphological budgets, given their valid representation of surface topography (Fuller et al., 2003). DEMs of difference (Fig. 5) depict patterns of sediment gains and loss, indicating complex patterns of cutting and filling of the Tarndale fan between December 2004 and August 2007. Table 2 summarises volumes and quantities of sediment eroded and deposited in the Tarndale fan between successive survey periods. Quantities are based on a dry bulk density of 1840 kg m^{-3} (De Rose et al., 1998). Errors associated with these volumetric estimations using TLI-derived DEMs are in the order of ±5% (Fuller and Hutchinson, 2007). It should however be noted that volumes are a lower-bound estimation of total sediment transfers (Fuller et al., 2003), neither do they account for suspended sediment, which forms the majority of sediment generated from the Tarndale gully complex (Gomez et al., 2003b). This assessment of sediment transfer is therefore limited to the coarse

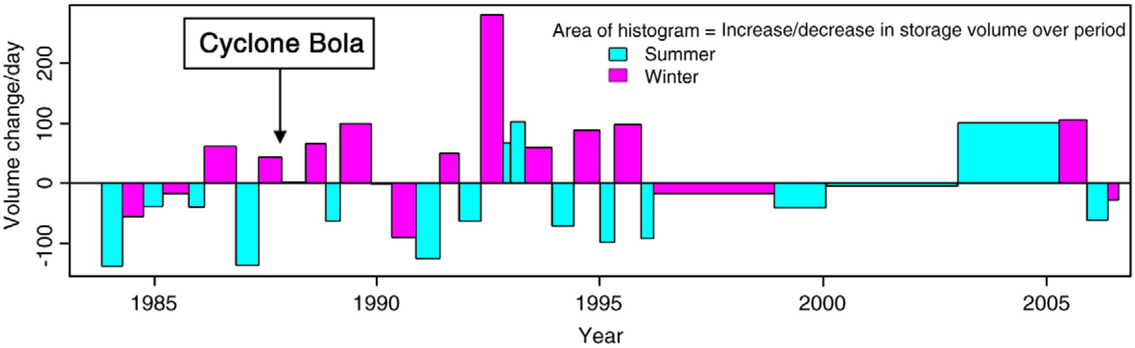

Fig. 4. Net volumetric changes in the Tarndale fan between 1983 and 2004 based on cross-section surveys.

Table 1
Error analysis showing standard deviation and Mean Error for each DEM, derived from Eqs. (2) and (3).

Date	*S*	ME (m)
December 2004	0.116	0.0007
April 2005	0.155	−0.0067
August 2005	0.121	−0.0067
December 2005	0.087	−0.0023
May 2006	0.116	−0.0014
August 2006	0.102	−0.0035
November 2006	0.108	−0.004
April 2007	0.111	−0.0021
August 2007	0.099	−0.0032

Table 2
Sediment volumes and tonnes produced by cutting and filling of the Tarndale fan between successive survey periods, based on DEM differencing to provide a morphological budget (Fuller et al. 2003).

Period	Volumes (m^3)			Tonnes	
	Erosion	Deposition	Net	Net	Yielded[a]
December 2004–April 2005	11 997	6424	−5573	−10 254	~10 000
April 2005—August 2005	6174	24 452	+18 278	+33 632	–
August 2005—December 2005	11 162	31 528	+20 366	+37 473	~20 000
December 2005–May 2006	21 075	8078	−12 997	−23 915	~24 000
May 2006–August 2006	13 936	25 689	+11 753	+21 626	~25 000
August 2006–November 2006	3100	6912	+3812	+7014	~5000
November 2006–April 2007	4247	14 935	+10 688	+19 666	–
April 2007–August 2007	10 125	11 270	+1144	+2105	–

[a] This figure is a lower-bound estimate based on a morphological budget. It takes no account of throughput or yield of fines in suspension, which is likely to be far higher (cf. De Rose et al. 1998). Whether eroded sediment is yielded depends on where the erosion takes place. Hence, whilst net change may be positive, suggesting accumulation and minimum yield, if the erosion takes place in the lower fan, that material may be considered as a yield from the fan to the Te Weraroa Stream.

fraction, which conditions channel morphology (Leopold, 1992; Martin and Church, 1995). The coarse fraction is here defined as that which thus behaves as bedload; the D_{50} of which has been measured at 1.4 mm and 60% is finer than 2 mm (Phillips, 1988; Gomez et al., 2001). Patterns of cutting and filling are discussed below.

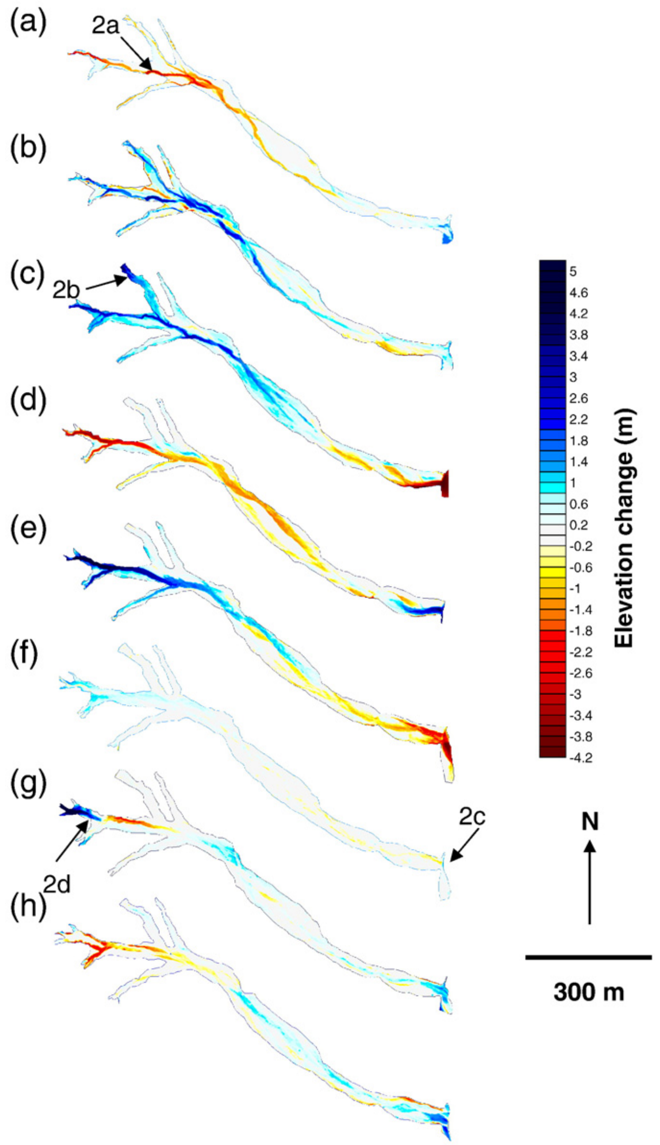

Fig. 5. DEMs of difference for successive surveys: (a) December 2004–April 2005, (b) April 2005–August 2005, (c) August 2005–December 2005, (d) December 2005–May 2006, (e) May 2006–August 2006, (f) August 2006–November 2006, (g) November 2006–April 2007, (h) April 2007–August 2007. Numbers indicate location of photos in subsequent Figures (Fig. 6).

4. Discussion

Superficially, DEM analysis indicates a degree of seasonal dependence, with the fan mostly filling during winter and cutting during summer (Fig. 5). However, the increased frequency of survey demonstrates a greater complexity. Patterns of cutting and filling are briefly discussed for each survey period, highlighting both this complexity and the volumes of sediment transferred in connection with cut and fill activity.

4.1. December 2004–April 2005

Incision generally characterises the upper fan, where up to 3 m deep channels have been cut (Fig. 5a and cf. Fig. 2). The intensity of incision is reduced in the lower fan, to a point where it aggrades in this period in its lowermost reach (Fig. 5a). This suggests that the lower fan stores a proportion of the sediment generated by upper fan incision. Nevertheless, the volume of sediment eroded exceeds that deposited, suggesting a net export of some 10 000 tonnes to the Te Weraroa Stream (Table 2), although this may be an overestimation given the bias in the two surfaces (Table 1). However, some deposition also occurred in this summer period in the upper fan, prior to incision, evidenced by the positive elevation change detectable adjacent to incised channels (Fig. 5a). The sequence of events is not straightforward: the upper fan continued to aggrade in early summer (December 2004), before being incised.

4.2. April 2005–August 2005

Infilling is evident across the entire fan and channels cut in late summer have been refilled. Lateral erosion in the lower fan (true right) produces a negative elevation change (Fig. 5b). However, new channels are evident in both upper and mid-fan (Fig. 5b). This indicates a rapid cutting in response to an absence of heavy rain events, notably from July (Fig. 6), preceded by a similarly rapid filling (April–June wetter, cf. Fig. 6b). Given the absence of incision in the lower fan and a tendency to aggrade, the morphological budget

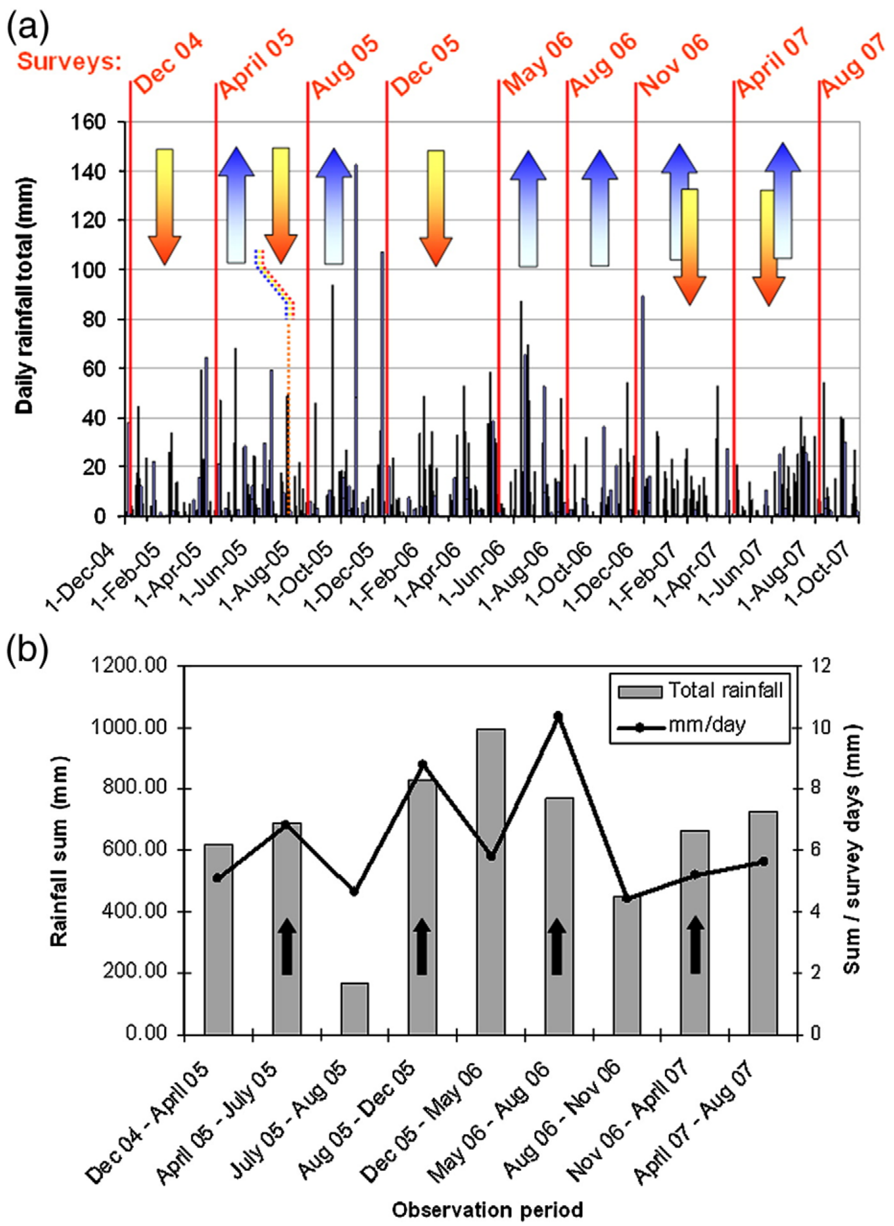

Fig. 6. (a) Rainfall record for December 2004–August 2007, Te Rata rain gauge (cf. Fig. 1). Survey timings are indicated. Arrows indicate predominant cutting / filling activity between survey periods. An ad hoc field visit in July 2005 observed no incised channels on the fan (i.e. summer channels had been filled). This suggests filling occurred between April and July and incision between July and August. (b) Total rainfall volumes between observations (note no survey in July 2005, as above). The rainfall sum / number of days between observations or surveys give an index of wetness in terms of average rainfall for the period (mm per day). Arrows indicate periods of significant filling by sediment delivered from the Tarndale gully complex (cf. Fig. 5 and Table 2).

suggests the fan acts as an effective buffer to sediment supplied from the Tarndale gully complex (Table 2). However, throughput and suspended material are not accounted in this approach and inevitably sediment will be yielded from the system (cf. Table 2 note and De Rose et al., 1998; Gomez et al., 2003b).

4.3. August 2005–December 2005

Cutting and filling in the late winter–spring of 2005 are sharply delineated between upper and lower fan (Fig. 5c). The upper fan accumulates some 30 000 tonnes of sediment supplied from the Tarndale gully complex, whilst the lower fan incises dramatically (4 m elevation change, cf. Fig. 5c). Aggradation of the upper fan responds to large scale mass movements from the gully complex, (Figs. 5c and 2b); whilst the lower fan was trimmed by the Te Weraroa Stream, resulting in headward migration of a knickpoint and incision, delivering ~20 000 tonnes of sediment to the stream system (Table 2). Fan behaviour is again categorised by complexity.

4.4. December 2005–May 2006

In late summer 2005–2006, a large part of the fan incised, with two exceptions. In the lowermost fan, the void left by trimming by the Te Weraroa and associated incision is filled (cf. Fig. 5d). Secondly, whilst sediment starvation of the upper fan permitted incision of ~3 m deep channels, in the adjacent true left tributaries no incision is evident, suggesting continued supply of sediment from the gully complex and/or reworking of landslide debris inhibited cutting in these adjacent reaches. Deposition evident on the surface adjacent to incised channels, indicates aggradation in early summer prior to cutting. Given that the majority of deposition nevertheless occurred in the lowest reach, most of the net loss of sediment in this period (Table 2) is likely to have exited the fan into the Te Weraroa Stream (~24 000 tonnes). This period also demonstrates not only a differential response between lower and mid to upper fan, but also between upper tributaries, reflecting differential sediment generation from discrete components of the Tarndale gully-mass movement complex.

4.5. May 2006–August 2006

An extended period of wet weather in June (Fig. 6) generated a flood in the Te Weraroa Stream which re-trimmed the lower fan, prompting incision (Fig. 5e) and yield of ~25 000 tonnes of sediment to the Te Weraroa Stream (Table 2). At the same time, the gully complex contributed at least ~47 000 tonnes of sediment which was deposited in the upper fan, infilling all of the previously cut channels and aggrading the fan surface. The focus of this activity switched from the true left tributaries to the mainstem and true right (Fig. 5e).

4.6. August 2006–November 2006

The gully complex continued to predominantly supply the mainstem of the fan, which continued to aggrade (Fig. 5f), although detectable volumes were reduced to a quarter of the preceding period (~12 000 tonnes). Elsewhere there is a degree of stability, with the exception of the lower fan which incised slightly, delivering sediment to the Te Weraroa Stream. A new fan built out into the Te Weraroa Stream in this period in response to this sediment supply (Fig. 2c). Given most deposition took place in the upper fan, and the lower fan primarily incised, it is probable that most of the eroded sediment was evacuated from the fan system (~5000 tonnes).

4.7. November 2006–April 2007

A major mass movement again delivered sediment directly to the fan (mainstem, cf Figs. 5g and 2d). However, this material was delivered into an incising channel, indicating cutting of the fan was underway at the time of this mass movement. This incision is evident immediately down fan in the mainstem (cf Fig. 5g). A proportion of sediment evacuated from this upper cutting has been deposited in an area of positive elevation change at the head of the mid-fan. Further down fan, the response is primarily depositional, as the fan continued to build into the Te Weraroa Stream. The predominantly aggradational response is in contrast to anticipated summer cutting. However, the full extent of incision has not been detected due to infilling of the upper channels by a single mass movement event. Nevertheless, this again illustrates the event-dependence of fan behaviour and the significance of a single mass movement from the Tarndale gully-mass movement complex, furthermore, this demonstrates the speed at which channels may infill in this system, i.e. instantaneously.

4.8. April 2007–August 2007

The majority of the upper fan mainstem and true right tributary incise up to 3 m (Fig. 5h), as channels cut the debris flow deposit delivered in the previous period (cf. Fig. 2d). However as sediment is generated from the northern part of the Tarndale gully complex the two true left tributaries aggrade slightly and early signs of infilling are evident at the very head of the mainstem fan. Eroded material from the upper fan is deposited in the mid and lower fan, which fills, augmented by sediment supplied by lateral erosion in this area (Fig. 5h). Given the lateral nature of this lower fan erosion, and cutting of the upper fan, the eroded sediment recorded (Table 2) has been redeposited within the fan, with limited export to the Te Weraroa Stream.

4.9. Synthesis

Enhanced resolution of the behaviour of the Tarndale Fan afforded by high-resolution RTK-dGPS survey, generating DEMs for analysis presents a picture of complex, rapid, a-seasonal cutting and filling. Sediment is delivered from the gully complex, conveyed down fan and most effectively delivered to the Te Weraroa Stream by trimming of the lower fan during high flows (unquantifiable). This behaviour is driven by storm events at the end of October 2005, November 2005 and June 2006 (Fig. 6). Trimming produces a knickpoint, which headcuts to mid-fan, incising the lower portion of the fan and generating sediment to the stream system. The behaviour of the lower fan is thus conditioned both by interaction with the Te Weraroa Stream and sediment supplied from up-fan.

Fryirs et al. (2007) identify the importance of switches at critical junctions within the sediment cascade for effective transfer of sediment through a catchment. In the Tarndale gully-fan complex there are two such key switches. The first is the slope-channel nexus at the top of the fan. Channel behaviour here is conditioned strongly (exclusively) by sediment supply from the Tarndale gully-mass movement complex. Generation of sediment from the complex by large scale mass movements including landslides and debris flows causes rapid fan infilling, in such circumstances, as during storms or periods of wetter weather, the switch is 'on' and sediment is conveyed from slope to fan. The fan then buffers the Te Weraroa Stream from this sediment supply. Marden et al. (2005) indicate a progressive aggradation of the fan over the past ~50 years. Indeed, the cutting and filling observed between December 2004 and August 2007 are superimposed on continued progressive filling as evidenced by overtopping of the 1983 surface in the upper fan in August 2006. Cessation of sediment supply to the fan in the form of mass movements (switch 'off'), results in rapid channel incision as runoff from the gully complex incises the fine grained substrate (D_{50} 1.4 mm, Gomez et al., 2001).

The second switch is located at the nexus between the fan and Te Weraroa Stream. This is turned 'on' during trimming of the fan by high flows in the Te Weraroa, but also where incision up-fan delivers large quantities of sediment. Similarly, sediment supply to the trunk stream system is reduced (switch 'off') when the lower fan is in aggradational mode and insufficient sediment is being delivered from up-fan. Ultimately this too is conditioned by the sediment supply and behaviour of the gully complex, which over-supplies or under-supplies sediment to the fan system.

This suggests a highly sensitive channel system in the Tarndale Fan, which responds rapidly to sediment supply variability from the contributing gully complex. Discrete severe rainstorm or wet weather periods appear to be significant in controlling sediment supply. Fig. 6b identifies the total rainfall received between each survey period, best expressed in terms of an index of average rainfall per day to account for the variable lengths between surveys, demonstrating a relationship between wetter periods and filling episodes driven by sediment contributed from the gully complex. Wetter weather enhances mass movements in the gully complex, notably increasing debris flow activity which contributes large quantities of sediment (as observed by Betts et al. (2003) elsewhere in the region), filling the fan. Gage and Black (1979) viewed the swelling clay content of late Cretaceous sediments which underlie the gully complex as rendering the material susceptible to mass movements. Susceptibility is further enhanced by acid sulphate weathering and crushing which further reduces rock strength (Pearce et al., 1981). However, the gully complex is not behaving as a single entity, as it appears from the cut and fill patterns on the upper fan that contributions from discrete zones within the gully complex vary temporally. Mass movements in one area of the complex are not necessarily in phase with other parts of the system, and the precise timing and location of sediment delivery is dependent upon mass movement history. Once a major mass movement has delivered sediment to the fan, it appears to be followed by a period of relative stability. This has been observed elsewhere in terms of landslide susceptibility being (partially) dependent on the extent of previous regolith stripping (e.g. Brooks et al., 2002). Here this degree of susceptibility has an impact on cutting and filling of channels in the coupled channel/fan domain and such cyclicity is arguably demonstrable in the differential responses of the upper fan mainstem and tributaries, which are supplied by discrete zones of the gully complex (cf. Figs. 1–3).

During drier periods, mass movement activity is inhibited and runoff incises channels. This behaviour has also been observed in other small headwater tributaries of the Waipaoa (Oil Springs and Matakonekone, Marutani et al., 1999). Marutani et al. (1999) suggested an instantaneous aggradation in response to extreme storms, followed by a progressive excavation of channels. This indicates similarly highly-responsive systems typify the upper Waipaoa. The behaviour of the Tarndale system, based on a more temporally intensive investigation, is therefore consistent with that identified over the longer term by Marutani et al. (1999). However, unlike the Tarndale, these adjacent tributaries have shown a larger-scale degradational trend since an episode of aggradation attributed to Cyclone Bola in 1988 (Kasai et al., 2001). This contrast in longer-term behaviour reflects reforestation in the Oil Springs and Matakonekone which has reduced sediment supply from gullies, whilst the Tarndale gully complex remains unforested and the speed of aggradation in the Tarndale fan has increased recently (Marden et al., submitted for publication). The impact of Cyclone Bola on the Tarndale system did not appear to show a significant increase in fan volume at the time, although a preceding trend of volume reduction, i.e. incision, was reversed in the winter of 1988 following Cyclone Bola (Fig. 4). Subsequent storms appear to have had a more significant impact (e.g. the wet winter of 1992, cf. Fig. 4). Similarly, a 140 mm event in October 2005 contributed the largest volume of material to the fan in this study (Table 2) and Marden et al. (submitted for publication) demonstrate a recent increase in the rate of sediment storage in the fan. This increase may be attributable to extension and activity of the Tarndale gully complex in recent years (De Rose et al., 1998). The effects of a large storm are therefore modulated by the intrinsic structure and sensitivity of any given system. It is of note that a smaller storm in June 2006 (87 mm) contributed more coarse sediment to the Te Weraroa Stream (Table 2); however Fig. 6b indicates this was connected with a wetter period overall and during which mass movement failures were observed by the authors elsewhere within Waipaoa catchment. Whilst between November 2006 and April 2007 a similar size storm (90 mm) contributed no detectable coarse material to the Te Weraroa and far less sediment to the fan from the gully complex (Table 2). This event occurred within a drier period (Fig. 6b). These scenarios demonstrate the control of antecedent conditions on the generation and transfer of sediment associated with any single storm event which, with the higher temporal resolution of this study, is quantified here (albeit lower-bound estimates) for the first time.

Scaling up from the Tarndale, this study highlights the significant role played by fans in amplifying or modulating sediment supplied from active gully complexes in the Waipaoa. These fans act as both storage and transfer zones for sediment supplied from contributing gully complexes and are therefore significant to the Waipaoa sediment cascade. However, many gully-fan systems have stabilised since the commencement of reforestation in the 1960s and sediment input from them has reduced over time (Marden et al., 2005). Notwithstanding, the total volume contributed by the numerous untreated gullies that continue to supply sediment to the Waipaoa fluvial system remains unquantified.

The emphasis of this study has been on the coarser material (bedload), which conditions fan morphology. Suspended sediment has not been measured and is beyond the scope of this paper. The throughput of such material will clearly be far greater than the coarse clastic sediment. The impact upon the Te Weraroa Stream is, nevertheless, significant. Given the fine nature of the Tarndale bed sediment (D_{50} only 1.4 mm); the transfer of this material to the Te Weraroa Stream impacts the grain sizes measured by introducing a slug of finer bedload. Gomez et al. (2003b) report a reduction in D_{50} in the Te Weraroa from 11 mm upstream of the Tarndale feeder channel to 6.8 mm downstream. The present study demonstrates ongoing supply of this material to the Te Weraroa Stream, fed by sediment transferred from the Tarndale gully complex via cutting, filling and trimming of the Tarndale fan in response to a range of intrinsic and extrinsic controls. However, given that the material in the Te Weraroa remains coarser than the Tarndale fan in spite of the slug of finer material, it is likely that the Tarndale sediment, which is far smaller than the Te Weraroa bedload (D_{50} 11 mm) at the confluence (cf Fig. 2c), is readily transported by the stream, especially during trimming events. This suggests that even the coarse material contributed to the Te Weraroa by the Tarndale fan, as described in this paper, is effectively transported in the Waipaoa sediment cascade.

5. Conclusion

This paper has assessed short-term behaviour of a fan fed by a major fluvio-mass movement gully complex at the head of the Waipaoa Source-to-Sink system which contributes ~3% of total sediment yielded to the ocean from the Waipaoa (De Rose et al., 1998). Whilst only assessing a small proportion of total sediment generated (necessarily given the morphological budgeting approach adopted), we have nevertheless demonstrated complex behaviour of the fan system in response to evacuation and storage of the coarse fraction of sediment supplied from the gully complex. The fan has at times both amplified sediment delivery to the Waipaoa trunk river system and acted as a buffer, storing a significant quantity of sediment delivered from the Tarndale gully complex. In addition we have demonstrated the sensitivity of cutting and filling of channels in the fan to sediment supplied from the gully complex, especially in response to over- and under-supply of sediment from the gully system, as well as trimming by the Te Weraroa Stream. This paper therefore demonstrates clearly, and uniquely through relatively high-precision DEM analysis, the interaction between sediment supplied from a gully complex and its associated fan, as well as the interactions between the fan and Te Weraroa Stream. Temporal and spatial controls on sediment fluxes imposed upon these components of the Source-to-Sink system have been detected, which are conditioned both by intrinsic susceptibility of a gully complex to mass movement and the extrinsic driver of rainfall, as well as intrinsic response to local base-level change when trimmed. However, due to the speed of processes operating in this environment, a further increase in survey frequency and analysis is required to better constrain cutting and filling of the Tarndale fan, which appears to be event-driven within the constraints of antecedent conditions and internal structure of contributing landscape components.

Acknowledgements

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