Connectivity in steep-land environments: gully–fan coupling in the Tarndale system, Waipaoa catchment, New Zealand

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Abstract Digital Elevation Models (DEMs) of the Tarndale Fan derived from nine RTK-dGPS surveys between 2004 and 2007 demonstrate a rapid cutting and filling of the fan surface over the course of two and a half years. Repeat DEM analysis permits an assessment of the transfer of sediment supplied from a fluvio-mass movement gully complex (Tarndale Slip) through the fan to the Te Weraroa Stream. This demonstrates considerable complexity in patterns of erosion and deposition on the fan and, ultimately, sediment delivery to the stream system. Discrete mass movements in the gully complex, triggered by rainstorm events, frequently deliver sediment to the upper fan. Extreme rainfall events are particularly effective at delivering large quantities of sediment. Enhanced sediment delivery promotes rapid aggradation (up to ~30 000 m^3) of the upper fan. This infilling may then propagate down-fan, particularly when the upper fan equally rapidly incises these deposits. However, floods generated in the Te Weraroa Stream by the same extreme rainstorm may trim the lower fan prompting up-fan incision in response to changed local base level. This process may evacuate up to ~10 000 m^3 of sediment to the stream. This see-saw behaviour in response to sediment supply and evacuation is superimposed on an overall aggradational trend in which the Tarndale Fan is buffering the trunk channel system from the full quantity of sediment supplied by the Tarndale Slip. This study demonstrates a need for intensive investigation of such systems so as to understand more fully complex behaviour at this critical nexus within the fluvial system.

Key words gully complex; fan; DEM; sediment transfer; sediment cascade

INTRODUCTION

Connectivity within and between landscape units is critical to both the functioning of sediment cascades and sensitivity of the landscape to change (Harvey, 2001; Fryirs *et al.*, 2007). The impact of sediment- and flood-producing events is conditioned by the degree of connectivity within a catchment, such that well-coupled systems effectively transmit sediment generated by these events from slopes to channels, generating a response to that event (Harvey, 2001). The nature and spatial propagation of that response is conditioned by connectivity between landscape units, with the operation of buffers, barriers, blankets and boosters (Fryirs *et al.*, 2007). The better connected the landscape components, the greater the sensitivity to change, as this permits the free transfer of energy and matter between landscape components, reducing the structural resistance to change (Brunsden, 2001). This paper examines these connections in the context of propagation of sediment generated from a fluvio-mass movement gully complex (Tarndale Slip) through a fan to the Te Weraroa Stream, a significant tributary of the Waipaoa River, East Cape, New Zealand (Fig. 1).

At the head of the sediment cascade in this steep-land region, gully erosion may be enhanced by mass movement processes and the two mechanisms of sediment delivery may combine, developing large amphitheatre-like fluvio-mass movement gully complexes (DeRose *et al.*, 1998; Betts *et al.*, 2003). In these systems, mass movements tend to comprise debris flows, 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. More than half of the sediment load of the Waipaoa and adjacent Waiapu rivers is derived from these complexes (Marden *et al.*, 2005; Page *et al.*, 2008). De Rose *et al.* (1998) suggest that ~3% of the Waipaoa's current sediment yield of 15 million tonnes per annum (Hicks *et al.*, 2000) is derived from a single fluvio-mass movement gully complex known locally as the Tarndale Slip. The contribution from this gully complex to the Te Weraroa Stream 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

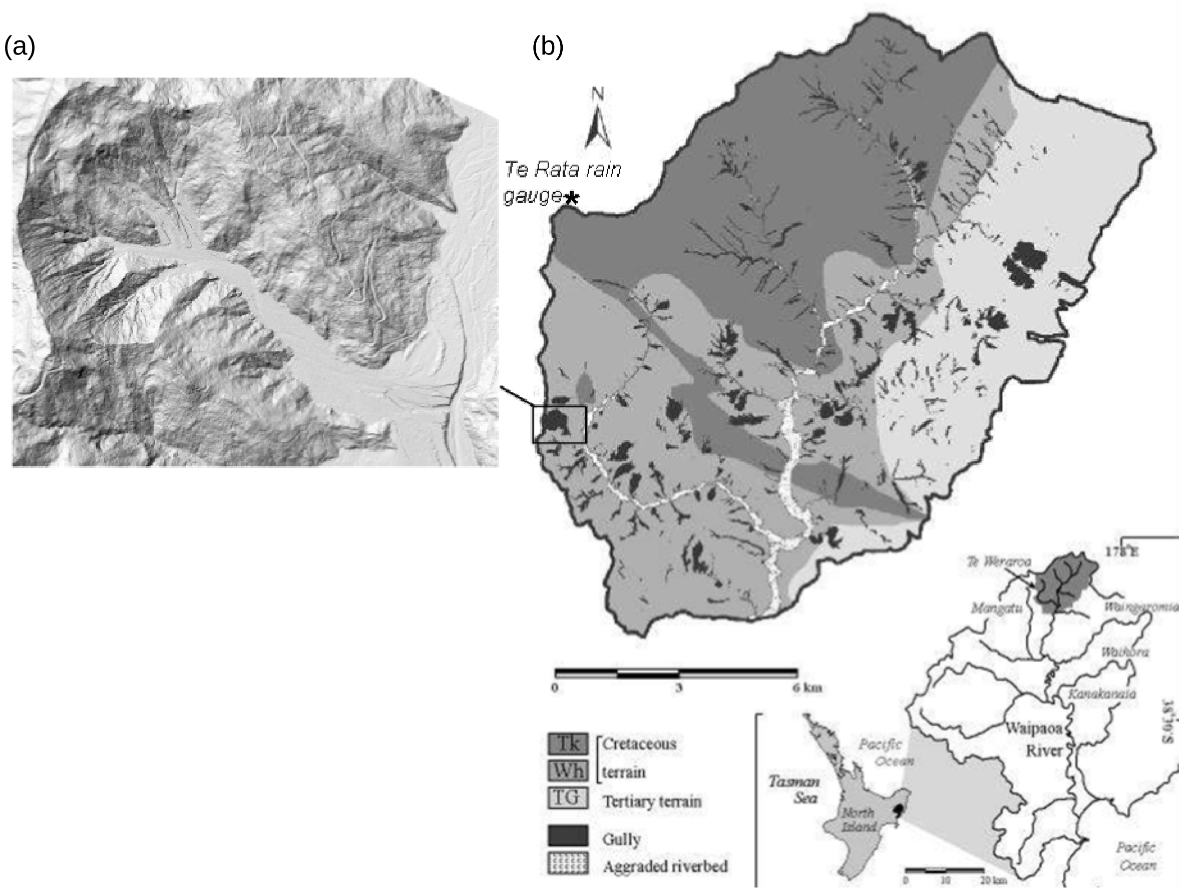

Fig. 1 Location map of the Tarndale gully complex and fan in the context of the upper Waipaoa catchment: (a) LiDAR derived digital elevation model of the gully–fan complex (LiDAR data © Gisborne District Council, courtesy Dave Peacock), (b) upper Waipaoa catchment showing major lithologies and gullies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

Tarndale complex (Gomez *et al*., 2003). The underlying geology predisposes this region to instability and mass movement, because acid sulphate weathering of crushed Cretaceous shales (Fig. 1) results in dramatically reduced rock strength (Pearce *et al*., 1981).

The Tarndale gully complex is buffered from the channel system by a small (~11 ha) depositional fan (Fig. 1). 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 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 these sources. The extent of buffering is temporally variable, and requires assessment to better understand sediment delivery processes and connectivity in this upper component of the sediment cascade.

METHODS AND RESULTS

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 set up permits rapid data acquisition using one-second occupation time per observation and real time coordinate calculation using on-the-fly algorithms (Stewart & Rizos, 2002). The minimum acceptable vertical accuracy of observations was set at 0.05 m. The 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 (Lee, 1991; Tsai, 1993). 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).

DEM validity

The accuracy of the DEMs is assessed using an approach recommended by Fisher & Tate (2006), which derives the error standard deviation (S), equation (1). This permits estimation of bias using the Mean Error, ME, which may be positive or negative (Table 1):

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

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:

$$ME = \frac{\sum(z_{DEM} - z_{ref})}{n} \qquad (2)$$

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 & 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. the interpolated surface lying above the data points), and the subsequent surface slightly negatively biased suggests that when comparing these two consecutive surveys, volumetric estimates will be biased towards scour.

Table 1 Error analysis showing standard deviation and *ME* for each DEM; from equations (1) and (2).

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

DEM differencing and sediment transfer estimation

Elevation changes between successive DEMs may be used to derive sediment gains and losses based on morphological budgets (e.g. Fuller *et al*., 2003). DEMs of difference (Fig. 2) depict patterns of sediment gains and loss, indicating complex patterns of cutting and filling of the Tarndale Fan in the study period. 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 & Hutchinson, 2007). However, it should be noted that volumes are a lower-bound estimation of total sediment transfers (Fuller *et al*., 2003), and also that they do not account for suspended sediment, which forms the majority of sediment generated from the Tarndale gully complex (Gomez *et al*., 2003). This assessment of sediment transfer is therefore limited to the coarse fraction, which conditions channel morphology (Leopold, 1992; Martin & Church, 2005). However, coarse is a relative term: 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). The coarse fraction of the Tarndale Fan is therefore relatively fine.

The figure of sediment yielded in Table 2 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), the suspended sediment yield from the Tarndale gully complex exceeds 10 000 t ha $year^{-1}$ (Phillips & Gomez, 2007). Whether the eroded coarse-fraction sediment

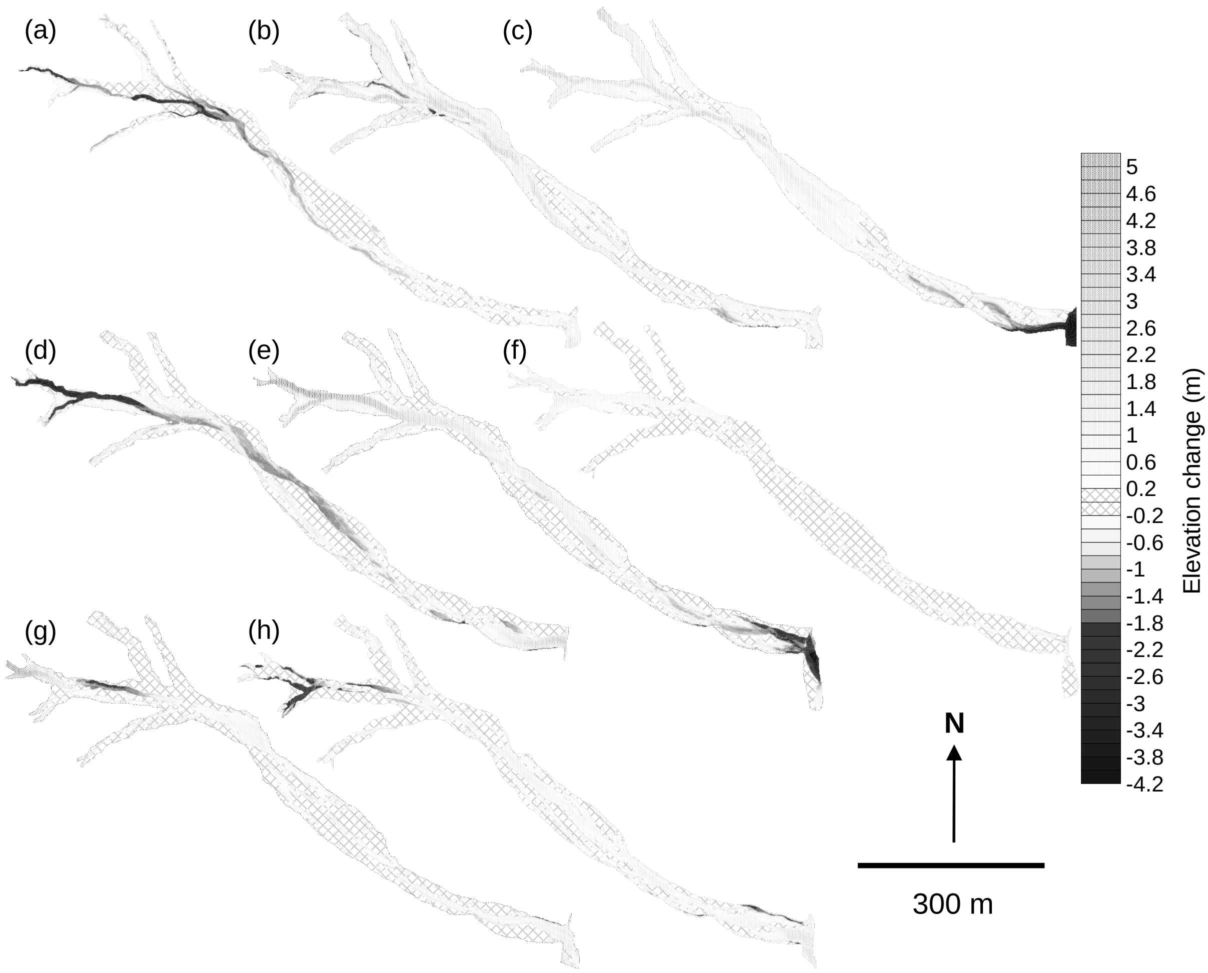

Fig. 2 DEMs of difference for successive surveys: (a) December 2004–April 2005; (b) April 2005–August 2005; (c) August 2005–December 2005; (d) December 2005–May 2006; (e) May 2006–August 2006; (f) August 2006–November 2006; (g) November 2006–April 2007; (h) April 2007–August 2007.

Table 2 Sediment volumes and tonnes produced by cutting and filling of the Tarndale Fan between successive survey periods, based on a DEM-derived morphological budget (Fuller *et al*., 2003) assessing change in coarse fraction only.

Period	Volumes (m^3)			Tonnes	
	Erosion	Deposition	Net	Net	Yield
December 2004–April 2005	11 997	6 424	–5573	–10 254	~10 000
April 2005–August 2005	6 174	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	8 078	–12 997	–23 915	~24 000
May 2006–August 2006	13 936	25 689	+11 753	+21 626	~25 000
August 2006–November 2006	3 100	6 912	+3812	+7014	~5 000
November 2006–April 2007	4 247	14 935	+10 688	+19 666	-
April 2007–August 2007	10 125	11 270	+1144	+2105	-

shown in Table 2 is yielded depends on where the erosion takes place. Hence, while net change may be positive, suggesting accumulation and minimum yield, if erosion takes place in the lower fan, that material may be considered as a yield from the fan to the Te Weraroa Stream. The spatial distribution of erosion and deposition on the fan is depicted in Fig. 2.

DISCUSSION

Superficially, DEM analysis indicates a degree of seasonal dependence, with the fan mostly filling during winter and cutting during summer (Fig. 2). This has been the generally accepted pattern of change to date (e.g. Marden *et al*., 2008). However, Fig. 2 demonstrates both spatially and temporally complex patterns of cutting and filling (described in detail by Fuller & Marden, 2008). Enhanced resolution of the behaviour of the Tarndale Fan, afforded by high resolution RTK-dGPS survey, presents a picture of complex, rapid, a-seasonal cutting and filling. In terms of slope–channel connectivity, 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 (ungauged). Trimming produces a knickpoint, which headcuts to mid-fan, incising the lower portion of the fan and generating sediment to the stream system. This was observed between August–December 2005 and again between May–August 2006 (Fig. 2(c) and (e)). The behaviour of the lower fan is thus conditioned by both interaction with the Te Weraroa Stream and sediment supplied from up-fan. The supply of sediment from the upper portion of the fan is in turn conditioned by cycles of repeated aggradation and incision. The upper fan aggrades rapidly in response to sediment supplied from the Tarndale gully complex predominantly via debris flow activity during wetter phases of weather (e.g. Fig. 2(b), (c), (e) and (g)). During drier periods, in which mass movement activity ceases, but sufficient runoff is maintained, these deposits are incised and material is fed down-fan (e.g. Fig 2(d) and (h)). Connectivity between gully–fan–channel is therefore discontinuous, with a "jerky-conveyor belt" (Ferguson, 1981) clearly in operation. These findings concur with Phillips *et al*. (2007), who comment on the discontinuity of links between erosion and sediment yield and note the complexity and nonlinear relationships between sediment generation, storage and transfer.

Fryirs *et al*. (2007) have identified 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 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 as sediment is moved along the jerky conveyor belt. Marden *et al*. (2008) indicate a progressive aggradation of the fan over the past ~50 years. The cutting and filling observed between December 2004 and August 2007 is 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 (Fig. 2(c) and (e)), but also where incision up-fan delivers large quantities of sediment to the lower fan (Fig. 2(a) and (d)). 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 (Fig. 2(g)). 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.

Despite the jerkiness of the conveyor, these patterns of behaviour suggest a highly sensitive channel system in the Tarndale Fan, which responds rapidly to sediment supply variability from the contributing gully complex. Discrete, severe rainstorms or wet weather periods appear to be significant in controlling sediment supply (Fig. 3). 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 (Fig. 2(c) and (e), Fig. 3). However, it also appears that contributions from discrete zones within the gully complex vary temporally. Aggradation between August–December 2005 (Fig. 2(c)) was prominent in the true left tributaries, as well as the mainstem, whilst in the next major aggradation event, between May–August 2006, only the mainstem has contributed large quantities of sediment (Fig. 2(e)). Mass movements in one area of the complex are therefore 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 (true left tributary, Fig. 2(c)), 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 the degree of connectivity between sections of the gully complex and associated fan components, effectively switching on or off the critical junction switch at discrete locations in the gully–fan nexus.

Mass movement activity is inhibited during drier periods and any runoff generated incises channels. This behaviour has been observed elsewhere in small headwater tributaries of the

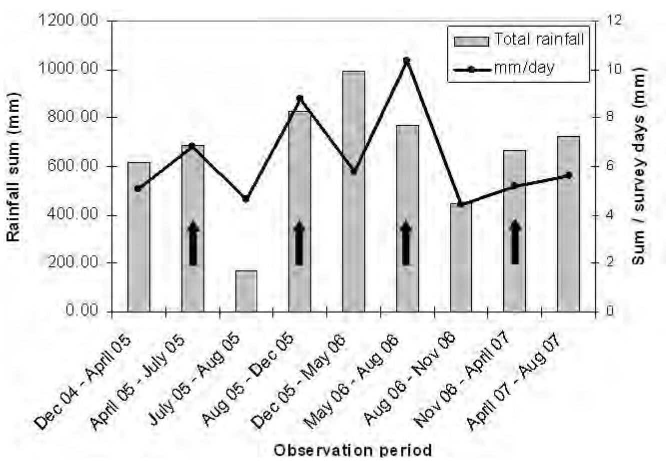

Fig. 3 Total rainfall volumes between observations. Rainfall measured at Te Rata (cf. Fig. 1). The rainfall sum/number of days between observations or surveys gives an index of wetness in terms of average rainfall for the period (mm/day). Arrows indicate periods of significant filling by sediment delivered from the Tarndale gully complex (cf. Fig. 2 and Table 2). An *ad hoc* field visit in July 2005 observed no incised channels on the fan (i.e. summer channels had been filled, cf. Fig. 2(a) and (b)). This suggests filling occurred between April and July, and incision between July and August.

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, which has been identified over a very short timescale (6 months) in the Tarndale system (cf. Fig. 2(c) and (d)). This suggests the upper Waipaoa is typified by similarly highly-responsive systems. 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*., 2008).

CONCLUSION

This paper has assessed connectivity in a geomorphically-active steep-land environment by quantifying cut and fill patterns and volumes of coarse sediment transfer taking place in a fan in a first-order tributary in the upper Waipaoa catchment. 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 feeder 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 Tarndale gully, especially in response to over- and under-supply of sediment from the gully system, as well as trimming by the Te Weraroa Stream. A pattern of up-fan filling and down-fan incision periodically reverses in response to sediment supply, leading to a see-saw behaviour as material is supplied and evacuated from the system. This paper demonstrates uniquely, through relatively high-precision DEM analysis, the connections made by sediment transfers between a fluvio-mass movement gully complex, its associated fan, and the trunk-stream system. Temporal and spatial controls on sediment fluxes imposed upon these components of the sediment cascade 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.

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