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Title page image: Debris flow from the headwall of the Tarndale Gully into a channel on the upper Tarndale Fan, April 2007.
Photo I.C. Fuller

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Quantifying slope-channel coupling in an active gully and fan complex at Tarndale, Waipaoa catchment, New Zealand.

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Abstract

Two RIEGL LMS-Z420i scanner surveys (November 2007 and November 2008) of the Tarndale Gully complex and its associated fan were used to generate a digital elevation model (DEM) of difference in order to quantify gully-fan-channel connectivity. The Te Weraroa Stream, into which the first order Tarndale system feeds, is buffered from sediment generated by the gully complex by a fan. Sediment yields and the role of the fan in buffering Te Weraroa Stream are inferred from the TLS of the entire complex. DEM analysis suggests that c.25% of material derived from the gully is buffered from the stream by being stored in the fan. This figure was applied to fan behaviour since December 2004, mapped on nine successive occasions using detailed GPS surveys to get a longer-term picture of sediment supply within the system and appraise a qualitative assessment of connectivity constructed on the basis of fan behaviour alone.

Key words: connectivity, gully, DEM, Terrestrial Laser Scanning, GPS mapping, buffer

Introduction

The supply of sediment to a stream or river channel is critical in defining the morphology and sensitivity of that system (Fuller and Marden, 2008). This sediment supply is governed by many variables, including slope stability and material, distance from the channel and the presence of buffers (Fryirs *et al*., 2007a). These factors may act to impede the passage of event-generated material to a channel and as such reduce the potential morphological response (Fuller and Marden, 2008). The sensitivity of a catchment determines the level of change that occurs when an event takes place and the delimiting of sediment supply reduces sensitivity (Brunsden and Thorne, 1979). Well connected slope channel systems are referred to as coupled, and coupled landscapes tend to be more sensitive since material generated by an event (e.g. a debris flow) is delivered effectively to the coupled stream, eliciting a response in the channel to the influx of sediment (Harvey, 2001). The better the degree of connectivity, the more sensitive the landscape is with material and energy being transferred readily through the system (Fuller and Marden, 2008). A more robust landscape, however, will tend not to respond readily to an event as the sediment supply may be interrupted, limiting the ability of thresholds to be crossed (such as thresholds of slope failure) and will rather exhibit flexibility through minor adjustment to an event without major morphological change (Harvey, 2001). Connectivity thus plays a large part in the sediment cascade, the "jerky" conveyor belt of sediment transport from source to sink, speeding up or slowing down the transfer of sediment downstream depending on the extent of buffering (Brierley and Fryirs, 2005).

The significance of buffers in de-coupling landscapes has been highlighted in other studies (Fryirs and Brierley, 1999; Harvey, 2001; Betts *et al*., 2003) but they play a particularly large role in the Tarndale complex in the Waipaoa catchment on the East Coast, New Zealand where a large fan buffers the entire gully complex from the adjacent Te Weraroa Stream (DeRose *et al*., 1998). "Buffers are landforms that prevent sediment from entering the channel network" (Fryirs *et al*., 2007a). The definition of a buffer is clear, but the effectiveness of a buffer is less so. Fryirs *et al*. (2007a) have given indicative time periods of sediment residence times in a range of buffers. While this is a good indication of how long sediment will be buffered for in these particular buffer forms, it does not describe how much of the sediment it buffers from the total that is supplied to it. There is a need, therefore, to quantify the extent of slope-channel coupling occurring in an area, by providing figures of sediment gain and loss on different parts of the Tarndale system which is the focus of this study.

Past studies of the Tarndale area have used digital elevations models (DEMs) to observe the change in gully and fan (DeRose *et al*., 1998; Fuller and Marden, 2008; 2010). Comparisons of these DEMs give volumes of sediment gains and losses which can be used to quantify and infer connectivity. This study uses terrestrial laser scanning techniques to study the entire gully complex and fan as a whole. These data were then examined to estimate the actual supply of material from the gully to the fan. The results can be applied to other DEM studies of past years to estimate the level of gully erosion in those years, given an approximate ratio of fan aggradation values to gully erosion.

The results will be used to examine the extent of connectivity and the role of buffers within the Tarndale system, and as such the sensitivity of the landscape. The extent of connectivity will be assessed through inferred sediment supply from the gully during the Fan survey periods, and also inferred sediment yield as sediment yield is seen as critical in sediment loss in the East Coast of New Zealand (Phillips and Gomez, 2007). Suspended sediment yield is not measured in this study; however, this figure too is important in the consideration of sediment loss in this region (Hicks *et al*., 2000)

Regional setting and site description

The Tarndale Gully complex feeds a first order tributary of the Te Weraroa Stream, in the upper Waipaoa catchment, East Coast Region in New Zealand's North Island (Figure 1). The Waipaoa catchment is underlain by Cretaceous and Tertiary rocks of the 'East Coast Fold Belt', a tectonically active and structurally complex zone. These sheared and crushed mudstones and sandstones make this area naturally susceptible to erosion (Rosser *et al.*, 2008; Kasai *et al.*, 2005). The East Coast region has a maritime climate, which is periodically disturbed by high rainfall events and localised storms (Hicks *et al.*, 2000). The Waipaoa Catchment covers an area of 2205 km^2 and has an annual sediment yield of 6800 t km^{-2} yr^{-1}, which is very high by global standards (Page *et al.*, 2001a and Marden *et al.*, 2008).

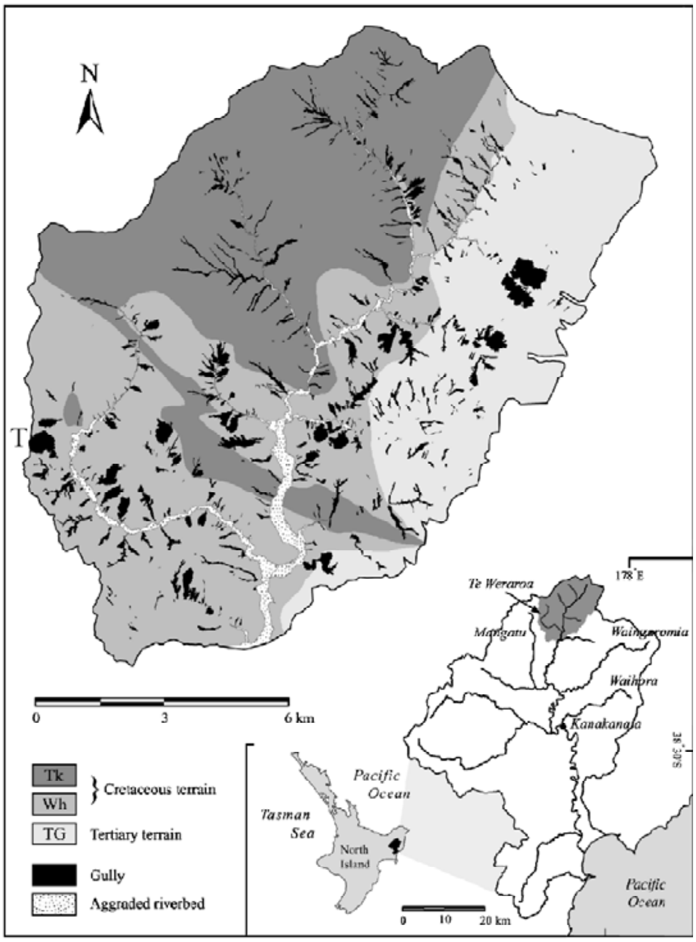

Figure 1. Location and underlying geology of Tarndale Gully (T) in the upper Waipaoa catchment (after Marden *et al.*, 2005).

Tarndale Gully is one of the largest gully complexes in the catchment and was thought to have been initiated on the site of an existing slump in the winter of 1915 (Marden *et al.*, 2005). The size, amphitheatre like appearance, and fast development of the gully complex can be attributed to the lithology beneath it (Parkner *et al.*, 2006 and DeRose *et al.*, 1998). The Tarndale Gully complex is situated on the Whangai Formation where the highest densities of gullies occur in this region. The Whangai Formation is a well-bedded, alternating mudstone and sandstone sequence, Cretaceous to Palaeocene in age. This lithology crushes easy along fault zones and the argillite rocks that it contains are especially susceptible to acid sulphate weathering (Marden *et al.*, 2005). The majority of sediment production and enlargement of the gully complex is dominated by mass-movement processes (i.e. debris flows and slides) rather than incision, therefore called a fluvio-mass movement gully complex (Fuller and Marden, 2008 and Parkner *et al.*, 2006). The Tarndale gully complex also consists of a large rotational slump due to the inevitable back cutting into the disturbed terrain (Marden *et al.*, 2005).

The Tarndale Gully complex is only one of 447 gullies in the Waipaoa Catchment (Marden *et al*., 2008) and gully erosion is only one of numerous erosional processes present here yet it contributes around 3% of the total annual sediment yield of the Waipaoa (DeRose *et al*., 1998). At peak gully erosion the Tarndale contributed around 62% of the sediment produced by gully erosion in the Te Weraroa stream from 1970-1988 (Gomez *et al*., 2003). Tarndale's dominance in the landscape can be further seen by its activity before and after the area was reforested. Tarndale produced 5% of all material generated by all gullies within the Cretaceous terrain in the Waipaoa catchment before reforestation. After reforestation (1970-1988) Tarndale's contribution increased to 14% (Marden *et al*., 2005; Gomez *et al*., 2003). This suggests that while other gullies were shut down by reforestation the Tarndale complex was unaffected and continued to contribute large amounts of material to the Waipaoa catchment.

The Tarndale fan at the base of the Tarndale gully complex buffers sediment supply to the Te Weraroa stream. Sediment is supplied to the stream channel from the fan irregularly, but this process is controlled not only by the entrainment ability of the stream but also by the supply of sediment to the fan from the gully complex (Fuller and Marden, 2008). Within this system Fuller and Marden (2010) identified two key switches that control the movement on sediment from one area to the next (i) at the gully-fan nexus and (ii) at the fan-channel confluence. Fryirs *et al*. (2007b) highlighted these kinds of switches as important for effective sediment transfer through a catchment. The control of these switches and the transfer of sediment to the stream ultimately rest in the mass movement processes of the gully. Gully processes occurring in the Tarndale complex tend to be event driven and so can vary highly from year to year (Fuller and Marden, 2008). Large storms can be drivers of larger landslides, slumping and earthflows, while active translational slides, creep and overland-flow erosion processes (rilling and gullying) tend to be linked to periods of wetter weather (Massey *et al*., 2009); these processes directly contribute material to the fan and understanding of them is vital to a holistic view of the connectivity across the complex and the catchment. The Tarndale fan has generally aggraded over the past 50 years with increasing sediment supply from the gully resulting in similar aggradation being observed in the Te Weraroa stream, indicating connectivity between the supply of sediment from the gully to the fan, and onwards to the stream channel itself (Fuller and Marden, 2008).

Method & Results

Surveys & DEMs

The entire gully and fan complex was surveyed in November 2007 and November 2008 using a RIEGL LMS-Z420i scanner (range 1000 m) using up to 26 set-up locations. CGPS was used for control. Each survey was carried out over three days. The laser scans covered the entire gully area as well as the area of the fan covered in each RTK-GPS study since December 2004 (Massey, 2009). The geomorphic components of the system are shown using a DEM based on 2008 data (Figure 2). DEM differencing gives a map of change (Figure 3).

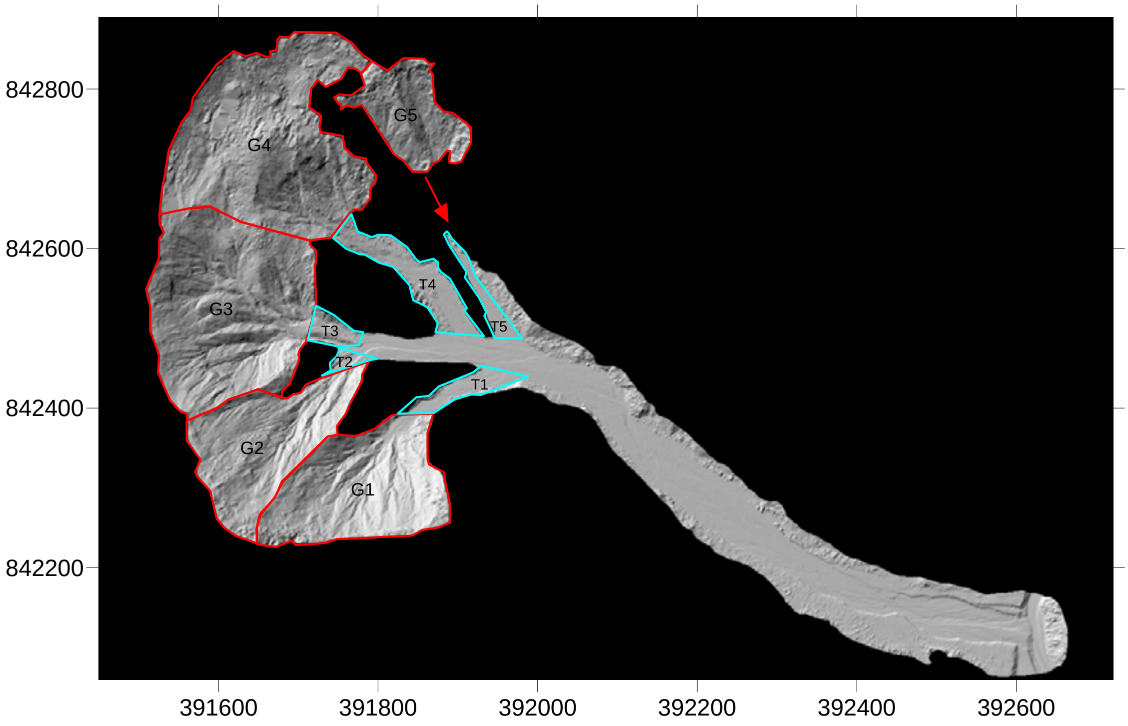

Figure 2. Tarndale gully and fan geomorphology using November 2008 TLS data. G denotes gully source area, T denotes tributary stem of the fan. Vegetated areas are blacked out.

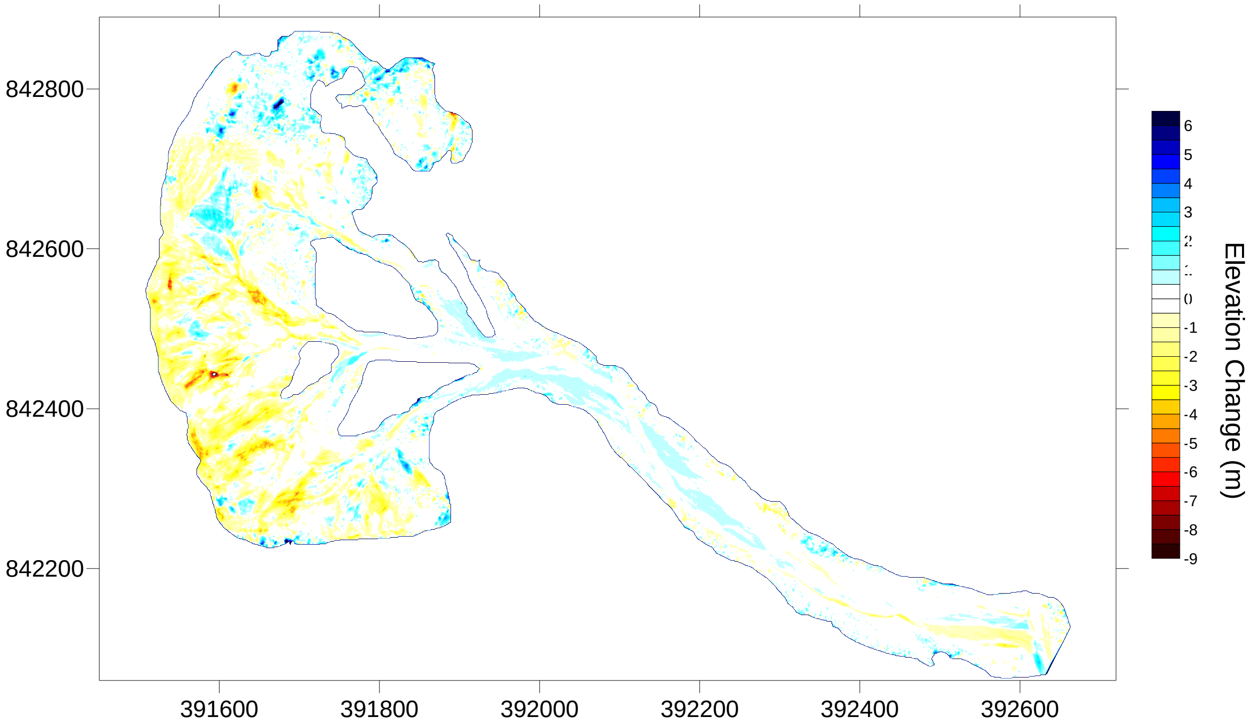

Figure 3. DEM of difference (November 2007- November 2008) for the entire Tarndale system from the gully, left, to the edge of the Te Weraroa Stream, right. The x-axis is Eastings and the y-axis in Northings (NZ Map Grid).

Fan survey:

In July 2009 the entire surface of the Tarndale fan was surveyed using a Real Time Kinematic-Global positioning system (RTK-GPS) and, where necessary, a Theodolite-EDM Total station. Two Trimble® R8 GPS receivers and two Leica units (System 1200) were used to deploy the RTK-dGPS survey. One of the 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 (Fuller & Marden, 2010). The minimum vertical accuracy of the observations was set at 0.1 m; however, the average observation accuracy was 0.02 m. Approximately 25,000 data points were surveyed to a precision of 0.001 m. The method and parameters used were modelled from previous surveys done on the Tarndale fan by Fuller and Marden (2010). The July 2009 survey and data from 10 other surveys constructed by Fuller and Marden (2010), between December 2004 and April 2008, were used to generate Digital elevation models (DEMs) of difference to construct three-dimensional fan surface change (Figure 4). There were approximately 15,000 data points per survey, with an average of 0.3 points per m^2. Data were imported in Surfer 8 where DEMs were constructed of each of the two surveys using TLI analysis and fan surveys. The DEMs were created using 1-metre spacing rather than the maximum 0.25-metre spacing as the higher resolution data made the program prone to crashing during calculations. The error of these DEMs is assessed as per Fuller and Marden (2008) and Fisher and Tate (2006) using the Mean Error (*ME*) and the error standard deviation (*S*) (Table 1). *ME* is derived from equation 1 and *S* from equation 2:

$$ME = \frac{\sum (z_{DEM} - z_{ref})}{n} \qquad (1)$$

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

where z_{DEM} is the DEM elevation measurement and z_{ref} is the elevation measurement from the original data source with *n* points, which is more accurate than the produced DEM.

This method does not consider interpolated points however, as both these methods use only surveyed points. Table 1 shows the error for the fan DEMs from December 2004 to April 2008, and the error for the 2007 and 2008 TLS surveys. The negative values for ME in both tables indicate underestimation of the surface, while the positive value indicates an overestimation. In the case of December 2004 versus April 2005, this would suggest that the volumes of that particular period of difference would be slightly biased towards scour.

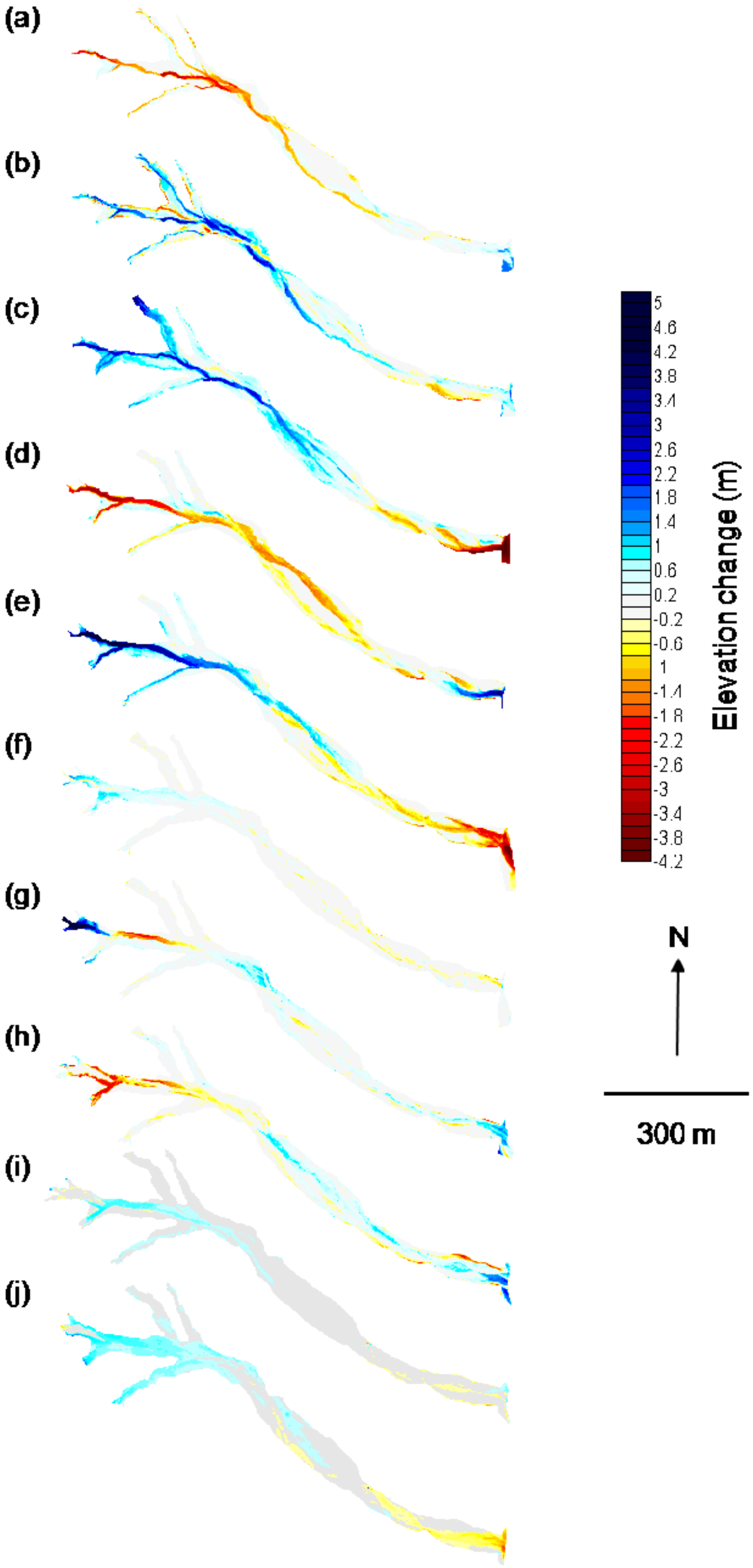

Figure 4. DEMs of difference for the ten survey periods of the fan.
(a) 04 Dec – 05 Apr,
(b) 05 Apr – 05 Aug,
(c) 05 Aug – 05 Dec,
(d) - 05 Dec – 06 May,
(e) 06 May – 06 Aug,
(f) 06 Aug – 06 Nov,
(g) 06 Nov – 07 Apr,
(h) 07 Apr – 07 Aug,
(i) 07 Aug – 08 Apr,
(j) 08 Apr – 09 Jul.

Table 1 Error analysis showing mean error and error standard deviation from equations 1 and 2 for the fan DEM data (adapted from Fuller and Marden, 2008) and the TLS DEM data

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	-0.0040
April 2007	0.111	-0.0021
August 2007	0.099	-0.0032
November 2007 (TLS)	0.123	-0.0014
April 2008	0.131	-0.0035
November 2008 (TLS)	0.142	-0.0064
July 2009	0.115	0.0001

Sediment volumes

DEMs of difference visually represent change between surveys (Figures 3 & 4). The following equations were used to work out the unbuffered sediment supplied to the stream from the gully (S_U), the total sediment supplied to the stream ($S_{S\text{ (Te Weraroa)}}$), and the percentage of the sediment supplied by the gully that is buffered by the fan ($G_{P(TLS)}$).

(3) $$S_U = GS_L - S_{B(TLS)}$$

(4) $$S_{S\text{(Te Weraroa)}} = S_U + FS_L$$

(5) $$G_{PS(TLS)} = S_{B(TLS)}/GS_L \text{ X } 100$$

Where GS_L is the sediment lost from the gully, $S_{B(TLS)}$ is the sediment gain on the fan, and FS_L is the sediment lost from the fan. The $G_{P(TLS)}$ is then used to approximate the sediment supplied by the gully to the fan for each of the fan DEMs of difference ($GS_{S(DEM)}$) using equation 6:

(6) $$GS_{S(DEM)} = S_{B(DEM)}/G_{P(TLS)} \text{ X } 100$$

where $S_{B(DEM)}$ is the sediment gain on the fan from each of the fan DEMs since December 2004 (Table 3).

Table 2 shows the figures of change for the Tarndale system, isolating the gully sediment input from the fan input and output to give the total sediment supplied to the Te Weraroa Stream during the one-year survey period. Of the 95,198 m^3 of sediment lost from the gully, 25% was buffered by the fan. 75% was contributed to the stream channel over the course of the year though, with an extra 17,195 m^3 being added from material already stored in the fan.

Table 2 2007-2008 Tarndale TLS figures

Gully sediment loss	95 198 m^3
Fan sediment gain	23 423 m^3
Percentage of material effectively buffered	**25%**
Fan sediment loss	17 195 m^3
Unbuffered Gully sediment	71 775 m^3
Total sediment supplied to Te Weraroa Stream	**88 970 m^3**

The material in the fan is supplied entirely from the gully complex (Fuller and Marden, 2008). Therefore, if the sediment delivery ratio (SDR) of 0.75, calculated for the November 2007-2008 period, was assumed to be constant since 2004, then the aggradation seen in the fan in each of the DEMs since December 2004 equates to c. 25% of the material supplied from the gully, and from this an approximate figure can be calculated for each of these periods; see Table 3. It should be acknowledged that this is an untested inference and further work on a more expansive dataset is required to set the 0.75 SDR figure in a wider temporal context. The figures in Table 3 are therefore a simplified approximation.

Table 3 2004-2008 Tarndale Fan DEM figures

Period of change	***Gain (m^3)***	***Loss (m^3)***	***Inferred gully supply (m^3)***	***Unbuffered inferred gully supply (m^3)***	***Sediment supplied to Te Weraroa Stream (m^3)***
Dec 04 – Apr 05	8 042	12 396	32 168	24 126	36 522
Apr 05 – Aug 05	24 153	5 142	96 612	72 459	77 601
Aug 05 – Dec 05	30 210	8 056	120 840	90 630	98 686
Dec 05 – May 06	7 976	20 458	31 904	23 928	44 386
May 06 – Aug 06	25 561	11 617	102 244	76 683	88 300
Aug 06 – Nov 06	6 643	2 818	26 572	19 929	22 747
Nov 06 – Apr 07	13 941	4 137	55 764	41 823	45 960
Apr 07 – Aug 07	10 880	9 010	43 520	32 640	41650
Aug 07 – Apr 08	12 662	5 121	50 488	37 826	42 947
Apr 08 – Jul 09	26 483	12 989	105 932	79 449	92 438

The figures from Table 3 are plotted in Figure 5 as a time series of sediment supplied from the complex to Te Weraroa Stream per day. While the x-axis is not continuous, there does not appear to be trend associated with the length of the study period. TLS data are highlighted.

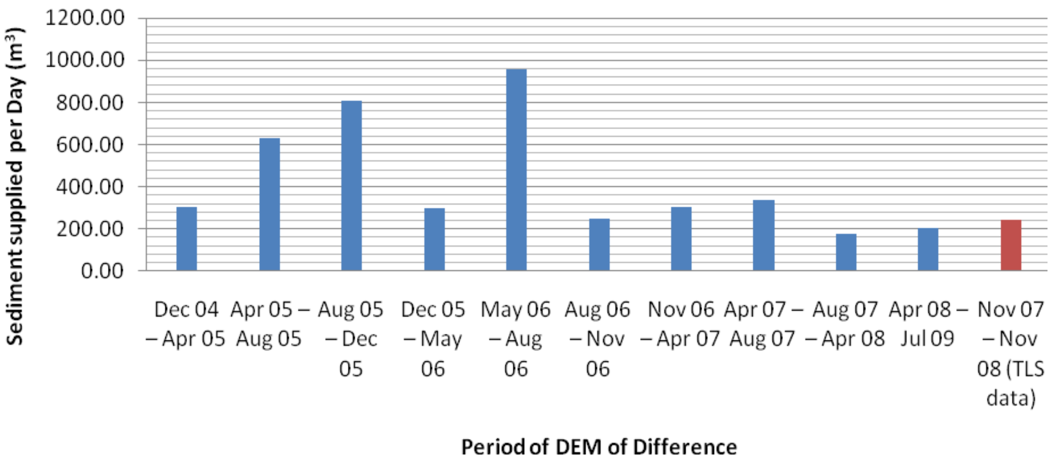

Figure 5. *Inferred sediment supplied per day from the Tarndale gully complex and the Tarndale fan to the Te Weraroa Stream during the DEM periods and the TLS period (shown in red).*

The volumes calculated in Tables 2 and 3 were converted into annual sediment yields using the dry bulk density figure of 1840 kgm^{-3} given in DeRose *et al.*, (1998) (Table 4). The sediment yields are calculated from the inferred gully sediment supply from Table 3. Table 5 gives the volume changes for the gully sections and fan tributaries from Figure 2 and their sediment yields. The high values for annual sediment yield seen in tables 4 and 5 are a product of the small area of the study site.

Table 4 sediment transfer volumes from the gully to Te Weraroa Stream for the fan DEM and TLS data

Period of study	***Sediment supplied to Te Weraroa Stream (m^3)***	***Average sediment volume supplied per day (m^3)***	***Annual Sediment Yield ($T\ km^{-2}\ yr^{-2}$)***
Dec 04 – Apr 05	36 522	302	820 634
Apr 05 – Aug 05	77 601	631	1 715 310
Aug 05 – Dec 05	98 686	809	2 199 257
Dec 05 – May 06	44 386	296	804 517
May 06 – Aug 06	88 300	960	2 609 475
Aug 06 – Nov 06	22 747	250	679 615
Nov 06 – Apr 07	45 960	306	833 046
Apr 07 – Aug 07	41 650	339	920 641
Aug 07 – Apr 08	42 947	177	482 501
Apr 08 – Jul 09	92 438	203	551 145
Nov 07 – Nov 08 (TLS)	88 970	244	662 721

Table 5. Gully and Fan Tributary Volumes of Sediment Transfer (refer to Figure 2)

	Gully (G) sediment loss (m^3) [% of total gully loss]	***Fan (T) sediment gain (m^3)***	***Percentage of gully sediment buffered***	***Sediment Yield ($T\ km^{-2}\ yr^{-1}$)***
Gully section 1	16 944 [18]	1 489	~9%	1 047 427
Gully section 2	22 923 [24]	646	~3%	1 740 959
Gully section 3	37 848 [40]	1 632	~4%	1 617 218
Gully section 4	14 692 [15]	2 151	~15%	575 589
Gully section 5	3 250 [3]	973	~30%	428 269

Figure 6 shows the daily rainfall patterns over the periods of study and figure 7 shows the comparison of sediment yields (Table 4) with average rainfall over the survey periods.

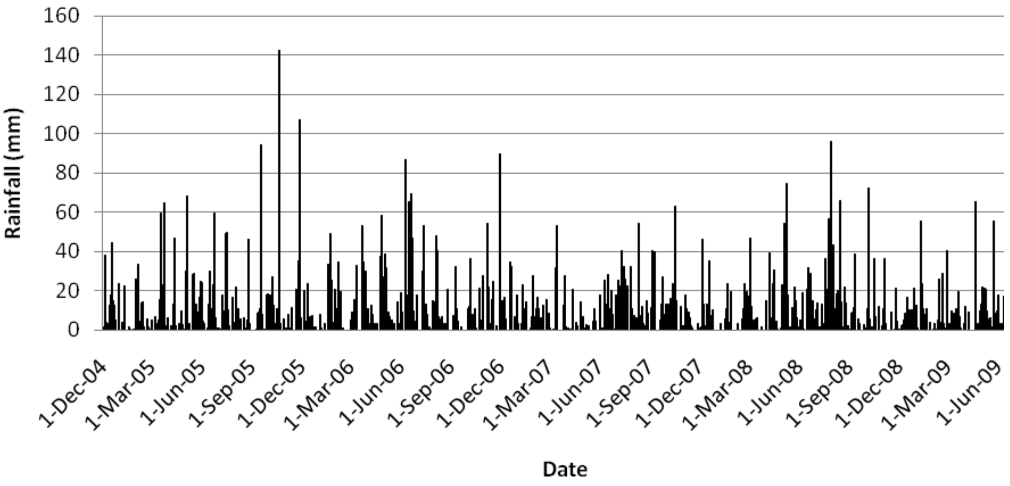

Figure 6. Daily rainfall patterns over the period of study from Te Rata station in the upper Waipaoa, December 2004 to June 2009. Data Source: Gisborne District Council.

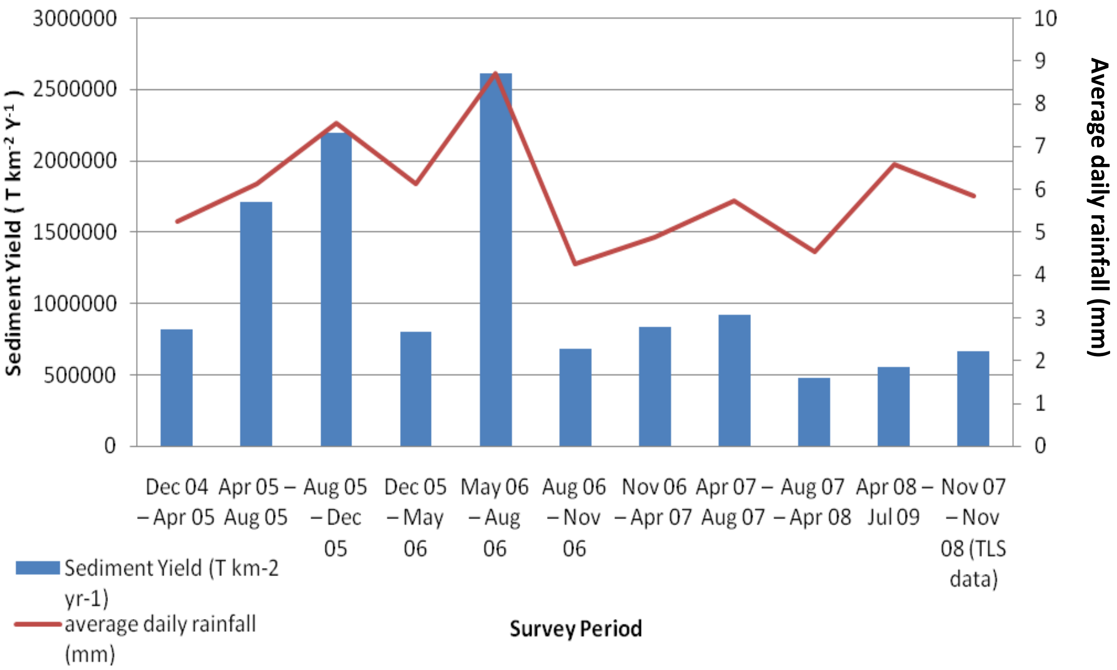

Figure 7. Inferred annual sediment yield and average daily rainfall for the survey periods.

Discussion

The Tarndale fan buffers the Te Weraroa Stream from the Tarndale Gully, effectively storing c. 25% of material supplied by the gully, giving a sediment delivery ratio of c. 0.75 for the November 2007-2008 period, which has been tentatively applied to the period since 2004. It must be acknowledged that this is very much an inference and further work is required to assess the variability of SDR in this system over time, which may vary between discrete storms, let alone survey periods (Kasai *et al*., 2001). Furthermore, the unarmoured surface of the fan lends itself to ready erosion by runoff and lateral erosion may also trim the base of the fan during floods in the Te Weraroa Stream. This means that the fan is also a sediment source for the Te Weraroa Stream. DeRose *et al*. (1998) suggested that the Tarndale fan effectively buffered 13% of sediment produced by the gully for the period 1939 to 1958, and 16% for the period 1958 to 1992. The adjacent Mangatu fan however, buffered only 2% from 1939-1958 and 6% from 1958 to 1992 of the sediment supplied by the Mangatu gully (DeRose *et al*., 1998). This is a function of accommodation space and valley width: the Mangatu fan is much narrower and also shorter than Tarndale and thus less effective as a buffer. In 1992 the Tarndale gully was 0.2 km^2 with a 0.098 km^2 depositional fan while the Mangatu gully was 0.272 km^2 with a 0.042 km^2 fan (DeRose *et al*., 1998). In 1958 the ratios between the two systems were similar too, and in 2008 the Tarndale gully was 0.147km^2 with a 0.099 km^2 fan, an even more effective fan to gully size ratio. Elsewhere in the upper Waipaoa, the Oil Springs and Matekoneknoe catchments have higher sediment delivery ratios (0.93), which Marutani *et al*. (1999) attribute to rapid scouring of deposits after a storm. However, these systems again are smaller than Tarndale and a lower sediment delivery ratio may be expected as a result of the larger buffer in the form of the Tarndale fan.

The supply of sediment to the fan is complex and the response of the fan is not merely to aggrade or incise as a whole. The five different gully sections (Figure 2) act independently of one another and as such the response of their individual fan tributaries are independent. Fuller and Marden (in review) considered the response of these different fan areas and what they inferred about gully processes. In general gullies G1-3 (Figure 2) produce sediment through surface erosion processes, rilling, gullying and debris flows, while gullies G4-5 are more subject to slumping and larger mass movements (Massey *et al*., 2009). The dominant processes supplying sediment to the fan are thus rilling, gullying and debris flows, since these gullies generate c.82% of sediment from the complex as a whole (Table 5). Gullies G4-5 have the potential to produce large quantities of sediment, but would do so in larger, less frequent events. The surveys of April 2005-August 2005 and December 2005-May 2006 (Figure 4, b and d) show aggradation in fan tributaries T4-5 indicating larger activity in gullies G4-5 as suggested in Fuller and Marden (2010).

Figure 7 suggests that the annual sediment yields of the Tarndale gully system is linked to the average daily rainfall in the area. The inferred annual sediment yields for the Fan DEM studies from December 2004 to July 2009 follow the trend of the rainfall line; higher sediment yields are associated with higher average daily rainfall values. This suggests that while surface erosion processes commonly seen in gullies G1-3 are driven by rainfall, so too are the larger mass movements seen across the whole gully complex, particularly in gullies G4-5. These mass movements are threshold driven and could be triggered by high intensity rainfall events and/or seismic activity (Betts *et al*., 2003; Fuller and Marden, 2010).

Recent studies have focused on sediment yield as critical in the source to sink issue of high sediment loss in the East Coast of New Zealand (Hicks *et al*., 2000; Gomez *et al*., 2003; Phillips and Gomez, 2007). Yield is important as a reference figure but does not show residence times of sediment in storage or the rate of supply to the channel (Kasai *et al*., 2005). The badlands in Mocatán, southeast Spain, showed increasing connectivity between slopes and channels with increased erosion, and runoff became more efficient resulting in the removal of depositional (buffering) features (such as fans) in or near the channel (Faulkner *et al*., 2008). With increased coupling, limited buffering and smaller residence times, sediment supply became much more efficient downstream resulting in a much more sensitive landscape. The Tarndale system is arguably less sensitive due to a high degree of buffering by the fan. The length of the fan means that material being transported down it has greater opportunity for deposition, although steepening of the slope by fan head deposition may cross thresholds of incision in response, triggering trenching (Fuller and Marden, 2010) and a see-saw behaviour of fan filling, cutting and re-filling (Fuller and Marden, 2008). Re-vegetation is seen as vital to the stabilization of gully systems in New Zealand (Marden *et al*., 2005) and buffers may be able to aid this process. Revegetation at the margins of the Tarndale fan stabilise the buffer and lock-up this sediment in a long-term store.

Conclusion

This study has quantified the extent of buffering of the Tarndale gully system by the Tarndale fan using TLS data of the entire gully-fan complex, which generated a SDR of 0.75. This figure was tentatively applied to approximate past sediment yields from the gully using only cut and fill data from the fan. However, catchments with extensive gullying are not simply described using sediment yields or delivery ratios. More understanding of buffering and connectivity is needed in order to properly assess the effectiveness of buffers, and to better understand their role in the stabilisation of these erosional systems. Future studies need to be done on this site using laser scanning techniques to improve understanding of processes and rates of sediment delivery in this system. In particular, the SDR of 0.75 calculated in this study needs to be tested in further analysis of whole-system behaviour, as and when data become available from future terrestrial laser scans and LiDAR surveys. Similar studies should also be carried out elsewhere in New Zealand to better understand catchment connectivity and sediment transfers from slopes to channels.

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