Elsevier Editorial System(tm) for Geomorphology
Manuscript Draft

Manuscript Number: GEOMOR-1941R1

Title: Assessing debris flows using LIDAR differencing: 18th May 2005 Matata event, New Zealand

Article Type: Research Paper

Keywords: LIDAR differencing, slope failure, debris flow, sediment pathways, Matata, hazard assessment, LIDAR

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Abstract: The town of Matata in the Eastern Bay of Plenty (New Zealand) experienced an extreme rainfall event on the 18th of May 2005. This event triggered widespread landslips and large debris flows in the Awatarariki and Waitepuru catchments behind Matata. LIDAR (Light Detection and Ranging technology) data sets flown prior to and following this event have been differenced and used in conjunction with a detailed field study to identify the distribution of debris and major sediment pathways which, from the Awatarariki catchment, transported at least 350,000 ± 50,000 m3 of debris. Debris flows were initially confined to stream valleys and controlled by the density and hydraulic thrust of the currents, before emerging onto the Awatarariki debris fan where a complex system of unconfined sediment pathways developed. Here, large boulders, clasts, logs and entire homes were deposited as the flows decelerated. Downstream from the debris fan, the pre-existing coastal foredune topography played a significant role in deflecting the more dilute currents that in filled lagoonal swale systems in both directions. The differenced LIDAR data has revealed several sectors characterised by significant variation in clast size, thickness and volume of debris as well as areas where post-debris flow cleanup and grading operations have resulted in man-made levees, sediment dumps, scoured channels and substantial graded areas. The application of differenced LIDAR data to a debris flow event demonstrates the techniques potential as a precise and powerful tool for hazard mapping and assessment.

***Response to Reviewers**

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16th August 2010

Takashi OGUCHI
Co-Editor-in-Chief: Geomorphology (Elsevier)

Dear Takashi,
Revised Manuscript for Geomorphology - Ms. Ref. No.: GEOMOR-1941. Title: Assessing debris flows using LIDAR differencing: 18th May 2005 Matata event.
Thank you for your and the two reviewers comments. I have now completed the revisions and uploaded the manuscript
With regard to the figures I have combined Figures 9 and 10 into a new Figure 9. This was to simplify and enable the reader to see the whole area that has been differenced. Figures 3 and 7 are provided as both black/white and colour so that the colour can be used on-line. We now have three colour figures (2, 8 and 9).

I indicate below in detail how we have responded to the detailed comments on the manuscript.Please do not hesitate to contact us if you require more information.

Yours sincerely
Jon

Professor Jonathan Bull

Response to Reviewers' comments:
Responses are indicated in italics.

Reviewer #1:
line 26: add (New Zealand) after Plenty – *Done.*
line 42: The last sentence of the abstract is too general. The impact of the debris flow has been assessed in this paper. – *We have amended the last sentence to make this clear*.

-line 70: I think that a great advantage of the LIDAR is that it gives a synoptic view of large areas. That is not the case of conventional geodetic techniques. – *A useful comment – sentence added at line 80-81*

-line 102 to 114: the parts 2 and 3 could be presented in an other way. I think that you could be more precise on rainfalls, topography and geology in the part 2. For example, you indicate the thickness of the ignimbrite in part 3. You could also precise if historic debris flows have occurred.

We don't agree with these comments. The Regional Geologic Setting section is exactly that, it lays down the regional context and highlights some important detail that is referred to throughout the paper (i.e. the Matahina ignimbrite whose distribution is not only regional in scale but it is an important lithology in the debris flow story).

-fig 3 not necessary, or can be completed by a 3D view of the geology -*This figure gives the reader a much better vision of the field area, the scale of the coastal cliffs and a perspective on the source and sink of the debris flows relative to the township of Matata.*

-fig 7: there is a problem in the overlap of the aerial images, mainly for the two western bands. This is a very minor point. *There is a small issue, hopefully partially resolved by better presentation of new Fig 7.*

fig 8: the scale of Height is too small and difficult to read. *Scale now bigger*

table 2 and discussion: Could you add explicitly the surface covered by the debris flow ? How is estimated the error for the total volume ? from the error bar on the LIDAR data ? *We are not keen to add surface area as we do not think it a significant parameter – volume is most important. Errors are discussed in the text.*

Reviewer #2:
Lines 115-478: Sources of descriptions are not clear. The title of the section is "Eyewitness, Photo and Field Observation of ...". It is not clear descriptions are based either on Eyewitness, Photo, or Field Observation. It is preferable for the authors to indicate this point in the text.
I have added text to show, specifically, the source of the descriptions.

Line 124: Is the return period 500 years obtsained from a calculation by the authors or referred to other data from e.g. an agency of meteorological survey? How long: how many years is the duration of actual rainfall observation data for the calculation of the rainfall return period for this gauging site?

I have sited the reference for the 500 year return period in the text and I have also added a sentence to explain how it was obtained. It is a probability thing as opposed to records of similar intense rainfall events. In other words it is possible that a similar rainfall event could occur in less than 500 years.

Lines 124, 167, and 172: Is it appropriate to use "c." instead of the term "about" in the manuscript of original article? *We see no problem with using c. – please advise otherwise.*

Line 175: Description "100s of m" is hard to be understood. *Now sorted.*
Line 210: Is the location of the description "(Fig. 7)" is appropriate in the sentence? *Now removed*
Line 216: Why you say "are not significant"? I think it preferable to say "are meaningless". *Changed*.

Line 222: Please supply the exact acquisition dates of LIDAR data and the aerial photography data. It would be necessary that there are no significant changes in the topography of the study terrains between two data sets.
We have included dates for LIDAR, there is some uncertainty about photo dates, but we know they pre-date the debris flow event.

Lines 274-276: The authors indicate "the presence of irregular fingers of higher elevation. Is it capable to differentiate those deposits from "debris lobe" or "debris-flow lobe" which were defined and used by e.g. Hooke (1967), Johnson (1970), Lowe (1976), Pierson (1980) and Suwa and Okuda (1983)?
These fingers may very well be debris lobes but post debris-flow cleanup makes it difficult to ground-truth these features (i.e. measure the dimensions, morphology and grainsize distribution of these features). In addition, where we mention these in this section we are trying to demonstrate observations that can be made from the Lidar differenced data and not interpret the processes responsible for there formation. Later in the Discussion section we do provide some interpretations of the processes based on a comparison of field, photo and Lidar data (i.e. the formation of the broad fan area and the lobate structure at the distal margins as well as the smaller fan structures emanating from the front of the broad fan.

Lines 338-341: Source of the data described should be referred here in the text. *Done.*
Line 396: Why "?" is attached to "Hayden Reed"? Is it appropriate? *Question now removed*
Line 397: What does "HM" mean? *Sorted*
Line 493: Indication of the exact date of the image would be preferable. *See comment above.*
Lines 499-516: Indication of the exact dates when these photos were taken is preferable. *Where known this has been added to figure caption.*
Line 521-532: It would be preferable to indicate and draw lines in each map to show the extents of the remediation and subsequent clean-up operations were executed. *This is included in Figure 11 (now improved), and in discussion.*

Editor's comments:
I have addressed all your comments on style in the revised manuscript.
We have uploaded high resolution images of figures now. Please note that we have improved clarity of many of the figures.

Assessing debris flows using LIDAR differencing: 18th May 2005 Matata event, New Zealand.

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ABSTRACT

The town of Matata in the Eastern Bay of Plenty (New Zealand) experienced an extreme rainfall event on the 18th of May 2005. This event triggered widespread landslips and large debris flows in the Awatararariki and Waitepuru catchments behind Matata. LIDAR (Light Detection and Ranging technology) data sets flown prior to and following this event have been differenced and used in conjunction with a detailed field study to identify the distribution of debris and major sediment pathways which, from the Awatararariki catchment, transported at least 350,000 ± 50,000 m^3 of debris. Debris flows were initially confined to stream valleys and controlled by the density and hydraulic thrust of the currents, before emerging onto the Awatararariki debris fan where a complex system of unconfined sediment pathways developed. Here, large boulders, clasts, logs and entire homes were deposited as the flows decelerated. Downstream from the debris fan, the pre-existing coastal foredune topography played a significant role in deflecting the more dilute currents that in filled lagoonal swale systems in both directions. The differenced LIDAR data has revealed several sectors characterised by significant variation in clast size, thickness and volume of debris as well as areas where post-debris flow cleanup and grading operations have resulted in man-made levees, sediment dumps, scoured channels and substantial graded areas. The application of differenced LIDAR data to a debris flow event demonstrates the techniques potential as a precise and powerful tool for hazard mapping and assessment.

1. Introduction

High-resolution mapping techniques, such as LIDAR (Light Detection and Ranging technology) have the potential to precisely identify and quantify morphological change following a geomorphic event, predict hazard pathways, and map coastal evolution to a high level of accuracy (Revell et al., 2002; Stockdon et al., 2002; Sallenger Jr et al., 2003; White and Wang 2003; Shrestha et al., 2005; Joyce et al., *2009*). LIDAR technology has been applied in a number of scientific investigations to rapidly produce detailed topographic models which provide advancements in geomorphological and coastal research (Stockdon et al., 2007). LIDAR is an optical technique that uses the time taken for reflected light to return from objects or surfaces to determine the range, in a similar manner to radar.

In this paper, we present an analysis of LIDAR data flown prior to and following a debris flow event at Matata, Bay of Plenty, New Zealand, to identify, map and precisely quantify morphological change. In particular, the study proposes a methodology for LIDAR differencing, and demonstrates this is an effective and valid approach for analysis of sedimentary processes and landscape evolution following a terrestrial slope failure event.

Debris flows are a type of terrestrial slope failure or landslide characterised by rapidly moving, water-saturated, non-plastic debris in a steep channel (Hungr, 2005; McSaveney et al., 2005). The principal factors controlling debris flow formation include the duration and intensity of rainfall, the geology and topography of the catchment, rock and soil types, climate, runoff, groundcover and moisture conditions (Manville *et al*., 2005). This form of slope failure has huge erosive and destructive potential due to its mass, volume, velocity, mobility and run out distance. Debris flows are typically initiated as a landslide on a steep slope before developing into a rapid flow confined by a steep channel, ultimately depositing material downstream on a debris fan (Davies, 2005). The debris fans that develop at the distal end of the depositional zone are often preferred sites for urban development and modification, and they consequently present an increasing hazard to human settlement (Wilford et al., 2004).

Geophysical mapping techniques have aided identification of such areas prone to debris flows; however there is only a minor appreciation of the threat posed by such phenomena as a result of the infrequent nature of debris flows within any one stream (McSaveney and Davies, 2005). Scientific investigations using LIDAR have highlighted the broad applications of this technology, however there currently is very little research applying this technology for debris flow hazard analysis and morphological change recognition. A recent study that was able to characterise 92% of the lahar (a similar gravity driven flow phenomena to debris flows) path from the 2007 Crater Lake breakout on Mt. Ruapehu in New Zealand revealed that LIDAR is most effective as a mapping and hazard analysis tool when used in combination with other remote sensing data such as satellite imagery (Joyce et al., *2009).* The advantage of LIDAR over conventional geodetic techniques is that it can give a synoptic view over a large area.

LIDAR data sets flown before and after a debris flow event are compared in this paper, and used for mapping morphological change and for identification of transport and sedimentary processes operating in a dynamic coastal zone. The paper aims to offer one of the first comprehensive assessments of morphological change using LIDAR differencing, to augment understanding of sedimentary transport processes from field and eyewitness accounts, and to more accurately determine the volume of the debris fan deposits and the post event clean-up and rehabilitation measures. These components are important for land-use planning for future hazard mitigation.

2. Regional Geologic Setting

Matata is a small township, located at the coastal fringe in the Eastern Bay of Plenty, in the North Island of New Zealand (Figs. 1 and 2). It sits on the western edge of the Whakatane Graben which is a regional tectonic feature undergoing active extension and forms the northern part (both onshore and offshore) of the Taupo Volcanic Zone (TVZ) (e.g. Beanland et al., 1990; Beanland and Berryman, 1992; Wilson et al., 1995; Rowland and Sibson, 2001; Taylor et al., 2004; Lamarche et al., 2006; Rowland et al., 2009). The TVZ is a rifted volcanic arc (Wilson et al., 1995) that is the product of the coupling between the Pacific and Australian lithospheric plates at the Hikurangi subduction margin off the east coast of the North Island of New Zealand. Rifting in the TVZ is manifest in a series of fault systems, the most active of which is now within the Whakatane Graben. From offshore seismic reflection data, Lamarche et al. (2006) determined a crustal extension rate of 12.6 ± 3.5 mm/yr for the last 20 kyr across the Whakatane Graben. The extension rate decreases to the southwest, along the axis of the TVZ, to < 4 mm/yr at the distal southern end of the zone (Villamor and Berryman, 2006).

The coastal zone in this part of the Bay of Plenty region is characterised by inland and coastal sand dunes, as evident at Matata, and also drained peat swamps and flood plains composed of pumiceous alluvium (i.e. the Rangitaiki Plains; Pullar and Selby, 1971; Nairn and Beanland, 1989). The town itself is situated between the former wetlands and the steeply rising hills behind, which are composed of mid to late Pleistocene fluvial gravels, marine sediments and interbedded rhyolitic airfall tephra deposits erupted from the TVZ. The stratigraphic sequence is capped by the Matahina ignimbrite, also erupted from the TVZ, which is ~300 ka (Bailey and Carr, 1994; Manning, 1996) and extends back into and above the Awatarariki and Waitepuru catchments behind Matata. The Matahina ignimbrite rests directly on marine/beach sediments at a maximum elevation of ~250 metres above modern sea level which corresponds to significant uplift (c. < 1 mm yr^{-1}) post c. 300 ka (Gravley et al., in prep). The northern edge of the uplifted block experienced coastal erosion up until c. 7 ka with the remnant coastal cliffs visible today.

3. Eyewitness, Photo and Field Observations of The Matata Debris Flows, 18th May 2005

Matata was originally settled on an elevated plateau in front of relatively stable and well-vegetated hills, and has since spread to a less safe and active depositional fan area. On the 18th of May 2005, a band of intense rain passed over the hills behind Matata, generating several landslides that coalesced to form two large debris flows within the Awatarariki Stream (catchment area 4.5 km^2) and Waitepuru Stream (catchment area 1.3 km^2) (Bassett, 2006) (Figs. 2 and 3). The closest automatic rain gauge to Matata is about 5 km SSE of Matata (V15: 412 555, near Awakaponga) and on 18th of May 2005 this station recorded a 24-hour rainfall of 322 mm. The intensity of the rainfall event is further highlighted by a 1-hour rainfall of 94.5 mm, peaking at 30.5 mm in 15 minutes (McSaveney et al., 2005). Despite little data on past rainfall events of this intensity, 94.5 mm in an hour represents a c. 1 in 500 year return period event at this location based on an intensity (rate) that is 30% greater than the 1%-annual-excedence-probability (see McSaveney *et al*., 2005 and references therein).The debris flows ultimately emerged from the steep catchments and spread across a fan head at the coastal fringe, destroying 27 homes and transport infrastructure within Matata (Hikuroa et al., 2006).

Rapid and recent uplift, combined with the presence of a resistant cap rock (the Matahina ignimbrite) has produced an immature landscape susceptible to debris flows. The Matahina ignimbrite is 20 to 30 metres thick, forms vertical cliffs and has a uniform and relatively impermeable flat-topped surface that protects the underlying, weak to very weak mudstones and siltstones from pervasive erosion (Costello, 2007). From field observations, Costello

(2007) modelled a scenario for slope failure whereby the mudstone and siltstones form over-steepened slopes with weathered surfaces that are susceptible to shallow, scallop-shaped slope failures that deliver debris to the stream valleys below. The head scarps from these failures subsequently undermine the overlying ignimbrite, triggering instability and toppling of large slabs of rock. These failure processes are compounded by the presence of unconsolidated sand beds lower in the stratigraphy and close to stream level, allowing for massive undercutting of thick mudstone. The result is massive rock failure and the development of near-vertical and boxed canyon-shaped cliffs with steep debris fans containing up to 100 m^3 of boulder to mud-sized grains (Costello, 2007). Together, these slope failures at different levels within the catchment stratigraphy occur on a semi-annual basis and the result is a continuous recharge and supply of boulders, gravels, sand, silt, mud and woody debris to the base of the stream valleys (recharge topple events have been witnessed and recorded by Costello, Gravley and Hikuroa since the May 18 2005 event). The debris then sits perched and ready to be mobilised in the next extreme rainfall event like the one that occurred on May 18 2005.

On May 18 2005, the peak rainfall event triggered several landslides within the Awatariki catchment. As described above, these landslides delivered a mixture of boulders, gravels, fines and large woody debris to a rapidly rising stream (McSaveney et al., 2005; Costello, 2007). The result was an increase in the mass and volume within the surging current which was then able to mobilise existing and perched ignimbrite boulder beds in the upper catchment and further scour and undermine the channel walls which created fresh debris downstream (Costello, 2007). Based on eyewitness accounts from the landowner adjacent to the stream channel, and oblique aerial photo interpretation (including Fig. 4 and 5), the following sequence of events have been re-constructed. The first surging, debris-laden currents to emerge from the hills passed beneath the railroad bridge and followed an existing stream channel that delivered fresh sediment to the south-eastern lagoon (see Fig. 4). As debris began to pile up behind the rail bridge, it became a sediment barrier that cut off flow into the aforementioned channel and ultimately failed from the back pressure of the subsequent debris flow pulses that were more voluminous and carried the large ignimbrite boulders. Following the failure of the bridge, the debris flows became unconfined, spread out across the pre-existing debris fan, and quickly decelerated which triggered rapid deposition of the heavy boulders and logs (Fig. 5). The rapid loss of mass created a transition from debris to hyperconcentrated flows that carried finer sediment 10's of metres further before it was deposited as smaller lobate fan structures (Fig. 5) and debris floods developed as the currents became even more dilute (Costello, 2007). The debris floods were topographically controlled by the coastal foredunes and followed pathways parallel to the coast, delivering sediment to the lagoon systems (Fig. 6).

The spatial distribution of boulders is not uniform over the debris fan: larger boulders of mudstone and ignimbrite are generally deposited on the seaward side of State Highway 2, and a less confined, c. 250 m stretch of the Awatarariki Stream prior to reaching the debris fan. Smaller and less dense boulders of material were transported further and can be found in the distal areas of the fan. Fines and gravels can be found in all areas of the debris fan, and provided the material strength to transport larger boulders. Further evidence of the ability of the flow to transport objects is the presence of large woody debris. Whole-sized trees make up c. 10% of the debris, and were particularly deposited in the lagoon and distal parts of the fan where flow momentum decreased. Anthropogenic debris such as cars, sheds and houses etc are present throughout the debris flow, and some of the larger objects have been transported several hundred metres. While the debris flow deposits from the Waitepuru Stream have a similar lithologic content they lack the abundance of large boulders present in the deposits of the Awatarariki Stream. In this paper, we focus primarily on the depositional fan and associated sedimentation from the Awatarariki debris flows.

4. Methods

This study is based on three high-resolution LIDAR data sets (Fig. 7) which surveyed the coastal zone and wider Rangitaiki Plains in the Bay of Plenty, New Zealand in 2000 and 2006. Prior to the Matata debris flow event, a LIDAR data set was collected on the 31st May and 1st June 2000 covering the coastal strip at Matata (Run 5 and 6 - an area of 7.4 km^2). After the Matata event, LIDAR data was acquired on the 26th June 2006 specifically over the debris fans. This data images a 3.2 km^2 swath of ground which covers Matata town and the adjacent coastal and lagoonal environments. Finally, a component (Rang 3 and 4) of the larger Rangitaiki Plains LIDAR data set flown on 14th December 2006 that covers the coastal strip and Rangitaiki Plains adjacent to Matata (an area of 5.2 km^2) was used. In the following section we describe analysis of the different data sets, the formation of a single year (pre-debris flow) 2000 data set and a single year (post-debris flow) 2006 data set, and the differencing of the 2006 and 2000 data sets. Begg and Mouslopoulou (2009) describe the complete December 2006 dataset, but do not discuss the Matata debris flow event.

The LIDAR data was collected using different systems at different times, and therefore there was an initial stage of pre-processing and inspection of the data to determine the point density/spatial resolution, and comparability. Point density was calculated in areas where the data sets overlapped by analysis of 50 m^2 bins. This analysis indicated that Krigging of the data onto a 4 m spaced grid was appropriate. In the vast majority of the survey area there were between 2 and 5 data points within each 4 m bin (Miller, 2008).

Testing of the vertical accuracy of the LIDAR data can be achieved by comparing RTK (real-time kinematic) terrestrial topography data from the Matata region with the recently acquired

LIDAR data (see Miller, 2008 for more details). Due to the sporadic nature of the bench mark sites, only one point is found in a location of both 2000 and 2006 data coverage. The differences between the ground point and LIDAR data in this instance range between +0.34 m and +0.4 m. Although this is slightly higher than best-case vertical accuracy estimates for the LIDAR data (± 0.15 m), the difference suggests that the LIDAR datasets are comparable to surface topography data.

In order to check on the validity of combining the different gridded LIDAR data sets, a comparison of the vertical height differences was made between the different data sets (Fig. 7) in areas of overlap away from man-made features, where topography was relatively subdued, and away from the dynamic coastal fringe. We examined areas of overlap between Run 5 and Run 6 for the 2000 LIDAR data. For the 2006 data, Rang 3 and Matata, Rang 4 and Matata and the overlap between Rang 3 and Rang 4 were analysed.

From the vertical difference of the selected area, an error range was selected to represent the mean differenced value ± 1 standard deviation (Table 1). The largest error range is calculated to be ± 0.2 m (Table 1), which means that when differencing the LIDAR data sets elevation changes less than ± 0.4 m are meaningless.

Following vertical accuracy testing of the data, the two separate runs from the 2000 data (Run 5 and 6) were combined. A composite file was also produced for the 2006 data using the Matata, Rang 3 and Rang 4 data sets. The two composite rasters (gridded at 4 m) were differenced and the output image interpreted. Drawing upon the results above, data values which fell within the defined error range of ± 0.4 m were excluded.

Georeferenced aerial photography provided a high-resolution collection of images covering Matata town, the coastal zone and the wider Rangitaiki Plains, which helped validate the findings of the LIDAR data, and enabled further insights into the terrain, sedimentary processes and hazard assessment.

5. Results

The topographic maps using the LIDAR data record the land surface pre- and post-event (Fig. 8). The spatial extent of these maps range from the base of the steeply rising hills located behind Matata to the coastal and dune system. This region fully covers the area where the Awatarariki Stream channel loses confinement and also maps the township of Matata and the surrounding coastal flats and lagoon environment. The more recent 2006 LIDAR data set also includes data mapping the Awatarariki Stream and catchment, which extends into the hills behind Matata.

The quality of the pre-event LIDAR data is reduced in comparison with the 2006 data set, the latter having higher point density and greater vertical accuracy and horizontal resolution. This accounts for the sporadic data gaps in the 2000 topography (Fig. 8). Despite this, change in topography over the intervening period is clearly visible, and areas where previous low elevation has preferentially increased in height are identifiable. The changes in topography show a general increase in elevation across the coastal flats, with up to 2 m of height increase in certain locations. This sediment deposition is in the form of a fan, the apex of which is at the point where the Awatarariki Stream loses confinement (i.e. the drainage point of the Awatarariki Stream catchment). The topographic data further illustrates that a more defined channel flowing into the lagoon has developed in the intervening period between 2000 and 2006 (Fig. 8). This channel is characterised by flanking levee deposits of increased elevation (see later discussion for the origins of this change). In addition, the lagoon environment which this channel flows into is also well defined by the LIDAR data.

The LIDAR data in the topographic plots is used primarily to examine the key region of interest, and has demonstrated significant change in topography following the Matata debris flows. This can be further assessed and built upon through comparison with the differenced plots, which precisely map the distribution of morphological change following the debris flow event in 2005. These plots illustrate quantifiable areas of erosion and deposition in the form of sedimentary features and geomorphic landforms associated with the Awatarariki Stream course. Erosion scarps and pockets of deposition are captured in the differenced image along the coastal hill slopes west of Awatarariki catchment (Fig. 9a, area A).

The Awatarariki Stream, which conveyed a large proportion of the debris flow, can be identified in the differenced plot as an s-shaped channel traversing the coastal flats from west to east and connecting with the lagoonal depositional environment (Figs. 9a and b, Line B-B’). There is evidence for 1 – 2 m removal of material at the channel bed and a further removal of up to 2 m to the east of the channel (Figs. 9a and b, areas C and D respectively). Elongated levee deposits flank this channel and are approximately 10 m in width (although this is variable and can be as wide as 20 m) and have a mean height of around 1 m, with a maximum height of 4.5 m (Fig. 9b, Line B-B’). These mapped changes in elevation are comparable to the findings of the topographic plots.

Deposition of material on the coastal flats in the vicinity of Matata is in the general form of a fan, with sediment deposition taking place at the point where the Awatarariki Stream loses confinement (Fig. 9a, Point E). We define the main depositional fan as the area between the point of flow expansion (Point E) and the lobate fan structures (J-J’; Figs 5 and 10), where the transition between debris flows/hyperconcentrated flows and debris floods occurs (see Section 3)

Both the topographic plots and the differenced data show that at point E, there is an increase in depositional area due to lateral flow expansion and material expelled onto the debris fan in a process which built topography. The same data clearly shows, beyond the debris fan, infilling of topography that parallels the coastline to the northwest (where a wetland existed, Fig. 2., prior to the flow event) and to the southeast towards the lagoon (Fig. 10). Another factor characterising fan development is the presence of irregular fingers of higher elevation (Fig. 9, area F). At the margins of the debris fan is an anomalously large, oval shaped deposit approximately 200 m in length, 50 m in width and of a maximum height of 11 m (Fig. 9a, area G).

The lagoonal system is characterised by patchy data coverage because the water prevents consistent reflected LIDAR returns and no elevation can be calculated. However where water depth is particularly shallow then some elevation data (e.g. bathymetry) could be obtained. Despite these issues, there are a number of data points which map elevation in the western lagoon section which show that there is a net increase in residual silt levels following the debris flow and subsequent debris flood. The differenced plot suggests the silt level equals, and in places is up to 0.7 m higher than the original bathymetric level (Fig. 9b, area H). The difference plots delineate the lateral extent of deposition within the lagoon (Fig. 9b, area I). This coincides with the presence of a causeway which bisects the lagoon and appears to have effectively acted as a barrier to the spread of debris further to the east.

6. Discussion

The LIDAR data has successfully identified, mapped and precisely quantified morphological change following the terrestrial slope failure event at Matata. The differenced data identified the location of sediment deposition and erosion and has been used to confirm the sediment transport and deposition processes described by eye witnesses and subsequent field observation. However it is important to recognise that the differenced data delineates landscape change due to both the debris flow and flood, but also the subsequent clean-up operations. The post-event clear up operations are best shown by the oval-shaped sediment deposit (area G, Fig. 9a), which is the largest positive elevation in the differenced plot in an area of previously low topography and was the site where material was moved to and dumped during clean-up operations. Additional anthropogenic modification detected in the LIDAR data include the build up of levees (B-B', Figs. 9a and b) from material (up to 2 m deep) excavated from the stream channel floor (Fig. 9a, area C). These levees have been constructed to augment a confined flow path within the excavated channel and, thus, constitute the surface morphology visible today. These examples of post-event modification of morphology demonstrate LIDAR differencing can be a valid and effective tool to identify mass movement and precise changes in the landscape over a small area. However, LIDAR cannot be used in isolation and complementary field studies are required to validate anthropogenic modification. Furthermore, it is desirable that LIDAR data should be flown immediately following an event (i.e. before clean-up operations) if the natural landscape-modifying processes are to be fully understood.

Eyewitness and field observations were used to determine the spatial variations in flow processes (Section 3), but the differenced plot (Fig. 9a) clearly detects mini finger-like levee structures on top of the debris fan (from point E to Line J-J') and the lobate boulder train deposit at the edge of the fan. This arcuate-shaped feature in the differenced LIDAR data marks the point at which the boulder front stalled and the more dilute material from the main body of the flow broke through (Hungr, 2005), developing smaller subsequent fans and feeding an area of low topography to the northwest (the elongate wetlands seen in the coastal strip northwest of the Awatarariki debris fan in Fig. 2). Comparison of topographic maps (Fig. 8) of the land surface pre- and post-event reveal that this area, of previous low elevation, preferentially increased in height due to deposition of material that was transported along identifiable pathways controlled by pre-existing topography (Fig. 10). This is the most obvious example of topography-driven flow.

The topographic and differenced LIDAR data further identify a sediment pathway to the southeast (Fig. 10), where a proportion of material was transported to the lagoon system via a pre-existing channel. The presence of debris including large trees at the exit of this channel in the lagoon (Fig. 9b, area H) suggests that to begin with, this channel provided a conduit to the lagoon. It can be inferred that this channel was infilled relatively quickly following the initiation of the debris flow event, given the volume of material and the clast rich and boulder bearing surges which characterised the event. Hard to very hard (welded) ignimbrite boulders from the Matahina formation and weak siltstone and silty sandstone boulders which originate from the Pleistocene marine sediments found in the catchments behind Matata are the source of these clast rich and boulder-bearing surges (McSaveney et al., 2005). Eye witness studies suggest that the channel was subsequently bypassed after the rail bridge initially trapped material, and then failed allowing the debris fan to become unconfined (Fig. 10).

The differenced LIDAR data can be used for precise quantification of morphological change following the terrestrial slope failure event at Matata but it has some limitations. The raised foredune system prevented loss of material to the sea, however a substantial amount of material entered into the lagoon system, and this material was not fully detectable by the LIDAR differencing due to the water layer absorbing the light. Recently collected core data acquired within the lagoon as part of Matata Regeneration works by Tonkin and Taylor Ltd, found that between 0.4 and 1.8 m of debris from the 2005 event was deposited in the lagoon with an average thickness of 1.0 m. Our approach is to use the differenced LIDAR data to calculate the volume of the debris flow outside of the lagoon, and the core data to calculate the amount deposited within the lagoon. These volumes can then be compared to the estimates of Costello (2007) who used field surveying to estimate the amount of material outside of the lagoon.

In our calculations we divide the area of deposition into the main debris fan and the area of the debris flood to the northwest of the fan. We add in the material moved as part of the clean-up operation into our estimate where this was easily identified. Table 2 summarises the total volumes calculated from the field observations, and from the LIDAR data. For the areas outside of the lagoon we find 300,000 m^3 derived from field observations, and 260,000 m^3 from the LIDAR differencing. Errors on these estimates are large, perhaps ± 50,000 m^3, and therefore the estimates from the two different approaches are broadly consistent. Any systematic difference is most likely to be due to difficulties in estimating the thickness of deposits in areas of low lying relief in the field observations.

The 27 boreholes acquired were concentrated within the centre of the lagoon system, and therefore we do not have good control on deposition at the margins of this area which were flooded during the event. Taking a conservative approach we find that a minimum of 90,000 m^3 was deposited within the lagoon, beyond the detection limits of the LIDAR data (under water). We therefore find a total debris flow volume of 390,000 ± 50,000 m^3 estimated by field observations and 350,000 ± 50,000 m^3 estimated by the LIDAR data. These figures are both substantially higher than the estimate made by rapid reconnaissance immediately after the debris flow of c. 250,000 m^3 (McSaveney et al., 2005). The major reasons for this discrepancy are likely to be underestimates of the material deposited by the debris flood in areas of originally low topography.

These findings demonstrate the capabilities and huge potential of LIDAR to precisely quantify change following a mass movement event, and build upon field observations to calculate volumetric change. Such accurate measurements of morphological change are vital in precise hazard assessment studies. In particular, accurate calculations for the volume of debris that came from the Awatarariki catchment during the 2005 event are essential to making future land-use planning decisions and mitigating damage to infrastructure and lifelines (i.e. rail and road bridges) through appropriate engineering and design. The frequency of debris flows emanating from Awatarariki catchment is poorly understood, but what is known is that the catchment has been destabilised and landslips continue to deliver fresh sediment to the valley floor today. As a consequence, the triggering of a future debris flow event of a similar magnitude may not require a 500-year rainfall event. If and/or when the next debris flow event occurs, it is clear that LIDAR could be used to accurately assess volumetric change and significantly aid clean-up operations.

7. Conclusions

A terrestrial slope failure event in New Zealand has been successfully mapped and investigated using a LIDAR differencing technique. This investigation confirms the capabilities and validity of using high-resolution differenced LIDAR data sets as a geophysical mapping tool for coastal science and mass movement assessments. LIDAR differencing permits precise quantification and accurate mapping of a dynamic environment following a terrestrial slope failure event, and is useful for hazard assessment.

The LIDAR differencing technique estimated a minimum volume of 350,000 ± 50,000 m^3 for the debris flows which is comparable to estimates from detailed field observations 390,000 ± 100,000 m^3. The LIDAR data gives a comprehensive overview of the deposit, and identified volumes deposited by both the debris flow, but also the debris flood. The infilling of pre-existing low topography by the debris flood was notable in the Matata event.

While LIDAR differencing can be successfully used to study landscape evolution and make volumetric estimates of change, it is important that the post-event survey occurs immediately following the event, and before any major site remediation has taken place.

Acknowledgements

We are grateful to Environment Bay of Plenty Regional Council, New Zealand, for provision of the LIDAR and terrestrial topography data, and thank Peter West and Mark Langridge for their assistance. Helen Miller was supported by the University of Southampton (Richard Newitt Bursary) and the Society for Underwater Technology (Educational Support Fund). Without the ground support of Anthony Olsen and the Matata Community Centre, the field work would not have been possible. In addition, the eyewitness accounts provided by Neville Harris were invaluable to this research. We thank David Bouma of Tonkin and Taylor Ltd for making available core information within the lagoon. We thank Colin Wilson, Julie Rowland and Pierre Cazenave for their support.

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Figure Captions

Fig. 1. Regional setting of Matata on the northern edge of the Taupo Volcanic Zone (TVZ), New Zealand. Major rivers are indicated draining northward into the Bay of Plenty.

Fig. 2. Aerial photo (260-V15) showing location of Awatarariki and Waitepuru catchments behind the coastal cliffs around Matata, Bay of Plenty, New Zealand. These catchments produced the damaging 18th May 2005 Matata debris flows. The image was taken prior to the debris flow and shows wetlands in the coastal strip west of the Awatarariki Stream which were covered by the debris flow.

Fig. 3. 3D perspective of Awatarariki and Waitepuru catchments created using a 5 m DEM from LINZ 1:50,000 contours, and spot heights. The position of Matata and the coastal corridor seaward of the palaeo-cliffs are indicated.

Fig. 4. Aerial Photograph (courtesy Terrain Consultants) showing in detail where the debris flow emerged from the confinement of the Awatarariki Stream. The first debris-laden currents passed beneath the railroad bridge and followed an existing stream channel (indicated by the white dotted line). After debris build-up behind the bridge and its failure,

the main debris flow bypassed the channel and spread out in an unconfined way across the pre-existing fan with huge truck-sized boulders visible in the proximal fan. Remediation efforts had just commenced when this photograph was taken.

Fig. 5. Aerial photograph (courtesy Whakatane Beacon, taken 18th May 2005) showing the debris flow from the Awatarariki Stream. The emergence of the Awatarariki Stream onto the flat coastal plain is visible, as is the lobate boulder train. This photograph was taken before any remediation activity and is a good record of the immediate aftermath of the debris flow. Large boulders were limited to the area between the line of the buildings and the base of the hill. Fine debris was deposited as a debris flood in the foreground, while the dashed white lines indicate small lobate fan structures.

Fig. 6. Oblique aerial photograph (courtesy Whakatane Beacon, taken 18th May 2005), looking southwest, showing debris entering the western portion of the Matata lagoon, and associated silt-laden waters. Much of the fine sediment was not confined to the fan from the Awatarariki Stream, but was carried into the lagoon.

Fig. 7. Location of LIDAR data files – Run 5, Run 6, Matata, Rang 3 and Rang 4. Aerial photographs for context were flown in March 1987 by New Zealand Aerial Mapping Ltd. Areas of overlap used for analysis in producing the integrated pre-debris flow (2000) and post-debris flow (2006) topography are indicated.

Fig. 8. Composite figure of a selected area affected by the debris flow. **A**: 2000 topography **B**: 2006 topography. All contours at 1 m intervals.

Fig. 9. Difference in vertical height between the 2000 and 2006 LIDAR data (a) for an area including the Awatarariki stream and (b) an area to the east including Matata lagoon (locations shown in Fig. 2). Contours are at 1 m intervals. Lettered areas are referred to in

main text. Classification of heights around the mean has resulted in high values assigned no colour, as at area G. In this location, the maximum height is 11 m.

Fig. 10. Sediment pathways map, showing deposition following the 2005 Matata debris flow event. Arrows show the sediment transport pathways. Line J – J' is discussed in the main text.

Table 1. Vertical height comparison in areas of data overlap (Fig. 7). The range of vertical height difference of clipped areas is biased by the inclusion of outliers, and therefore a better measure of the differences is the mean ± 1 standard deviation.

Year flown	Data sets compared in overlap area	Range of vertical height differences (m)	Error range (m) Mean ± 1 Stdev	Overall max error range
2000	Run 5 + Run 6	-1.44 – 0.76	**-0.07 ± 0.18**	**± 0.4 m**
2006	Rang 3 + Matata	-0.31 – 1.00	**0.18 ± 0.125**	
	Rang 4 + Matata	-0.87 – 0.86	**0.1 ± 0.16**	
	Rang 3 + Rang 4	-0.02 – 0.20	**0.1 ± 0.1**	

Field Observations	Location	Volume (m^3)
	Main Debris Fan	110,000
	Debris Flood (to the north-west)	190,000
	Total Field	**300,000**
LIDAR Differenced data		
	Main Debris Fan	120,000
	Debris Flood (to the north-west)	80,000
	Material moved before LIDAR acquired	60,000
	Total LIDAR	**260,000**
Sediment Cores in Lagoon		
	Sediment deposited in lagoon (Minimum)	90,000
Total LIDAR-based (Minimum)	Field observations + Lagoon	**390,000**
Total Field-based (Minimum)	LIDAR + Lagoon	**350,000**

Table 2. Estimates of volume of debris flow produced by Awatariki Catchment in Matata 2005 debris flow calculated from field observations (Costello, 2007) and using LIDAR differencing (this paper), and using thicknesses of 27 sediment cores within the lagoon. Some of differences between seen in estimates of Debris Fan and Debris Flood deposits between the field observations and LIDAR data, could be due to clean-up prior to the second LIDAR flight. Where known, the volume of material removed (e.g. to location G, Fig 9a) has been incorporated in the estimates.

Figure1

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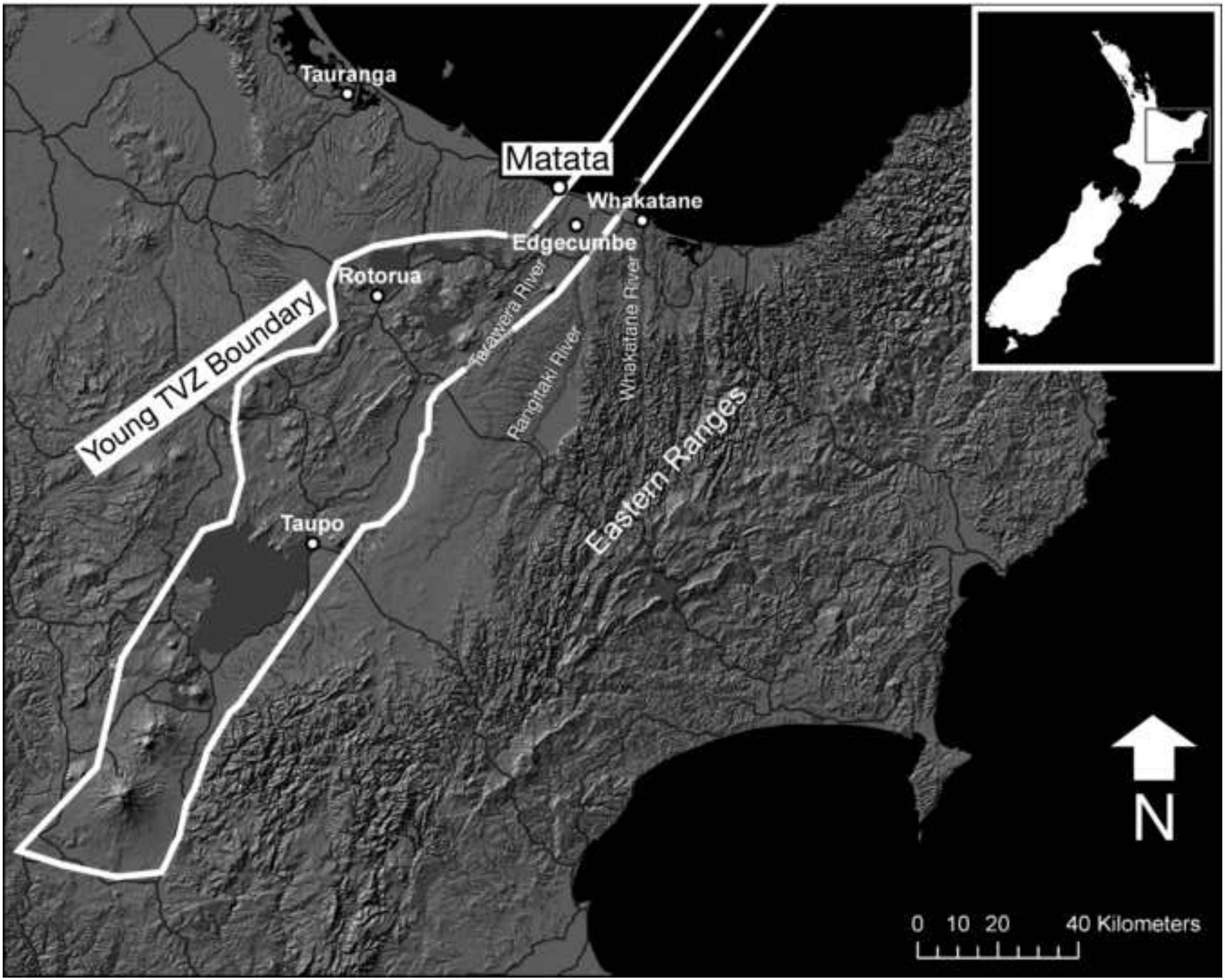

Figure2

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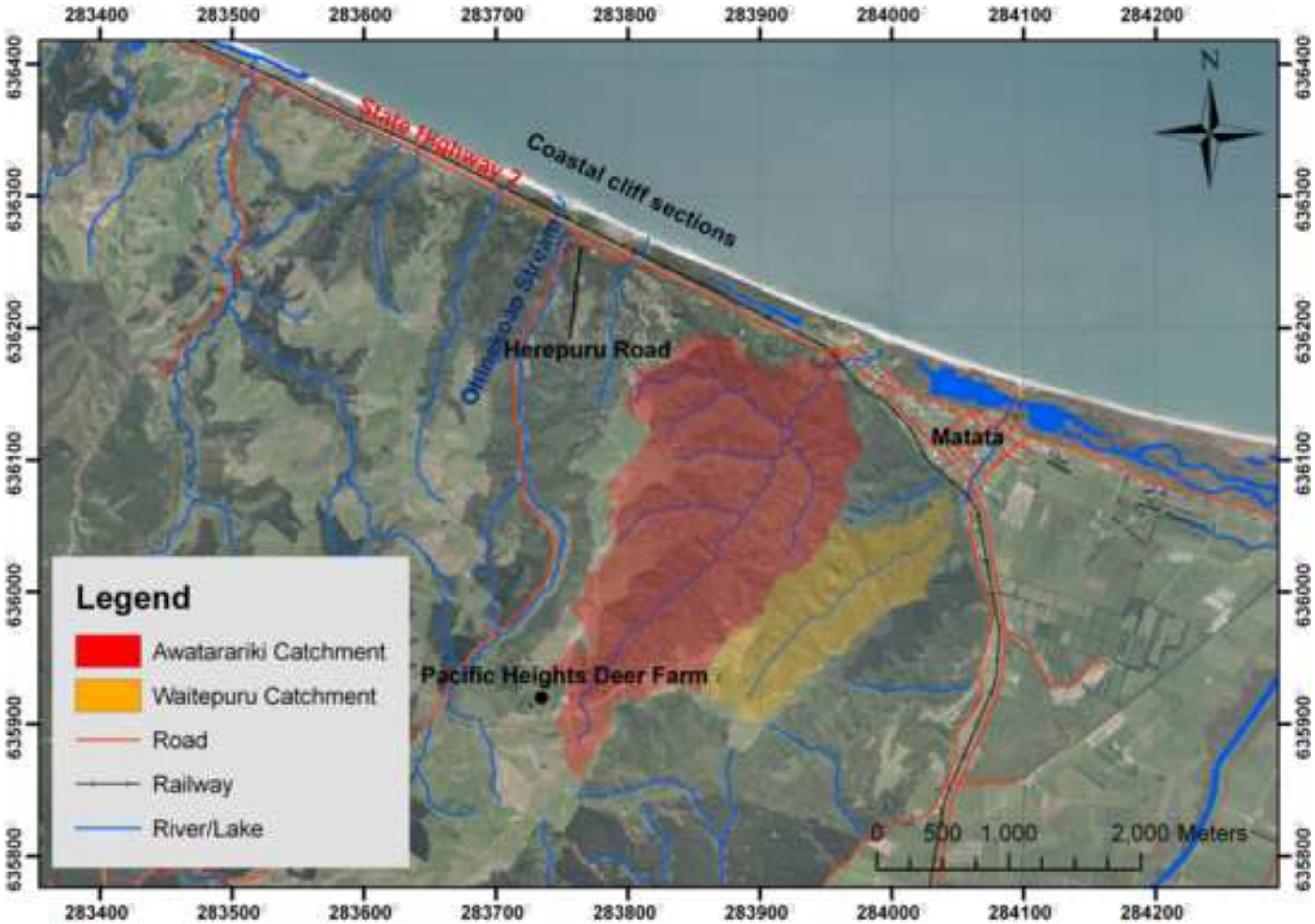

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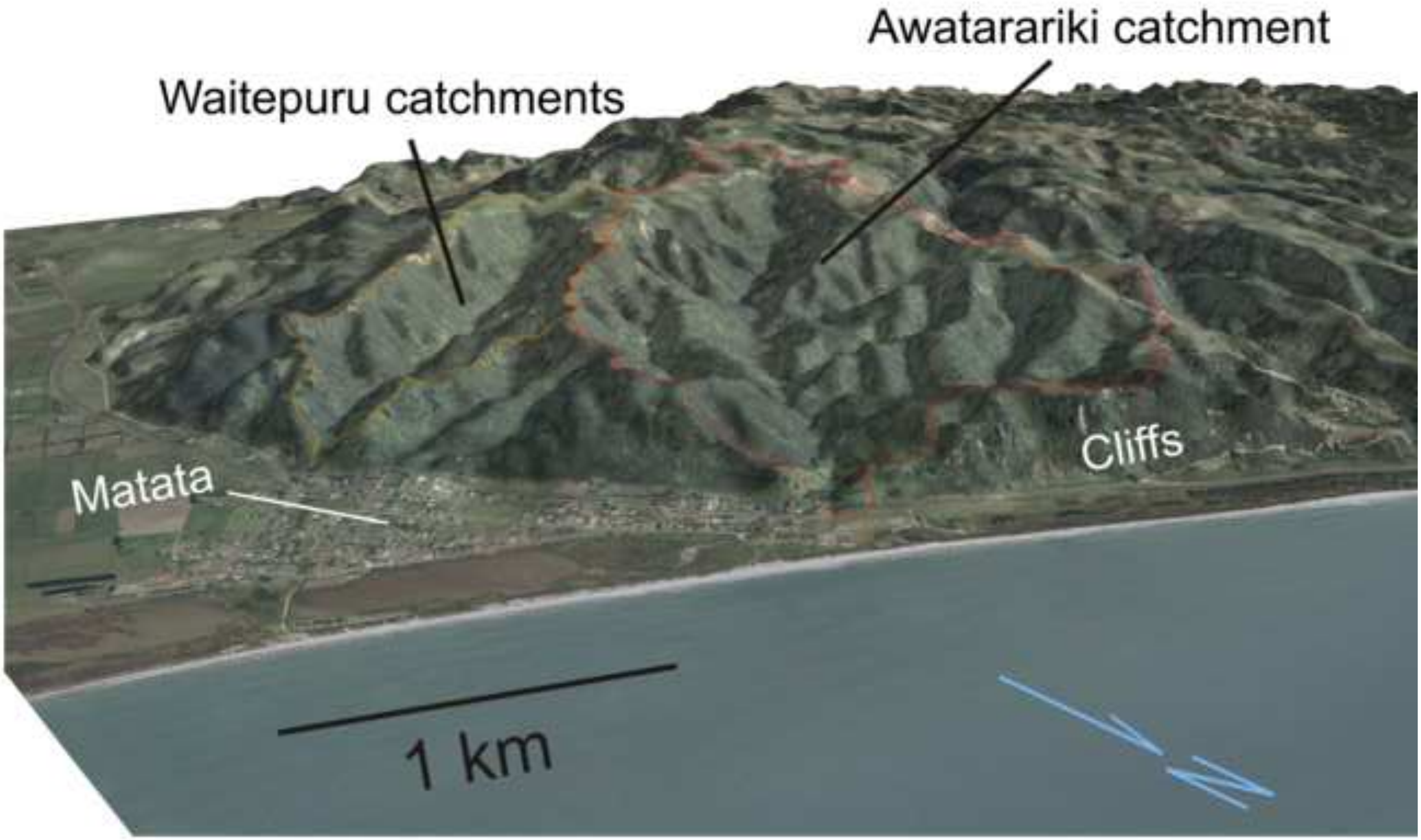

Fig. 3. 3D perspective of Awatarariki (red) and Waitepuru (yellow) catchments created using a 5 m DEM from LINZ 1:50,000 contours, and spot heights. The position of Matata and the coastal corridor seaward of the palaeo-cliffs are indicated.

Figure3_bw

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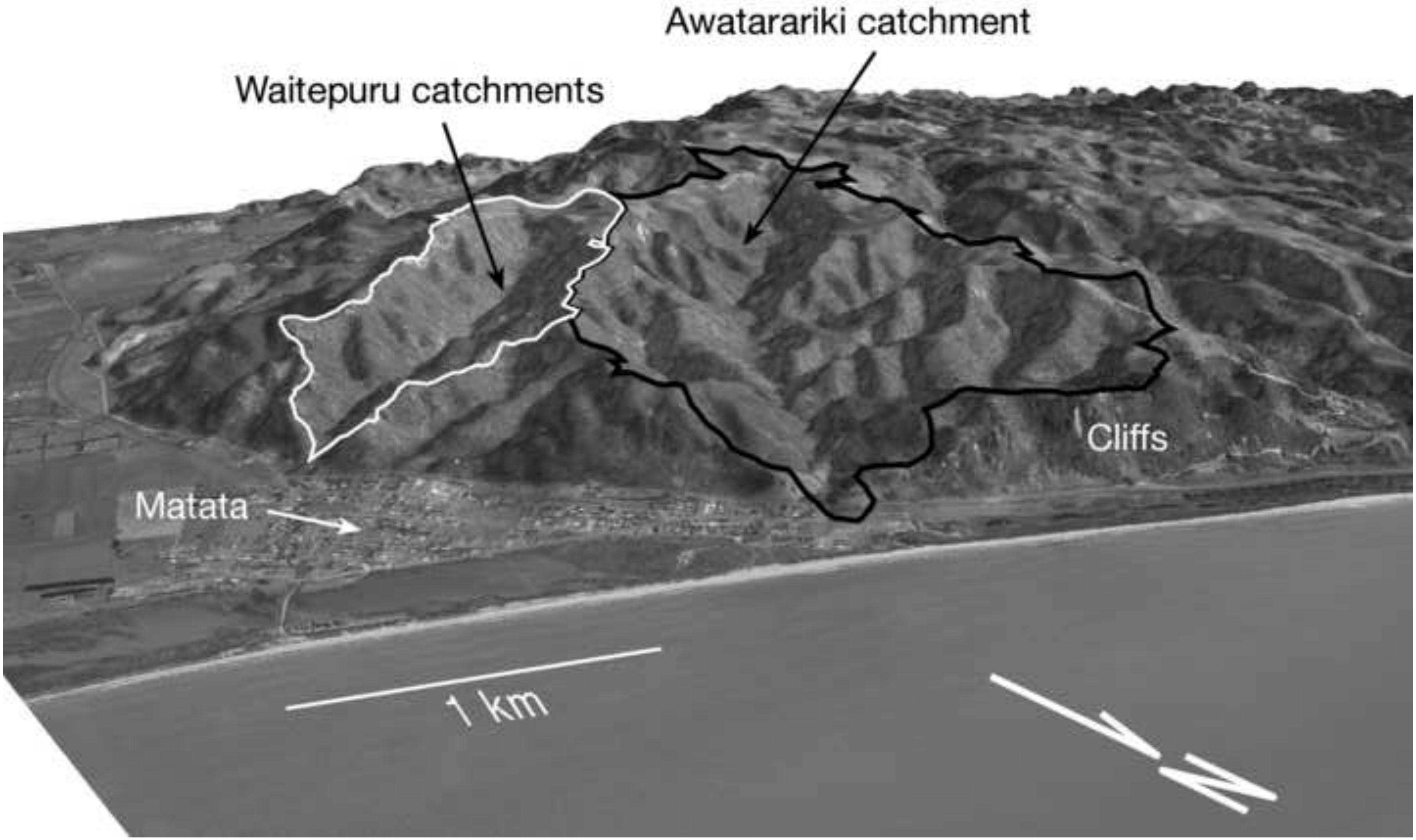

Figure4

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Fig. 4. Aerial Photograph (courtesy Terrain Consultants) showing in detail where the debris flow emerged from the confinement of the Awatarariki Stream. The first debris-laden currents passed beneath the railroad bridge and followed an existing stream channel (white dotted line). After debris build-up behind the bridge and its failure, the main debris flow bypassed the channel and spread out in an unconfined way across the pre-existing fan with large truck-sized boulders visible in the proximal fan. Remediation efforts had just commenced when this photograph was taken.

Figure5

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Figure6

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Figure7_colour

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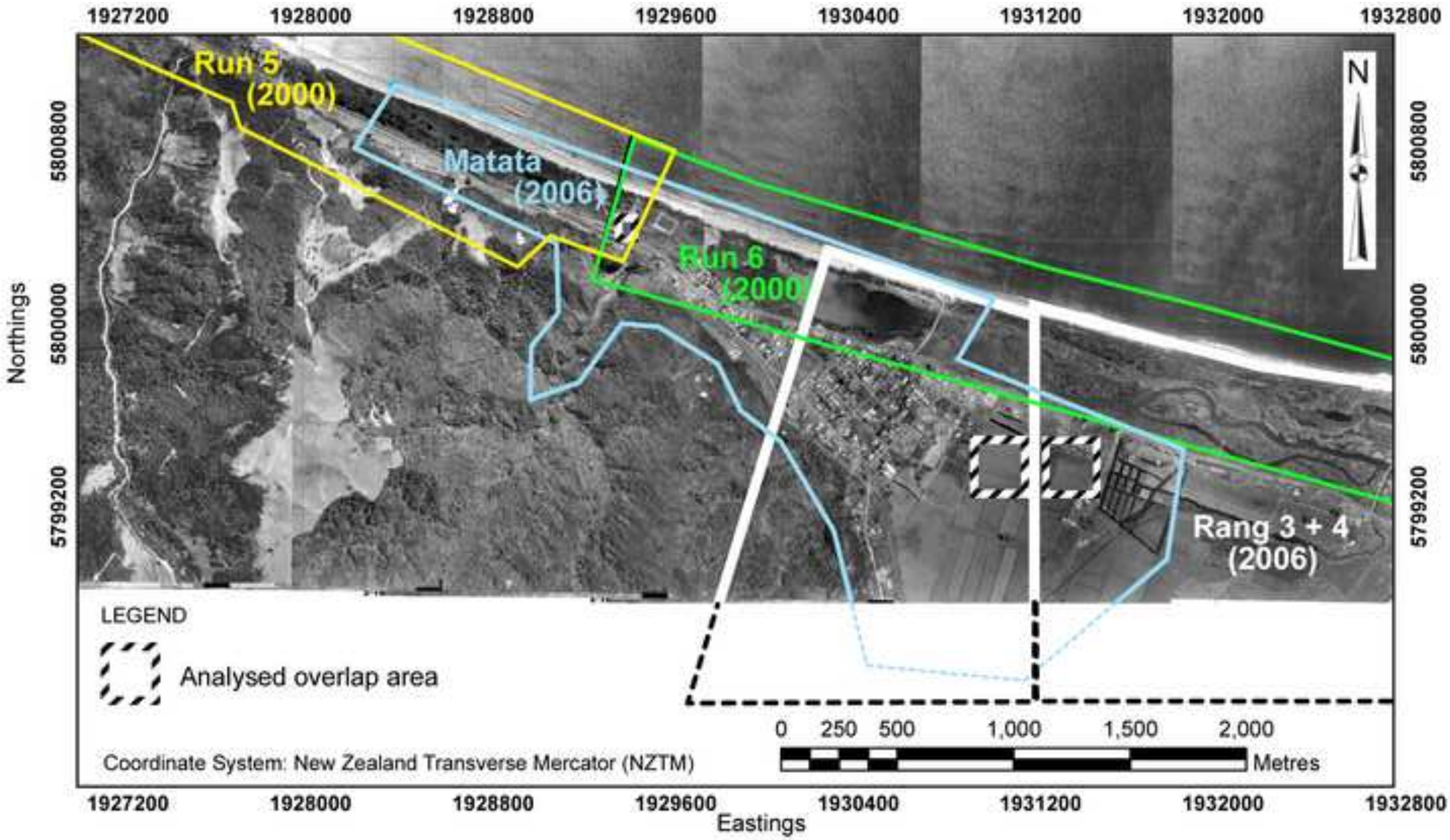

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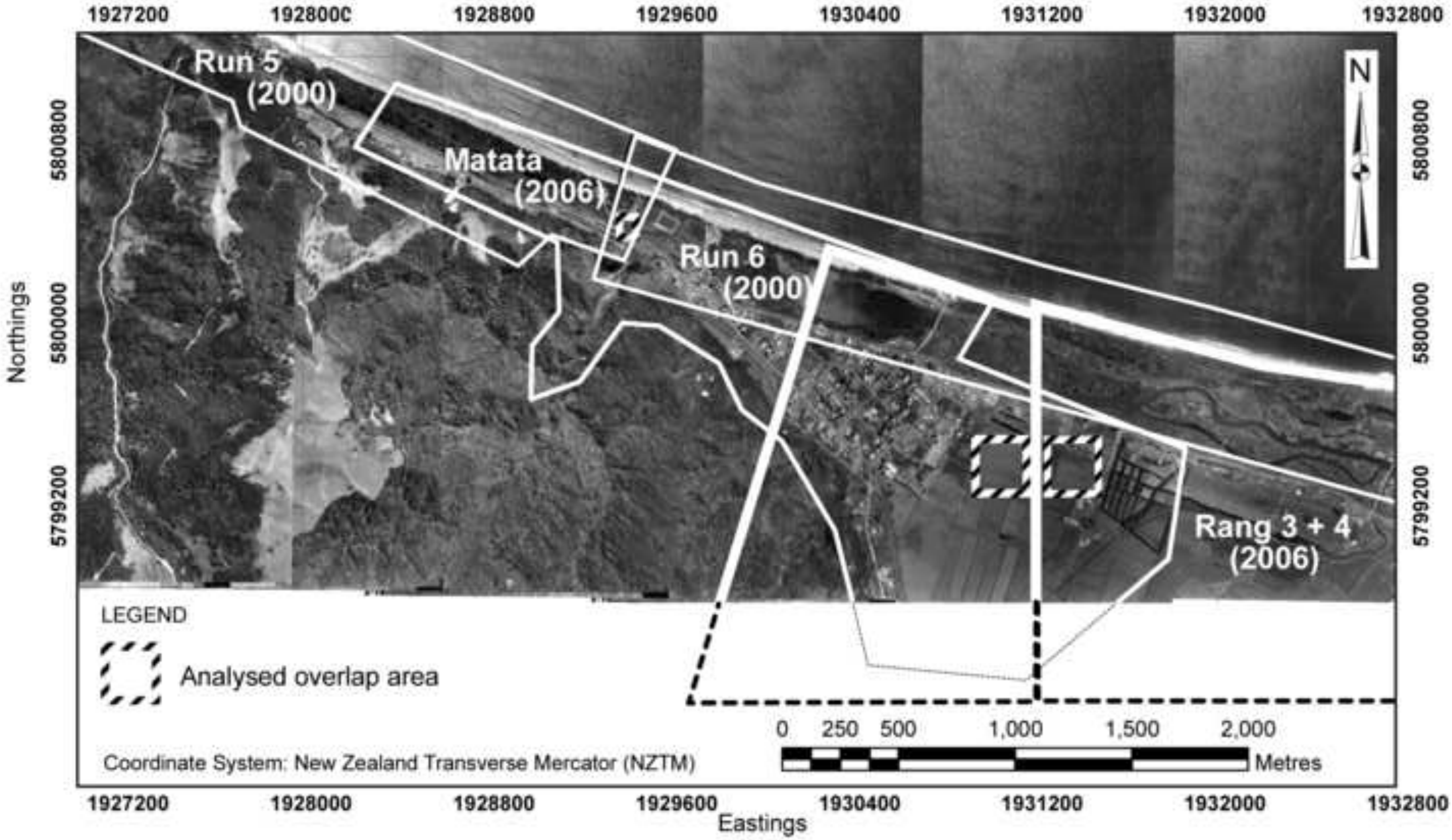

Figure8

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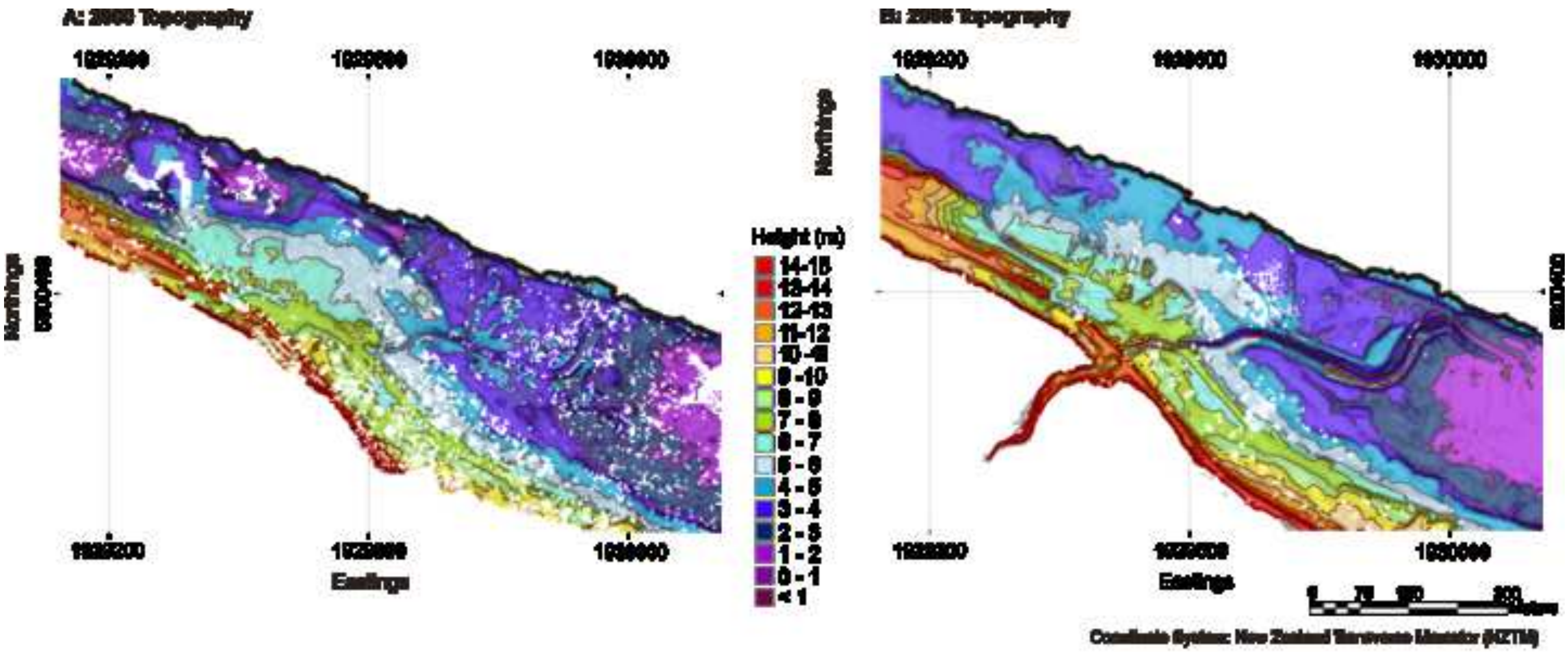

Fig. 8. Composite figure of a selected area affected by the debris flow. A: 2003 topography B: 2006 topography. All contours at 1 m intervals.

Figure9

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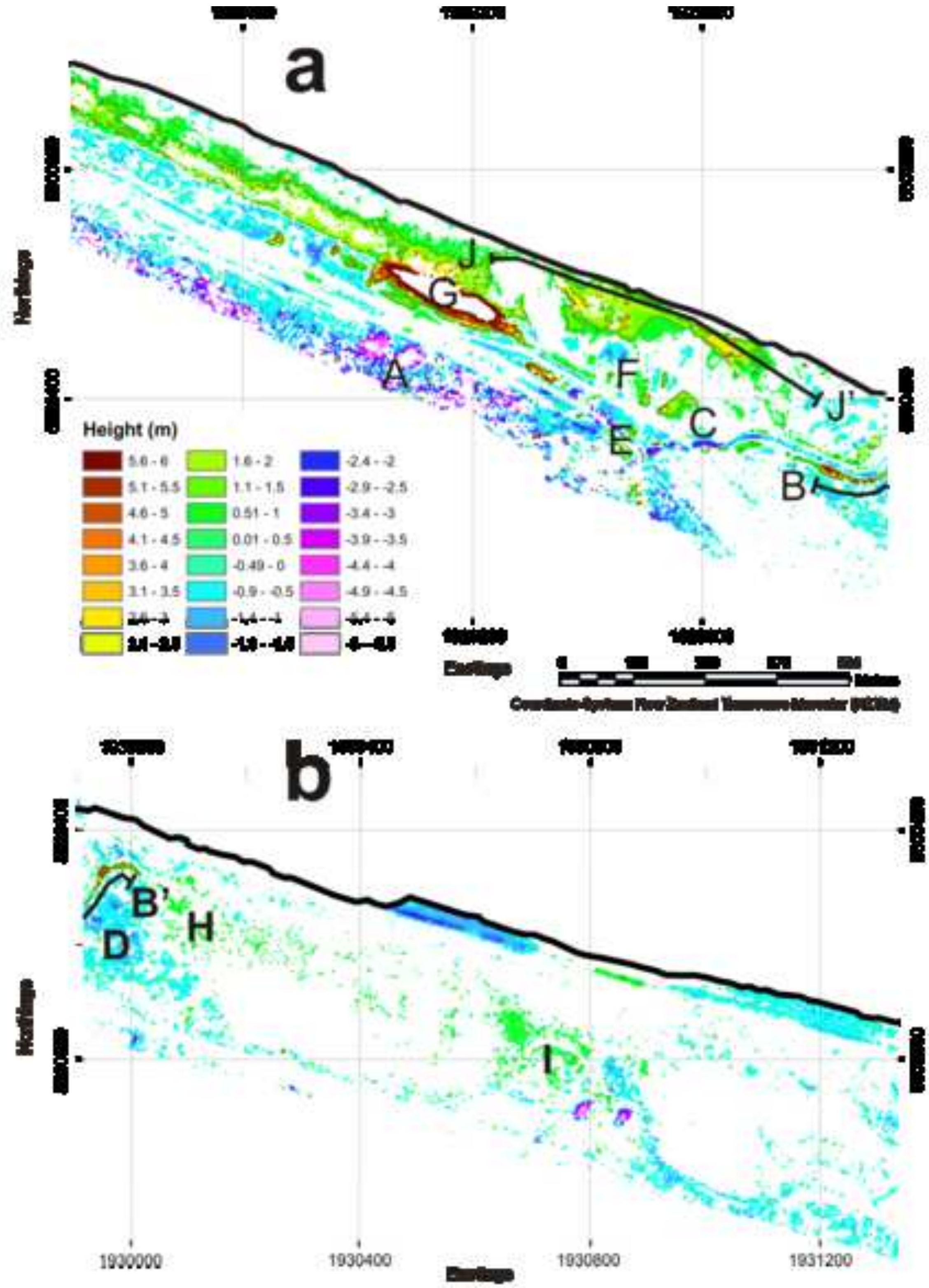

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Figure10
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