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Research Article

Morphological dynamics of upland headwater streams in the southern North Island of New Zealand

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Abstract: Short-term channel dynamics of mountain stream reaches in the southern North Island of New Zealand were assessed over two successive 3-month periods using morphological budgeting. Response to floods varies between reaches, even when the catchments were located close to each other and had similar characteristics. The reaches on the Central Volcanic Plateau experienced least morphological change, while streams with steep catchments and migrating planform in the Tararua and Ruahine Ranges showed frequent channel adjustments. Channel response is conditioned by intrinsic variables rendering reaches responsive or robust to the effects of floods, and this is likely to reflect the degree of connectivity between slopes and channels, and reaches.

Key words: bedload, DEM, gravel-bed river, morphological budget, sediment transfer, stream bed stability.

Mountain streams are commonly defined as having a steep gradient (e.g. >0.002 m m^{-1}), gravel-to-boulder-dominated substrate and spatially limited flood plain width (Wohl & Merritt 2008). Tectonic activity, glacial history, large woody debris and sediment input from hillsides and tributaries cause segmentation of the longitudinal profile (Chin & Wohl 2005; Wohl & Merritt 2005), and result in a variety of channel types that are not positioned in a typical sequence (e.g. cascade to riffle–pool in downstream direction). Evolution of these channel typologies is rather determined by transport capacity and sediment supply which reflect local lithology (grain size and shape), slope and land cover (Thompson *et al.* 2006).

On a global scale, New Zealand mountain streams are regarded as severely impacted by loss of biotic integrity, and moderately impacted by anthropogenic channel alteration and land use (including past deforestation and mining) (Wohl 2006). Despite human influence on channel dynamics, headwater reaches in New Zealand are often perceived as having naturally relatively unstable beds (e.g. Mosley & Blakely 1977) which implies high rates of sediment transfer. This in turn suggests a sufficient supply of sediments from the catchment,

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as well as competent flows to move them. The geologically young axial ranges in the southern part of the North Island consist of shattered and faulted rocks (Williams 1991), and experience high rates of uplift and erosion (Whitehouse & Pearce 1992). In addition, earthquakes may trigger substantial mass movements in these catchments (Goff & McFadgen 2002), and in the central plateau volcanic activity also contributes to the potential to provide large amounts of material to river systems (Manville *et al.* 2009). Furthermore, high rainfall variability promotes not only weathering, but can also cause frequent floods and flashy discharge regimes. Hence, there is reason to believe that upland streams are morphologically dynamic. However, to date, no research has compared short-term dynamics of different mountain stream systems in New Zealand.

This paper explores the morphological responses of 12 mountain streams to floods and spates over 7 months. We focus on topographic changes of the stream channel rather than on bedload transport rate as an indicator of overall stream dynamic which incorporates both morphological change of banks and bed. Morphological budgeting is well suited for this purpose because it allows quantification of spatial patterns in sediment transfer within the channel (Ashmore & Church 1998; Fuller *et al.* 2003a, 2005), and provides a lower bound estimate of sediment flux (Fuller *et al.* 2002; Lindsay & Ashmore 2002). Comparison of digital elevation models (DEMs) of river morphology before and after a flood event directly reveals processes such as erosion and deposition, while the interpretation of DEMs of change in combination with site knowledge can lead to the identification of processes driving the topographic changes observed.

The factors influencing the morphological dynamics of a reach act on different spatial and temporal scales. While slope, substrate characteristics, connectivity and sediment supply vary between reaches (Hooke 2003; Fryirs *et al.* 2007), the influence of land cover (vegetation) on flood generation is higher at the catchment scale. The magnitude and recurrence interval characterise an event, but the (long-term) processes occurring between events are also important for the morphological response to increased flows. We used catchment parameters from the Freshwater Environments of New Zealand database (Wild *et al.* 2005) to evaluate their importance to explain the differences in morphological dynamics between the 12 reaches investigated here.

Sites and methodology

Sites

Topographic surveys were carried out at 12 second- to fifth-order mountain rivers and streams in the southern part of the North Island of New Zealand. These reaches were chosen because their catchments have relatively low anthropogenic modifications and their position within larger catchments is comparable. Within groups of sites, geographical setting and catchment land cover are similar. They form part of the Manawatu, Tukituki, Ruamahanga, Otaki, Tongariro and Wanganui catchments, which drain the eastern and western slopes of the north-east–south-west stretching Ruahine and Tararua Ranges and the Central Volcanic Plateau, respectively (Fig. 1). Vegetation within the catchment upstream of the study reaches is dominated by native broadleaf–podocarp forest in the axial ranges, and by tussock grassland and scrub around Mount Ruapehu. Andesitic volcanic deposits constitute the bedrock on the Central Plateau, whereas folded mesozoic greywacke and argillite of varying decomposition prevail in the Tararua and Ruahine Ranges (Mosley 1978a).

Hydraulic and substrate characteristics of the study reaches varied considerably representing the variety of mountain streams in the lower North Island (Table 1). Substrate composition ranges from heterogeneous assemblages with a relatively high proportion of boulders (e.g. Pukeonake) to well-sorted gravel-dominated stream beds (e.g. Mangapuaka) (Fig. 2). The channels comprise distinctive features including step–pool sequences (e.g. Pukeatua), plane bed sections (e.g. Tamaki), riffle–pool units (e.g. Manawatu) and bedrock-confined sections (e.g. Ohau). Lateral confinements by stable banks or steep valley sides are common, although at some sites, channels could shift freely in a wide active flood plain (e.g. Waipawa).

Survey

Between October 2007 and May 2008, three topographic surveys at each of the 12 reaches

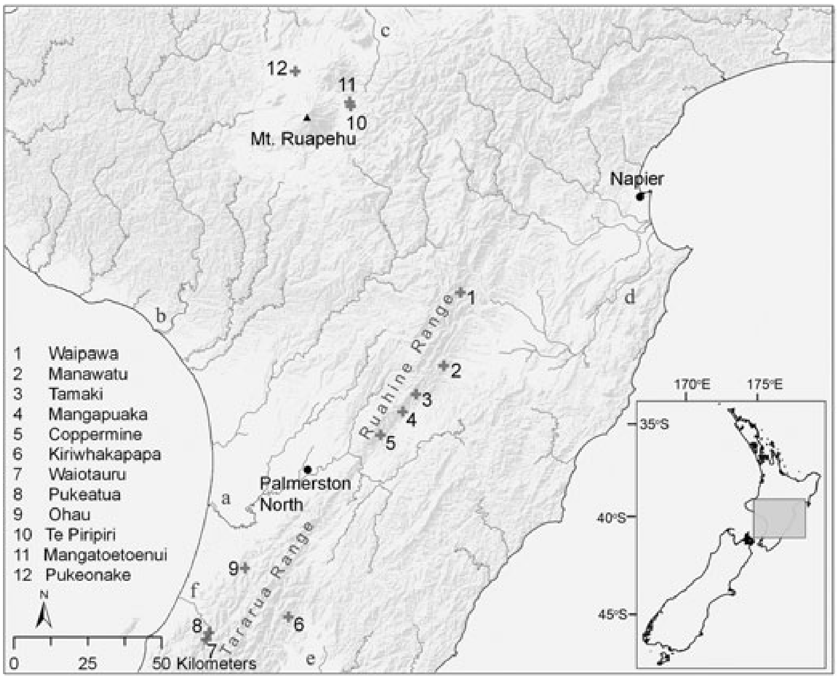

Figure 1 Study sites in the southern part of the north island of New Zealand and important rivers: a, Manawatu; b, Wanganui; c, Tongariro; d, Tukituki; e, Ruamahanga; f, Otaki.

Table 1 Hydraulic and substrate characteristics of the study reaches

Site	Stream order (Strahler 1952)	Slope ($m*m^{-1}$)	Mean hydraulic radius at bankfull (m)	Mean bankfull width (m)	Mean substrate D_{50} (mm)	Substrate composition (in order of relative proportion of s, sand; g, gravel; c, cobbles; b, boulders)
Waipawa	3	0.032	0.481	48.6	58.5	g, c, b
Manawatu	3	0.047	0.232	7.4	64.9	c, g, b
Tamaki	2	0.021	0.195	19.0	35.2	g, c
Mangapuaka	2	0.029	0.129	25.5	28.0	g, c
Coppermine	3	0.042	0.328	7.0	51.2	g, c, b
Kiriwhakapapa	3	0.011	0.517	9.5	58.7	c, b, g
Waiotauru	5	0.012	0.803	42.8	84.4	c, g, b
Pukeatua	3	0.047	0.912	24.2	83.9	c, g, b
Ohau	4	0.012	0.701	18.0	64.0	c, g, b
Te Piripiri	3	0.014	0.198	2.8	34.9	g, c, (b, s)
Mangatoetoenui	4	0.025	0.369	11.5	97.2	c, g, b, (s)
Pukeonake	4	0.034	0.357	12.1	157.8	b, c, g

Figure 2 Selection of the study reaches: Te Piripiri (a), Waiotauru (b), Coppermine (c), Ohau (d), Waipawa (e) and Mangapuaka (f).

were conducted. Three-dimensional point coordinates were measured using a differential GPS system (R8, Trimble Navigation Limited) in RTK mode (cf. Brasington *et al.* 2000) in combination with an electronic total station GTS 701 (Topcon Corporation) when satellite reception was limited. The GPS base receiver was installed some distance from each reach in order to prevent multipath errors (Kennedy 2002). Survey point density was terrain sensitive (i.e. adjusted according to the surface complexity being highest at breaks in slopes) (c.f. Fuller *et al.* 2003a). Consequently, total point density varied between very structured sites and relatively smooth reaches. Substrates larger than cobbles require a grain scale resolution to be represented adequately in a DEM together with gravelly surfaces. As this is

Table 2 Point density and survey area of all surveys between October 2007 and May 2008

Survey	1 (October/November 2007)		2 (January/February 2008)		3 (May 2008)	
Site	Area (m^2)	Point density (m^{-2})	Area (m^2)	Point density (m^{-2})	Area (m^2)	Point density (m^{-2})
Waipawa	1897.22	0.58	2437.94	1.54	1467.79	1.89
Manawatu	131.84	9.41	159.69	11.73	162.84	7.48
Tamaki	902.64	2.05	886.20	3.86	917.70	3.01
Mangapuaka	1449.22	1.56	1515.63	2.04	1559.97	1.97
Coppermine	405.91	4.92	493.51	6.52	440.69	7.78
Kiriwhakapapa	278.21	1.29	310.87	1.77	259.15	3.15
Waiotauru	2892.44	0.73	2942.07	1.32	2601.62	1.20
Pukeatua	613.49	1.95	1002.41	2.11	792.17	2.17
Ohau	972.61	0.66	1113.24	1.03	1053.17	1.20
Te Piripiri	160.75	4.40	216.40	7.49	267.08	6.83
Mangatoetoenui	835.39	1.71	859.21	2.96	852.88	2.53
Pukeonake	439.74	2.85	511.57	5.24	161.21	6.31

impractical for large survey areas, boulders (*b*-axis > 300 mm) were not considered for the budgeting and were excluded from the DEM. Concomitant tracking of *in situ* marked boulders showed that only 3% of them moved during floods (Schwendel, unpubl. data). The surveyed length of stream ranges from 30 to 200 m, and was chosen to include all characteristic features of the reach. Survey area varies between 132 and 2942 m^2, and the average point density lies between 0.6 and 11.7 points m^{-2} (Table 2).

Although, compared to errors induced by surface roughness, the precision of dGPS and electronic theodolites is high (Brasington *et al.* 2000), atmospheric interference and satellite constellation can be a problem. To assess this, frequent measurements of a limited number of independent check points during a survey were utilised (Brasington *et al.* 2000), which revealed a vertical precision of 0.015 m. This compares well to the vertical error derived from survey-specific internal quality control data generated by the measurement device which range between 0.014 and 0.049 m (means per site in Table 3). The error induced by surface roughness (e.g. if the measuring pole is set on top of a particle or in a gap between grains) is often identified by a percentile of the substrate size distribution (Brasington *et al.* 2000; Chappell *et al.* 2003). We used the corrected substrate size (upper threshold 300 mm) of the surveyed bed for which 84% is finer (D_{84corr}), which for each survey and site significantly exceeds instrument precision (Table 3). Additionally, independent cross-sections and local temporary benchmark points were measured the same day as each survey. These were used for DEM quality analysis as recommended by Fisher and Tate (2006).

Substrate composition was assessed using the Wolman pebble count method (Wolman 1954), which measures the *b*-axis of >100 randomly selected substrate particles. The measurements were classified according to a modified Wentworth scale.

Interpolation

After a detailed check in order to eliminate gross and systematic errors, the data were interpolated to a regular gridded DEM with Surfer 8.01 (Golden Software) using triangulation with linear interpolation and a grid size of 0.1 m. This grid width has been used in similar environments (Lane *et al.* 1994), and is suitable to account for small-scale variation in densely surveyed areas. It is also sufficiently large compared with surface roughness to avoid the occurrence of spurious artefacts (Brasington & Richards 1998). Preliminary analysis (Schwendel, unpubl. data) revealed that interpolation with triangulation was most effective

Table 3 Mean values per site for vertical survey precision and accuracy, vertical digital elevation model accuracy and the LOD of genuine change

Error	Survey precision			Interpolation accuracy						
Source	Quality control		Substrate	Residuals		Independent checkpoints		Cross validation		
Site	ME (m)	SD (m)	D_{84corr} (m)	ME (m)	SD (m)	ME (m)	SD (m)	ME (m)	SD (m)	LOD (m)
Waipawa	0.024	0.017	0.132	–0.001	0.009	–0.014	0.049	0.012	0.111	0.187
Manawatu	0.020	0.018	0.158	–0.003	0.054	0.027	0.147	0.004	0.155	0.223
Tamaki	0.030	0.020	0.058	0.000	0.008	–0.004	0.060	–0.001	0.062	0.082
Mangapuaka	0.024	0.016	0.057	0.000	0.007	0.009	0.046	0.002	0.067	0.080
Coppermine	0.027	0.019	0.140	–0.001	0.019	0.038	0.084	0.005	0.100	0.198
Kiriwhakapapa	0.047	0.024	0.161	–0.000	0.008	–0.012	0.125	0.016	0.201	0.227
Waiotauru	0.015	0.008	0.177	–0.000	0.007	0.007	0.133	0.006	0.073	0.251
Pukeatua	0.029	0.017	0.145	–0.000	0.013	0.080	0.153	0.005	0.122	0.205
Ohau	0.030	0.019	0.149	–0.001	0.007	–0.010	0.071	0.009	0.089	0.210
Piripiri	0.014	0.006	0.097	–0.003	0.025	0.004	0.073	0.010	0.120	0.138
Mangatoetoenui	0.015	0.012	0.182	–0.001	0.012	–0.003	0.130	0.007	0.083	0.257
Pukeonake	0.025	0.018	0.177	–0.001	0.018	0.081	0.167	0.004	0.091	0.250

LOD, level of detection; ME, mean error; SD, standard deviation.

among the exact interpolation methods available in Surfer in representing the surfaces of topographically variable stream reaches. In particular, the modelling of longitudinal features (e.g. bars and trenches), channel side walls and the channel bottom was more realistic than using other interpolation methods without the need to introduce breaklines. The latter would be very time intensive when analysing a large number of data sets such as 36 in this study. Furthermore, triangulation with linear interpolation is well suited for a terrain-sensitive survey (Brasington *et al.* 2000, 2003; Fuller & Hutchinson 2007), and is unaffected by problems like over- and undershooting of surfaces near a jump discontinuity (Gibbs phenomenon) (Florinsky 2002). Effects of anisotropy (*sensu* Fuller *et al.* 2003a) were found to be negligible because the length of the reaches was not much higher than the width (Schwendel, unpubl. data).

Comparison of DEMs

For each site, subtraction of DEMs from successive surveys revealed areas and volumes of change. However, DEMs and derived sediment budgets are affected by multiple sources of error (Lane 1998), which need to be quantified in order to gain an estimate of a threshold of detectable change in topography (Wheaton *et al.* 2007). This threshold accounts for propagated random errors emerging from measurement, as well as interpolation errors. Thus, a level of detection of genuine change was assessed, considering precision of measurement, as well as interpolation errors identified by residual analysis, independent data and cross-validation (quasi-independent data). Mean errors of all three measures are mostly small (e.g. <0.02 m) and scattered around zero, indicating little overall systematic bias, whereas mean deviation from independent data is highest, reaching up to 0.08 m (Pukeatua and Pukeonake) (Table 3). Standard deviations derived from independent and quasi-independent data are significantly higher than the standard deviation of the residuals, and of similar size than the error emerging from data acquisition (D_{84corr}). In contrast, the precision between surveys (e.g. mean error ± 1SD of all subsequent surveys is 0.023 ± 0.026 m), which was measured using local temporary benchmark points, is much lower. Surface roughness is, at most sites, the highest error component and was thus chosen as a rigorous means of assessing DEM quality and used for generating a level of change detection.

The propagation of error during the subtraction process was calculated using appropriate error propagation formula (Equation 1), where δ_u is the propagated error (level of detection) derived from the errors δ_1 and δ_2 of the input DEMs (cf. Brasington *et al.* 2003; Lane *et al.* 2003):

$$\delta_u = \left[(\delta_1)^2 + (\delta_2)^2\right]^{0.5} \quad (1)$$

The calculated level of detection ranges from 80 to 257 mm (Table 3), which compares well to other studies of gravel-bed rivers (e.g. 80–82 mm (Tamaki and Mangapuaka), 80–110 mm (Fuller *et al.* 2003b) and 100 mm (Brasington *et al.* 2000)).

Tracer stones

As an independent indicator of substrate stability, five tracer stones in each of three size classes (D_{50}, D_{70} and D_{90}) were marked in riffles with RFID tags (23 mm glass tags, Texas Instruments). The latter were attached *in situ* to the stones where turbulence and flow velocity permitted underwater application (89% of all particles) using wet curing epoxy-concrete (K273, Nuplex Construction Products). The remaining stones were removed from the river bed for tag attachment, and afterwards carefully re-embedded. The percentage of entrained *in situ* marked tracer stones was significantly correlated with the percentage of entrained re-embedded stones (Spearman rank correlation, $R = 0.78$, $\alpha = 0.0001$). Tracer stones were relocated and identified up to a depth of 0.6 m in the substrate using a portable antenna and datalogger (OregonRFID). Relocation surveys, which took place approximately every 2 months or after high-discharge events, encompassed the entire channel and active flood plain at least 50 m downstream of the last position of each tracer particle.

Channel changes

October/November 2007 to January/February 2008

Between the set of first surveys in October/November 2007 and the set of second surveys in January/February 2008, each catchment was influenced by at least one flood event that was competent to move at least part of the bed (Fig. 3). The areas and volumes of change varied considerably between sites (Table 4). Most of the reaches in the western Tararua Range showed high changes dominated by scour under the influence of the 8 January flood. The high volume of scour at the Pukeatua site was mainly the erosion of a fan from a steep tributary stream at the north-western margin of the site, and was therefore not representative for the entire stream bed of the relatively steep reach (Fig. 4). However, erosion was dominant throughout the entire site (64% of area scoured) with only a small area on the right side of the main channel being affected by deposition. At Waiotauru, mainly the right bank was eroded, in particular at a steep medial bar upstream of the confluence with a side channel. The latter and the left side of the upper main channel experienced some aggradation. In the centre of the main channel, deep and swift flow prevented surveying (area excluded from the DEM and separated from surveyed areas by a hairline in Fig. 4), but few morphological changes adjacent to that zone indicate that no large-scale sediment transfers occurred there. At the Ohau site, scouring occurred in the central areas of the channel and the western side of the lower baseflow channel, while deposition took place only locally at the margins. In contrast at Kiriwhakapapa on the eastern side of the Tararua Range, only few local morphological changes (mainly scour) could be detected reliably.

Waipawa, Mangapuaka and Tamaki in the eastern Ruahine Range experienced substantial topographic changes, whereas at Manawatu and especially the southernmost site there, Coppermine, few sediment transfers were detected (Fig. 5). Waipawa and Mangapuaka were dominated by erosion, while Tamaki was aggrading. At Waipawa, scour occurred throughout the reach but mainly at the channel margins, whereas some sections of the central channel showed deposition. These patterns point towards a widening of the river bed, probably as an effect of previous aggradation (c.f. Grant 1977). At both the Tamaki and Mangapuaka sites, the shifting of the whole channel in the gravel body is clearly visible. The relative amount of change is probably underestimated because, compared with sites constrained by stable vegetated banks, a wider part of the flood plain was surveyed to capture all potential lateral migration. Some smaller topographic changes on the flood plain relatively distant to the active channel indicate that these zones were eventually inundated with competent flow to entrain surface materials. The Tamaki reach is less braided than at Mangapuaka, and channel migration resulted in the abandoning and fill of an old side channel on the true left side. The complexity of the patterns at Mangapuaka suggests several phases of development. At the less dynamic sites of Coppermine and Manawatu, scour and fill are limited to small zones. Bank erosion is common, but depositional areas on the southern channel margin of the Manawatu River result from bank collapse after being washed out during a previous flood. Fresh flood debris higher on the banks than bankfull level was found on both sides, which shows that potentially competent flows have occurred, and the absence of sediment dynamics reflects a high degree of bed stability.

All the sites on the Central Volcanic Plateau showed little detectable channel change (Fig. 6), although a gauge downstream (Te Piripiri and Mangatoetoenui) and in a neighbouring catchment (Pukeonake) experienced a considerable flood on 20 December (Fig. 3).

January/February 2008 to May 2008

During the second period from January/February to May 2008, several spates and floods occurred, many of them visible in the hydrographs of most catchments (Fig. 3). Hence, in this second time period only, the compound effects of all these events were captured. Morphological changes were greatest at the Waipawa, Mangapuaka, Tamaki and Te Piripiri sites (Table 4), and lowest at the remaining reaches on the Central Volcanic Plateau. Fill at one spot where a bank collapsed was the only topographic change registered at Kiriwhakapapa in the eastern Tararua Range (Fig. 7), although substantial tracer stone movement occurred (Table 5). The Ohau reach shows mainly small amounts of local erosion, while erosion of the medial bar on the right of

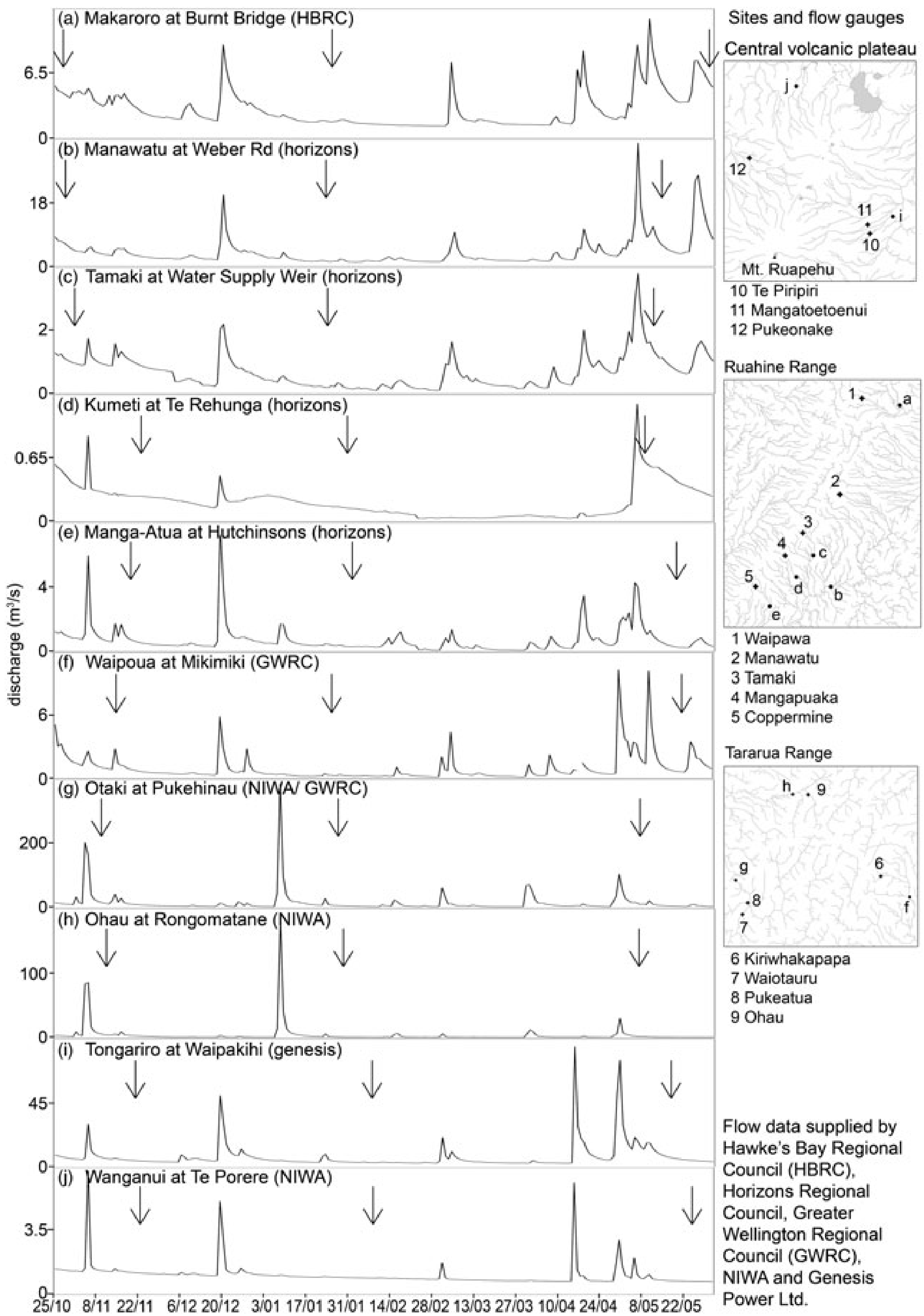

Figure 3 Flow hydrographs of gauges in neighbouring catchments or downstream of the study sites; arrows mark the survey dates at the respective reaches (site–gauge match: (a) 1, (b) 2, (c) 3, (d) 4, (e) 5, (f) 6, (g) 7 and 8, (h) 9, (i) 10 and 11, (j) 12.

Table 4 Volume and area of geomorphic change relative to the planar digital elevation model area between October/November 2007 and January/February 2008, and between January/February 2008 and May 2008 (bold)

	Volume				Area		
Site	Fill (10^{-3} m^3*m^{-2})	Scour (10^{-3} m^3*m^{-2})	Net (10^{-3} m^3*m^{-2})	Total change (10^{-3} m^3*m^{-2})	Fill (%)	Scour (%)	Total change (%)
Waipawa	15.529	31.114	–15.585	46.643	11.4	18.9	30.3
	1.469	**42.794**	**–41.325**	**44.264**	**3.3**	**23.7**	**27.0**
Manawatu	1.930	3.035	–1.105	4.965	1.3	3.9	5.2
	0.295	**0.625**	**–0.330**	**0.920**	**0.4**	**0.6**	**1.0**
Tamaki	54.202	15.025	39.177	69.228	32.3	13.7	46.0
	32.510	**14.568**	**17.943**	**47.078**	**27.6**	**17.1**	**44.7**
Mangapuaka	25.301	38.828	–13.526	64.129	22.8	23.5	46.3
	41.328	**5.068**	**36.260**	**46.395**	**25.1**	**5.8**	**30.9**
Coppermine	0.372	0.420	–0.048	0.793	0.7	0.6	1.3
	0.203	**0.513**	**–0.310**	**0.715**	**0.3**	**0.6**	**0.9**
Kiriwhakapapa	0.024	1.818	–1.794	1.842	0.1	2.7	2.8
	0.274	**0.000**	**0.274**	**0.274**	**0.5**	**0.0**	**0.5**
Waiotauru	3.801	26.532	–22.731	30.334	4.5	17.3	21.8
	3.762	**1.925**	**1.837**	**5.687**	**4.3**	**2.4**	**6.8**
Pukeatua	24.327	284.250	–259.922	308.577	10.8	63.6	74.4
	8.816	**10.362**	**–1.546**	**19.178**	**9.1**	**8.4**	**17.5**
Ohau	0.809	4.617	–3.808	5.426	2.5	8.5	11.1
	0.248	**0.400**	**–0.152**	**0.647**	**0.5**	**1.2**	**1.6**
Piripiri	0.867	0.762	0.105	1.629	1.1	0.8	1.9
	40.795	**5.252**	**35.543**	**46.048**	**39.6**	**5.6**	**45.3**
Mangatoetoenui	0.075	0.029	0.046	0.104	0.1	0.0	0.1
	0.000	**0.053**	**–0.053**	**0.054**	**0.0**	**0.2**	**0.2**
Pukeonake	0.282	0.102	0.181	0.384	0.5	0.1	0.6
	0.000	**0.003**	**–0.003**	**0.003**	**0.0**	**0.0**	**0.0**

the upper main channel at Waiotauru continues. At the latter site, some parts in the thalweg became scoured deeply, which prevented high-resolution surveying. In contrast, some deposition occurred in the centre of a shallow run between the two riffles of the reach, resulting in an overall positive sediment budget. At Pukeatua, erosion of the aforementioned fan has nearly ceased, and limited deposition appears in that zone. The material could be sourced from erosion of a riffle–pool unit further upstream causing movement of coarse substrate. This stream, also known as 'Roaring Meg', has a very flashy flood regime with longer periods of stable baseflow in between, allowing growth of algae throughout the wetted channel. In contrast, flood discharges and water levels can be high (drift wood deposited 1.5 m above baseflow stage; Schwendel, pers. obs.) which leads, when combined with high sediment supply from the many slope failures in the narrow valley, to a complex pattern of scour and fill. The patchy, but non-size-selective, entrainment of tracer stones points also towards an irregular pattern of highly competent discharge.

The characteristic dynamic morphologies of the first period are repeated between January and May at the reaches in the eastern Ruahine Range (Fig. 8). Manawatu and Coppermine are stable with only minor channel changes (mainly scour) close to the banks. In contrast, the other sites show highly dynamic morphological change. At Waipawa, erosion is dominant, again affecting point bars and the channel bottom, which causes an overall straightening of the

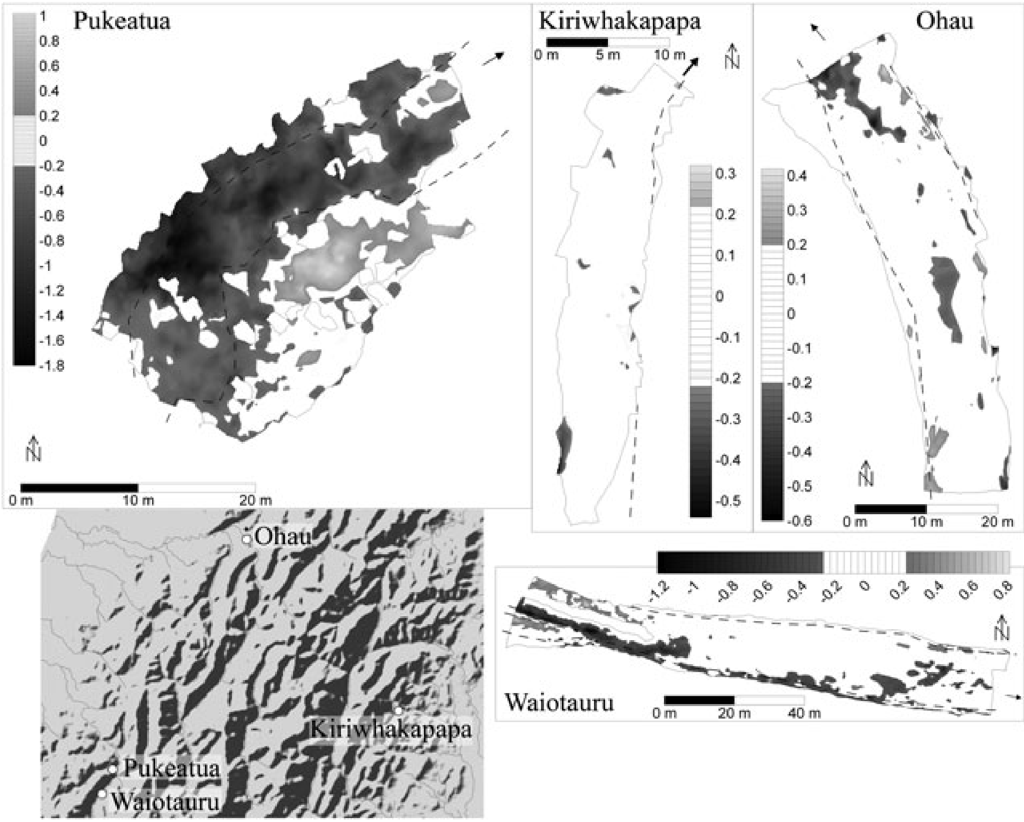

Figure 4 Digital elevation models of topographic change (m) between October/November 2007 and January/February 2008 of the reaches in the Tararua Range with application of individual levels of detection; wetted channel zone at the more recent survey is outlined (broken line), and arrows indicate flow direction.

reach. The upper middle part of the reach could not be surveyed for logistic reasons, but the subjective impression was that scour prevailed here as well (Schwendel, pers. obs.). At Mangapuaka, the channel system at the southern part of the site was filled, and the flow was directed north of this zone with locally high erosion visible. Although surface flow ceased at this reach during summer, Mangapuaka has the highest fill-dominated net budget among all sites (Table 4). The Tamaki reach showed considerable widening of the channel with lateral erosion and mid-channel deposition. This channel adjustment leads again to a positive net budget.

In contrast to the previous period, the Te Piripiri experienced aggradation which affected nearly the entire baseflow channel (Fig. 9). The steep banks on the left of the upper part and the outside bend in the middle part of the reach were subject to some scour. The flow was relatively stable, but flash floods can occur which lead to erosion of the scarcely vegetated banks of fine-grained volcanic ash, and provides the material for aggradation downstream. Again, the Mangatoetoenui and Pukeonake sites experienced only few detectable topographic modifications. Especially for the Mangatoetoenui site, this finding is surprising because more than 90% of tagged tracer stones moved during this period. It is reasonable to infer that the relatively high surface roughness, which controls the level of detectable morphological change, masks these sediment fluxes (see also at Kiriwhakapapa). In such a heterogeneous reach, incorporation of the spatial variation in substrate composition into the level of detection might improve modelling of sediment budgets

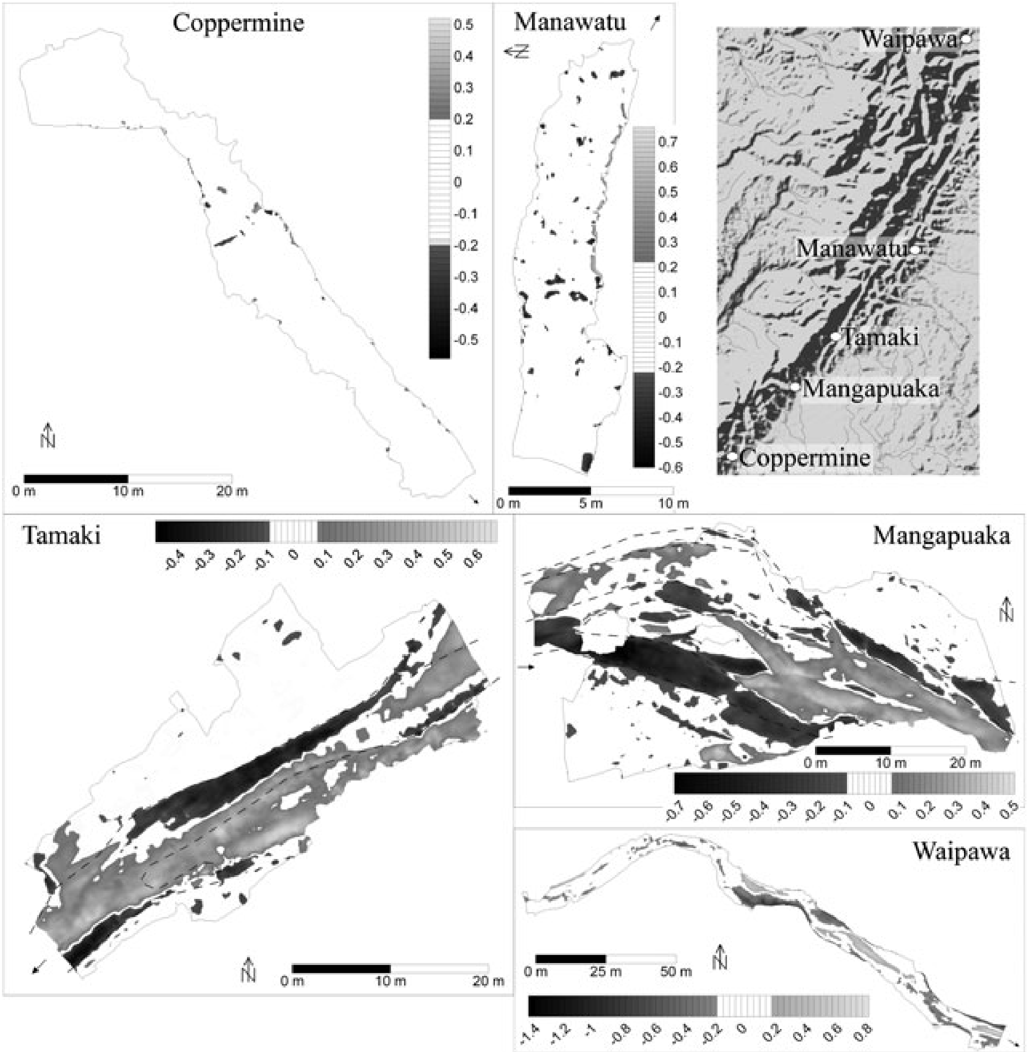

Figure 5 Digital elevation models of topographic change (m) between October/November 2007 and January/February 2008 of the reaches in the Ruahine Range with application of individual levels of detection; wetted channel zone at the more recent survey is outlined (broken line), and arrows indicate flow direction.

(Heritage *et al.* 2009). However, this is beyond the scope of this paper. The Pukeonake reach cuts through lahar deposits and has a highly compacted bed, lined with allochthonous boulders. Its substrate can be characterised as very stable because of a strong embeddedness in a matrix of fine and coherent volcanic deposits. Additionally, flow ceased at this site over short periods during summer, resulting in ponds and puddles on the stream bed temporarily not connected by surface flow.

Discussion and conclusions

Over both 3-month study periods, few sites showed any clear trends towards incision (e.g. Waipawa) or aggradation (e.g. Tamaki), which reflects the variability in flood characteristics and sediment supply within the region's upland headwater streams. Nevertheless, some groups of reaches with distinctive adjustment to floods can be identified over this time-scale. There are highly active reaches which have high erosion

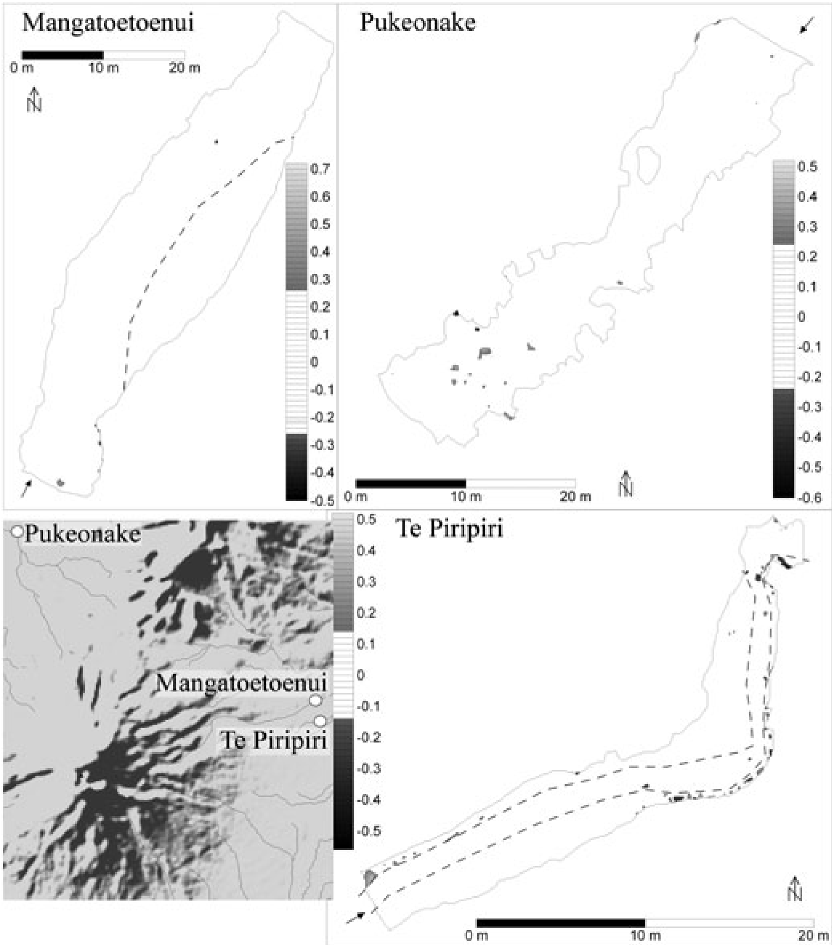

Figure 6 Digital elevation models of topographic change (m) between October/November 2007 and January/February 2008 of the reaches on the Central Volcanic Plateau with application of individual levels of detection; wetted channel zone at the more recent survey is outlined (broken line), and arrows indicate flow direction.

rates in their steep catchments (e.g. up to 10 m^3 ha^{-1} a^{-1}) (Mosley 1978a). Although most of these landslide-derived sediments are momentarily stored in the upper catchment, they provide an abundant long-term sediment supply (Grant 1982; Dymond & Hicks 1986). Some reaches respond dramatically by shifting channels even in smaller flood events (Mangapuaka and Tamaki) (c.f. Mosley 1978b). However, the Waiotauru, Pukeatua, Ohau and Te Piripiri sites require larger floods to trigger channel changes, which usually affect only parts of the bed. The Waipawa reach, which stands in between those groups in terms of channel stability, is less responsive to floods than Tamaki and Mangapuaka, probably because of the coarser substrate compared with streams of the first group. It maintains the position of its active channel relative to the flood plain, although considerable adjustments affecting the entire wetted channel occur. The stream beds of Manawatu, Coppermine and Kiriwhakapapa showed over the study period only local small-scale response to floods in their laterally constrained channels, often associated with bank collapse (e.g. Mosley & Blakely 1977). However, at some streams, the latter might also be influenced by infrequent stock grazing on

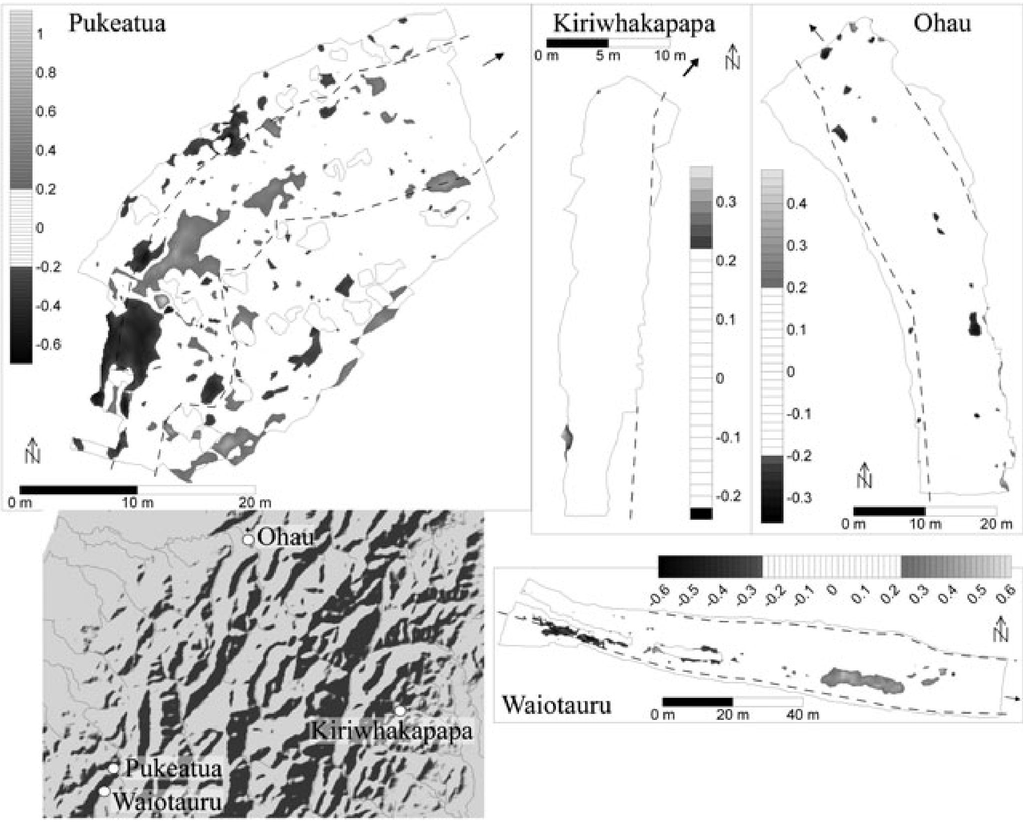

Figure 7 Digital elevation models of topographic change (m) between January/February and May 2008 of the reaches in the Tararua Range with application of individual levels of detection; wetted channel zone at the more recent survey is outlined (broken line), and arrows indicate flow direction.

Table 5 Mean percentage of entrainment and mean travelled distance of *in situ* marked tracer particles in each of the size classes D_{50}, D_{70} and D_{90} of the substrate

	Entrainment (%)			Travelled distance (m)		
	D_{50}	D_{70}	D_{90}	D_{50}	D_{70}	D_{90}
Waipawa	100.0	100.0	100.0	85.3	76.3	79.2
Manawatu	50.0	40.0	0.0	19.8	5.3	0.0
Tamaki	100.0	100.0	100.0	68.3	72.6	59.0
Mangapuaka	87.5	75.0	33.3	25.9	28.1	16.7
Coppermine	88.9	70.0	20.0	22.6	11.0	0.2
Kiriwhakapapa	66.7	70.0	37.5	29.3	17.1	18.8
Waiotauru	100.0	75.0	87.5	40.2	41.3	36.6
Pukeatua	57.14	50.0	55.6	22.1	8.4	12.1
Ohau	100.0	60.0	20.0	43.6	28.0	1.3
Piripiri	40.0	20.0	40.0	5.8	1.1	3.4
Mangatoetoenui	83.3	62.5	55.6	37.2	31.9	6.6
Pukeonake	0.0	0.0	0.0	0.0	0.0	0.0

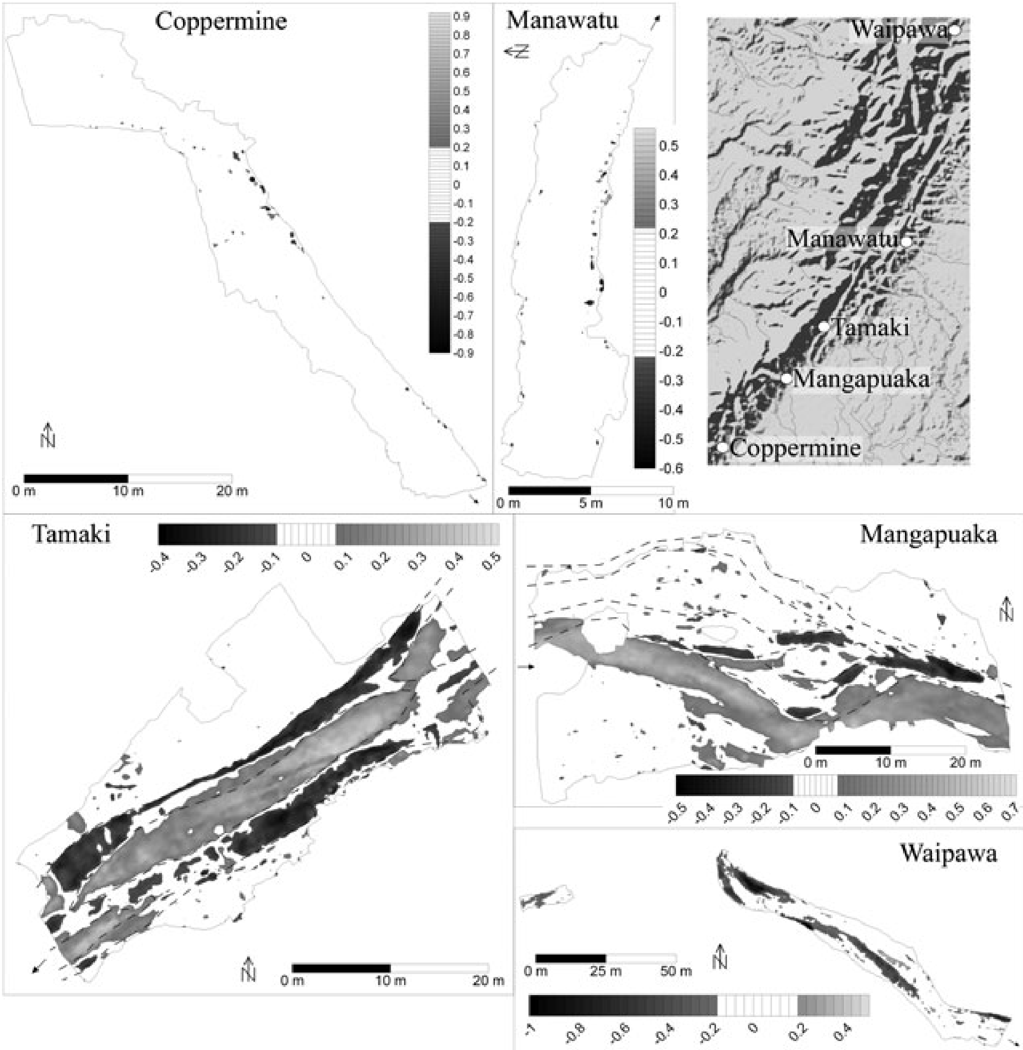

Figure 8 Digital elevation models of topographic change (m) between January/February and May 2008 of the reaches in the Ruahine Range with application of individual levels of detection; wetted channel zone at the more recent survey is outlined (broken line), and arrows indicate flow direction.

the banks, but even so they can be still classified as relatively stable. It should also be noted that there can be considerable sediment flux within a reach (as measured with tracer stones), which is not necessarily expressed as morphological change (e.g. Kiriwhakapapa or Mangatoetoenui) because of scour–fill compensation. According to the calculated morphological change, Mangatoetoenui and Pukeonake can be classified as very stable, although the question arises whether morphological budgeting without incorporating the spatial variance in error into the level of detection of genuine change is applicable for the former reach.

The different characteristics in sediment transfer between catchments are obvious, even when these catchments are located close to each other and experienced comparable flood events. Although no flow records were available from the study sites, hydrographs from further downstream exhibit parallel occurrence of major high-discharge events in neighbouring

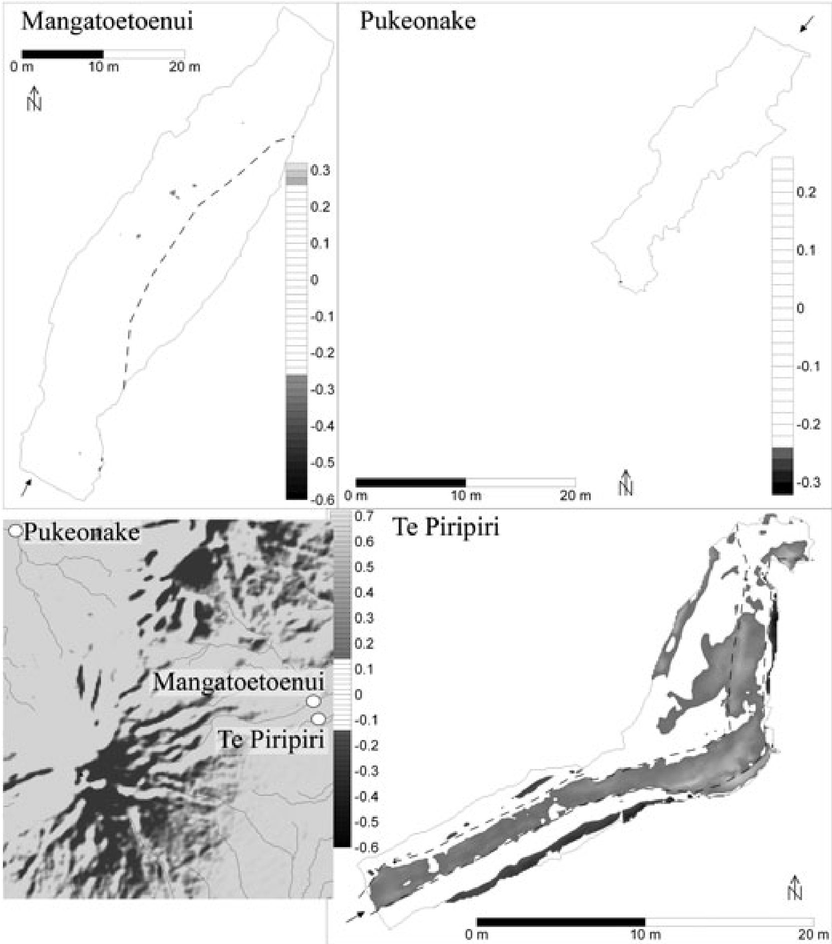

Figure 9 Digital elevation models of topographic change (m) between January/February and May 2008 of the reaches on the Central Volcanic Plateau with application of individual levels of detection; wetted channel zone at the more recent survey is outlined (broken line), and arrows indicate flow direction.

catchments (Fig. 3). Catchment scale parameters (Table 6) can explain the varying behaviour only partially. Average catchment slope is lowest on the Central Volcanic Plateau where reaches are relatively stable. This is also apparent at the Ruahine sites which are probably most comparable because of their similar catchment characteristics, although slopes are generally higher there. Low bare ground and high tussock cover (Table 6) are typical for Pukeonake, but it is rather likely that the high bed stability there arises from the strong embeddedness of coarse substrate particles in a matrix of fine and coherent volcanic deposits. The Ruahine Range sites with high forest cover and less pasture (Table 6) are the least stable. An explanation would be that the steep catchments (e.g. 62% steeper than 30° at Waipawa) are less suitable for farming, and the larger pasture land cover in the lower parts of the Manawatu and Coppermine catchments is a result of the availability of stable flood plain at these sites. As to whether land use variables or slope can explain the differences in the Tararua Range, it is suggested that other factors such as connectivity and sediment supply (Fryirs *et al.* 2007) are more important. Large landslips observed by the authors upstream of the Pukeatua, Waiotauru and Waipawa sites offer evidence to support this. These mass move-

Table 6 Catchment characteristics of the study reaches derived from Freshwater Environments of New Zealand database (Wild *et al.* 2005)

Site	Mean slope (degrees)	Bare ground (%)	Pasture (%)	Tussock (%)	Forest (%)	Catchment area (10^3 km^2)
Waipawa	30.4	10.0	1.0	9.0	77.0	15.1
Manawatu	23.2	0.0	33.0	0.0	66.0	5.2
Tamaki	27.8	0.0	0.0	0.0	99.0	14.8
Mangapuaka	28.8	0.0	0.1	0.0	99.0	6.5
Coppermine	23.1	0.0	16.0	0.0	82.0	4.5
Kiriwhakapapa	24.2	0.0	0.0	0.0	99.0	11.0
Waiotauru	28.1	0.6	1.0	3.0	94.0	244.0
Pukeatua	23.0	0.8	0.1	0.0	98.0	24.1
Ohau	28.5	0.2	0.2	0.9	98.0	84.6
Piripiri	5.5	48.0	0.0	51.0	0.0	13.6
Mangatoetoenui	13.8	84.0	0.0	13.0	1.9	62.6
Pukeonake	4.7	0.5	0.7	98.0	0.0	23.4

Mean slope and land cover are runoff weighted within the catchment.

ments depend primarily on slope (Dymond *et al.* 2006) and forest cover deterioration, which is in turn influenced by weather patterns, climate change, moisture stress and introduced mammals (Mosley 1978a; Grant 1989). However, well-developed downstream channel geometry relations found in some New Zealand headwater streams in similar geomorphic settings indicate that channel adjustment to discharge can be dominant despite substantial colluvial input (Wohl & Wilcox 2005, and references therein).

This research indicates that reaches such as Tamaki and Mangapuaka could be considered as demonstrating responsive behaviour, adjusting form via sediment transfers accomplished by frequent and low-magnitude flood events. These reaches are presumably primed for instability (*sensu* Brewer & Lewin 1998) because availability of highly erodible substrate, frequent variation in local channel slope and frequent floods favour crosssing of intrinsic theresholds. In contrast, reaches where minimal change has been detected are best understood as being robust. Similar flood magnitudes and frequencies fail to result in detectable morphological change, and while sediment transport may still take place, it is not sufficient to register a morphological adjustment. The perception that mountain streams are generally characterised by instability is therefore inappropriate. As with any fluvial system, some systems will be primed for instability and exist close to thresholds of change (Brewer & Lewin 1998), while others are far more robust (Werritty & Leys 2001). Far more important to upland stream behaviour is likely to be the role of sediment supply from upstream reaches and slopes (Harvey 1991), which in turn reflects the connectivity characteristics of the discrete system (Harvey 2001). Strongly coupled systems which feed sediment efficiently from slope to channel, and then from reach to reach (e.g. Hooke 2003; Fuller & Marden 2008) are much more likely to behave responsively to discrete and subtle flow events. This suggests that the catchments demonstrating such responsive behaviour are likely to reflect higher degrees of intrinsic coupling within the fluvial system above the reach. Robust behaviour with minimal detectable morphological change reflects a less strongly coupled system, with fewer sediment inputs contributing to and working their way downstream. This is based on the premise that channel morphology and morphological change are strongly conditioned by bedload flux (Leopold 1992). This topic of responsive and robust behaviour in association with catchment coupling characteristics demands further attention than is feasible in this paper, and is subject of further work in progress.

This study documents the high degree of variability between short-term channel dynamics and sediment transfers within mountain streams in the lower North Island of New Zealand. It finds no evidence for any consistent region-wide response of these reaches to flood events. Future research needs to better quantify the causes behind variable reach-scale sediment transfers, especially in conjunction with catchment connectivity characteristics. However, it is feasible to suggest that differing degrees of catchment connectedness may underlie the high degree of variability in reach behaviour identified.

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