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Connectivity in forested upland catchments and associated channel dynamics: The eastern Ruahine Range

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Abstract

This study relates connectivity of sediment sources to the channel to the high variability in short-term channel dynamics and stream bed stability in mountain stream reaches of the eastern Ruahine Range in New Zealand's North Island. Despite similar geographical and geological characteristics of the catchments upstream of these reaches, the morphological response to flood events ranges from almost none to frequent migration of the channel in a wide active channel zone. These dynamics are mainly driven by sediment supply from slopes and gullies over the last decade and from in-channel storage. The latter is particularly important where recent erosion on hill slopes has decreased. In the upper Waipawa catchment 22% of the area, dominantly gullies, could potentially supply sediment to the studied reach whereas in the Tamaki and Mangapuaka catchments, 3.7% and 1.9% of the area was affected by erosion and coupled to the respective study reaches. In contrast, in the Manawatu and Coppermine catchments this figure was less than 0.3%. In these potentially connected catchments where sediment supply is scarce, coupling between slopes and channel exerts an important control upon channel dynamics. In the connected catchments such as Tamaki, Mangapuaka and Waipawa, reach-to-reach connectivity is effective, with transport barriers such as large woody debris having a relatively short-term modulating effect on coarse sediment conveyance.

Keywords

Landscape connectivity, coupling, erosion, sediment, channel morphodynamics

Introduction

Landscape connectivity refers to the physical coupling of landforms, thus enabling the exchange of water, solid material or air (Bracken and Croke, 2007). In general terms, terrestrial water and sediment transport in catchments is usually unidirectional downslope. Coupling between sediment sources on slopes and stream channels and the propagation of material through the channel network is critical to the functioning of sediment cascades and the sensitivity of the landscape to change (Harvey, 2001; Hooke, 2003; Fryirs *et al.*, 2007). The impact of floods on sediment transfer is conditioned by the degree of coupling between landscape compartments, such that sediment transport is maximised in strongly connected systems (Hooke, 2003; Lopez-Tarazon *et al.*, 2009). This renders these systems especially responsive to floods and environmental change (Harvey, 2001; Macklin *et al.*, 2010). Landscape elements which operate as buffers and barriers (Fryirs *et al.*, 2007) may modulate and amplify sediment conveyance and thus control responsiveness of a system via energy expenditure and structural resistance (Brunsden, 2001).

Schwendel *et al.* (2010) investigated short-term channel dynamics in New Zealand mountain streams and found that the responsiveness of reaches in terms of morphological adjustment to floods varied substantially between catchments. Previously, the Ruahine streams have been viewed as generally inherently unstable (Schumm, 1977). Schwendel *et al.* (2010) suggested that channel dynamics reflect the proportion of steep slopes within a catchment, as this determines the location of sediment sources (Dymond *et al.*, 2006). However, they did not quantify the extent of erosion on slopes and in gullies or the conveyance of sediments within catchments. These considerations need to be addressed to understand the mechanisms and temporal pattern of sediment transport (Schumm, 1977).

Although the short-term causes for varying morphological responsiveness of some reaches to floods may lie in local substrate and hydraulic characteristics (Schwendel *et al.*, 2010), the latter are related to catchment processes over longer time-scales. It has been suggested that rainfall patterns and the resulting flood frequency and magnitude, as well as steepness of slopes, faulting and bedrock structure, are the main influences on increased levels of erosion and bedload transport in these river systems (Stephens, 1975; Marden, 1977; Grant, 1983). Earthquakes may also trigger mass movements (Stephens, 1975), but this seems to be a minor variable compared with geological, geomorphological and climatic factors (Grant, 1983). The deterioration of podocarp-beech forest due to climatic change (Elder, 1965) and browsing mammals is not seen as a primary reason for increased erosion (Grant, 1989), but their impact on the regeneration of forest cover after landslides is recognised (Hubbard, 1978). Thus rainstorm frequency and magnitude may be responsible for the long-term temporal variability in erosion (Reid and Page, 2003; Page *et al.*, 1994), while differences in reach-scale channel dynamics between catchments are a function of catchment-specific controls such as the proportion of threshold-exceeding slopes and availability of stored alluvium (Schumm, 1977; DeRose *et al.*, 1998; Parkner *et al.*, 2007; Brierley *et al.*, this volume). These relationships are underpinned by the catchment geological and tectonic settings.

This study investigates the connectivity of geomorphic units with regard to coarse sediment transport upstream of five study reaches. These reaches demonstrate contrasting channel behaviour, even though their catchments have similar geographical, geological and tectonic settings (Schwendel *et al.*, 2010). Findings from this study aid to contextualise investigation of channel dynamics through analysis of longer-term (e.g., decadal) causes to explain contrasting short-term behaviour, with particular emphasis on landscape connectivity.

The selected catchments in the eastern Ruahine Ranges (Fig. 1) were the subject of intensive research in the 1970s and early 1980s due to increased aggradation in piedmont areas (e.g., Mosley, 1978a; Neall, 1981). Erosion in the headwaters was aggravated by deforestation of the valley throats after 1870—a valley throat is the point in the upper catchment where channel slope abruptly declines and valley floor width increases (Mosley, 1977). This resulted in retrograding incision upstream, scour of old in-channel deposits and slope failure induced by bank erosion (Blakely, 1977). Substantial widening and aggradation of the active channel zone has been observed in the Tamaki catchment (e.g., between 1910 and

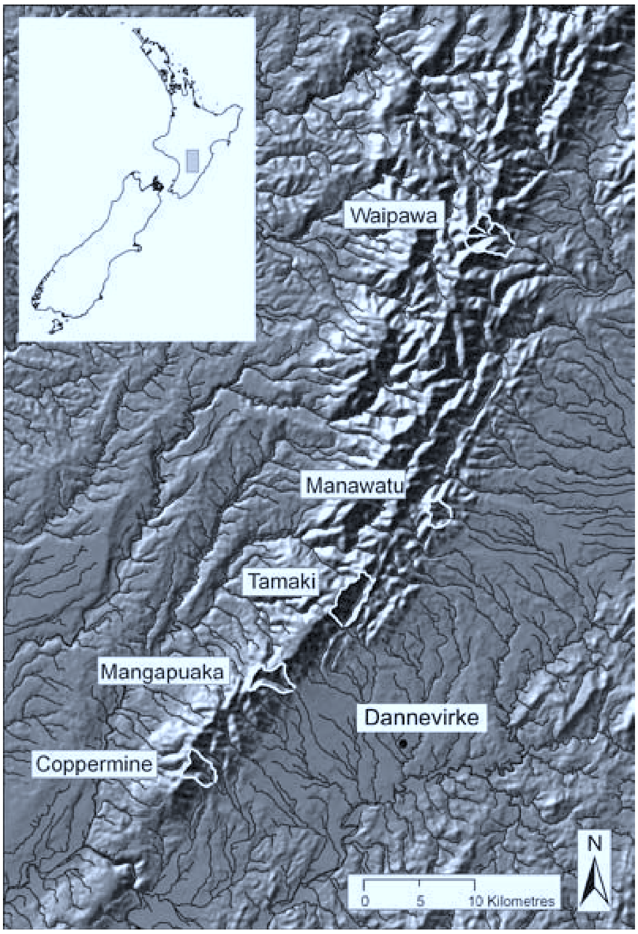

Figure 1 – Studied catchments in the Ruahine Range, North Island, New Zealand.

1940) (Hubbard, 1978) and elsewhere, in particular after rainstorms such as cyclone Alison in 1975 (Grant *et al.*, 1978). For instance, Stephens (1975) recorded a 120% increase in eroded slopes between 1946 and 1974 in two catchments in the southern Ruahines. Grant (1981a) identified historic and recent periods of erosion in the Ruahine Ranges, with the most recent period ongoing at the time of publication. It is unclear whether this phase has ended, and few studies have assessed how these catchments have developed since the 1980s.

Furthermore, although mechanisms of sediment transport and coupling between geomorphic units have been investigated for individual catchments elsewhere (e.g., Fuller and Marden, 2008, 2011), we are not aware of a study which quantifies landscape connectivity over a recent timescale for coarse sediment transport in a larger geographical context within New Zealand (but see Marden *et al.*, 2008, for the Holocene period). This study fills this gap and extends local studies of catchments in the eastern Ruahines. A detailed understanding of what triggers morphologically responsive or robust behaviour of stream reaches to floods is important in relation to managing the ecological implications of substrate instability, gravel mining and flood control.

Sites

In this study we examined the headwater catchments of the Coppermine Stream, Mangapuaka Stream, Tamaki River, Manawatu River and Waipawa River in the eastern Ruahine Ranges, in New Zealand's central North Island (Fig. 1). These five catchments were chosen because in a previous investigation, Schwendel *et al.* (2010) found marked differences in channel dynamics and stream bed stability in reaches situated where the streams emerge from the ranges (Fig. 1). These catchments have similar geographical settings, e.g., south-east orientation, and they are of broadly comparable size (Table 1). Their land cover consists dominantly of native broadleaf-podocarp forest and scrub, with the Manawatu catchment having the highest fraction of low-intensity pasture (10.7%). Much of the forest is regenerating from clearance in the early twentieth century, which ceased after the First World War (Roche, pers. comm.). Above the treeline at ~1000 m, the upper slopes of the southern Ruahines are dominated by leatherwood (*Olearia colensoi)* to ~1300 m and above this, sub-alpine tussock grasses (Jackson, 1966). Grant (1981b) suggests that the bare slopes of the upper Waipawa catchment have probably not been covered by vegetation for many centuries.

The prevailing geology is folded Mesozoic greywacke and argillite of varying decomposition (Mosley, 1978b). Steep valley

Table 1 – Areas affected by erosion and reworked channel area (in 10^3 m^2) and fraction of total catchment area (% in brackets) in the study catchments and sub-catchments in the eastern Ruahine Ranges.

	Upper Waipawa	**Waipawa N-Branch**	**Waipawa Centre Branch**	**Waipawa S-Branch**	**Manawatu**	**Tamaki**	**Mangapuaka**	**Coppermine**
Catchment area	5316*	1614	1143	2560	3883	9337	6207	5885
Erosion area	1361 (25.6)	382 (23.6)	389 (34.1)	590 (23.0)	39 (1.0)	187 (2.0)	70 (1.1)	12 (0.2)
Disconnected	246 (4.6)	78 (4.9)	3 (0.3)	164 (6.4)	27 (0.7)	27 (0.3)	2 (0.0)	1 (0.0)
Coupled and connected	1114 (21.0)	303 (18.8)	386 (33.8)	425 (16.6)	11 (0.3)	159 (1.7)	68 (1.1)	11 (0.2)
Reworked channel area	75 (1.4)	3 (0.2)	31 (2.7)	41 (1.6)	0 (0.0)	191 (2.0)	49 (0.8)	0 (0.0)
Total sediment supply area	1190 (22.4)	306 (19.0)	417 (36.5)	466 (18.2)	11 (0.3)	350 (3.7)	117 (1.9)	11 (0.2)

*The area of the entire catchment upstream of the study reach is 10.0 km^2

slopes, in combination with high weathering rates, result in frequent landslides after rain events. Shallow translational sliding has been identified as the dominant mechanism of sediment generation in the southern Ruahines (Marden, 1984). Hubbard and Neall (1980) suggest that over time the vegetation that recolonises erosion scars increases in weight, rendering the steep, vegetated slopes in this terrain susceptible to renewed slipping that may be triggered by an intense rainstorm or earthquake. Earthquakes are common in the Ruahines, which are bounded in the east by the Mohaka Fault Zone, with the Ruahine Fault zone lying along the range axis (Hubbard and Neall, 1980).

In the Waipawa catchment, mean annual rainfall increases from 2800 mm at 640 m to 4000–5000 mm at altitudes above 1000 m (Grant, 1982); while further south rainfall is lower: Coppermine (519 m): 1780 mm, Kumeti (Mangapuaka, 864 m): 2540 mm, Stanfield Hut (Tamaki, 548 m): 2800 mm, Takapari Road (Tamaki, 1140 m): 2920 mm (Mosley, 1977). Storm rainfalls may exceed 30 mm hr^{-1} (Grant, 1982) at lower elevations and are unquantified at higher elevations, although Grant (1982) estimated high altitude rainfall associated with Cyclone Alison at 540 mm for the entire storm (10-12 March 1975) in the Waipawa catchment.

Methods

Reach-scale sediment budgets

Three topographic surveys were conducted in a stream reach at the lowest point of each of five investigated catchments between October 2007 and May 2008 (Schwendel *et al.*, 2010). These surveys were undertaken using a differential GPS system (R8, Trimble Navigation Limited, Sunnyvale, USA) in RTK mode or an electronic total station (GTS 701, Topcon Corporation, Tokyo, Japan). From these datasets DEMs were interpolated using a triangulation algorithm with linear interpolation in Surfer 8.01 (Golden Software, Golden, USA) (Schwendel *et al.*, in press). Subtraction of DEMs from successive surveys revealed patterns of scour and fill above a minimal level of genuine detectable change. Details of survey methods, interpolation and error analysis are given in Schwendel *et al.* (2010).

Catchment connectivity

Geomorphological information was derived from geo-rectified aerial orthophotography with a resolution of 0.75 m. Aerial photos of the upper Waipawa were taken in summer 2008/2009, while the other catchments were photographed in January 2005. The aerial extent of recent erosion and deposition features such as slips and fans, as well as recently reworked alluvial surfaces, were mapped in Arc Map 9.2 GIS (ESRI Software, Redlands, USA). The erosional features were classified according to whether they appeared to be active or inactive, and their state of coupling to the active channel zone at the time of photography. These classifications were verified during field surveys in October 2010, during which geomorphic features impeding reach-to-reach connectivity and slope-channel coupling were also investigated.

The significance of tributaries in terms of alteration of substrate size characteristics and potential sediment input was explored by analysing the ratio between tributary and main stem catchment areas (Rice and Church, 1998). The function given in Rice (1998) calculates the slope-area ratio of the tributary (derived from the FWENZ database, Wild *et al.*, 2005) as an exponential function of the relative catchment area. Although this specific parameterisation is not directly transferable to other catchments with differing topography, climate and geology, it provides an indicator for the potential relative significance of tributaries (Rice, 1998).

Quantification of sediment volumes delivered from slopes is beyond the scope of this study, since mapping simply determined aerial extent and coupling of erosion scars based on one period of aerial photography. It is not the intention and focus of this paper to reappraise and extend published erosion rates in these catchments (e.g., Mosley, 1977; Marden, 1984).

Results

Short-term relative area and volume of change between Spring 2007 and Autumn 2008 were greatest at the Tamaki and Mangapuaka reaches and not much smaller at Waipawa (Table 2). In contrast, these changes were at least an order of magnitude smaller at Manawatu and Coppermine. The balance between channel scour and fill varied, with degradation prevailing at Waipawa, Manawatu and Coppermine, while the Tamaki reach predominantly aggraded.

Manawatu and Coppermine

The Manawatu and Coppermine reaches showed only small patches of scour or fill (Fig. 2B, C and 3B, C) and thus relative stability. Most parts of the Manawatu and Coppermine channels were armoured. Although floods occurred during both periods (Fig. 4A and D), they did not cause identifiable morphological change.

The Coppermine catchment comprises only 0.2% eroded area, 89% of which was coupled to the main channel and connected to the study reach (Table 1, Fig. 5). The slips were mainly isolated and ephemeral features (Fig. 3A). Since 2005, additional shallow slides or slumps were initiated, but the coupling of coarse material to the channel was limited. No reworked dry channel substrate was identifiable from aerial photos. Most of the tributaries were of low significance according to their relative area and comparatively low slope (Table 3).

The upper Manawatu catchment is characterised by a mixture of scrub and grassland on the ridges and native bush on the valley slopes. The patches of erosion visible on the aerial photo are mostly on the ridges and disconnected from the channels

Table 2 – Volume and area of geomorphic change relative to the planar DEM 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})	change (10^{-3} m^3 m^{-2})	fill (%)	scour (%)	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**

(Fig. 2A). These erosion scars may date to previous landslide activity caused by forest disturbance, but their disconnection from the channels means that they have little or no influence on coarse sediment transport and channel dynamics. The largest recent, coherent slip coupled to the channel was in the northern branch, but it was not active in 2005. Only 1% of the area (Table 1) was subject to erosion in 2005, of which only 30% was coupled to the channel (Fig. 5). As a result, the single thread channel was armoured (D_{50}: 65 mm) and the active channel zone was not much wider than the wet stream width.

Mangapuaka and Tamaki

In contrast to the sites described above, significant changes in channel alignment and geometry occurred at the Tamaki and Mangapuaka reaches, where a greater proportion of each catchment was subject to erosion (Table 1). Substrate size was much smaller than at the other sites and surface armouring was rare (D_{50}: 35 mm and 28 mm respectively).

The multi-channel Mangapuaka reach showed a complex pattern of change, suggesting several phases of development (Fig. 6B). Here, the channel incised in the first period, followed by part infilling of previous channels (true right) in the second period (Fig. 6C). Changes in absolute surface elevation were up to 0.7 m. The gravel retention structures downstream of the reach, which were built in the 1950s (Blakely, 1977), have subsequently been buried.

At Mangapuaka 1.9% of the catchment area is identified as morphologically active (Table 1). This figure comprises 41% reworked channel area, 57% gullies and slopes connected to the main channel and only 2% eroded areas disconnected from the channel (Fig. 5). The main sediment sources are in a major true-left tributary approximately 1.5 km upstream of the study reach (Fig. 6A), which is also by far the most significant tributary (tributary 1 in Table 3). Although its catchment area is approximately 3 times smaller than the main stem, it is clearly responsible for the majority of the sediment supply to the main channel below the confluence. This is indicated by a dramatic widening of the active channel, restriction of willows to the valley floor margins and the switch to a mostly multi-

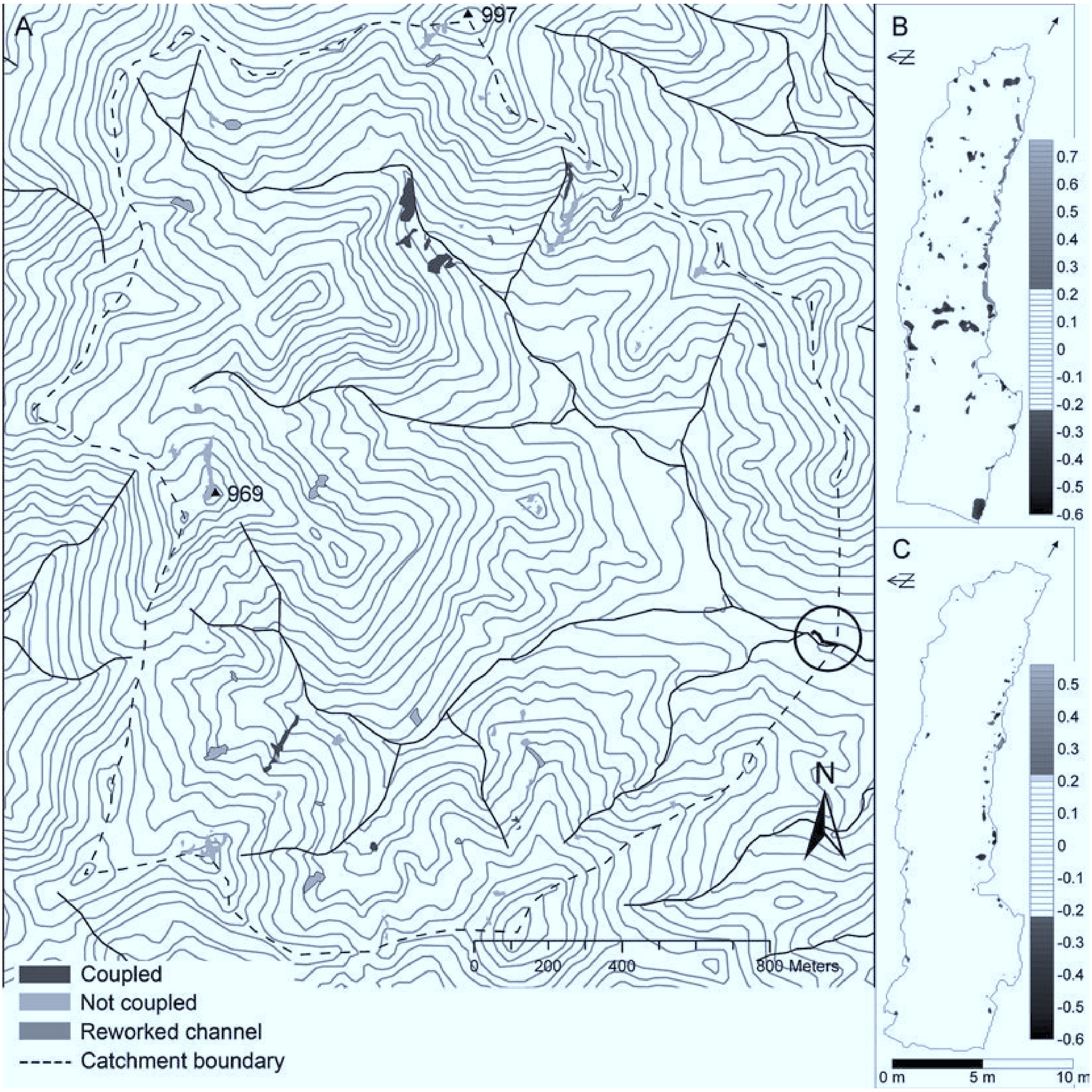

Figure 2 – (A) Areas of recent erosion within the Manawatu River catchment (contour lines at 20 m intervals) and their connectivity (coupled or not) to the study reach (circled); scour and fill (in m) at the study reach (B) between October 2007 and January 2008 and (C) between January and May 2008.

threaded channel below this junction. The channel of this northern tributary was not incised in 2010 and appears to have been regularly reworked since 2005, actively transferring sediments to the trunk channel, mainly as debris torrents during spates when transport capacity is sufficient. In contrast, the main channel upstream of the confluence narrows significantly, is tightly encroached by willows and has coarser substrate. It may still transport finer material from sources upstream, but morphological activity is low. The sources of sediment are almost entirely coupled to the channel and are evenly distributed throughout the catchment.

The channel of the Tamaki study reach was highly dynamic, first shifting to the true right and later considerably widening, with lateral

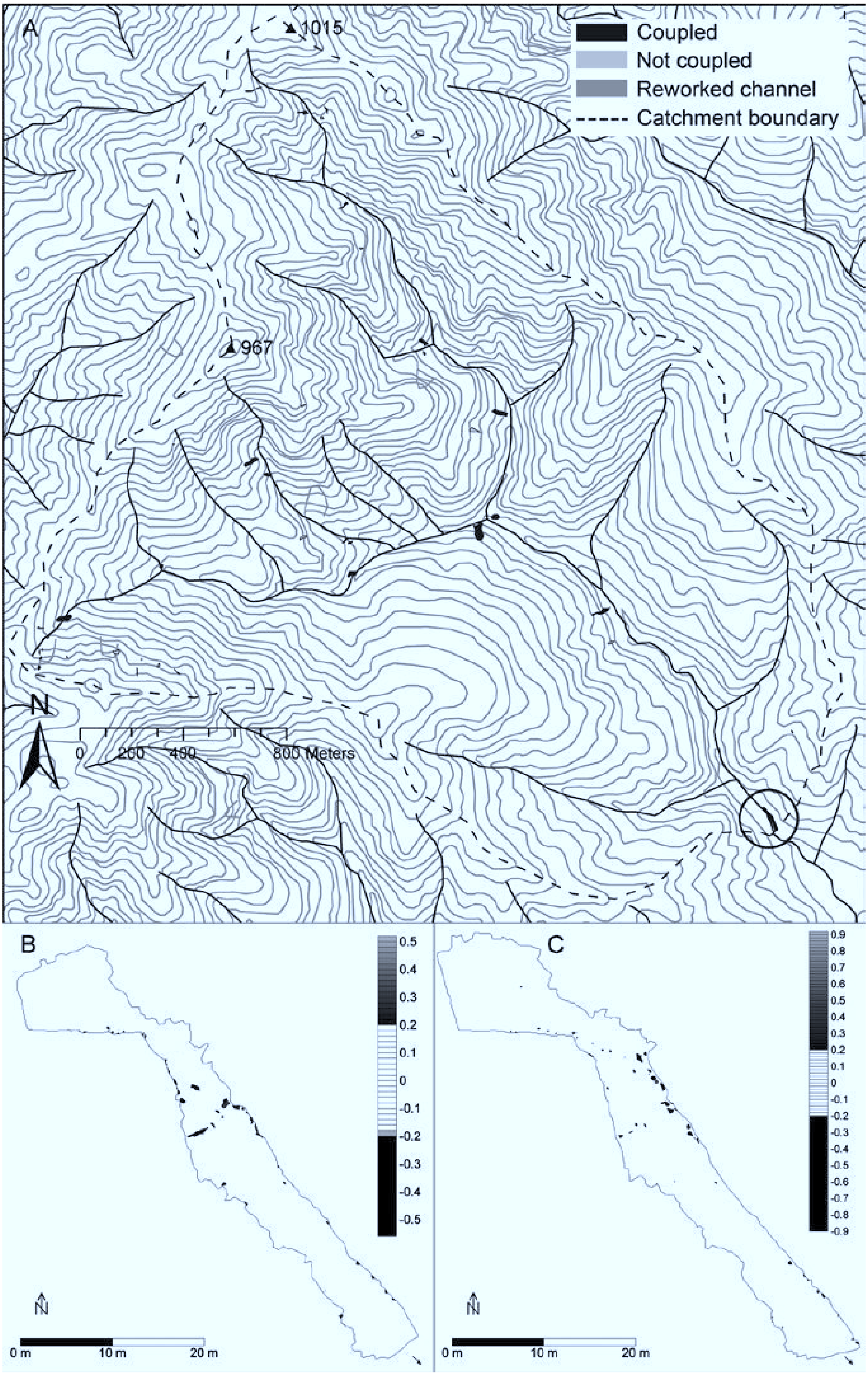

Figure 3 – (A) Areas of recent erosion within the Coppermine Stream catchment (contour lines at 20 m intervals) and their connectivity (coupled or not) to the study reach (circled); scour and fill (in m) at the study reach (B) between November 2007 and February 2008 and (C) between February and May 2008.

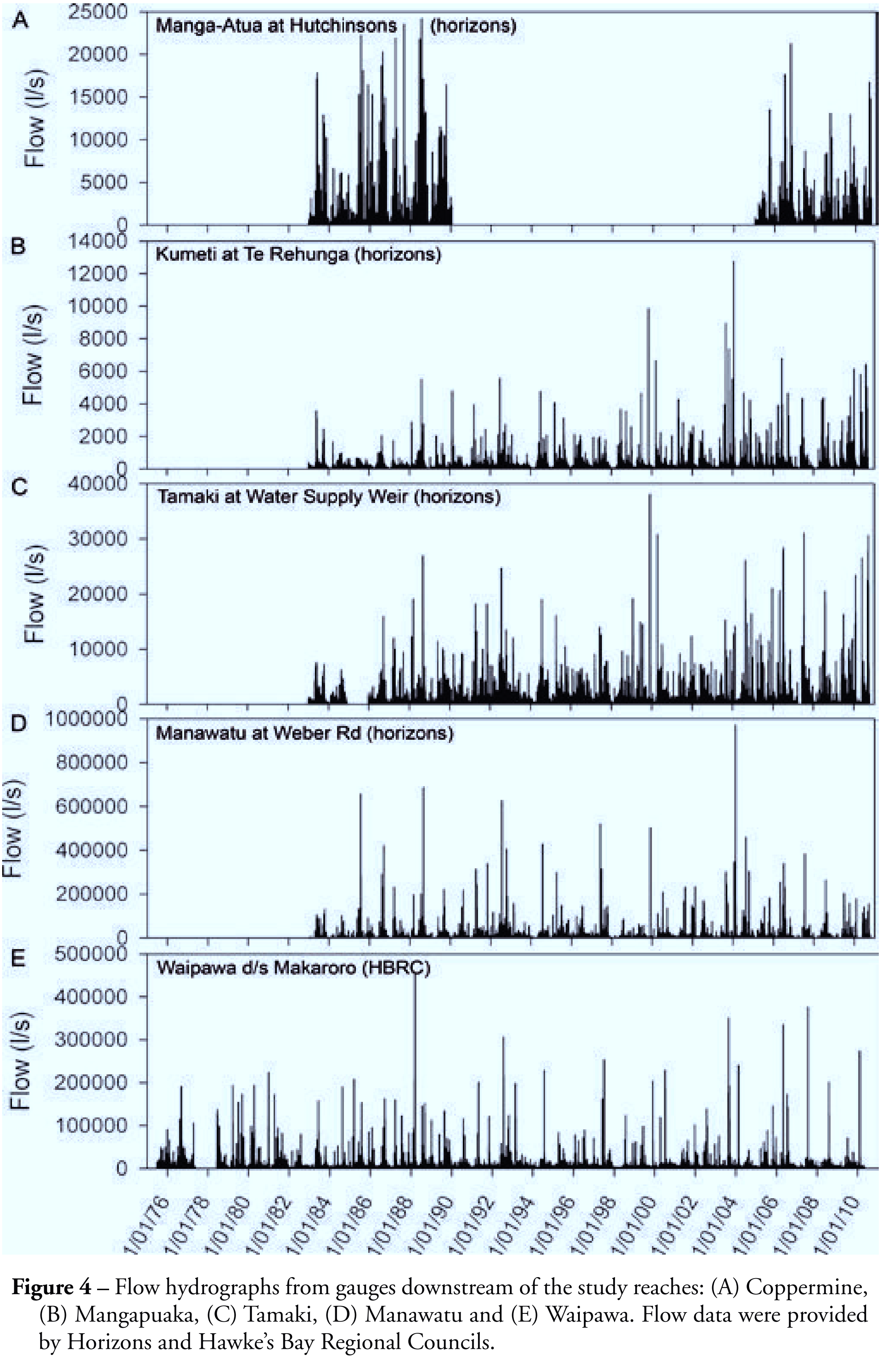

Figure 4 – Flow hydrographs from gauges downstream of the study reaches: (A) Coppermine, (B) Mangapuaka, (C) Tamaki, (D) Manawatu and (E) Waipawa. Flow data were provided by Horizons and Hawke's Bay Regional Councils.

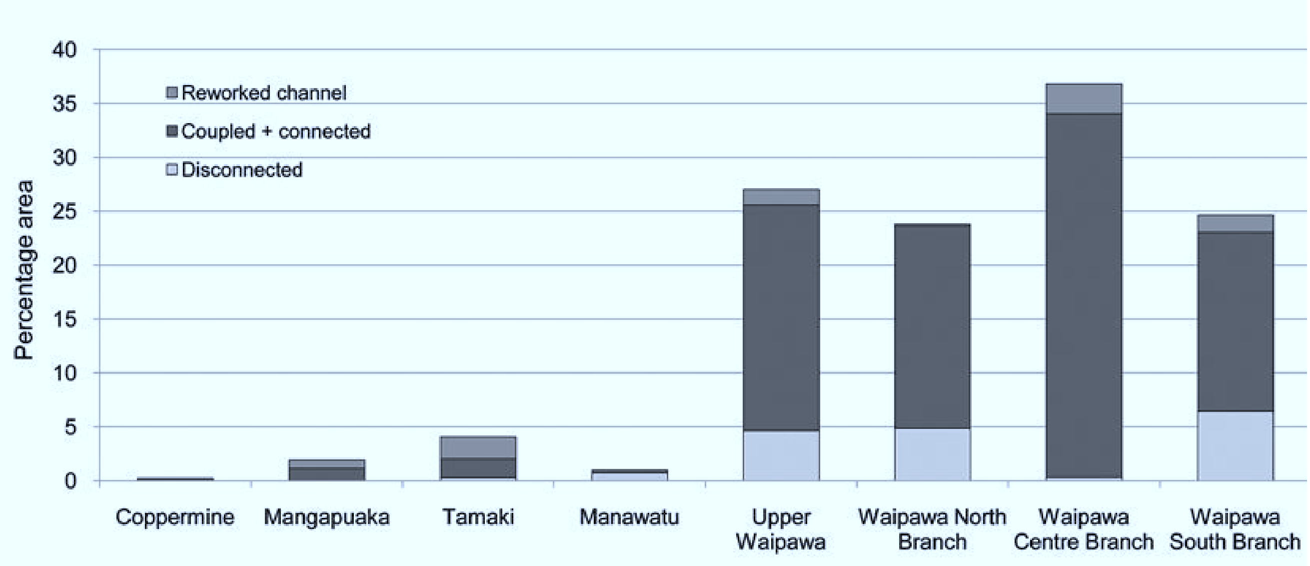

Figure 5 – Percentage of catchment area subject to erosion or reworking, coupled and connected, or disconnected from the study reach at five mountain stream catchments in the eastern Ruahine Range.

Table 3 – Significance of selected tributaries and branches for alteration in sediment characteristics in the main channel at the confluence and thus for potential sediment transfer. The significance ratio depicts the ratio between the actual slope-area product of a tributary, and the slope-area product calculated from the relative tributary area using the formula given in Rice (1998). Ratios greater than 1 indicate significance. Data derived from Wild *et al.* (2005).

Catchment	Number of tributaries	Significance ratio	Tributary channel slopes (m m^{-1})	Trunk channel slopes (m m^{-1})	Tributary area (km^2)
Upper Waipawa	3	12.64 – 32.05	0.29 – 0.55	0.17 – 0.31	1.151 – 2.581
North Branch	3	2.64 – 6.81	0.29 – 0.55	0.27 – 0.30	0.243 – 0.288
Centre Branch	2	4.41	0.42 – 0.50	0.31	0.356 – 0.464
South Branch	3	2.30 – 3.05	0.37 – 0.55	0.17 – 0.27	0.293 – 0.791
Lower Waipawa	3	3.33 – 10.12	0.20 – 0.46	0.07 – 0.14	0.250 – 1.409
Manawatu	4	4.28 – 11.59	0.12 – 0.27	0.09 – 0.12	0.235 – 0.983
Tamaki trib. 1	1	14.09	0.35	0.25	0.497
Tamaki trib. 2	1	8.43	0.35	0.20	0.631
Tamaki trib. 3	1	15.86	0.26	0.08	0.936
Tamaki trib. 4	1	9.90	0.36	0.09	0.983
Tamaki trib. 5	1	7.17	0.32	0.15	0.816
Tamaki trib. 6	1	6.49	0.34	0.10	0.842
Tamaki trib. 7	1	2.19	0.39	0.07	0.480
Tamaki trib. 8	1	8.37	0.38	0.11	1.197
Upper Mangapuaka	5	1.81 – 4.67	0.24 – 0.48	0.26 – 0.35	0.233 – 0.720
Mangapuaka trib. 1	1	21.08	0.28	0.20	1.421
Coppermine	7	2.00 – 8.03	0.22 – 0.44	0.15 – 0.31	0.270 – 1.014

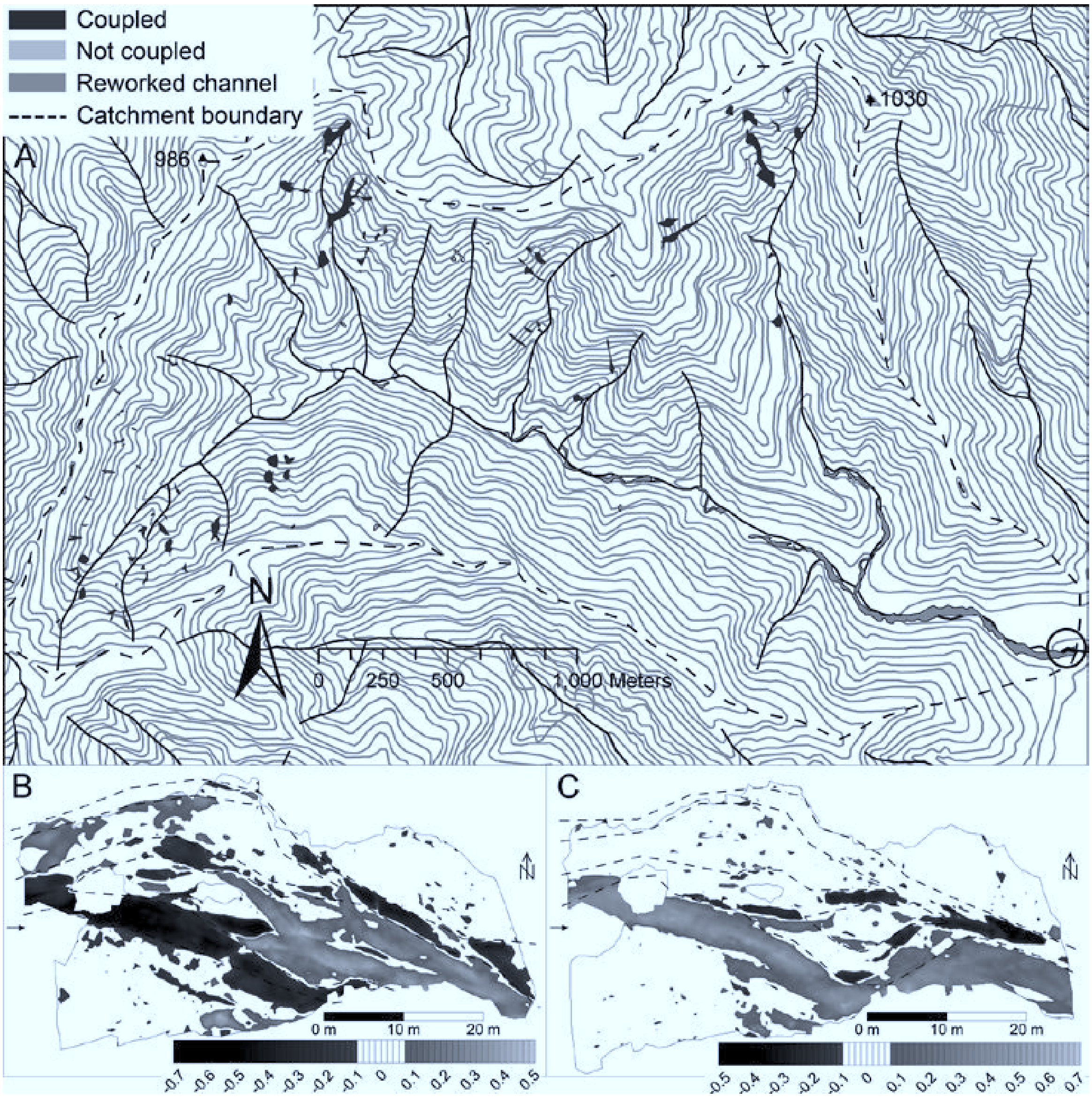

Figure 6 – (A) Areas of recent erosion and reworked channel within the Mangapuaka Stream catchment (contour lines at 20 m intervals) and their connectivity (coupled or not) to the study reach (circled); scour and fill (in m) at the study reach (B) between November 2007 and January 2008 and (C) between January and May 2008.

erosion and development of a mid-channel bar (Fig. 7B and C). The active channel zone was constrained by willows, which might have prevented fundamental channel migration.

The Tamaki catchment in 2005 comprised 2.0% (0.187 km^2) of eroded area, 85% of which was connected to the main channel (Table 1). The area affected by erosion has decreased since 1974 (0.495 km^2) to almost the level measured in 1946 (0.174 km^2) (Stephens, 1977). The main sources of sediment were situated in the true right tributaries and the headwaters of the main stem (Fig. 7A). The latter sub-catchment is characterised by substantial gully erosion, with unstable slopes regularly delivering unquantifiable amounts of rock and large woody debris to the channel. Tree trunks and boulders form temporary barriers for sediment transport in the narrow valley, but over longer time-scales sediment input appeared to be continuous.

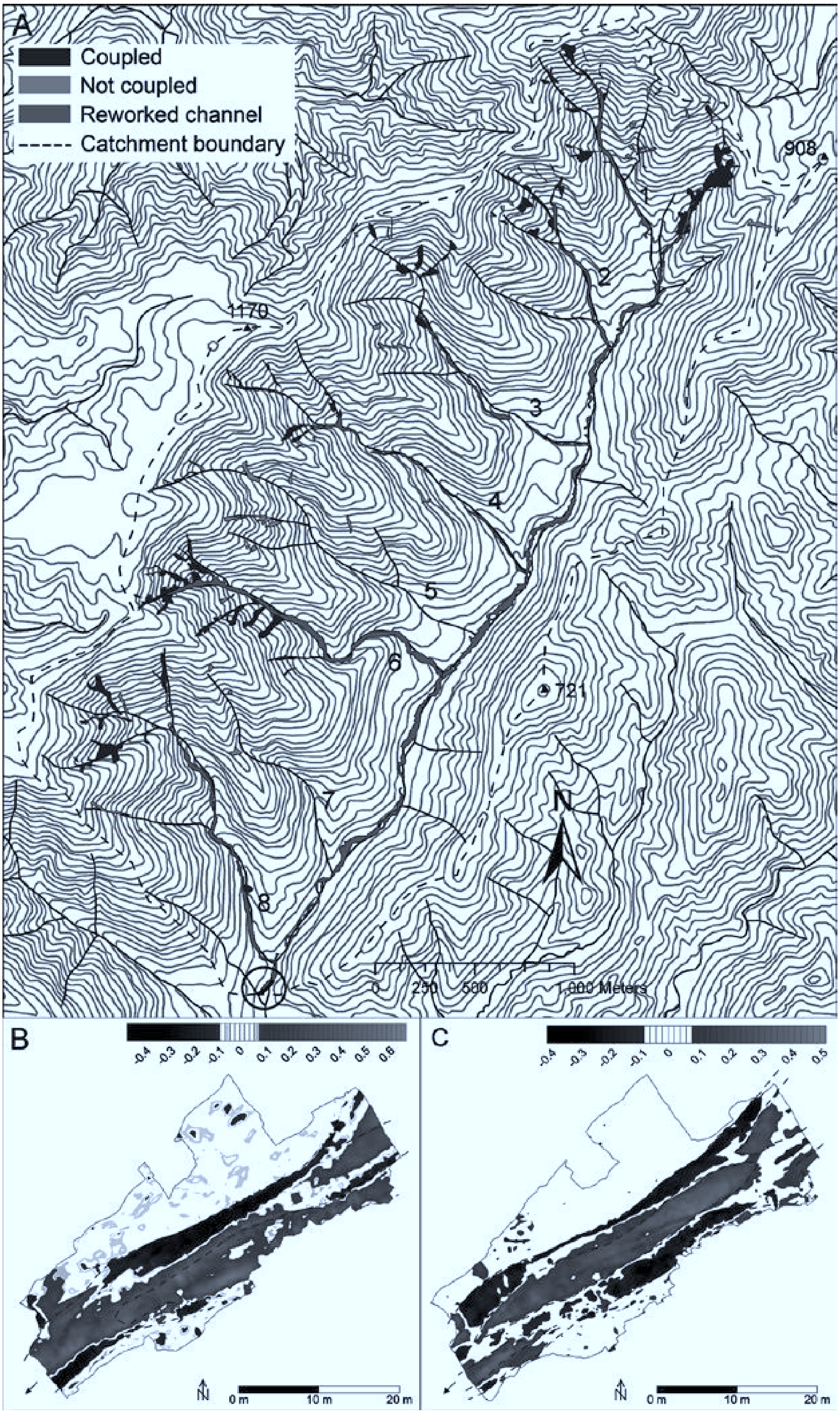

Figure 7 – (A) Areas of recent erosion and reworked channel within the Tamaki River catchment (contour lines at 20 m intervals) and their connectivity (coupled or not) to the study reach (circled); scour and fill (in m) at the study reach (B) between November 2007 and January 2008 and (C) between January and May 2008.

The second true right tributary was in 2005 strongly connected to the main stream. Cut banks in alluvium of up to 6 m height at the confluence and slips in the headwaters give evidence of previous accumulation of debris layers (sheet deposits) (Fig. 8). The age of vegetation on this upper surface indicates that this likely occurred during a major flood in February 2004. Since then incision has dominated and in 2010 the bed was armoured and the gravel banks were partly vegetated. An older and higher fan surface of this tributary to the north of the current confluence was deposited around 1880 (Grant, 1981c), indicating regular morphological activity in this sub-catchment.

At the first and third tributaries the situation is similar, although the old channel fill is not as deep and sediment supply is less substantial. These are the most significant tributaries according to their relative area and slope (Table 3). The fourth tributary conveyed mostly fine sediment sourced from the headwater gullies to the main channel and was also quite significant. In contrast, the channel of the fifth tributary showed no sign of recent connectivity (within the last 10 years). However, deposits up to 2 m thick indicate that earlier phases of slope erosion were connected to the channel and resulted in the accumulation of alluvial deposits. This sub-catchment currently contains only a few small, active slips.

The sixth tributary has a very steep catchment dominated by gully erosion. Frequent debris torrents produced sediment that was actively conveyed to the main channel during rain storms. The seventh tributary showed no evidence of recent sediment conveyance to the main channel and was much less significant (Table 3), while the eighth generated an alluvial gravel fan, indicating stronger connectivity between the substantially eroded areas in the headwaters and the tributary, although the fan acts as a buffer to the main stem. Since 1946 erosion in this sub-catchment was always high, ranging between 3.4% (1946) to 5.6% of catchment area (1974) (Hubbard, 1978). A considerable amount of the finer substrate material that was deposited and reworked in the study reach appeared to be sourced from this tributary. The tributaries to the true left played only a minor role in sediment production, with only small signs of recent erosion visible (Fig. 7A).

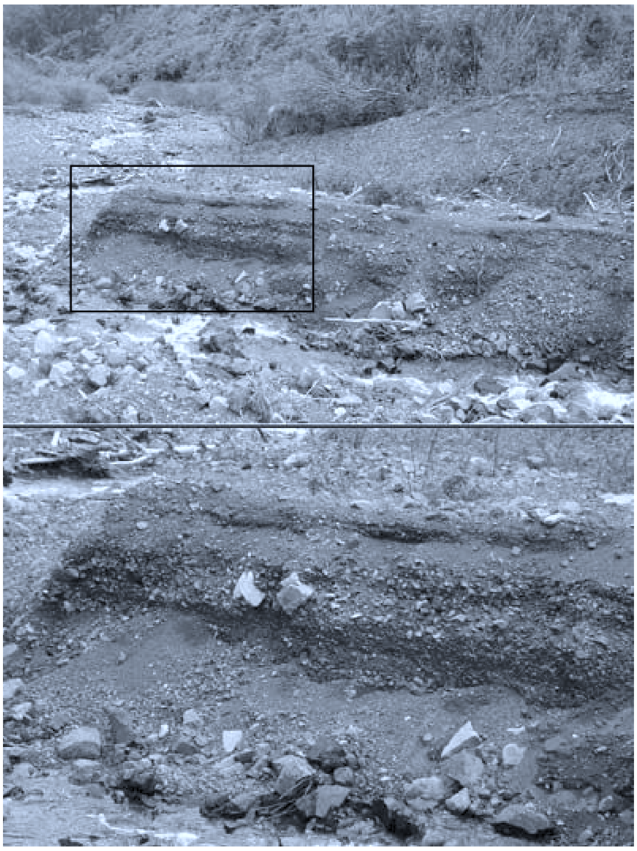

Figure 8 – Confluence between the second true-right tributary and the Tamaki trunk channel (top) showing cut banks of up to 6 m height with detail of the sheet deposits (bottom), probably deposited during the 2004 flood.

Photo: A.C. Schwendel, 4 October 2010.

The main trunk channel itself migrated within a wide active zone that was frequently reworked and constituted 2.0% (0.191 km^2) of the catchment area (Table 1). Thus it more than doubled the area potentially supplying sediment to the study reach. This figure declined from 0.455 km^2 in 1974, but was higher than in 1946 (0.135 km^2)

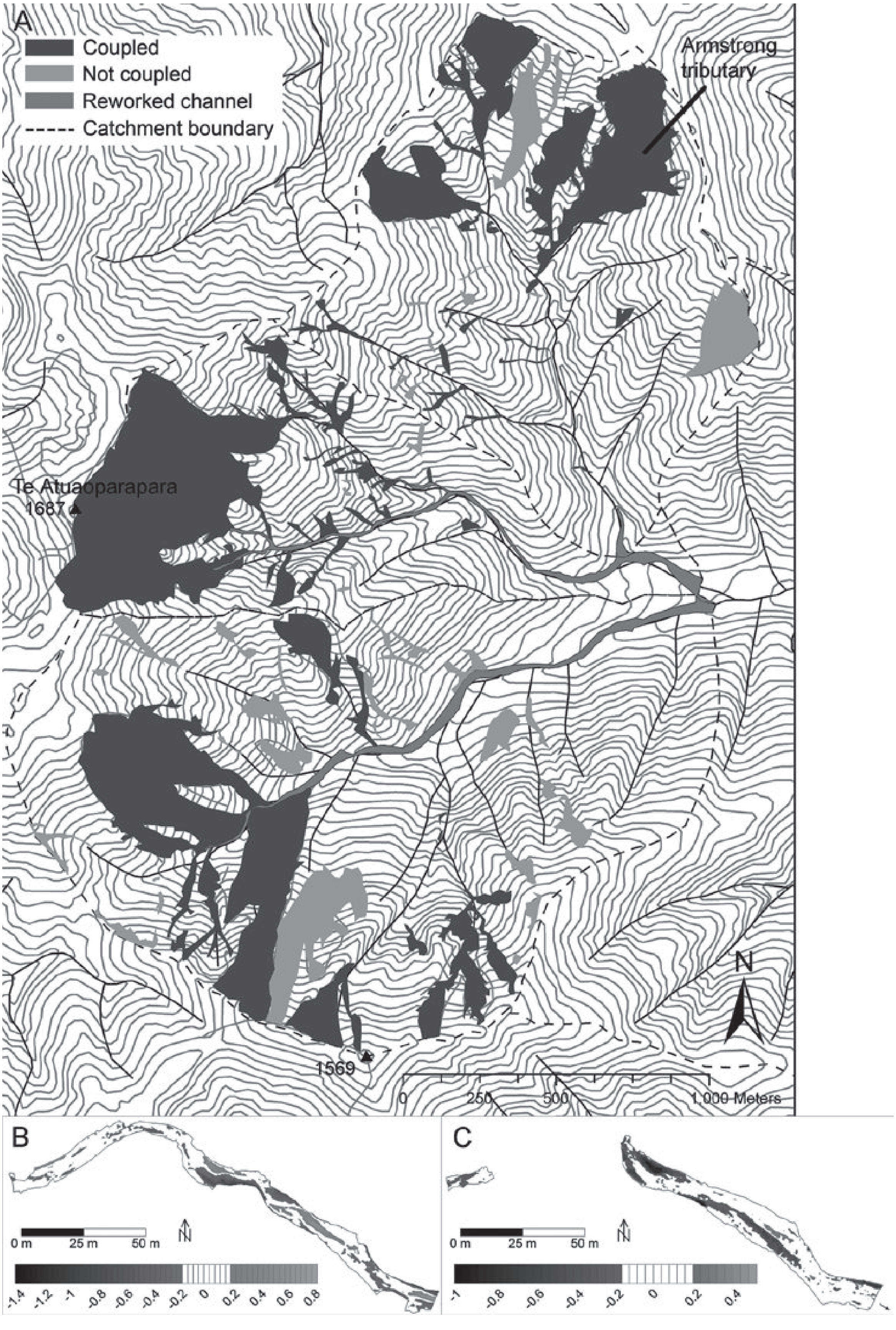

Figure 9 – (A) Areas of recent erosion and reworked channel within the Waipawa River catchment upstream of Waipawa Forks (contour lines at 20 m intervals) and their connectivity (coupled or not); scour and fill (in m) at the study reach (B) between October 2007 and January 2008 and (C) between January and May 2008.

(Stephens, 1977). A multi-thread planform was common, in particular upstream of the influence of willow and poplar plantings, which have probably increased sediment storage and limited channel migration in the lower valley downstream of the confluence with the fourth tributary. Between the fourth and fifth tributaries bed slope increased substantially compared to neighbouring reaches (Table 3). Connectivity between those reaches was largely effective, as there are no obvious long-term barriers to downstream conveyance of material, although some fallen trees caused temporary alteration in sediment flux.

Waipawa

Although over longer periods (2008 to 2010) the Waipawa reach migrated laterally within the wider active channel zone, the principal position of the channel has remained fixed over the six-month study period. However, channel margins and point bars experienced some scour while, especially in the lower part, channel morphology was highly dynamic, with alternating deposition and erosion of longitudinal bars and an overall widening and straightening of the channel (Fig. 9B and C). Nevertheless, during the survey periods some sections of the channel bottom remained armoured and relatively stable. Historically this reach has experienced substantial widening (e.g., 43 m in active channel width between 1950 and 1975) and aggradation (e.g., 1.1 m in mean bed level between 1960 and 1975) since the 1930s (Grant, 1977).

The Waipawa catchment was divided into four sub-catchments: South Branch, Centre Branch, North Branch and the lower part of the investigated catchment (Fig. 9A), following Grant's (1982) description. For the latter sub-catchment no detailed aerial photography was available, however lower resolution imagery and field reconnaissance showed that there were no major sediment sources connected to the channel and that sediment conveyance was unimpeded in the main channel, even in the gorge sections (Fig. 10). The main channel had a single-thread channel planform, with occasional branching.

The South Branch drains the largest of the three upper sub-catchments. Landslides and gully erosion occupied 23% of the planimetric catchment area (Fig. 5). Of this eroded area, 72% or 0.425 km^2 (Table 1) was coupled to the channel. In particular, the true-left headwater gullies and slopes were highly active, frequently supplying

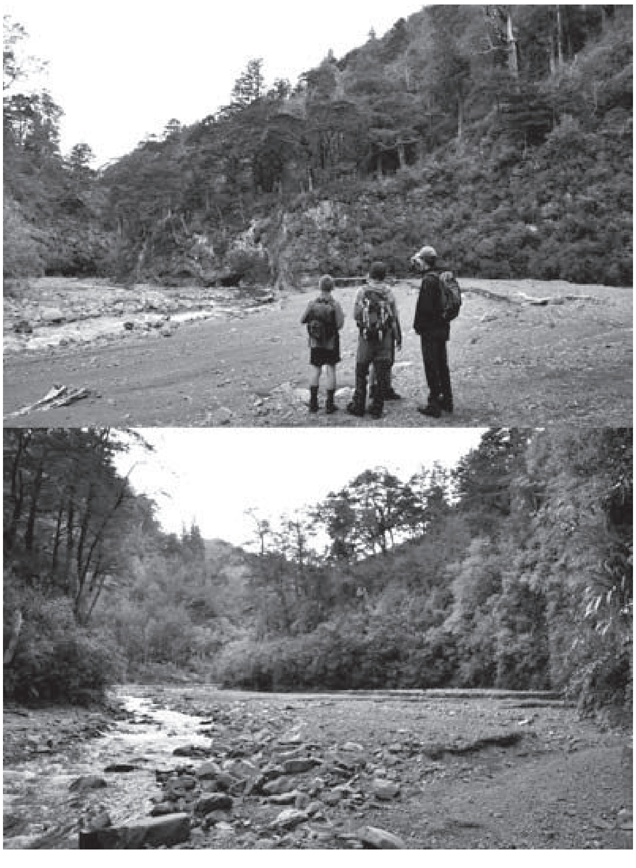

Figure 10 – Gorge section of the Waipawa looking downstream (top) and upstream (bottom), showing both storage and conveyance of finer alluvium. Recent activity has filled the valley floor which the stream is currently reworking and incising. The terraces are fresh and unvegetated and there is coarse lag in the current wetted channel where finer material has been flushed, consistent with Grant's (1982) observations in the upper catchment.

Photo: I.C. Fuller, 2 October 2010.

gravel- to boulder-sized sediment to the channel. Although substantial erosion occurred in their headwaters, two true-right tributaries were disconnected, in one case by a spectacular waterfall (Fig. 11). At the time of investigation the main channel of the South Branch consisted of mainly boulders and was armoured, but the active channel zone contained plenty of finer sediment that appeared to be frequently reworked during floods (1.6% of sub-catchment area).

The Centre Branch has the smallest area of the three upper sub-catchments. It consisted of 34.1% eroded area, of which 99% was connected to the channel (Fig. 5). The entire east-facing slopes of Te Atuaoparapara can be described as a large gully complex with a locally thin vegetation cover, but erosion is sufficiently frequent to prevent stabilisation and establishment of a thicker vegetation cover. The channel lacked any barriers or buffers that would impede sediment transport. It contained huge boulders and tree trunks and appeared to change course frequently. At the confluence between North and Centre Branch the latter was morphologically more active, with a wider active channel zone and a higher sediment load. Cut-banks of unconsolidated gravel-size sediments were up to 6 m high and interspersed with boulders and large woody debris. The area of active reworked channel was 2.7% of the entire sub-catchment (Table 1).

Figure 11 – Unconnected true-left tributary in the Waipawa South Branch catchment with bedrock constrictions that prevent regular coarse sediment transport and cause a waterfall.
Photo: I.C. Fuller, 2 October 2010.

In contrast, the North Branch appears to be less connected to the main trunk channel, at least under normal flow conditions. The valley floor upstream of the confluence with the Centre Branch was rather narrow, with only small reworked areas outside the wet channel (0.2% of sub-catchment) (Fig. 9A). The latter was strongly armoured. In the headwaters of this sub-catchment, however, erosion was substantial (23.6% of catchment area) and 79% of these gullies and slips were connected to the channel (Fig. 5). In particular the Armstrong tributary was characterised by intensive gully erosion in combination with shallow debris slides that in some parts reached up to the ridge crest. Its substrate was fine greywacke fragments and soil particles originating from volcanic ash deposits on top of the surrounding ranges (Grant, 1977). The bouldery, armoured nature of North Branch suggests that the fine material supplied from the Armstrong tributary is rapidly flushed through this steep upper section of channel during storms, which both convey the fine scree from the gully source and flush it through the upper reach. Based on distal tributary slope and catchment area, none of the three upper catchments dominated in terms of sediment characteristics and potential sediment supply

(Table 3). Since the impacts of Cyclone Alison in 1975 the area affected by erosion in the North Branch has decreased by 7% from 0.409 km^2 compared to a decrease of 38% from 1.81 km^2 in the entire Upper Waipawa catchment (Grant, 1982).

Discussion

The observed variation in channel dynamics can be related to variable connectivity between landscape compartments within the catchments. This connectivity incorporates the effects of flow regime, (e.g., insufficient competence in an unconnected system *sensu* Hooke, 2003), sediment supply and physical impediments to sediment transfer (e.g., dams in a disconnected system *sensu* Hooke, 2003). None of the five catchments examined qualifies as an unconnected or disconnected system. Rainfalls that resulted in floods that are competent to entrain and transport the dominant grain sizes occurred regularly (Fig. 4). However, over short time-scales in some catchments, coarse bedload transport is limited by transport capacity rather than sediment supply (Grant, 1983). For example, in the Waipawa North Branch, fine material originating from the eroded regolith is rapidly flushed through under normal flow conditions, leaving a boulder lag in the channel. In contrast, coarse sediment supply is buffered and stored in reaches with lower hydraulic energy gradients, e.g., upstream of the confluence with the Centre Branch, where sediment deposits from the latter lead to additional choking of the North Branch (Grant, 1982). Grant (1982) identified a flood stage of 12.4 m at Fletcher's Crossing (~7 km downstream of study reach) as a lower threshold to enable coarse sediment to be transported from the North Branch into the main channel. Flood events of this magnitude have occurred approximately 20 times since 1975 (Fig. 4E) and, given the high rates of sediment supply from the other two well connected upper sub-catchments, the study reach has adjusted accordingly. However, channel morphodynamics here are less responsive than at Tamaki or Mangapuaka, which operate closer to intrinsic thresholds (Harvey, 2007) and have the finest mean sediment size of all reaches. Armoured stream beds in parts of the catchment indicate that finer bedload is transported beyond the Waipawa study reach. Thus larger flood events than at Tamaki or Mangapuaka may be necessary to lead to responsive channel behaviour at the Waipawa study reach. Reach-to-reach connectivity in the main channels appears to be effective in all three catchments with the few observed barriers (e.g., logs) to sediment transport having only a temporary, modulating effect on sediment supply to the study reaches. Thus the Waipawa, Tamaki and Mangapuaka catchments can be classified as connected (*sensu* Hooke, 2003), with the latter two more responsive to external forcing factors. In contrast, the Coppermine and Manawatu catchments are potentially connected. In these instances, low supply of coarse material from slopes to the channel leads to more robust channel behaviour.

The Coppermine and Manawatu catchments were affected by some substantial mass movements such as the Coppermine landslide in 1976, but these isolated events do not produce abundant coarse material. Channel dynamics in the study reaches do not appear to be affected by these events. For example, Mosley and Blakely (1977) reported a D_{50} of 19 mm at the Coppermine landslide in 1976, whereas the D_{50} at the study reach is now 52 mm (Schwendel *et al.*, 2010). Thus isolated events are unlikely to have a measurable effect on reaches that are located at the trunk valley throat (Mosley and Blakely, 1977).

The aerial extent of erosion has decreased by varying amounts since the 1970s (Stephens, 1977; Hubbard, 1978; Grant, 1982), although the location of erosion scars appears to have remained relatively unchanged over time, with new sediment being derived by reactivation of former supply areas rather than erosion of previously vegetated areas. Hence, patterns of erosion identified by Mosley (1977) and Marden (1984) in the southern Ruahines appear to have remained constant over the past ~60 years. Marden (1984) attributed lower erosion rates in Coppermine relative to Tamaki and Mangapuaka catchments to steeper valley slopes, deeper valley and slope dissection, and higher rainfall in the northern catchments. A reduction in the extent of erosion in these catchments is not surprising, since the results in the 1970s and early 1980s were strongly influenced by the impact of Cyclone Alison in 1975. This suggests recovery in this landscape following a major perturbation.

In the upper Waipawa catchment, gully erosion is dominant, while in the Tamaki catchment, zones of erosion on steep convex creep slopes below the summit plateau are equally important (Fig. 7). These mass movements deliver sediment periodically to the channels, triggered by rainstorms and, potentially, by seismic events. For example, the Ruahine fault zone borders the catchment to the west and the main Tamaki valley is aligned along the Mohaka fault zone (Marden, 1977). Between those fault lines numerous splinter faults cause crush zones (e.g., in the fourth and sixth tributaries) that are highly susceptible to erosion. The examination of sediment supply needs to consider these issues along with the appraisal of landscape connectivity (Brierley *et al.*, this volume). The analysis of the potential of tributaries to supply sediment to the trunk reach reflected their observed relative contribution only partially, since it does not take these local parameters into account. The identified relative area affected by erosion which is coupled to the channel system and connected to the study reach can be interpreted as relative effective catchments areas (*sensu* Fryirs *et al.*, 2007) because it indicates the potential supply area of sediment to the study reach over approximately the last decade. However, since the origin and rate of conveyed material has not yet been established, it is difficult to determine which source of sediment and which transport pathway has produced the observed sediment budgets in any particular reach.

Although some sediment sources in the Waipawa catchment have not been coupled to the channel in the last 10 years and some tributaries are disconnected from the trunk channel, the large amount of sediment supplied from other components of the system, including the reworked channel deposits, provide a plentiful source of sediment over the long term. In both the Mangapuaka and Tamaki catchments, reworking of the substantial in-channel sediment storage, in combination with strong reach-to-reach connectivity, probably constitutes a significant sediment source for the respective study reaches. Hence, reworking of alluvial stores may constitute a significant proportion of the contemporary sediment load. This is a relatively understated aspect of river behaviour in New Zealand, but it has been reported as a dominant component of the sediment load in studies elsewhere (e.g., Fryirs and Brierley, 2001). This is important for maintaining channel dynamics and proximity of the system to thresholds despite declining erosion areas, although willow plantings enhance storage of alluvial sediment and allow mobilisation only during high discharge events. This suggests that the effects on reach dynamics of catchment disturbance by Cyclone Alison in 1975 may still be ongoing 35 years later and that the minimal recovery detected on the slopes (reduced areas of erosion) has yet to be manifest in the valley throats in these catchments, i.e., the system retains a memory of past events (Brierley, 2010).

Conclusions

The high variability in reach-scale morphodynamics within New Zealand mountain streams (Schwendel *et al.*, 2010) appears to be mainly driven by differences in sediment supply rate and is controlled by the coupling of sediment sources (slips and gullies) to channels. However, the role of valley and slope dissection may also contribute to this variability. In small headwaters reach-to-reach connectivity can limit sediment conveyance to lower reaches, but at a catchment scale it has a modulating effect. The examined catchments can be classified as either connected or potentially connected based on the effective catchment area of the study reaches and their upstream connectivity for coarse sediment transport. Since the extent of erosion in the more responsive catchments has decreased to a varying degree since the 1970s, sediment supply from in-channel storage has increased in importance. However, the exact origin and rate of conveyance of material remains unclear. Sediment tracing and routing is required to address this issue, thereby linking erosion, transport and storage processes with local channel morphologies in catchments that are strongly and frequently affected by erosion such as Tamaki, Mangapuaka and Waipawa. Furthermore, an assessment of erosion rates and their potential change in the decades since the 1970s would be of use to quantify the longer term pervading effects of catchment disturbance from Cyclone Alison, providing a clearer historic context of sediment flux in these catchments.

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