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Geomorphic impacts of a 100-year flood: Kiwitea Stream, Manawatu catchment, New Zealand

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Abstract

The geomorphic impacts of a 100-year flood are assessed in the Kiwitea Stream (254 km^2), a tributary within the Manawatu River catchment (New Zealand), using sequential aerial photographs and reach-based morphological sediment budgeting. Channel expansion and avulsion eroded in excess of one million cubic metres of sediment over 1 km^2 of floodplain along a 30-km-long reach of Kiwitea Stream. Channel transformation was spatially discontinuous and predominantly associated with large-scale bank erosion in response to a flood over 5 times bigger than the mean annual flood (annual recurrence interval (ARI) ~100 years). Total energy expenditure of this flood in the Kiwitea was ~14,900 × 10^3 J. The spatial discontinuity of channel transformation relates to valley floor and channel configurations. High stream powers generated in confined channels at bends produced catastrophic channel transformation. Where flood flows dissipated overbank, stream powers and the extent of channel transformation were reduced. Hydrologic, hydraulic and geomorphic variables can be invoked to thus explain the variability of geomorphic impacts encountered during this event.

Keywords: Geomorphic impact; Flood; River channel change; Erosion; Sediment budget

1. Introduction

1.1. Geomorphic impacts

The impact of floods on channel morphology is highly variable. Some major floods produce catastrophic change (e.g. Schumm and Lichty, 1963; Baker, 1977; Lisle, 1981; Gupta, 1983; Miller, 1995), while others have little effect (e.g. Costa, 1974; Costa and O'Connor, 1995; Magilligan et al., 1998). Floods of similar magnitude and frequency may therefore produce dissimilar morphological response, even within the same catchment (Costa, 1974; Nolan and Marron, 1985; Nanson, 1986; Miller, 1990; Magilligan, 1992; Butler and Malanson, 1993; Pitlick, 1993; Costa and O'Connor, 1995). Wolman and Gerson (1978) suggest the geomorphic importance of an event is a product of an array of factors, including magnitude, recurrence interval, processes occurring during the interval between recurrence and work performed during this intervening period. Therefore, given the variety of processes and boundary conditions, a spectrum of impacts for a given magnitude event in any one catchment is to be expected.

The role of flooding in fluvial geomorphology has been persistently controversial (Lewin, 1989) and much debated since Wolman and Miller (1960) advocated the view that channels were broadly adjusted to frequent

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events. Thus, for example, Harvey et al. (1979) suggest systems adjust to major flood events (recurrence interval (RI) up to 2 years), which control channel morphology, while moderate events (RI 14–30 times a year) influence adjustments within the overall morphology created by the major events. However, increasingly, the role of the extreme event has been recognized as significant in conditioning channel form (e.g. Reid and Frostick, 1994). Erskine (1994) suggested catastrophic floods (>10 times the magnitude of the mean annual flood) determine channel capacity, while smaller floods control the form of the channel bed. Similar conclusions were drawn by Pickup and Warner (1976), and Hack and Goodlett (1960) suggested that rare, large magnitude floods could have a dominant impact on some (mountain) landscapes (Miller, 1995). Erskine (1986) also described wholesale river metamorphosis during a series of large floods between 1949 and 1955 in the lower Macdonald River in NSW, Australia, which persisted more than 30 years. Such a response was also observed in the Cimarron River (Kansas) (Schumm and Lichty, 1963). Thus, large floods may either initiate long periods of river instability and give rise to a flood-dominated channel morphology (Hickin, 1983), or they may have little impact on a channel (Miller, 1990).

Richards (1999) suggests the morphological context in which the flood takes place is critical to conditioning the scale of its impacts (cf. Wolman and Gerson, 1978). Baker (1977) argued that there is a high potential for catastrophic channel response in small catchments with highly variable flood magnitudes. Within a broader context, catchment-scale boundary conditions may condition the geomorphic effectiveness of floods (Brooks and Brierley, 1997). Vegetation cover exerts a fundamental control on hydrology and sediment supply and may determine the sensitivity of a landscape (or channel) to flood-induced change, with the possibility of extreme impacts increasing in cleared catchments (Erskine and Bell, 1982; Erskine and Warner, 1988).

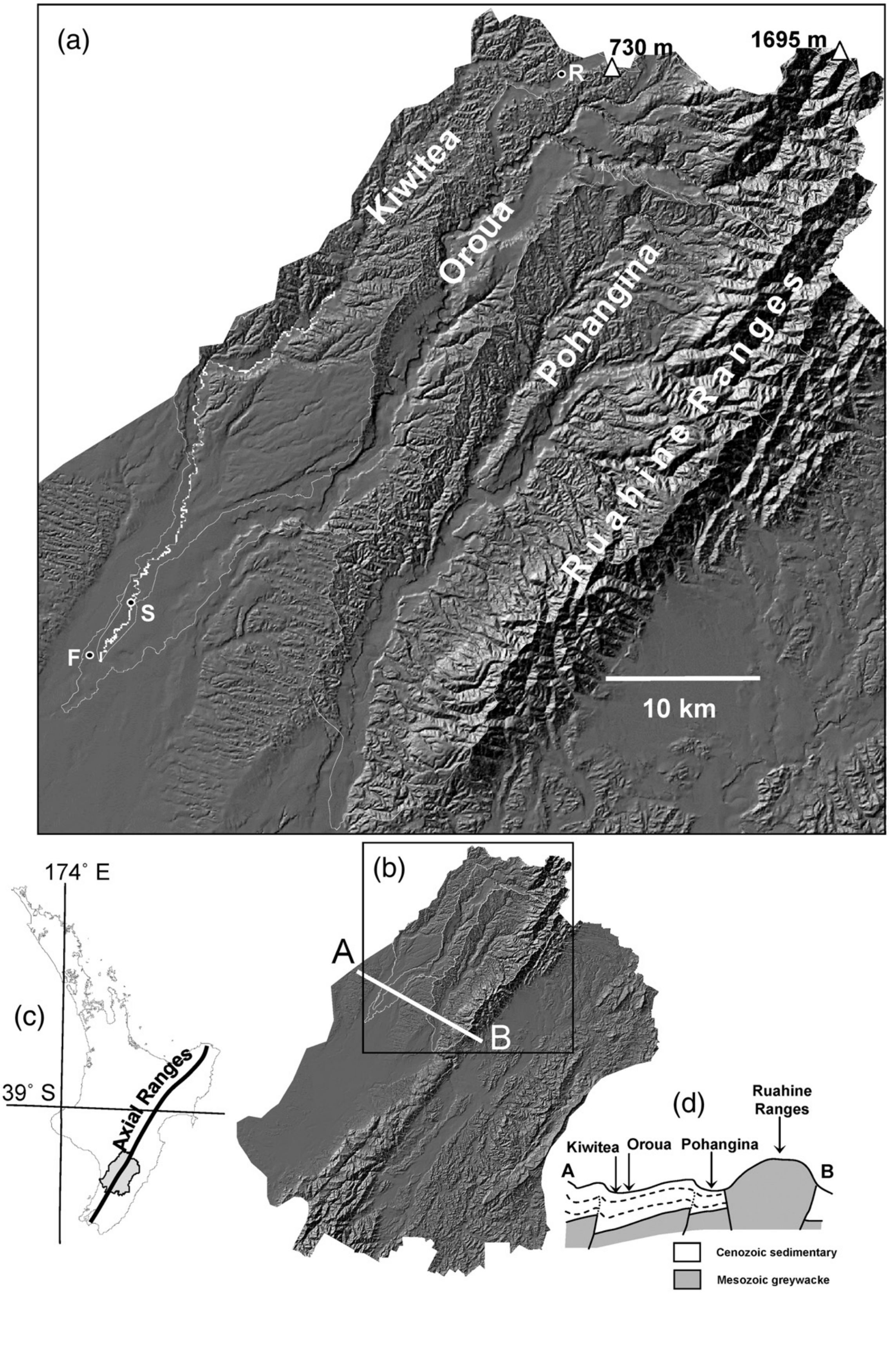
This paper seeks to quantify the impacts of a single flood event generated by a “150-year” storm in the Kiwitea Stream, Manawatu catchment, lower North Island of New Zealand, which occurred on 15–16 February 2004. The Kiwitea catchment within the western Manawatu drainage basin has been cleared of native forest cover within the last 150 years. The effectiveness of flooding in this system is thus likely to have increased. The ARI of the flood exceeded 100 years (Fuller and Heerdegen, 2005) and may thus be classified as large using Kochel’s (1988) definition (ARI > 50 years). This work examines the extent to which the channel system was modified by this rare event.

1.2. Study area

The western Manawatu catchment drains the south-western flanks of the Ruahine Ranges, which here rise to 1643 m, in the southern North Island of New Zealand (Fig. 1). The Range comprises highly fractured greywacke (alternating siltstone and sandstone) and forms part of the North Island’s axial ranges (Fig. 1). Uplift and erosion rates are high: up to 3 mm year^{-1} and 0.7 mm year^{-1}, respectively (Whitehouse and Pearce, 1992). Dissected hill country immediately to the west of the ranges forms much of the 254-km^2 Kiwitea catchment. This is located in the eastern margins of the Wanganui Basin, a major structural depression where up to 4000 m of marine sediment accumulated above the greywacke basement during the Plio-Pleistocene (Heerdegen and Shepherd, 1992). Poorly consolidated sands and gravels underlie the Kiwitea catchment. In terms of specific sediment yield, steepland grazed hill country in this area yields up to 2000–5000 t km^2 year^{-1} (Hicks and Shankar, 2003). Land use includes plantation forestry (pines), varying grades of pasture and scrub.

This physiographic setting places the long (48 km), narrow (average width 6.5 km) Kiwitea catchment at the upland fringe of the axial ranges, with a relatively steep gradient (0.005), gravely bed and highly erodible boundary conditions. The Kiwitea planform is best defined as wandering, using Neill’s (1973) and Ferguson and Werritty’s (1983) term. This represents a transitional pattern between multi-thread braided and single-thread meandering channels; lacking the sinuosity to be classified as meandering (1.44), or the degree of flow division to be braided, but combining both mid-channel bars and some well-developed bends, with extensive lateral bar forms often present. Wandering rivers are by nature dynamic (e.g. Ferguson and Werritty, 1983; Fuller et al., 2003a), although the active channel of the Kiwitea prior to the flood on 15–16 February 2004 was between 10 and 15 m wide and tree-lined for much of its length (Philpott, 2005), which compares with the 23-m-wide meandering channel of 1877 (Anon, 1980). Such channel constriction increases frequency of sediment transport (Laronne and Duncan, 1992). The result of this increased movement of sediment is bed degradation of the Kiwitea such that the 10-year flood would not overtop its banks (Anon, 1980). Prior to the February 2004 flood, the Kiwitea was therefore over-narrow and over-deep, largely due to riparian plantings in a narrow riparian strip.

There is a steep rainfall gradient moving up the catchment towards the ranges. Mean annual rainfall varies from 958 mm at Feilding to 1267 mm at Rangiwahia (locations shown in Fig. 1). Annual,


(a)
730 m
1695 m
R
Kiwitea
Oroua
Pohangina
Ruahine Ranges
S
F
10 km
174° E
(b)
A
B
(c)
39° S
Axial Ranges
(d)
Ruahine Ranges
Kiwitea
Oroua
Pohangina
A
B
Cenozoic sedimentary
Mesozoic greywacke

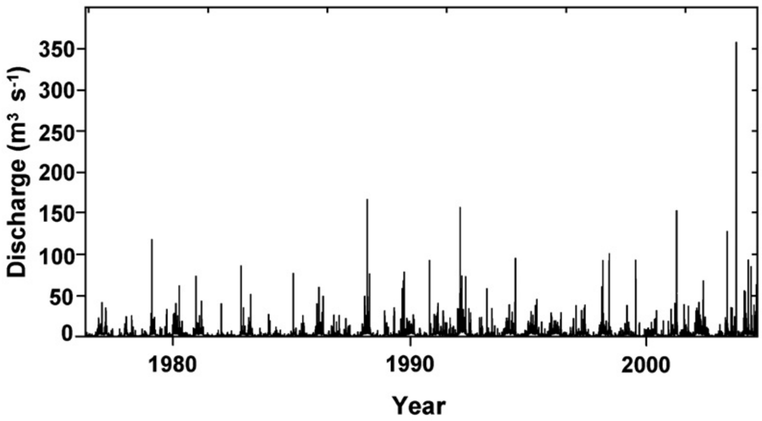


Fig. 2. Flood hydrographs for the Kiwitea at Spur Road, courtesy Marianne Watson, Horizons Regional Council.

seasonal and monthly rainfalls throughout the catchment are subject to variability of up to ±20%, with slightly more rainfall occurring in the winter–spring than summer–autumn (Anon, 1980).

1.3. The February 2004 storm and flood

Flooding was caused by a storm on 15–16 February 2004, which was one in a sequence of depressions to affect the North Island. Heavy rain also fell on 1–3, 4–5 and 10–12 February, saturating soils in the region (Parfitt, personal communication). On 15 February a cold-pool low became stationary just to the east of the North Island and intensified. Persistent heavy rain fell over most of the lower North Island, with rainfall in the Ruahine Ranges exceeding 200 mm in 24 h (Meteorological Society, 2004). The resulting large area flood was associated with a long duration rainfall event. Rainfall intensities did not generally exceed 10 mm h^{-1} (Fuller and Heerdegen, 2005), but much of the upper catchment had more than 20 h of rainfall at fairly constant intensities (Fuller and Heerdegen, 2005). Gauges at lower elevations recorded lesser totals and lower intensities (e.g. a rain gauge near Feilding at Halcombe Road (100 m) adjacent to the lower Kiwitea and Oroua recorded 115 mm over 19 h at an average intensity of 6.1 mm h^{-1}). The recurrence interval for the quantities of rainfall recorded in this region over a 24-h period is >150 years (Fuller and Heerdegen, 2005). Continuous rainfall records at Feilding extend from 1890 (Anon, 1980). Event magnitude in terms of discharge is more than twice any previous recorded flood event in the Kiwitea and more than five times the magnitude of the mean annual flood in this catchment (Fig. 2, Table 1) and in the adjacent Oroua and Pohangina catchments (Fuller and Heerdegen, 2005).

2. Methodology

2.1. Impact assessment

To assess the geomorphic impacts of the floods on the Kiwitea channel and floodplain, aerial photographs of a 30-km-long reach of the Kiwitea (cf. Fig. 1) were acquired in February 2004 in the immediate aftermath of the flooding. These were orthorectified and georeferenced before being overlaid on February 1999 orthophotos (2.5 m resolution) using ArcMap™ GIS. The positional accuracy of these orthophotos is given as ± 12.5 m (LINZ, 2005), with the 2.5-m photograph resolution setting the limit of features discernible. 2004 photography was taken 1 week after the flood, when river levels had subsided, but not returned to pre-flood baseflow conditions. Channel changes were identified from the photography and verified using field visits at selected sites. On-screen digitizing generated a series of metric polygons for the entire 30-km reach, identifying wetted channel, bars, active channel (wetted channel and bars combined) and areas of inundation (proximal

Fig. 1. (a) Location of river catchments referred to in this study: Kiwitea, Oroua and Pohangina, shown in the context of (b) the Manawatu catchment and (c) the North Island of New Zealand. A sketch section (d) shows the underlying structure and rock type (after Heerdegen and Shepherd, 1992). The 30-km reach of the lower Kiwitea river studied is highlighted in (a). Letters refer to the river gauging site mentioned in the text: S: Spur Road; and rainfall recording stations: F: Feilding, R: Rangiwahia.

Table 1
Flood flows in the Kiwitea, Pohangina and Oroua contextualized (based on Fuller and Heerdegen, 2005)

Gauging site [area km^2]	16 February 2004 flood (95% CI)	Average recurrence interval* (years)	Previous maximum flood (m^3 s^{-1})	Date of previous maximum	Mean annual flood ($Q_{2.33}$)**	Ratio 100 years:2.33 years flood	Years of record
Spur Road [224]	358 m^3 s^{-1} (±98)	100	166 m^3 s^{-1}	02.09.1988	72 m^3 s^{-1}	5.03	29

*GEV distribution (two-parameter); **based on EV2 and including the 15–16 February flood event. Details of these distributions are available in Fuller and Heerdegen (2005).

and distal to the channel) and floodplain (bank) erosion. Proximal inundation is defined as that adjacent to the channel, identifiable by thick drapes of sediment over the floodplain. Distal inundation is that further away from the channel, identified by discoloration of paddocks from water or fine sediment.

During the 1999–2004 period, several floods occurred (Fig. 2), thus geomorphic impacts identified may not wholly be attributed to the 15–16 February event, given that flows during the 1999–2004 period would have exceeded thresholds for bed sediment transport (Clausen and Plew, 2004). However, such changes would be limited to within the active channel.

2.2. Maximum stream power

Peak stream power was calculated using the narrowest flood channel width in the lower Kiwitea (55 m) where channel morphology remained stable. This method used Baker and Costa's (1987) equation:

$$\omega = \gamma QS/w \tag{1}$$

where ω is stream power per unit width; γ is specific weight of water (9800 N m^{-3} for clear water); Q is discharge (m^3 s^{-1}); S is energy slope; and w is water surface width.

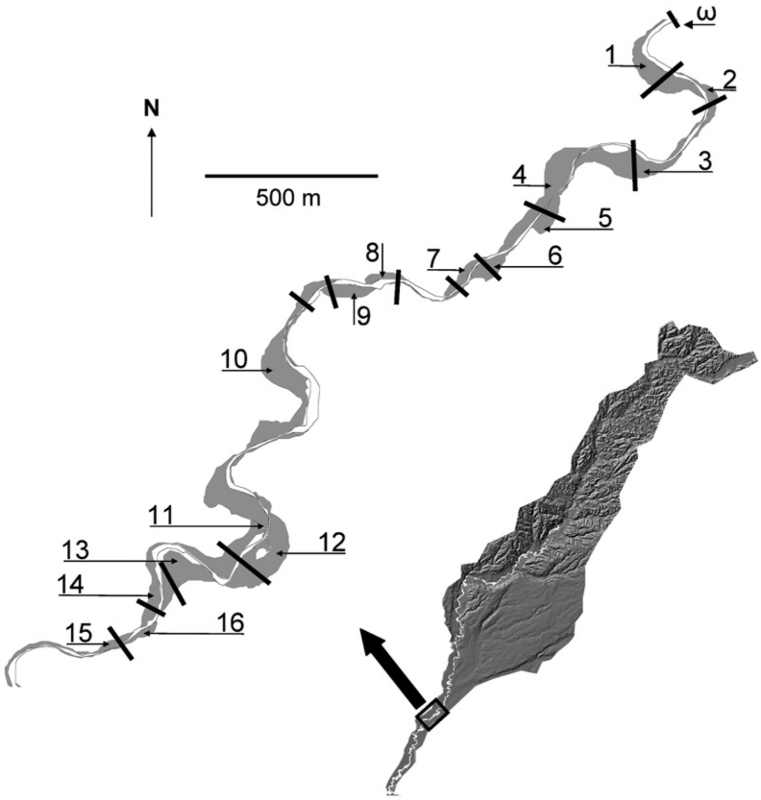


Fig. 3. Sub-reach of the Kiwitea used to derive estimation of sediment erosion budgets. Each bank erosion unit is numbered sequentially from upstream to downstream. Volumes of erosion are given in Table 3, derived using Eq. (1). The location used to measure maximum stream power is labelled: ω.

Table 2
Summary of channel changes observed along 30-km valley lengths of the Kiwitea, Oroua and Pohangina (after Fuller and Heerdegen, 2005)

Peak stream power ω[a] ($W\ m^{-2}$)	Total energy expended[b] ($J \times 10^3$)	Bar 1999 (km^2)	Bar 2004 (km^2)	Bar area increase (%)	Wetted channel 1999 (km^2)	Wetted channel 2004 (km^2)	Wetted channel increase (%)	Bank erosion (km^2)	Total inundation (km^2)	Overbank sediment drape (km^2)
319	14,928	0.2	1.4	600	0.24	0.65	171	1.1	4.4	2.8

[a] Minimum flood channel width used: 55 m.
[b] Assumes maximum stream power.

Values of discharge were taken from the stream gauge at Spur Road (cf. Fig. 1), no significant tributaries enter the river between the reach used to calculate stream power (Fig. 3) and this gauging station; thus, despite the spatial offset (~6 km), the values of discharge are considered to be far more reliable than those which could be reconstructed from channel cross-sections. The stream gradient at this site (0.005) is taken as a surrogate for energy slope. The maximum value of stream power is given in Table 2. Energy expended per unit area was derived by averaging the maximum stream power expended during the course of the 32-h duration flood and multiplying this by the total number of seconds to provide a value of energy expenditure per unit area (J) (cf. Costa and O'Connor, 1995). The average maximum stream power assumes a constant channel width of 55 m during the flood, which may not be unreasonable given the narrowness and stability of the channel at this location (cf. Fig. 3), although this may lead to an underestimation of power towards the start and end of the event; thus, the estimation of total energy expended is conservative. As gradient is also assumed to be constant, in this calculation stream power is a function of changing discharge as gauged during the course of the event. Gauge records provide a measure of discharge every half hour.

2.3. Sediment erosion

Morphological budgeting provides a first approximation of the volume of material eroded during the flood in a sub-reach of the lower Kiwitea (Fig. 3) and based on a profile × planform approach (Brewer and Passmore, 2002; Fuller et al., 2002, 2003b).

$$\mathrm{EV} = \left(\frac{\delta A_{xs}}{L} \times A\right) \quad (2)$$

where EV = erosional volume; δA_{xs} = change in cross-sectional area (pre- to post-flood); L = length of erosion unit along cross-section; and A = planform area of erosion unit: this area is derived from digitized polygons mapping discrete areas of bank erosion using the aerial photography described above.

Estimation of material eroded (only) was based on a reconstruction of pre-flood topography along surveyed cross-sections (cf. Fig. 4). The position of the pre-flood banks along each cross-section is derived from the 1999 LINZ orthophoto. The height of the pre-flood bank was extrapolated visually from the surveyed cross-section to the edge of the 1999 channel (cf. Figs. 4 and 5). Cross-sections were surveyed using a Topcon GT501 electronic total station in coarse mode (precision ±5 mm), having been fixed in position using RTK-GPS (Trimble R8 receiver and rover) with a horizontal precision of 25 mm and vertical precision of 50 mm. The precision of the ground survey greatly exceeded the precision of the orthophoto (2.5 m resolution). As such, volumes derived (Table 3) represent a first approximation of volumetric loss rather than exact values.

3. Results and discussion

3.1. Channel response

The geomorphic impact of large (*sensu*; Kochel, 1988) floods is variable. Sometimes impacts are major, while at other times only minor changes may occur (e.g. Magilligan, 1992; Costa and O'Connor, 1995). The changes observed along the lower 30 km of the Kiwitea are summarized in Table 2, and the impact of this 100 year event was categorized as severe (Miller, 1990) to catastrophic (Magilligan, 1992). The dimensions of the wetted channel enlarged by 171% and in some reaches active channel width increased by over 500%, providing accommodation space for substantial deposition of sand and gravel within the greatly widened active channel. Bar area thus increased by 600% in the lower 30 km. This represents substantial modification of the channel and adjacent floodplain. Given that true base-flow conditions did not prevail during the 2004 photo acquisition, some of the wetted channel increase could be attributed to higher discharge, but in turn this means the 600% increase in bar area is a conservative estimate.

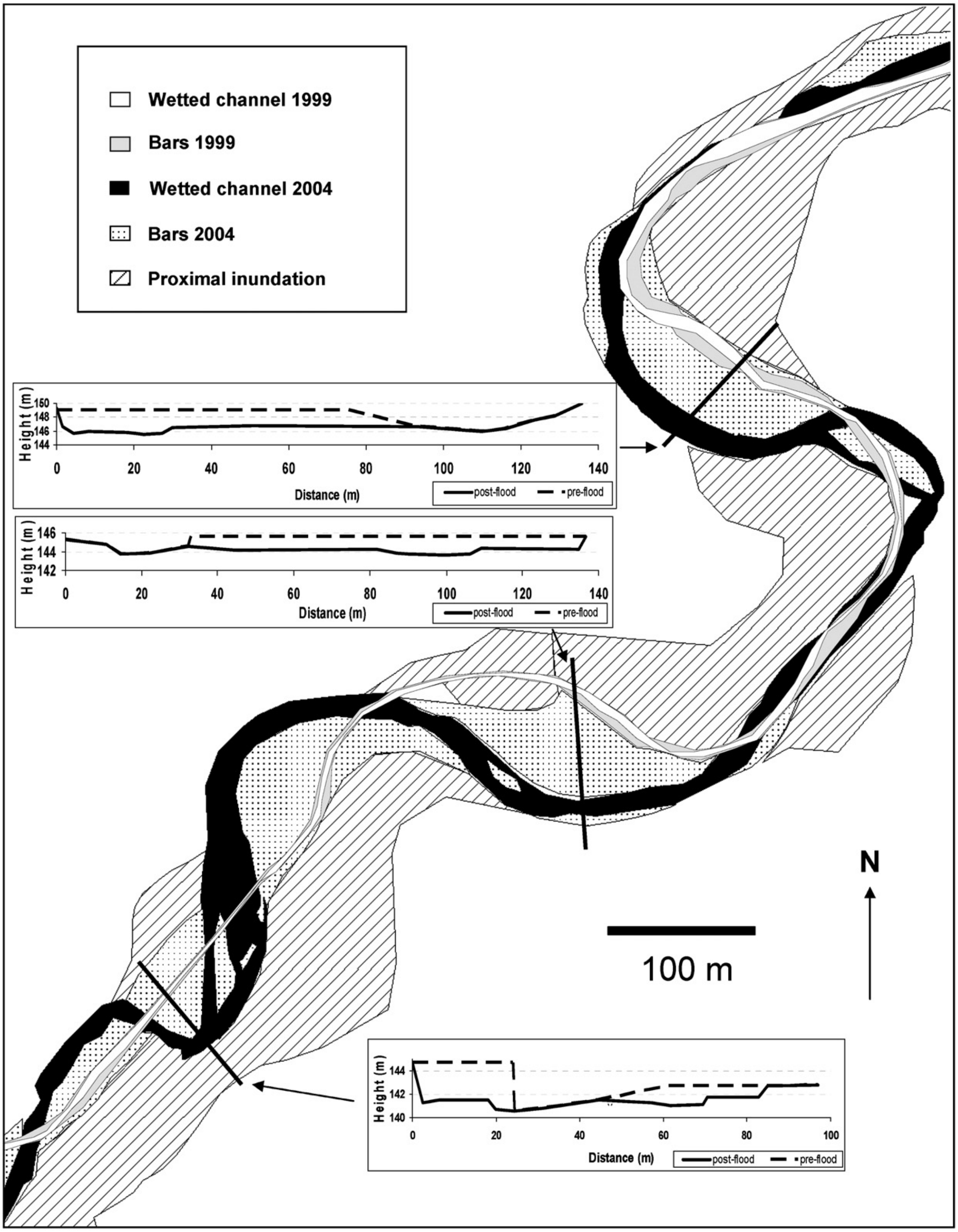


Fig. 4. Channel changes on the Kiwitea c. 11 km north of Feilding at NZMST23 349 132. Selected channel cross-sections, with reconstructed pre-flood profiles, are shown to illustrate the scale of change. Minimal overbank inundation indicates much of the flood flow remained contained within the stream channel. Severe erosion occurred on the outside of bends where stream powers were highest (cf. Miller, 1995).

Channel widening in response to moderate and large floods is common. For example, Sloan et al. (2001) cite a maximum 80% increase in width along the Eel River in California, and Nolan and Marron (1985) described width increases of between 7% and 105% elsewhere in California. Similarly, significant channel change occurred in the upper Hunter valley in New South Wales, Australia, in response to a series of large floods acting as effective geomorphic agents within a catchment cleared of native vegetation, including the erosion of 250 ha of floodplain, dramatic increase in channel width and reduction in sinuosity (Erskine and Bell, 1982; Erskine and Warner, 1988). However, the scale of the widening quantified in reaches in the Kiwitea is extraordinary. Fig. 4 illustrates the dramatic widening of the Kiwitea channel that typically occurred in discrete reaches along the lower 30 km of the valley. This is contrasted with the less dramatic (relatively) channel changes observed a short distance (3 km) downstream (Fig. 5), where the impact of the flood on the channel has been mitigated by substantial overbank flow, draping thick overbank fines across a broad area of floodplain. Lower banks in this reach permitted overbank flow at lower discharges, which limited the energy available for erosion in the

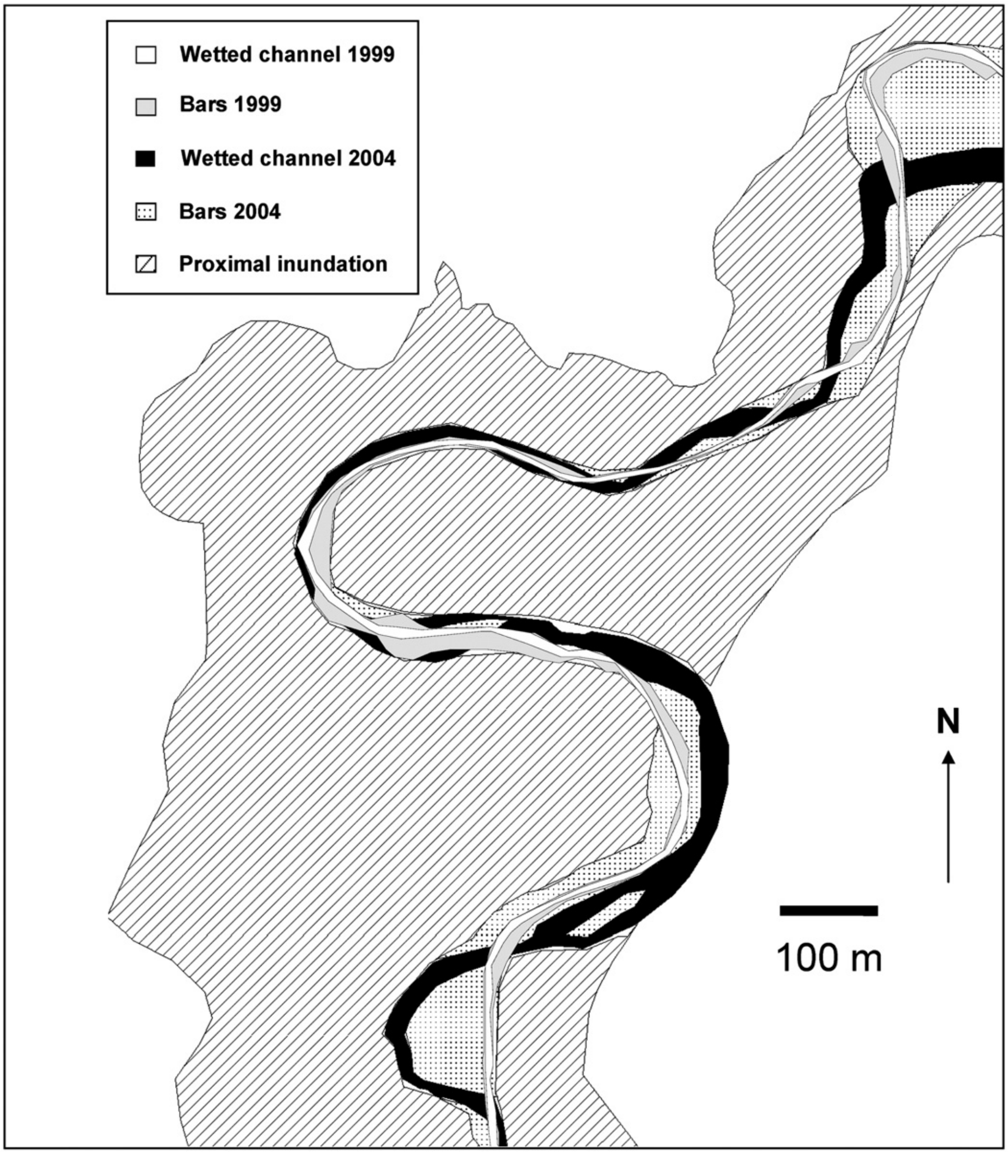


Fig. 5. Channel changes on the Kiwitea c. 8 km north of Feilding at NZMST23 330 106. Dissipation of flood flows overbank causing substantial inundation reduced stream powers and lessened geomorphic impacts of the flooding at this site.

Table 3
Erosion volumes calculated from a 3-km sub-reach of the Kiwitea defined in Fig. 3

Erosion unit*	Area (m^2)	Change in cross-sectional area (m^2)	Length of unit (m)	Volume (m^3)
1	12881	165	93	22853.4
2	3971	62	35	7034.3
3	15674	149.8	104.36	22498.7
4	16734	72.78	24	50745.9
5	5198	46	40	5977.7
6	5235	46	40	6020.3
7	3451	30	22	4705.9
8	2431	24	24	2431.0
9	5155	58.5	39	40645.5
10	27097	24	24	27724.0
11	27724	46.4	57.2	22489.4
12	21072	79.2	44	37929.6
13	13460	64	77	11187.5
14	7269	3.4	12	2059.6
15	5089	3.4	12	1441.9
16	1938	1	1.78	1088.8
			Total	266833.4

*Refer to Fig. 3.

active channel. While erosion still occurred in the channel, its effects are less dramatic than the site upstream (Fig. 4). Stream powers in this lower reach, given a flood flow width of 250 m, were 70 W m^{-2}; while in the upper reach (Fig. 4) widths of 55 m produced stream powers in excess of 300 W m^{-2}. This is significant, as Magilligan (1992) proposed a threshold of stream power for catastrophic change at 300 W m^{-2}, a figure which subsequently was supported by Lapointe et al. (1998). This pattern of alternating degrees of channel change is repeated along the entire 30 km valley reach.

Over the course of the lower 30 km of the Kiwitea, impacts of the flood are thus considerable. Erosion of adjacent floodplain totalled 1.1 km^2 (Table 2). In terms of volume of sediment eroded, a 3-km sub-reach of the lower Kiwitea (Fig. 3) generated ~266,833 m^3 (Table 3). This sub-reach is representative of the extents of erosion observed in the remaining 27 km of the river studied, in that both low terraces and active floodplain have been eroded. The mean multiplier of change in cross-section area (pre- to post-flood) divided by length of erosion unit for this 3-km reach (1.23) (in effect a surrogate for mean bank height in the reach) thus gives a tentative means of estimating sediment loss from the entire 30-km reach. Multiplication of this multiplier by the total area of valley floor eroded gives a volume of ~1,384,083 m^3. However, application of this mean multiplier to the total area of erosion in the 3-km sub-reach yields a figure of ~215,227 m^3, suggesting an underestimation of total volume of around 25%.

3.2. Conditioning factors

Channel morphology exerts a substantial influence on flood power at any given point in a river (Graf, 1983), and spatially varying boundary conditions affect the location and extent of flood impacts (Miller, 1995). Thus, geomorphic impacts in humid systems are normally maximized in steep, narrow channels, compared with broad, low-gradient valleys (Miller, 1995), as here stream power is maximized (Meyer, 2001). The 30-km reach assessed in this article cannot, however, be defined as a steep, narrow, mountain valley. Nevertheless, terrace bluffs confine reaches in the Kiwitea and generate higher flood powers than less confined reaches in the same river, or elsewhere where the floodplain is broader (cf. Magilligan, 1992; Fuller and Heerdegen, 2005). Furthermore, the bed of the Kiwitea had degraded to the extent that the 10-year flood would not overtop its banks (Anon, 1980). Similar affects of constriction (enhancing flood impacts) were observed by Butler and Malanson (1993). Nanson (1986) also identifies such narrowing of channels as being critical in concentrating erosional energy to the extent that high flows greatly exceed erosional thresholds, causing a catastrophic channel and floodplain stripping. The combination of high stream powers in some over-narrow channels has produced severe and in places catastrophic (*sensu*; Magilligan, 1992) erosion and channel transformation in the Kiwitea.

However, channel confinement in a narrow slot is not necessarily required to maximize stream power. Indeed, Fuller (in press) indicates that the valley floor width index (cf. Grant and Swanson, 1995) is not a good predictor of the spatial variability of erosion in the Kiwitea. Using flood flow modelling, Miller (1995) suggests that the shear stresses on the floodplain along the outside of a bend are comparable with the shear stresses generated in narrow, canyon-like reaches. Thus, local channel and floodplain configuration can maximize the available stream power. In reaches of the Kiwitea where the flood flow was confined between terrace bluffs at the outside of bends, the full force of the floodwaters was contained, and stream powers probably exceeded 300 W m^{-2}, considered by Magilligan (1992) and Miller (1990) as the threshold for catastrophic channel change. It is therefore not surprising that such reaches have undergone "major morphologic adjustments: major erosion, deposition or channel re-alignment" (Magilligan, 1992, p. 384). However, Miller (1990) acknowledges that stream power is in fact a poor predictor of the extent of erosion due to the array of factors that influence a reach's susceptibility to change (e.g. specific valley floor configuration, slope, planform, geometry, roughness, local flow obstructions), and Meyer (2001) suggested that major channel alteration occurred in an alluvial reach at stream powers in the range 50–200 W m^{-2}. Nevertheless, in reaches where flow overtopped lower banks (cf. Fig. 5), unit stream power was limited and did not exceed, or approach, the threshold for major morphological adjustment. This limited the geomorphic impact of the flood on these reaches. Thus, the bend shown in Fig. 5, which has been largely untouched by the flood in the Kiwitea, remains intact because lower banks upstream permitted substantial extra-channel flow, in effect by-passing this reach of channel.

3.3. Comparison with adjacent catchments

Similar amounts of rainfall fell on the adjacent Oroua and Pohangina catchments (Fuller and Heerdegen, 2005), but channel responses differ substantially (see Fuller, in press). Floods that were generated in these catchments had ARIs of 116 and 38 years respectively. The Pohangina flood could not therefore be classified as “large” (Kochel, 1988), but in terms of magnitude frequency, the Oroua flood was bigger than that in the Kiwitea. Despite the equivalence of flood magnitude and duration, changes in the Oroua were confined to relatively minor and localized channel widening. In this system, the river is not confined in a narrow, over-deepened channel but is relatively wide and shallow, with a 35-m-wide wetted channel and a 65-m-wide channel fairway (Horizons, 2002), which dissipates flood flow. Extensive inundation also occurred in the Oroua, which further limited the extent of erosion in this river, with just over half of the total bank erosion area measured in the smaller Kiwitea (Fuller and Heerdegen, 2005). Stream powers in the Oroua were lower, at a maximum of 106 W m^{-2} (Fuller and Heerdegen, 2005), which falls some way below Magilligan’s (1992) threshold for catastrophic change. In the Pohangina, the impacts of the smaller magnitude flood were largely limited to avulsion within the active channel belt and reworking of vegetated bars within the channel fairway, typical of processes observed in similar wandering rivers (e.g. Ferguson and Werritty, 1983; Fuller et al., 2002, 2003a, 2005). The area of bank erosion was approximately half that which occurred in the Oroua.

The magnitude of the February 2004 flood event relative to the mean annual flood was far higher in the Kiwitea than adjacent catchments (Fuller and Heerdegen, 2005). The Kiwitea channel was therefore comparatively poorly adjusted to accommodate the flood discharge of 15–16 February. The pre-February 2004 channel was on average just 10 to 15 m wide (Philpott, 2005), which compares with the 23-m-wide meandering channel of 1877 (Anon, 1980). The Kiwitea channel had over time adjusted to the smaller mean annual flood, which was several orders of magnitude smaller than the 100-year event of 2004. Richards (1999 p.15) suggests that “the geomorphological significance of an event depends on the circumstances encountered by that event—because the effect of the event is conditioned by pre-existing morphology”. The impact of the February flood event in the Kiwitea has therefore been enhanced by the pre-flood (narrowed) channel morphology. The same magnitude of event, had it occurred in the now much widened channel would not have had the same impacts. Gardner (1977) attributes minimal impacts of a 1 in 500 years flood event in Ontario to the valley floors being “well-adjusted to handling infrequent, high magnitude flows, particularly in the absence of man-made modifications and structures on the floodplain.” (Gardner, 1977, p. 2300).

4. Conclusions

The Kiwitea Stream eroded ~1.4 million m^3 of valley floor as the narrow and over-deepened channel responded to the largest recorded flood, which was five times bigger than the mean annual flood with an ARI of 100 years. Geomorphic impacts were, however, spatially discontinuous and highly reach specific. In some reaches, channel change was catastrophic while in others minimal changes occurred. The variability was conditioned by thresholds of flood power, in conjunction with the local channel configuration and planform geometry. Localized confinement of flood flows in the Kiwitea enhanced stream powers and thus reinforced the propensity towards major morphological adjustment. By contrast, in adjacent reaches and catchments, flood flows dissipated across the floodplain, limiting the unit stream power available for significant erosion and lessening the geomorphic impact of the 2004 flood.

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