Journal of Hydrology (NZ) 44 (2): 75-90, 2005

The February 2004 floods in the Manawatu, New Zealand: hydrological significance and impact on channel morphology

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Abstract

Catastrophic flooding occurred in the lower North Island in February 2004, associated with long duration, moderate intensity rain falling on saturated catchments. Average return intervals for the 24-hour rainfall amount exceeded 150 years across an unusually large area in the lower North Island. In some of the western tributaries of the Manawatu River the ratio of the resulting flood to the previous recorded flood maximum was up to 2.2. Regional analysis suggests the EV2 distribution should be used to estimate return periods of very large floods such as those that occurred in these catchments in February 2004.

This study examines the consequences of this large flood on the morphology of selected channels and quantifies the extent of changes caused by this event. Flooding produced considerable erosion of the wandering, gravel-bed rivers in the upland fringes of the western Manawatu catchment. Impacts in these channels were quantified using aerial photograph overlays of 30-km-long valley reaches of the Kiwitea, Oroua and Pohangina rivers in the western Manawatu catchment. The greatest impacts of the flood were measured in Kiwitea Stream, where the river eroded a total of 1.1 km^2 of floodplain (equating to an average of 3.7 ha km^{-1}) along the 30-km study reach. Areas of land loss appeared to be greatest where steep banks of unconsolidated alluvium confined the channel, and thus the energy of the floodwaters. Overbank flood flows dissipated the energy across the floodplain and limited channel erosion. Bank erosion in the Oroua and Pohangina rivers was of a lower magnitude, with erosional activity concentrated on reworking active and inactive bars in the macro-channel. Also prominent in these rivers was the large area of the valley floors draped with substantial overbank fines (Oroua: total 6.8 km^2, 23 ha km^{-1} and Pohangina: total 6.5 km^2, 22 ha km^{-1}). The differences in channel response to the flooding are attributed to the configuration of valley floor and the magnitude of the flood event relative to the mean annual flood.

Key words

storm, flood, wandering river, channel change, erosion

Introduction

In February 2004, extreme rainfall on already wet ground produced floods and slips, causing widespread damage across the lower North Island. In the Manawatu-Wanganui region four bridges were destroyed, 21 were damaged and 2500 people were displaced (Gray and Hancox, 2004). State highways were blocked by flood water and slips, and the Manawatu Gorge was closed for over two months. The storm has been rated on a par with Cyclone Bola (1988) for its severity and destruction (Meteorological Society, 2004), and is estimated to have had an economic impact of $300 million in the Manawatu-Wanganui region alone (Horizons Regional Council, 2004).

This paper examines the scale of the 2004 February flood in terms of the magnitude/frequency characteristics of the rainfall and various flood events and the geomorphological changes that took place in selected rivers. Assessment of channel changes in response to the magnitude and frequency of the rainfall and ensuing flood is important because it provides a basis for assessing options for future channel management.

The geomorphological effectiveness of floods and areas at risk from channel change are a central theme in fluvial geomorphology (Wolman and Miller, 1960; Baker and Costa, 1987; Gilvear and Harrison, 1991; Costa and O'Connor, 1995). However the role of flooding in fluvial geomorphology has been controversial (Lewin, 1989), with debate over the importance of frequent versus extreme events in determining channel form. Seminal work such as that by Wolman and Miller (1960) advocated the view that channels were broadly adjusted to frequent events. This also suits the engineering community, providing them with a single dominant discharge to work with. However, increasingly, the role of extreme events is being recognised as significant in influencing channel form (e.g., Reid and Frostick, 1994). Furthermore, magnitude-frequency effects vary with both catchment scale and environment (Wolman and Gerson, 1978); thus floods of similar magnitude and frequency may produce dissimilar morphological responses (Costa and O'Connor, 1995).

In examining channel changes caused by the flooding on 15-16 February 2004, we seek to contribute to the debate on the role of flooding in the geomorphic development of rivers in the western Manawatu. As Lewin (1989) notes, "observing flood effects... remains difficult, partly because of the logistical problems of being in the right place at the right time given the rather improbable chance of a rare event occurring." These floods provide an important opportunity to evaluate the magnitude-frequency characteristics of a rare, extreme rainfall and flood event and its effects on river channel morphology in New Zealand.

Study rivers and their management

The February 2004 flooding caused catastrophic (*sensu* Magilligan, 1992) channel change in a number of rivers in the western Manawatu catchment, notably the Pohangina, Oroua and Kiwitea (Fig. 1), with major morphological adjustments in the form of erosion, deposition and channel alignment. These rivers are located on an upland fringe, with the steep gradients and gravel beds typical of a piedmont setting. The rivers in this region are best defined as wandering, using Neill's (1973) and Ferguson and Werritty's (1983) term: they represent a transitional pattern between multi-thread braided and single-thread meandering channels. They lack the sinuosity to be classified as meandering, or the degree of flow division (multiple channels) to be classified as braided, but have both mid-channel bars and some well developed bends, with extensive lateral bar forms often present.

Wandering rivers are by nature dynamic (e.g., Fuller *et al.*, 2003), and have required management via catchment control schemes in this region (Oroua, Pohangina and the lower Kiwitea). The flood control approach taken by Horizons Regional Council in the Pohangina-Oroua catchment control scheme was demarcation of an acceptable channel

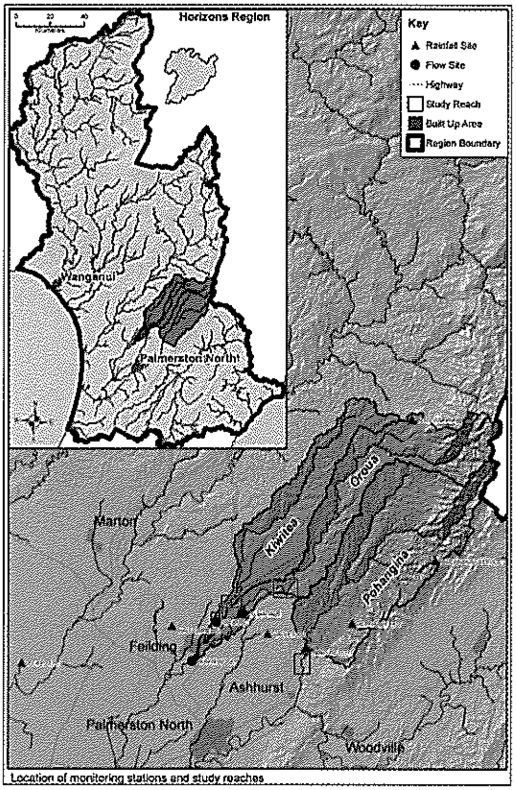

Figure 1 – Location of the western Manawatu tributaries: Pohangina and Oroua rivers and Kiwitea Stream, showing rainfall and river flow sites and detailed study reaches. Catchment areas shown are those contributing to the gauging sites.

alignment of the active channel belt or 'fairway' (Horizons, 2002), within which the active channel flows. The width of this fairway depends on the river dimensions, e.g., for the 60-m-wide wetted Pohangina channel, the width of the fairway is set at 110 m and for the 35-m-wide Oroua it is 65 metres (Horizons, 2002). These areas are set to provide flood capacity. Buffer zones of varying width (20 to 60 m) run adjacent to the fairway margin, and engineering is designed to keep the channel within these boundaries using a variety of approaches, including willow planting along bank margins and construction of groynes (also utilising willow plantings). However, an event such as the floods of 16 February 2004 could not be contained.

The storm

The flooding was caused by a storm on 15-16 February with a pattern more commonly associated with winter weather (Fig. 2). The hydrological record, however, shows insufficient seasonality to partition floods into summer or winter events. The storm was one in a sequence of depressions to affect the North Island, and the north and west of the South Island; heavy rain also fell on 1-3, 4-5 and 10-12 February, leading to saturated soils in the region. A "cold-pool" low became stationary just to the east of Hawke's Bay and intensified as warm moist air from the tropics collided with the colder air from Antarctica. Where cold-pool lows drift over warm sea, or pull in warmer air, there is intense convection and marked cyclonic characteristics, producing heavy rainfall, severe thunderstorms and squally winds. Normally in winter, the time when storms from the south usually strike New Zealand, rates of evaporation are less because air and sea temperatures are cooler, restricting the amount of rainfall. However, because this event occurred in summer, warmer air and sea temperatures facilitated much greater rates of evaporation, uplift and rainfall. Persistent heavy rain fell over most of the lower North Island (Fig. 3), with rainfall in the Ruahine Ranges typically exceeding 200 mm in 24 hours (Meteorological Society, 2004). Unusually, heavy rain fell on both sides of the ranges in the lower North Island (Fig. 3). Normally in a southeasterly flow, there is a rain shadow to the west of the ranges. However, rain-bearing clouds in this storm were at higher altitudes than usual (Gray, pers. comm. 2004), and lofted over the ranges, especially at the lowest point in the ranges, the Manawatu Gorge area. These conditions were enhanced by the high rates of uplift associated with the synoptic situation.

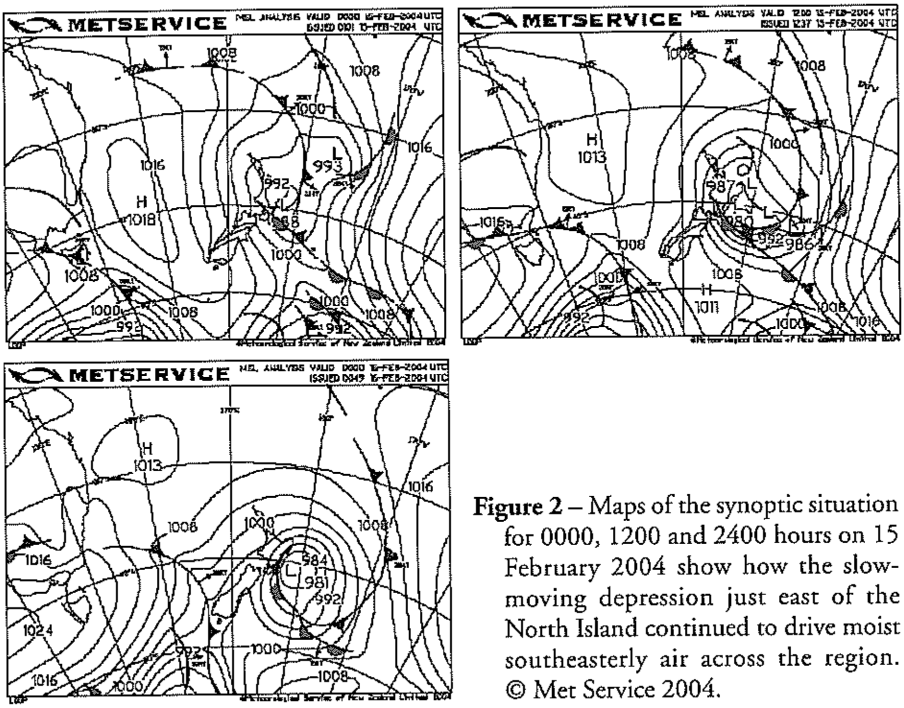

Figure 2 – Maps of the synoptic situation for 0000, 1200 and 2400 hours on 15 February 2004 show how the slow-moving depression just east of the North Island continued to drive moist southeasterly air across the region. © Met Service 2004.

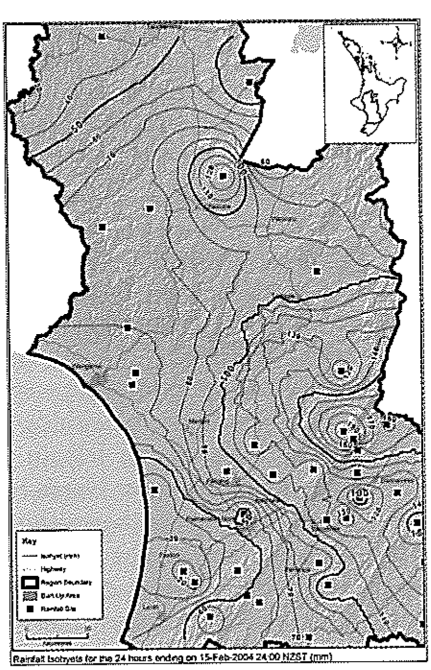

Figure 3 – Rainfall isohyets (in mm) for the 24 hours ending on 15 February 2004, 24:00 NZST. Courtesy Marianne Watson, Horizons Regional Council.

The 15-16 February 2004 floods were large-area floods associated with long-duration rainfall, with rainfall intensities generally not exceeding 10 mm hr^{-1}. Because the fronts and troughs that produce orographic rainfall in New Zealand generally move across the country at 25-35 km hr^{-1}, the normal duration of a rainfall event is usually less than 10 hours; slower moving systems with normal-intensity rainfall accumulate higher totals as the duration of the event lengthens. In this storm, much of the upper catchment areas had more than 20 hours of rainfall at fairly constant intensities, and the areas of highest rainfall depth were those with higher intensities. For example, the rain gauge on the Pohangina River at Makawakawa divide on the Ruahine Range had a total rainfall of 285 mm over 40 hours. The bulk of the rainfall (235 mm) occurred over a 19-hour period at an average intensity of 12.4 mm hr^{-1} (Fig. 4). This was one of the highest average intensities recorded during the storm. Gauges

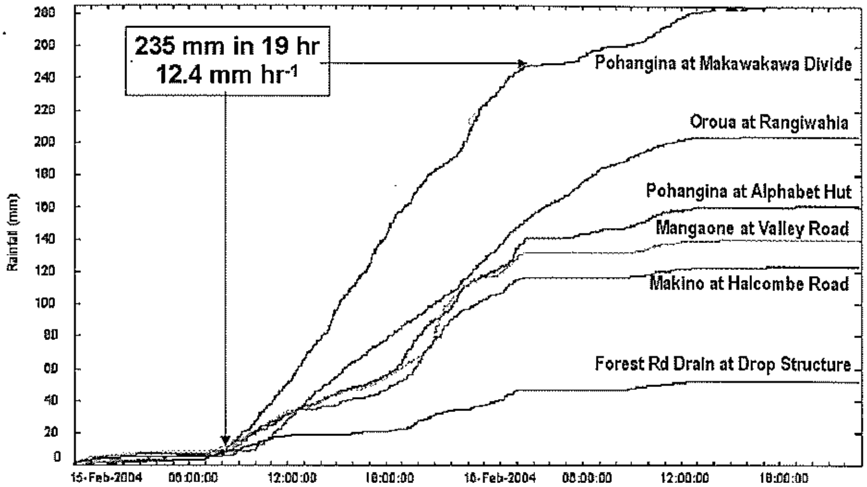

Figure 4 – Cumulative rainfall in the western Manawatu catchment. The sites range from the high altitude gauges in the Ruahine Ranges to lowland areas.

at lower elevations recorded lesser totals and lower intensities (e.g., the rain gauge at Makino Stream at Halcombe Road recorded 115 mm over 19 hours, at an average intensity of 6.1 mm hr^{-1}). As Figure 3 shows, however, the area of substantial storm rainfall was widespread.

Event hydrology

The widespread distribution of heavy rain during this event is shown by both the isohyet maps and average recurrence interval maps. However, the average recurrence interval for individual flood peaks in a number of catchments within the affected area is catchment specific—the catchments in turn vary in size, thus giving rise to significant differences in magnitude/frequency relationships. Figure 5 shows the average recurrence interval for 24-hour rainfall over the region for the 15-16 February 2004 event. The most immediate impression is that a substantial area is enclosed by the >150 year average recurrence interval isopleth, and it is not surprising that high magnitude floods occurred. The high rainfall area was spatially well defined and the most significant

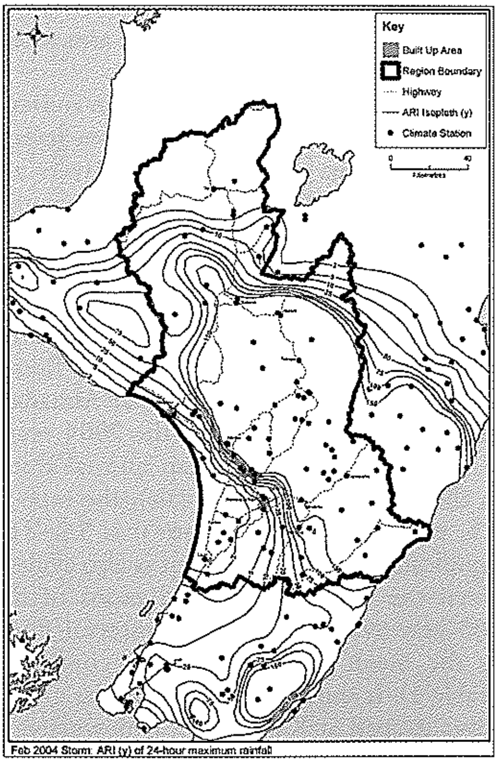

Figure 5 – Average recurrence intervals (ARI) (in years) of 24-hour maximum rainfall. Courtesy Marianne Watson, Horizons Regional Council. The ARIs are based on Thompson (2004).

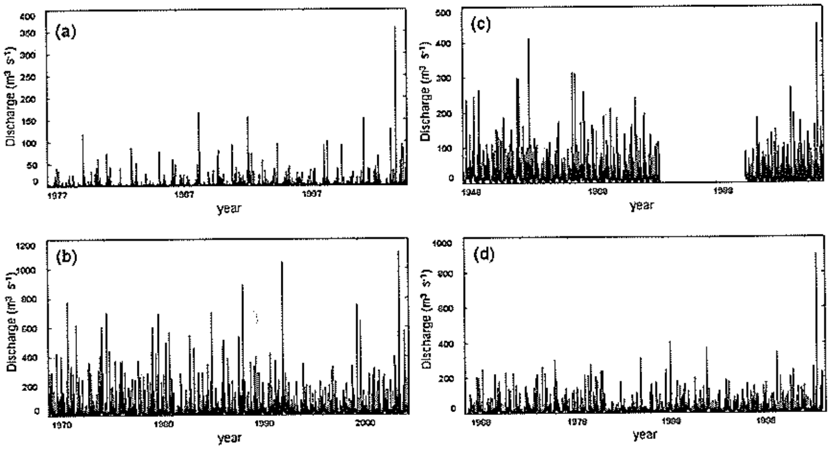

Figure 6 – Flood hydrographs to 1 January 2005 for (a) Kiwitea gauged at Spur Road (from 5 November 1976), (b) Pohangina gauged at Mais Reach (from 10 June 1969), (c) Oroua gauged at Almadale (from 3 December 1947), and (d) Oroua gauged at Kawa (from 3 February 1967). Data © Horizons Regional Council. Graphs courtesy Horizons Regional Council.

channel changes took place in the area where the highest rainfall was centred.

To set the February 2004 event in context, the long-term hydrographs of Kiwitea Stream and the Oroua and Pohangina Rivers are shown in Figure 6. Table 1 gives comparative data on the February flood flows and statistics on previous floods. The ratio of the 2004 event to the previous largest flood is 2.2 for the Kiwitea Stream (29 years), more than twice any previous recorded flood, and 1.09 for the Oroua River at Almadale (46 years of record). When the 2004 event is compared with the mean annual flood in the Oroua River (Almadale), the ratio is 2.6, while in Kiwitea Stream it is 5.0. The significance of the 2004 event is also evident when the regionally-derived ratios of the 100-year average recurrence interval flood to the mean annual flood are compared (Table 1). It should be noted that the Oroua River gauged at Kawa Wool is downstream of the confluence with Kiwitea Stream (cf. Fig. 1); these data indicate the significance of the Kiwitea Stream's contribution to the magnitude of the flood in the lower Oroua. This was a rainfall and flood event the likes of which had not been recorded before in the Kiwitea and lower Oroua.

The annual flood series for the Pohangina and Oroua Rivers and Kiwitea Stream show the previous EV1 distribution fitted to the series up to 2003 (Fig. 7). These are straight lines, which conform to the parameters for the distribution and would give hydrologists and engineers confidence to estimate return periods for bridges, culverts, stop-banks and floodways. However, when the distributions include the 2004 flood event, the EV2 distributions hook upwards, especially in the Kiwitea and Oroua at Kawa Wool gauging site, even with the use of the Gringorten plotting position (Fig. 7). This makes the estimated magnitude of previous 100-year average recurrence interval events about 60 per cent larger than before, but the values are still not included within the 95% confidence limits (EV1) of the 2004 flood event. This suggests that the previous active channel alignments (fairways) were based on estimates of average recurrence interval that in hindsight were much too low. The engineering implications of such a difference are significant.

Table 1 – Comparison of the February 2004 flood flows in Kiwitea Stream, and the Pohangina and Oroua rivers, with statistics for previous floods

River (Gauging) Site) [area km^2]	Flood Flows (m^3 s^{-1})											
	Feb 16 2004 Flood (95% CI)	Average Recurrence Interval (yr)		Previous Maximum Flood (m^{3}s^{-1})	Date	Average Recurrence Interval (yr)		Mean Annual Flood ($Q_{2.33}$)		Ratio 100 yr : 2.33 yr flood		Years of record
		EV1*	EV2**			EV1	EV2	EV1	EV2	EV1	EV2	
Kiwitea (Spur Road) [224]	358 (±98)	643	100	166	02/09/1988	27	26	81 (inc. 2004) 71 (exc. 2004)	72 71	3.32 (inc. 2004) 2.97 (exc. 2004)	5.03 3.08	29
Oroua (Almadale) [329]	450 (±80)	116	115	412	12/05/1958	106	219	172 (inc. 2004) 172 (exc. 2004)	172 166	2.55 (inc. 2004) 2.45 (exc. 2004)	2.56 2.21	46
Oroua (Kawa) [543]	900 (±204)	>1000	251	404	02/09/1988	43	62	207 (inc. 2004) 224 (exc. 2004)	205 210	2.53 (inc. 2004) 2.21 (exc. 2004)	3.39 2.02	38
Pohangina (Mais) [547]	1111 (±213)	51	38	1046	15/02/1992	54	44	484 (inc. 2004) 467 (exc. 2004)	466 457	2.56 (inc. 2004) 2.48 (exc. 2004)	2.91 2.67	36

* Gumbel Distribution   ** GEV Distribution (2-parameter)

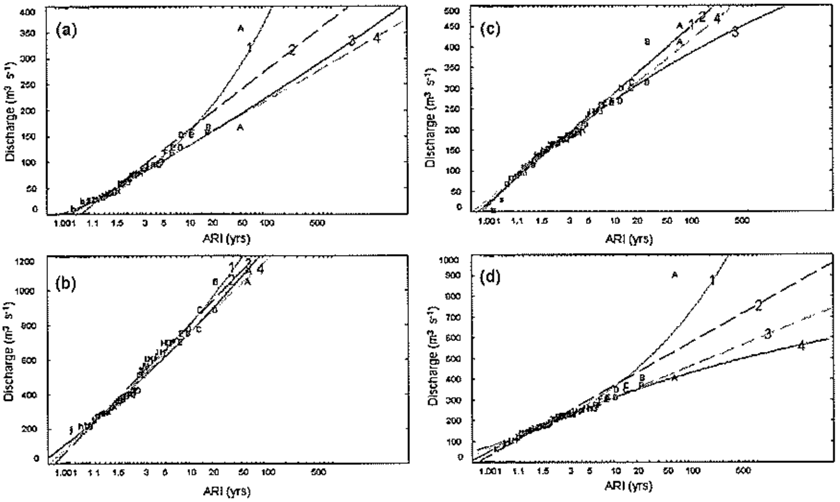

Figure 7 – Annual flood series for (a) Kiwitea gauged at Spur road, (b) Pohangina gauged at Mais Reach, (c) Oroua gauged at Almadale, and (d) Oroua gauged at Kawa. Including February flood: Curve 1 - EV2, Curve 2 - EV1, and excluding February flood: Curve 3 - EV2, Curve 4 - EV1. Graphs courtesy Horizons Regional Council.

Channel change

To assess the effects of this flood on the channel morphology of the western Manawatu tributaries, aerial photographs of 30 km long reaches of the Kiwitea, Oroua and Pohangina rivers (Fig. 8) were flown in February 2004 in the immediate aftermath of the flooding. These were then orthorectified and georeferenced before being overlaid on February 1999 orthophotos of these rivers, using ArcMap™ GIS. The positional accuracy of these orthophotos is given as ± 12.5 m (LINZ, 2005). Channel changes in the c. 30 km long valley lengths were identified from the photography and verified using field visits at selected sites. On-screen digitising generated a series of metric polygons for each river, with the following parameters identified: wetted channel, active channel, bars, and area of inundation (proximal and distal to the channel). Proximal inundation is defined as the area inundated adjacent to the channel, identifiable by thick drapes of sediment over the floodplain. Distal inundation is that further away from the channel, identified by discolouration of paddocks from water or fine sediment. In addition in the wider Oroua and Pohangina, workover area (*sensu* Lewin *et al.*, 1977) was also established, defined as the area swept (literally worked over) by the channel between the survey periods.

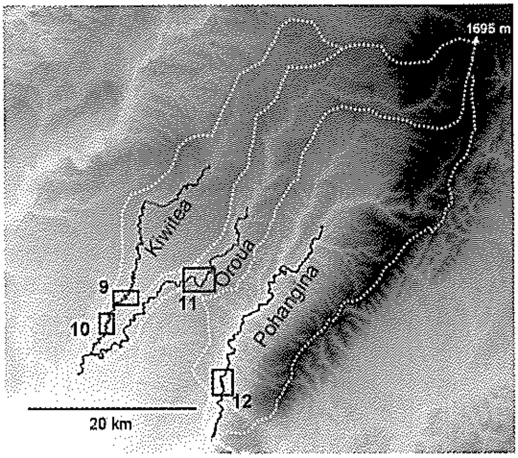

Figure 8 – Locations of the 30-km-long reaches of the Kiwitea, Oroua and Pohangina rivers used in analyses of channel changes. Numbered boxes refer to sites discussed in Figures 9-12.

The changes observed along the c. 30 km valley lengths of each channel studied are summarised in Table 2. Four sites were selected to demonstrate in more detail examples of the types of change observed on the Kiwitea (2 sites), Oroua and Pohangina (cf. Figure 8) river reaches; these changes are shown in Figures 9-12. Peak stream power was calculated for selected (minimum) cross sections at each of these sites using equation 1, based on Baker and Costa (1987).

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

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. Values of maximum stream power are given in Table 2. Energy expended per unit area was derived by averaging the maximum stream power expended during the course of the 32-hour duration flood and multiplying this by the total number of seconds to provide a value of energy expenditure per unit area (joules), simplifying an approach described by Costa and O'Connor (1995).

Most of the changes observed are assumed to have occurred during the 2004 flood. However, the orthophotos used as the baseline from which to identify morphological changes attributed to the February 2004 flood were five years old; changes prior to this flood in the intervening period are unknown. Nevertheless, in Kiwitea Stream, the 2004 flood completely transformed the channel (Fig. 9), and it is reasonable to assume that the changes identified in this river were wholly attributable to the February flood,

Table 2 – Summary of channel changes observed along 30 km valley lengths of the Kiwitea, Oroua and Pohangina

River	ratio 2004 flood: $Q_{2.33}$[1]	sinuosity	slope	Peak unit stream power[2] (W m^{-2})	Total energy expend. (joules) × 10^3)	bar 1999 (km^2)	bar 2004 (km^2)	bar area increase (%)
Kiwitea	5.04	1.44	0.005	319	14,928	0.2	1.4	600
Oroua	2.61[3]	1.43	0.003	106	5,294	0.49	0.81	65
Pohangina	2.38	1.3	0.004	290	14,428	0.9	2.4	167

River	wetted channel 1999 (km^2)	wetted channel 2004 (km^2)	wetted channel increase (%)	bank erosion (km^2)	workover (km^2)	total inundation (km^2)	overbank sedimentation (km^2)
Kiwitea	0.24	0.65	171	1.1	1.1	4.4	2.8
Oroua	0.7	1.1	57	0.6	1.4[4]	9.5	7.2
Pohangina	1.2	1.5	25	0.36	1.76[5]	9.3	6.3

[1] $Q_{2.33}$ defined as mean annual flood using EV1 distribution, excluding 2004 data

[2] minimum flood channel widths used: Kiwitea: 55 m, Oroua: 125 m, Pohangina: 150 (cf. Figures 9-12)

[3] as gauged upstream of the Kiwitea confluence at Almadale.

[4] vegetated bar erosion 0.8 km^2

[5] vegetated bar erosion 1.4 km^2

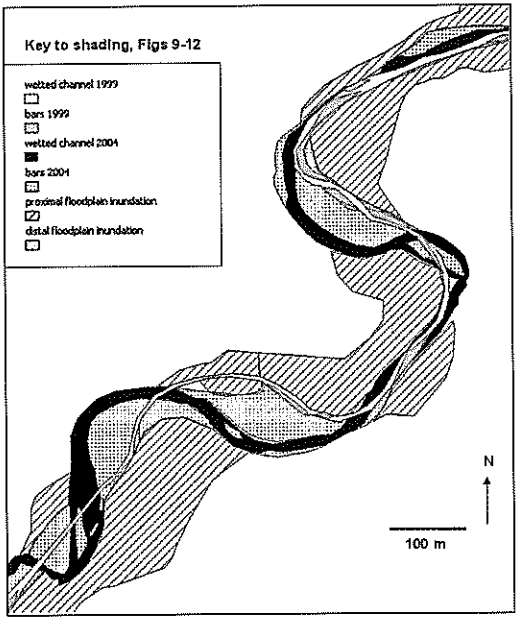

Figure 9 – Channel changes on Kiwitea Stream, c. 11 km north of Feilding, at GR T23 349 132.

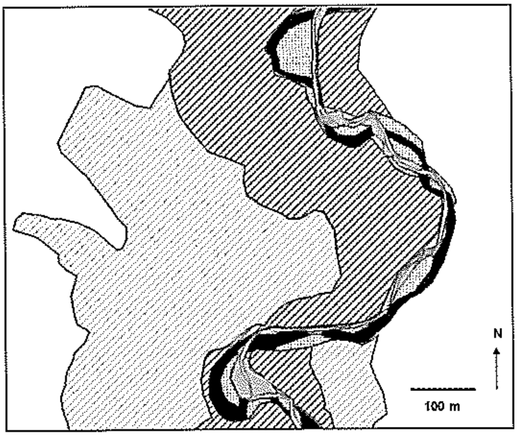

Figure 10 – Channel changes on Kiwitea Stream, c. 8 km north of Feilding, at GR T23 330 106

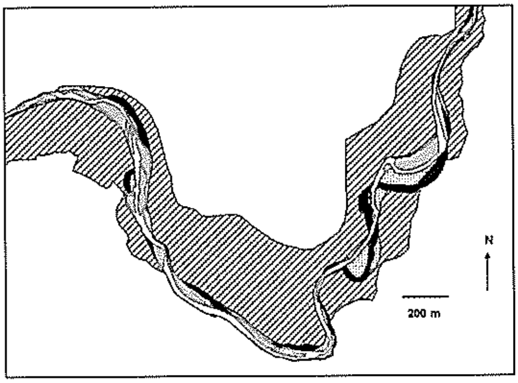

Figure 11 Channel changes on the Oroua River, c. 4 km southeast of Kiwitea Stream, at GR T23 435 145

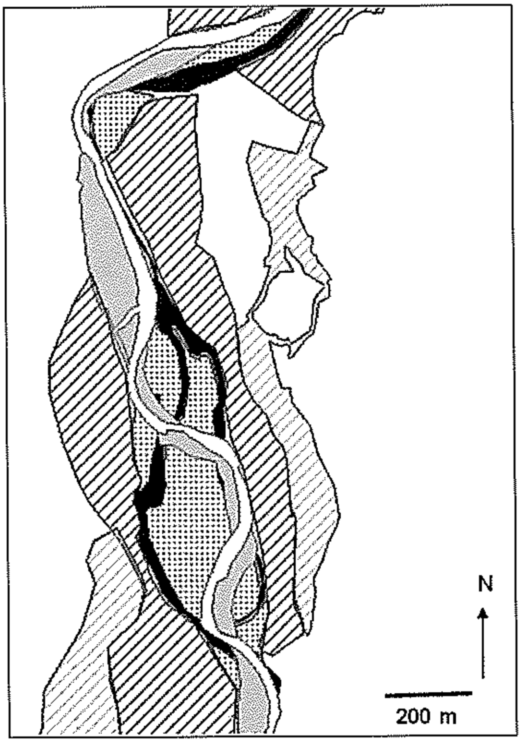

Figure 12 – Channel changes on the Pohangina River, c. 4 km north of Ashhurst, at GR T23 458 035

especially given the magnitude of this event compared with flood flows in the existing Kiwitea record (Fig. 6). In the Pohangina and Oroua, some floods during the 1999-2004 period would have been capable of causing morphological adjustment, as they greatly exceeding thresholds for bed sediment transport (Clausen and Plew, 2004). Thus some of the changes observed between 1999 and 2004 would have occurred prior to the February flood, but such changes would be limited to within the active channel.

Whilst parameters such as workover rate may be less meaningful to attribute wholly to the February flood, it is highly likely that a large part of bank erosion and change in the active channel may feasibly be equated to this event. Furthermore, in the Pohangina and Oroua a number of vegetated bars were evident within the active channel zone (i.e., between cut banks) in 1999, and the establishment of woody vegetation on these surfaces indicates infrequent inundation and lack of mobilisation at flows equivalent to the mean annual flood. Thus, areas where these vegetated surfaces have been worked over indicate change that may legitimately be attributed to the February 2004 flood.

Channel changes - Kiwitea Stream

Figure 9 illustrates the dramatic widening of the Kiwitea channel that typically occurred in discrete reaches along the lower 30 km of the valley. The wetted channel is much wider, and there has been substantial deposition of sand and gravel within the widened active channel, with its increased accommodation space for barforms. This is contrasted with the relatively less dramatic channel changes observed a short distance (3 km) downstream (Fig. 10), 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 active channel. Erosion still occurred in the channel, but its effects were less dramatic than at the site upstream. Stream powers in this lower reach, given a flood-flow width of 250 m, were 70 W m^{-2}, whilst in the upper reach (Fig. 9) widths of 55 m produced stream powers in excess of 300 W m^{-2}. This is significant, as 300 W m^{-2} is Magilligan's (1992) threshold of stream power for catastrophic change. This pattern of alternating degrees of channel change is repeated along the entire 30 km valley reach studied and is the focus of ongoing investigation. Nevertheless, overall wetted channel dimensions have increased by 171% and the area of bars has increased by 600% (Table 2).

Channel changes – Oroua River

The extensive area of inundation recorded in the valley reach studied in the Oroua (Fig. 11, Table 2) also appears to have limited the extent of erosion that occurred within the reach studied. The bank erosion was just over half of that measured in Kiwitea Stream (Table 2), which is commensurate with the lower stream power here, i.e., it was below Magilligan's (1992) threshold for catastrophic change. Similarly, whilst there is some increase in wetted channel area, it is approximately a third of the increase observed in the Kiwitea, and the increase in bar area in the Oroua is similar in degree to the increase in wetted channel area (Table 2).

Channel changes – Pohangina River

The Pohangina was the least affected of the three rivers studied, although the flow was sufficient to destroy the Saddle Road Bridge (Fig. 13) and total energy expenditure was nearly as high as that of Kiwitea Stream (cf. Table 2). However, the wetted channel increase was relatively small (25%), and the area of bank erosion was around half that of the smaller Oroua River. Nevertheless, there was a more dramatic increase in active bar area

Figure 13 – The Saddle Road Bridge, Pohangina River, February 2004. Photo: I.C. Fuller

in the Pohangina (167%, Table 2), associated with the reworking of extensive vegetated bars in the active channel zone. Channel change in the Pohangina was not limited to lateral change, but also included channel avulsion, with reoccupation of abandoned channels and chutes within the active channel (Fig. 12). Such processes suppress the workover rates observed, but are common in this type of wandering river (Fuller *et al.*, 2002; 2003; 2005).

Synthesis

Large floods sometimes produce major geomorphic impacts, whilst at other times only minor changes may occur (Magilligan, 1992; Costa and O'Connor, 1995). Although the flood event of 15-16 February 2004 was the largest on record in each catchment, the magnitude of the February 2004 flood relative to the mean annual flood in the Kiwitea was proportionally greater than that in the Oroua (as gauged at Almadale, which is towards the lower end of the 30 km study reach), which in turn was greater than that in the Pohangina (Table 2). Furthermore, in terms of total energy expended during the 32-hour flood event, even though the discharge in the Kiwitea was considerably smaller than in the Pohangina, energy expenditure was higher (Table 2). Thus, in terms of geomorphic impact, the effect of the flood in Kiwitea Stream was far greater than in the Oroua and Pohangina rivers. This explains why channel dimensions were so dramatically altered in the Kiwitea, compared with the Oroua and Pohangina.

Channel morphology exerts a substantial influence on flood power at any given point in a river (Graf, 1983), and varying boundary conditions affect the location and extent of flood impacts (Miller, 1995). Thus narrow, deep channels, such as the channel confined between terrace bluffs in the Kiwitea, for example, may generate higher flood powers than reaches in the same river (or elsewhere) where the channel is less confined (cf. Magilligan, 1992). In reaches of the Kiwitea where the flood flow was confined between terrace bluffs, stream powers exceeded 300 W m^{-2}, defined by Magilligan (1992) as a tentative threshold for catastrophic channel change. It is therefore not surprising that such reaches have undergone "major morphologic adjustments: major erosion, deposition or channel realignment" (p.384, Magilligan, 1992). In reaches where flow has dispersed across wider active channels (e.g., Pohangina) and/or overtopped lower banks, unit stream power has been limited and not exceeded the threshold for major morphological adjustment. The irregular patterns of change, both within and between these channel systems, are to be expected (Magilligan, 1992; Costa and O'Connor, 1995).

Channel systems become destabilised when flood power exceeds resistance thresholds (Baker and Costa, 1987; Magilligan, 1992). Although flood power is maximised in moderate-sized catchments such as the Kiwitea, Oroua and Pohangina, by the combination of steep channel gradient and sufficient flow depth to maximise shear stress during floods, only in selected reaches of the Kiwitea, the smallest of the catchments, did power appear to exceed those resistance thresholds. The rate and magnitude of channel change during this flood event was thus influenced by flood hydrology, hydraulics, boundary resistance, sediment supply and flow history (Wohl, 2000). Ultimately the patterns of erosion and deposition in these channels support the observations made by Kochel (1988), who suggested that streams which experience major morphological change during floods are characterised by flashy hydrographs with a high (not qualified) Q_{max}:Q_{mean} ratio (although this is dependent upon the length of record), steep channel gradient, abundant coarse bedload, low bank cohesion and a relatively deep, narrow cross-section geometry, which facilitates high shear stresses during flood flows. All these parameters apply to the Kiwitea prior to 16 February 2004, and to a lesser extent to the Pohangina and Oroua (which have greater width to depth ratios).

The role of catchment control schemes

Part of the problem with artificially confining a river in any way (e.g., as part of a catchment control scheme) is that flows that might have dispersed down side channels or across much wider active channel belts are now confined between banks, which are the focus of excess stream power and therefore are increasingly susceptible to erosion. Indeed, research elsewhere in New Zealand (Laronne and Duncan, 1992) has suggested that channel constriction increases the frequency of sediment transport in confined reaches. The result of this increased movement of sediment is potential lowering of the bed, unless the sediment supplied to the stream keeps up with the higher transport rates. The outcome in both the Pohangina and Oroua is slight trends toward bed degradation, which in turn have led to undercutting of banks (Horizons, 2002). Similarly, the bed of Kiwitea Steam had degraded to the extent that the 10-year flood would not overtop its banks (Anonymous, 1980). Deeper channels exacerbate the problem of high-energy flows, preventing energy dissipation across the floodplain. Furthermore, Horizons (2002) acknowledges that "the [Pohangina-Oroua] scheme has not created a river channel with a width of 120 metres with 10 metre bands of willows along each bank. In many areas the channel is much narrower than 120 metres." (Horizons, 2002, p.24). In Kiwitea Stream the pre-February 2004 channel was even narrower, at just 10 to 15 metres (Philpott, 2005), which compares with the 23-m-wide meandering channel of 1877 (Anonymous, 1980).

The pre-scheme channel patterns of the Pohangina, Oroua and Kiwitea rivers were arguably wider and more braided than the channels observed today. This has been heralded as evidence for success of the control scheme, which sought to stabilise the river, narrow the channel and close off abandoned river channels that still carried floodwater (Horizons, 2002). In the 19th century the *natural* channels were more akin to the current engineered channel, i.e. narrow and tree-lined. Catchment land use was substantially different then, with much more forest than at present, and with far fewer drains. Forest clearance and land drainage increased stream discharge and sediment delivery to the channels from slopes, producing much wider channels in response. For example, between 1877 and 1920 the width of the Kiwitea had increased by 260% (Anonymous, 1980). Removal of woody vegetation not only reduces the strength of soils, making them more prone to slippage (Dymond *et al.*, in press), but also increases runoff, in some cases by a factor of 10 (Goudie, 2000). Narrowing of the channel over the past 30 years, however, has increased the flood damage sustained (Horizons, 2002) and may have worsened the channel erosion that occurred during the February floods. In addition, lining the channels with trees may have substantially added to the woody debris transported during the flood, putting added pressure on bridges, and arguably causing the failure of some bridges. Interestingly, Gardner (1977) reports minimal impacts on channel morphology following a 1-in-500 year flood event in Ontario, Canada, which he attributes to valleys which are "well-adjusted to handling infrequent, high magnitude flows, particularly in the absence of man-made modifications and structures on the floodplain" (p. 2300, Gardner, 1977). Clearly, the rivers studied here, especially the Kiwitea, were not well adjusted to handling the flows of 15-16 February 2004, being too narrow (cf. Horizons, 2002). It is worth emphasising that although stream power, total energy expenditure and extent of erosion were greatest in the Kiwitea, the Pohangina and Oroua still lost nearly 1 km^2 of floodplain to bank erosion between them in the 30 km study reaches. This ought to be a lesson to all involved in flood management, protection and engineering. It also calls into question whether the single dominant discharge is indeed the channel-forming discharge of these rivers

Conclusions

Rainfall intensities in the lower North Island were not unduly high during the 15-16 February 2004 event, but extended storm rainfall produced record-breaking 24-hour rainfalls in the region. The subsequent flooding this produced challenged existing flood frequency estimates, and gave rise to new average return interval estimates for rivers in the region (Table 1).The EV1 distribution favours long-period flood series with no anomalies, but adding the 2004 events to these flood series favours the EV2 distribution, which should be used to estimate events with larger return periods (Thompson, 2004; Pearson, 2004).

This flooding produced catastrophic (*sensu* Magilligan, 1992) channel changes in some reaches of wandering, piedmont rivers in the region. The extent of the channel changes evident was influenced by thresholds of flood power. There is a need for further investigation of these thresholds in these river systems to explain further the variability both within and between the reaches studied in terms of the geomorphic impact of these floods. Nevertheless, this paper provides a first approximation of the consequences of very large floods on channel morphology and quantifies the extent of change caused by this event. Of the three rivers studied, the Kiwitea was worst affected, with spatially discontinuous channel transformation associated with large-scale bank erosion in response to a flood estimated to be over 4 times bigger than the mean annual flood (average return interval of 643 years (EV1) or 100 years (EV2) with a record length of 29 years). The Pohangina River and Oroua River at Almadale were less affected, as channels were better adjusted to this flood, which was estimated to be c. 2.5 times the size of the mean annual flood (average return intervals of 51 and 116 years (EV1) or 38 and 115 years (EV2), with record lengths of 36 and 46 years for the Pohangina and the Oroua at Almadale respectively). Channel erosion was also less in the Pohangina and Oroua Rivers, due to more widespread dissipation of flood flows across their floodplains than for Kiwitea Stream. The nature of these rivers (their location, gradient, bed and bank sediment and discharge regime) enhances their susceptibility to major morphological change during floods.

The lesson to be learned from this event is that while floodplain management is conducted with good reason, using well-founded flood magnitude/frequency techniques, an over-constrained channel will, in a very large event, likely exceed the design criteria and conduct its own dynamic adjustments to the delivered volume of water. Kiwitea Stream demonstrated its capacity to do just that.

Acknowledgements

We would like to thank Horizons Regional Council staff, especially Marianne Watson, for data, analyses, images and information. All the hydrological and meteorological data used in this paper were supplied through Horizons Regional Council. We thank David Livingston (Research Volunteer, Geography Programme, Massey University, spring 2004) for processing aerial photograph overlays, made available and possible through the Centre for Precision Agriculture, Massey University, whose co-operation is also gratefully acknowledged. We also thank Lawrie Cairns for having the foresight to fly the aerial photography in the immediate aftermath of the flooding in February, making this assessment of channel change caused by the flood possible. Finally, we thank Dr. Judy Haschenburger and an anonymous referee for their helpful comments on this manuscript.

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Manuscript received 28 May 05; revised; accepted for publication 1 November 05