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Title page image: The lower Rangitikei near Bulls.

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Quantification of channel planform change on the lower Rangitikei River, New Zealand, 1949-2007: response to management?

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Abstract

The Rangitikei River, a large gravel-bed wandering river located in the North Island of New Zealand, has outstanding scenic characteristics, recreational, fisheries and wildlife habitat features. Recently concerns have been raised over the potential negative impact that perceived channel changes in the latter part of the 20th century may be having on the Rangitikei River recreational fishery. This study describes and quantifies the large-scale morphological changes that have occurred in selected reaches of the lower Rangitikei River between 1949 and 2007.

This research utilised historical aerial photography and analysis in ArcGIS® to quantify channel planform change in three reaches, encompassing ~18 km of the lower Rangitikei River. This showed that the lower Rangitikei was transformed from a multi-channelled planform to a predominantly single-thread wandering planform, with an associated reduction in morphological complexity and active channel width of up to 74%, between 1949 and 2007. Bank protection measures instigated under the Rangitikei River Scheme have primarily driven these changes. Gravel extraction has also contributed by enhancing channel-floodplain disconnection and exacerbating sediment deficits. The findings of this study have implications for future management of the Rangitikei. Previous lower Rangitikei River management schemes have taken a reach-based engineering approach with a focus on bank erosion protection and flood mitigation. This study has confirmed the lower river has responded geomorphologically to these goals of river control. However questions as to the economic and ecological sustainability of this management style may encourage river managers to consider the benefits of promoting a self-adjusting fluvial system within a catchment-framed management approach.

Key words: Planform change; wandering gravel-bed river; morphological diversity, channel stability; river management

Introduction

Gravel-bed river channels are naturally dynamic, able to adjust to natural or anthropogenic changes in sediment supply or flow regime within the constraints imposed by boundary conditions (Lane and Richards, 1997; Brierley and Fryirs, 2005). The morphology of gravel bed rivers is conditioned by discontinuous sediment transport involving processes such as bank erosion (Couper and Maddock, 2001), riffle and pool formation (Booker *et al.*, 2001), Bar development (Ashmore, 1991), meander bend initiation and migration (Gilvear *et al.*, 2000), chute cutoff and channel avulsion (Fuller *et al.*, 2003). In gravel-bed rivers the coarse fraction of sediment, mobilised as bed-load and constituting the bed and banks, is the major determinant of channel morphology (Leopold, 1992; Martin and Church, 1995; Church, 2006). Finer sediments are carried in suspension, and although they may represent a greater fraction of the total sediment load carried by a river, are less important in channel adjustment and formation of gravel-bed rivers (Martin and Church, 1995; Ham and Church, 2000).

Alterations in the climate and flood regime can produce significant morphological adjustment in river channels (Martin and Johnson, 1987; Rumsby and Macklin, 1994; Werritty and Leys, 2001; Wishart *et al.*, 2008). Human activities can also have an impact on discharge or sediment transport processes that will drive morphological change in river channels (Gregory, 2006). Engineering works including channelisation (Williamson *et al.*, 1992; Simon and Rinaldi, 2006) and dam construction (Kondolf, 1997), flow regulation (Shields *et al.*, 2000; Winterbottom, 2000) and gravel extraction (Rinaldi *et al.*, 2005; Wishart *et al.*, 2008) can directly affect river channel morphology. Anthropogenic actions can also influence river channels indirectly by altering sediment and flow through landuse change (Liébault and Piégay, 2002), including deforestation (Brooks and Brierley, 1997), urbanisation (Roberts, 1989) and agriculture (Knox, 1987; Gregory, 2006).

Geomorphic river adjustment often involves a number of forcing mechanisms (Rinaldi and Simon, 1998; Wishart *et al.*, 2008). For example, channel changes in the River Wear, Northern England, were attributed by Wishart *et al.* (2008) to within-channel gravel extraction superimposed on a general trend of declining catchment sediment delivery and a twentieth century reduction in both flood frequency and magnitude. The tremendous diversity of natural river channels along with a plethora of forcing mechanisms and process interactions make it difficult to predict the trajectory of river channel change (Downs, 1995; Hooke, 1992). However case studies of fluvial systems that document spatial changes in channel form over time have the potential to identify some of the factors involved in geomorphic river adjustment and provide base line data for decision makers seeking an effective and sustainable approach to river management.

Morphological change in river channels can impact the ecology of riverine environments. Natural alluvial channels are dynamic, structurally complex environments containing a high degree of biodiversity (Ward *et al.*, 2002). In natural alluvial systems habitat patches are being continually created and destroyed, producing a shifting mosaic of diverse habitats suitable for different species of all age classes (Bormann and Likens, 1979). Anthropogenic modification of the river channel often leads to stabilisation resulting

in habitat alteration, destruction or homogenisation (Ward and Wiens, 2001). Channel floodplain interactions including flood scour and channel migration are important factors in maintaining a diversity of seral stages within the river corridor (Shields *et al.*, 2000; Ward *et al.*, 2002). Important aquatic habitats such as oxbow lakes, abandoned channels and backwaters are created by channel avulsion (Shields *et al.*, 2000). Disconnection of floodplain and channel processes reduces the level of disturbance and ultimately reduces habitat heterogeneity in riverine environments (Gurnell, 1995; Ward and Wiens, 2001; Ward and Tockner, 2001; Ward *et al.*, 2002; Amoros and Bornette, 2002).

Concern over the impact that humans have had on aquatic environments has driven a shift in recent years from an engineering reach-based river management approach to a ecosystem-based perspective with a focus on river rehabilitation (Brierley and Fryirs, 2008). An ecosystem-based approach seeks to 'work with nature', enhancing and maintaining river system processes responsible for the dynamic nature of rivers, promoting adaptive and self adjusting fluvial systems (Palmer *et al.*, 2005; Piégay *et al.*, 2005). However in some cases the capacity for rivers to naturally adjust is limited by past engineering interventions that have essentially fixed and entrenched the channel, restricting lateral movement and disconnecting the floodplain (Spink *et al.*, 2009).

Anecdotal evidence suggests that the lower Rangitikei River planform has changed considerably in the latter part of the twentieth century. There are concerns that channel changes will have a negative impact of the availability of suitable trout habitat and it is these concerns that have led to the instigation of this research. This study quantifies channel planform change on three reaches of the lower Rangitikei River, New Zealand, using historical aerial photography and GIS analysis. Indices of channel change, including sinuosity, extent of braiding, rate of lateral shift and change in active channel width are used to identify the temporal and spatial nature of channel adjustments that have occurred between 1949 and 2007. Quantification of the patterns of channel modification enable the identification of a number of processes involved in forcing channel planform change on the lower Rangitikei River and determines the nature of morphological response to channel management.

Regional setting and catchment management

The Rangitikei catchment covers an area of 3933 km² and is located in the lower North Island of New Zealand. The catchment is drained by the Rangitikei River and its main tributaries, the Moawhango, Hautapu, Whakaurekou and Kawhatau Rivers (Figure 1). The Rangitikei River rises in the Kaimanawa Ranges and flows approximately 240 km before reaching its outlet into the Tasman Sea near Tangimoana. The upper and middle Rangitikei River flows through deeply incised v-shaped valleys, steep sided gorge sections and between near vertical cliffs in the terraced valleys of the central catchment (New Zealand Ministry of Agriculture and Fisheries, 1985). The lower Rangitikei River flows across an alluvial floodplain and can be described as a wandering gravel-bed river.

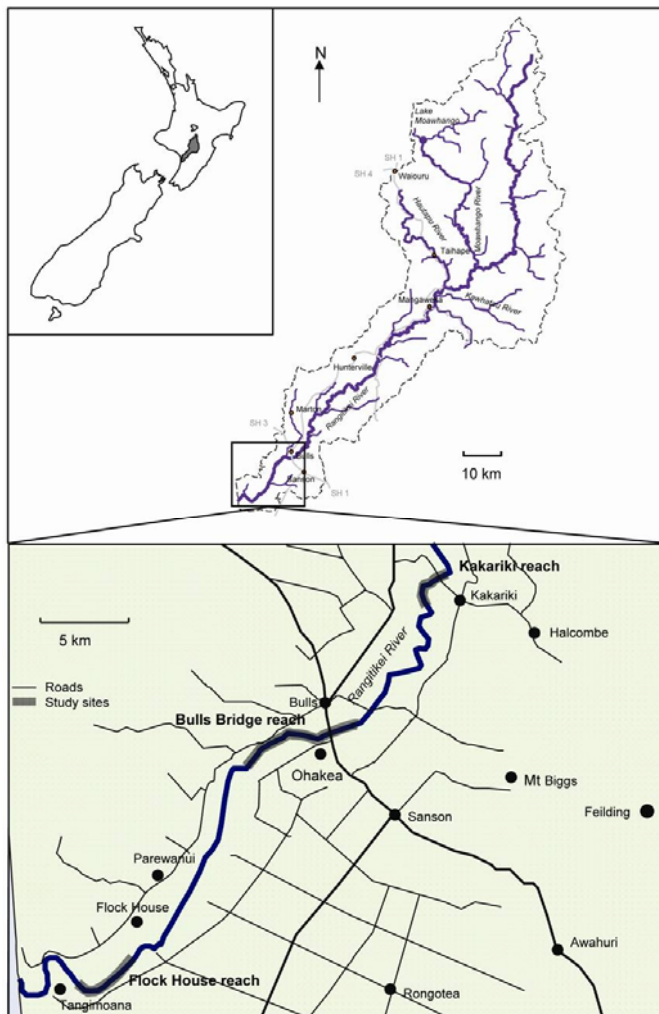


Figure 1. Location of study reaches within the Rangitikei River catchment, New Zealand

The lower Rangitikei catchment geology comprises loess, alluvium near the Rangitikei River and an area of windblown sand near the coastal margin (Horizons Regional Council, 2004). Catchment climate is relatively mild in the central mountains and lowlands, and cold in the central volcanic plateau environments (Horizons Regional Council, 2004). Average annual precipitation in the catchment ranges from 870 mm per year near the coast and in the rainshadow zone of the Ruahine, Kaimanawa and Kaweka Ranges, to over 2 200 mm per year in the Ruahine Ranges (Horizons Regional Council, 2004). Monthly flow statistics for the Rangitikei River illustrate the effect of seasonal rainfall variability on flow regime with the mean flow in the lower river ranging from between $35.6 \text{ m}^3\text{sec}^{-1}$ during February, to $135.4 \text{ m}^3\text{sec}^{-1}$ recorded in July (Horizons Regional Council, 2004). The mean annual low flow (2.33 year return period) recorded for the Rangitikei River at Mangaweka is $13.5 \text{ m}^3\text{sec}^{-1}$ (Horizons Regional Council, 2004). The flow data indicate that low-flow conditions dominate for most gauging sites between December and March (Horizons Regional Council, 2004).

The Tongariro Power Development (TPD) is a major abstractor of water from the headwaters of the Rangitikei River. A series of lakes, canals and tunnels, divert water through the Rangipo and Tokaanu power stations before discharging into Lake Taupo (Horizons Regional Council, 2004). The TPD scheme began to influence the Rangitikei River in 1978 when the upper Moawhango River was diverted out of the Rangitikei catchment upstream of the Moawhango Dam (Horizons Regional Council, 2004). The effects of the water diversion and impoundment in the Mowhango Dam on the flow in the Mowhango River is considerable, with reductions in mean flow of 55% and 30% reduction in 3-hour flood flows (Henderson, 2003). Below the confluence of the Mowhango River with the Rangitikei River the impact of the dam and diversion is reduced, but still detectable within the range of flows downstream (Henderson, 2003). At Kakariki the influence of the TPD abstraction is a reported as an 11% reduction in the mean flow, 16% for the low flow and 0.4% flood flow (Henderson, 2003). In addition to electricity generation, water is also abstracted for the purposes of agriculture, industry and water supplies.

Approximately 75% of the catchment's total abstraction from both groundwater and surface water is taken from the lower part of the Rangitikei River (Horizons Regional Council, 2004).

The Rangitikei River is also considered a valuable source of high quality gravel used in roading and the construction industry (Horizon Regional Council, 2000). The majority of the Rangitikei River gravel is supplied by the Kawhatau River which transports weathered greywacke from the uplifting Ruahine Ranges (Horizons Regional Council, 2000). Average annual gravel supply rates are estimated to be in the vicinity of 20 000-30 000 m³yr⁻¹, considerably lower than the estimated 120 000-240 000 m³yr⁻¹ that has been removed annually since 1961 (Horizons Regional Council, 2000). It is thought that gravel extraction is resulting in degradation of the river bed along some sections of the Rangitikei River, potentially jeopardising the Rangitikei River Control Scheme (Horizons Regional Council, 2000). Bed level lowering of up to 0.5 m between 1977 and 1990 has been reported for a section of the Rangitikei River from 4 km downstream of the Bulls Bridge to 15 km upstream of the Kakariki Bridge (Horizons Regional Council, 2000). However downstream from Bulls Bridge, between 2.5 km and 14 km from the river mouth, is considered a zone of aggradation (Horizons Regional Council, 2000). Silt accumulation on the river margins in this part of the river is responsible for reductions in the capacity of the stopbanks (Horizons Regional Council, 2000).

Rangitikei River Scheme

The lower part of the Rangitikei River is managed under the Rangitikei River Scheme, primarily devised to control flooding and erosion. Flooding is controlled by 14.3 km of stopbanking (levees) designed to contain a 50-year return period flood. Stopbanks are mostly on the northern bank downstream of Bulls but are also constructed downstream of the Kakariki Bridge, and some sections protect Tangimoana (Figure 2). Bank protection works include over 20 km of tree bank protection, over 150 000 tonnes of rock work and an erosion protection reserve, comprising 1 115 ha of willow tree and 71 ha of pine plantation (Horizon Regional Council, 1999).

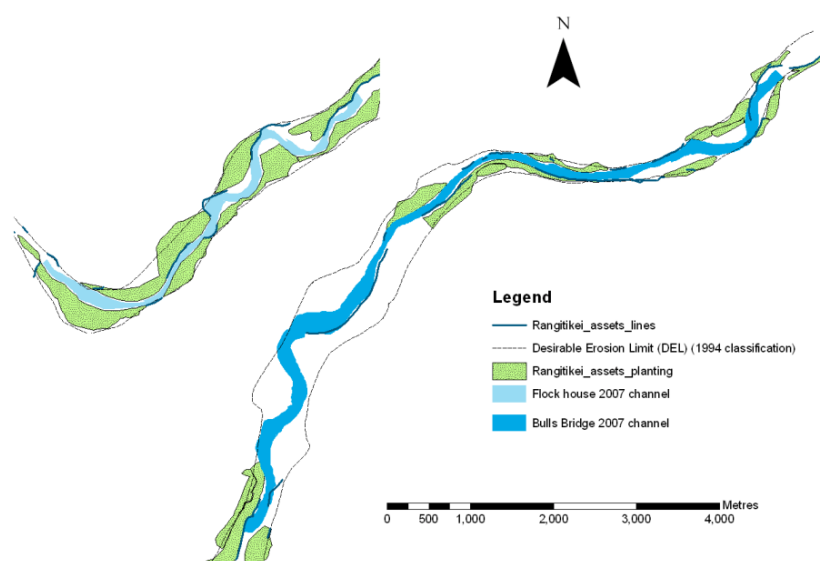


Figure 2. Rangitikei River Scheme assets and Desirable Erosion Limit map, Flock House and Bulls Bridge reaches.

The Rangitikei-Wanganui Catchment Board began the first Rangitikei River Scheme in 1952. These early river control works led to the reclamation of c.460 Ha of farmland as a result of bank protection works (Horizons Regional Council, 2000). River control works under the Rangitikei River Scheme No. 2 commenced in 1965 and were responsible for the construction of the majority

of the scheme stopbanks and further bank stabilisation works (Horizons Regional Council, 2000). Up until the late 1970s, when rip rap was more often used, bank erosion prevention was mainly achieved using protective planting and anchored trees (Horizons Regional Council, 2000).

A review of the scheme in 1983 found that channel degradation, caused by channel confinement and gravel extraction, was leading to undermining and failure of tree bank protection works. The 1983 scheme review concluded that the 300-400 m wide channel design specified by Scheme Reviews 1 and 2 was too narrow. The Rangitikei River Consolidation Scheme commenced in 1985 with a number of proposals for the future management of the river. These proposals included widening the central channel fairway to 500 m, the use of rip rap instead of tree protection for preventing bank erosion and the movement of gravel extraction sites from areas of degradation to aggrading reaches. In order to prioritise erosion control repair works, a riparian zone was delineated by the Consolidation Scheme, identifying areas where some risk of erosion would be acceptable.

An extensive review of the Rangitikei River Scheme was undertaken in 1993/1994 and was initiated in response to concerns over the effects of degradation and aggradation on scheme maintenance costs. In addition costly maintenance and removal of government subsidies in the late 1980s necessitated a consideration of the ways in which scheme expenditure could be reduced. The purpose of the review was to provide for the management of the Rangitikei River Scheme and the sustainable management of the gravel resources. The final report of the Rangitikei River Scheme Review (No. 3) adopted the River Management Programme for the Rangitikei River (Horizons Regional Council, 2000).

The Rangitikei Management plan divided the scheme into three zones, an aggradation zone from the river mouth to 19 km upstream, a degradation zone from 19 km to 37 km and a top section experiencing minor degradation extending from 37 km to Rewa (Horizons Regional Council, 2000). Gravel extraction rates were reduced from upstream of 15 km and encouraged from the Lower Rangitikei downstream of 14 km (Horizons Regional Council, 2000). The Rangitikei Management Plan also allowed for the prioritisation of river erosion protection by defining a 'Desirable Erosion Limit' (Figure 2). Included under the rules for prioritising river erosion protection was the restriction on placing rock protection in such a way that reduces the river meander zone to no less than 200 m width and ideally retains a meander zone of 4-500 m (Horizons Regional Council, 2000).

A fourth review of the Rangitikei river scheme is currently underway. One of the major issues facing the Regional Council is the costly maintenance of the scheme in its present form (pers. comm., Warren Wheeler, HRC).

Method

Study sites

This study examines three reaches of the lower Rangitikei River, the locations of which are shown in Figure 1. The Kakariki reach is approximately 3 km long and is located 30 km upstream from the river

mouth. Here the river is predominantly single thread, of low sinuosity (1.38) and comprising cobble-gravel-sand size substrate with expanses of bare gravel exposed on lateral bars during low flow conditions. The Bulls Bridge study reach covers an approximately 10 km section of the lower Rangitikei River downstream from the State Highway 1 bridge near the township of Bulls. This section of the river is mainly single thread with a well developed pool-riffle sequence, low sinuosity (1.2) and lateral bars composed of active and semi-vegetated gravel. The third study reach is 5 km long and located near Flock House, approximately 5 km from the river mouth. Here the river planform is predominantly single thread with some mid-channel bars present and a sinuosity of 1.35.

Historical data capture and analysis

Historical aerial photographs of the lower Rangitikei River taken during summer flow conditions were selected for their spatial and temporal coverage of three reaches near Flock House, the Bulls Bridge and the Kakariki Bridge. The aerial photographs were then scanned into TIFF[®] format and the data imported into ESRI ArcGIS[®] 9 Geographic Information System (GIS) for rectification and data processing. Aerial photographs were geo-referenced to New Zealand Map Grid co-ordinates in ArcMap[™] 9.2 GIS by rectifying images to 2000 ortho-imagery of the lower Rangitikei. Each aerial photograph was rectified using 15 ground control points consisting of well spaced, easily identified buildings and road intersections. The positions of these ground control points were then used to calculate the Root Mean Square error (RMS). The RMS quantifies how consistent the transformation is between the different linked ground control points and provides a good assessment as to the accuracy of the transformation.

Each aerial photograph was rectified using either a 1st order affine or 2nd order polynomial transformation with a resultant RMS of below 6.5. The older, smaller scale aerial photographs produced lower RMS values when an affine transformation was performed, while the more recent, larger scale aerial images required a 2nd order polynomial transformation to produce a low RMS. The RMS errors determined for this study are comparable to those quoted by other authors who have used rectified aerial images to quantify channel change (Gurnell *et al.*, 1997; Winterbottom, 2000). The RMS error suggests that positional changes greater than 6.5 m are likely to be the result of genuine movement rather than errors due to data handling.

Following rectification, aerial photographs were used in ArcMap[™] 9.2 GIS as the basis for digitising boundaries of discrete morphological units comprising the active channel. A major problem when using aerial photos to identify the channel margin is the inconsistencies introduced to channel planform measurements as a result of difference in water levels on different survey dates. In order to avoid these inconsistencies this study adopted the definition of channel boundary as described by Winterbottom (2000) and Wishart *et al.* (2008), which not only includes the wetted area but considers unvegetated and sparsely vegetated gravel as within the active channel zone. Lack of vegetation development suggests relatively regular inundation (once to several times per year) and indicates that semi-vegetated and bare gravel can be defined as part of the active bed. Areas completely covered in vegetation were only digitised as part of the active channel when surrounded by semi-vegetated gravel, active gravel or located within the wetted channel.

Polygon digitisation and attribute allocation in ArcMap™ GIS using sequential aerial photographs for the three study reaches, permitted the identification of not only the active channel boundary, but differentiated between vegetation cover, mid-channel and lateral bars. The digitised channel boundary was also used to measure reach length at the channel midpoint, direct length between reach endpoints, length of mid-channel bars and channel width for each date between 1949 and 2007.

Indices for assessing channel planform change

Data collected from digitised aerial photographs were used to quantify a number of indices of channel planform change between successive dates. Active channel width was measured as the shortest distance between channel margins at equally spaced cross-sections for each of the three reaches. Thirty cross-sections positions were identified in the earliest photos and were spaced at 300 m intervals in the Bulls Bridge reach, 150 m in the Flock House reach and 100 m apart in the Kakariki section of the river. Where significant channel changes had occurred between aerial photograph dates, channel width measurements were made closest to the original cross-section position.

Stability of the study reaches over space and time was also investigated using the ratio of the active channel width to the total width of floodplain (or floodplain swath) occupied over the period of study. The maximum extent of floodplain occupancy was derived by overlaying the active channel planform data from the total study period and the width measured at equally spaced cross-sections. This ratio has been used to assess planform change by a number of authors including Gurnell *et al.* (1994) and Leys and Werritty (1999). A high ratio of active channel to floodplain swath indicates that there has been channel movement or narrowing over time (Leys and Werritty, 1999). A low ratio reflects the inability of the river to rework floodplain sediments and indicates channel stability over time (Leys and Werritty, 1999).

An additional indicator of channel behaviour is lateral shift, involving processes such as bank erosion, bend migration and channel avulsion (Leys and Werritty, 1999). In order to quantify lateral shift in the study reaches, total shift in m^2 between channel midpoints in successive survey was calculated and this figure divided by length of the reach in metres. The results were reported in $m^2 m^{-1} year^{-1}$, obtained by dividing the amount of lateral shift by the time between aerial photographs, a similar approach to that used by Werritty and Leys (2001). In order to calculate comparable rates of lateral shift throughout the period of study the time elapsed between aerial photographs should be the same. In this study the period between photographs was determined by the availability of suitable aerial photography, which meant that the length of time elapsed between aerial photographs ranged from 3 to 12 years. Lateral shift rates calculated from longer periods may fail to capture the full extent of channel movement occurring between survey dates.

Historical planform reconstructions from sequential aerial photos permit definition of composition and nature of the different morphological units within the study reaches. Analysis of change in total active channel area over time is an index which gives some indication of channel behaviour, as only a significant change in boundary conditions or the crossing of a geomorphic threshold has the potential to substantially alter the area occupied by the channel (Leys and Werritty, 1999). This study also examines

the composition of the active channel in order to provide some clarification as to the nature of change occurring within the active channel.

Planform transition trends between single thread behaviour and a braided morphology in river systems has often been detected and analysed using indices such as a braiding index and changes in the number and area of mid-channel bars (Passmore *et al.*, 1993; Winterbottom, 2000; Wishart *et al.*, 2008). In this investigation the number, area and length of mid-channel bars was used to calculate a braiding index and determine the extent of braiding within the study reach and identify planform change over time. The braiding index was calculated as twice the total length of bars within the reach divided by the mid-channel length as defined by Brice (1960).

Channel sinuosity has often been used to examine channel behaviour as changes in sinuosity can result from alteration in sediment or hydrological regime (Werritty and Ferguson, 1981; Leys and Werritty, 1999; Werritty and Leys, 2001). In this investigation reach sinuosity was calculated for each survey period by dividing the reach length at the channel midpoint by the straight line length between reach endpoints.

Results

Historic planform reconstruction

Historic planform reconstructions of each reach (Figure 3) show that in 1949 and/or 1955 the wide active channel was multi-threaded, comprising numerous bare gravel, vegetated and semi-vegetated mid-channel bars, high flow chute channels, abandoned anabranches and extensive lateral bar surfaces displaying various degrees of vegetation development. By 2007 all three reaches narrowed considerably, display less morphological complexity and are predominantly laterally stable single thread reaches. The 2007 active channel almost entirely comprises active gravel surfaces, with relatively small isolated patches of semi-vegetated and vegetated lateral bars evident (Figure 3).

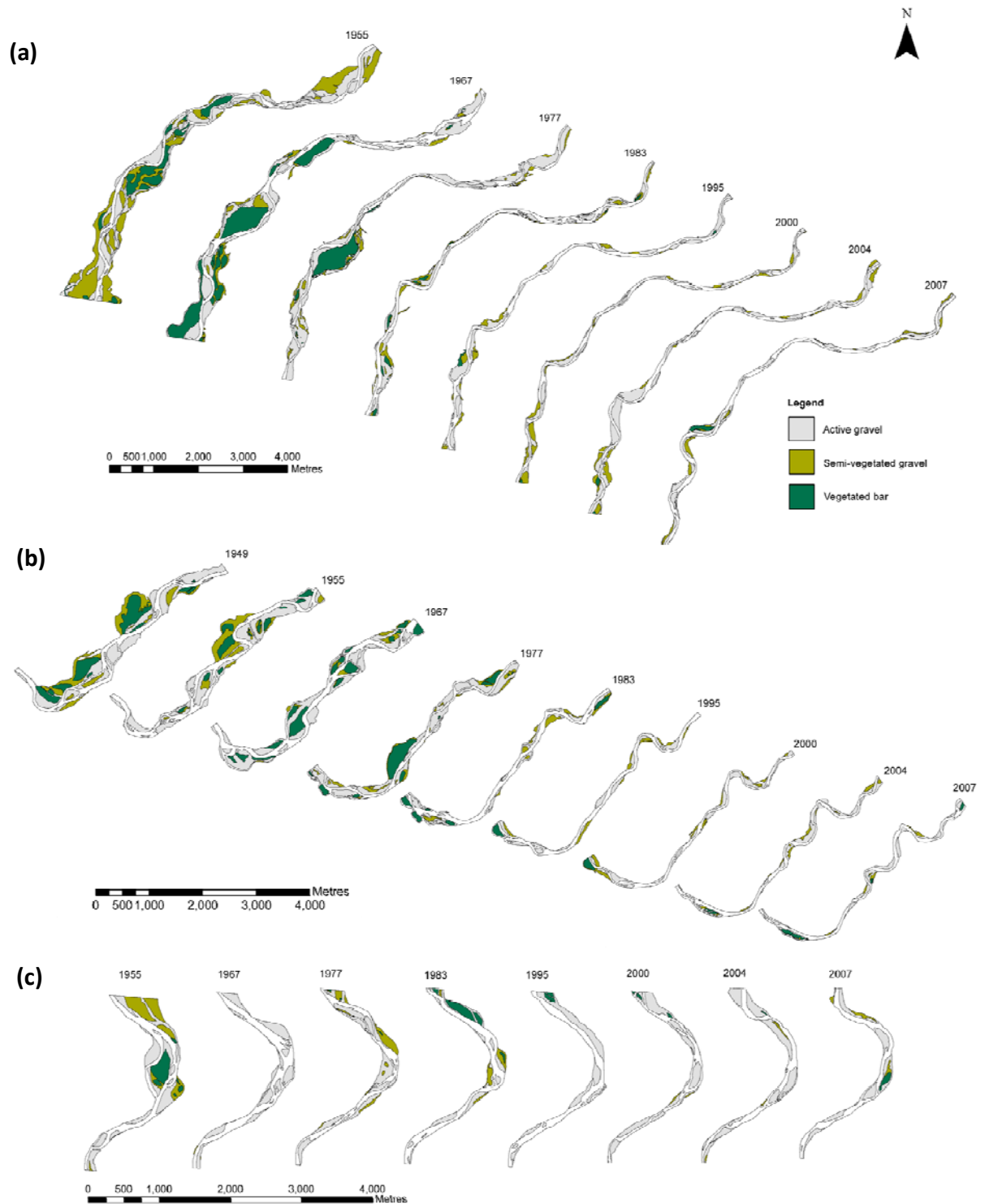


Figure 3. (a) Channel planform changes at the Bulls Bridge reach, lower Rangitikei River, derived from aerial photographs (1955-2007); (b) Channel planform changes at the Flock House reach, lower Rangitikei River, derived from aerial photographs (1949-2007); (c) Channel planform changes at the Kakariki reach, lower Rangitikei River, derived from aerial photographs (1955-2007). Flow is from north to south in each.

Active channel width and stability

The reduction in active channel widths derived from 30 cross sections in each reach is statistically significant (Figure 4). These results support the qualitative assessment of change derived from planform maps (Figure 3). Since 1983 the data suggest channel width has remained relatively stable with slight reductions in 2000 before an increase in 2004 (Figure 5). Overall between 1955 and 2007 the mean channel width of the Rangitikei River at Bulls Bridge reach has altered substantially, reducing by 74% (Figure 4). At Flock House mean active channel width reduced by 73% and at Kakairiki a 48% reduction occurred. Reach stability was also assessed by calculating the ratio of active channel width to total active channel width (or floodplain swath) for the three study the reaches (Figure 4). Channel width to floodplain swath ratios between 1955 and 1983 indicate a period of channel adjustment and narrowing before remaining relatively stable to 2007.

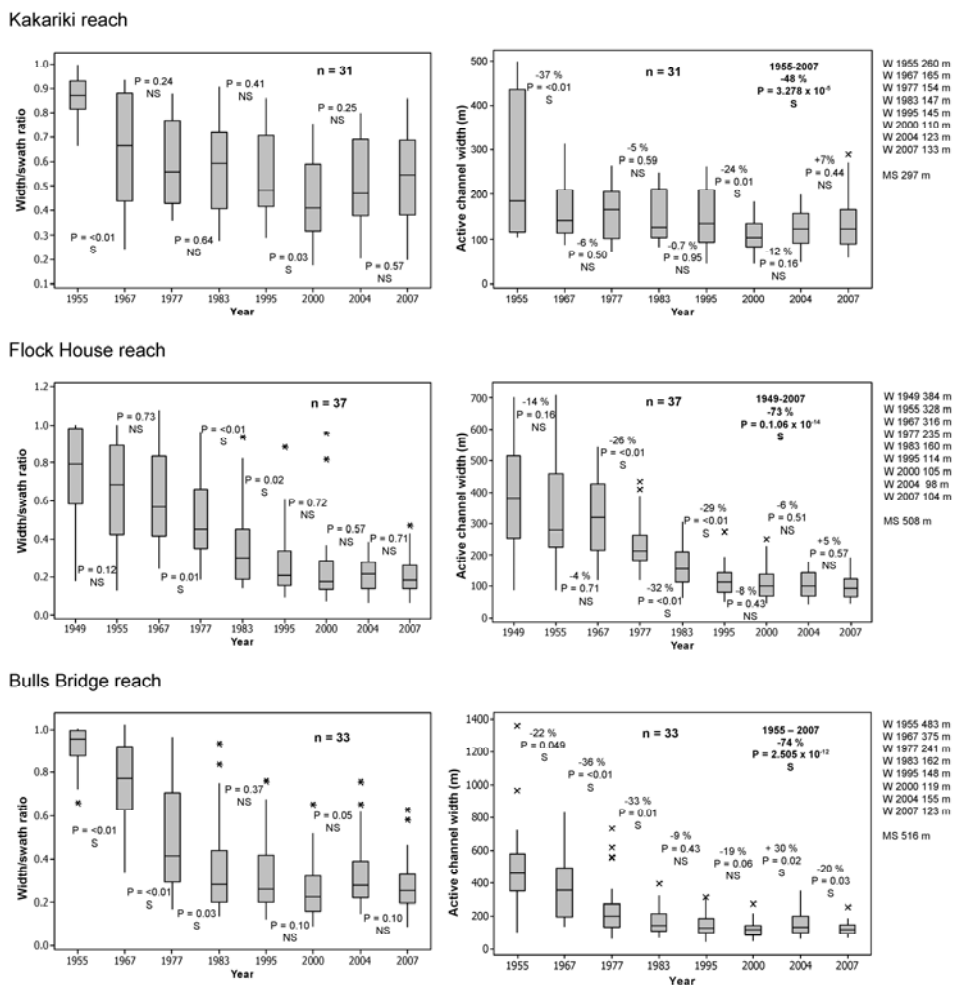


Figure 4. Rangitikei River active channel width and width/swath ratio changes in the study reaches between 1955 (1949 Flock House) and 2007; boxes represent inner and outer quartiles; vertical lines represent the upper limit = Q3 + 1.5(Q3-Q1) and lower limit = Q1 - 1.5(Q3-Q1); crosses are extreme values; n, number of width measurements; MS, mean value of floodplain swath; W, mean values of active channel width for each date; values in percent represents the rate of channel narrowing between dates; results of a parametric t-test are presented; S indicates significant differences of channel width and width/swath ratio between dates; NS, not significant.

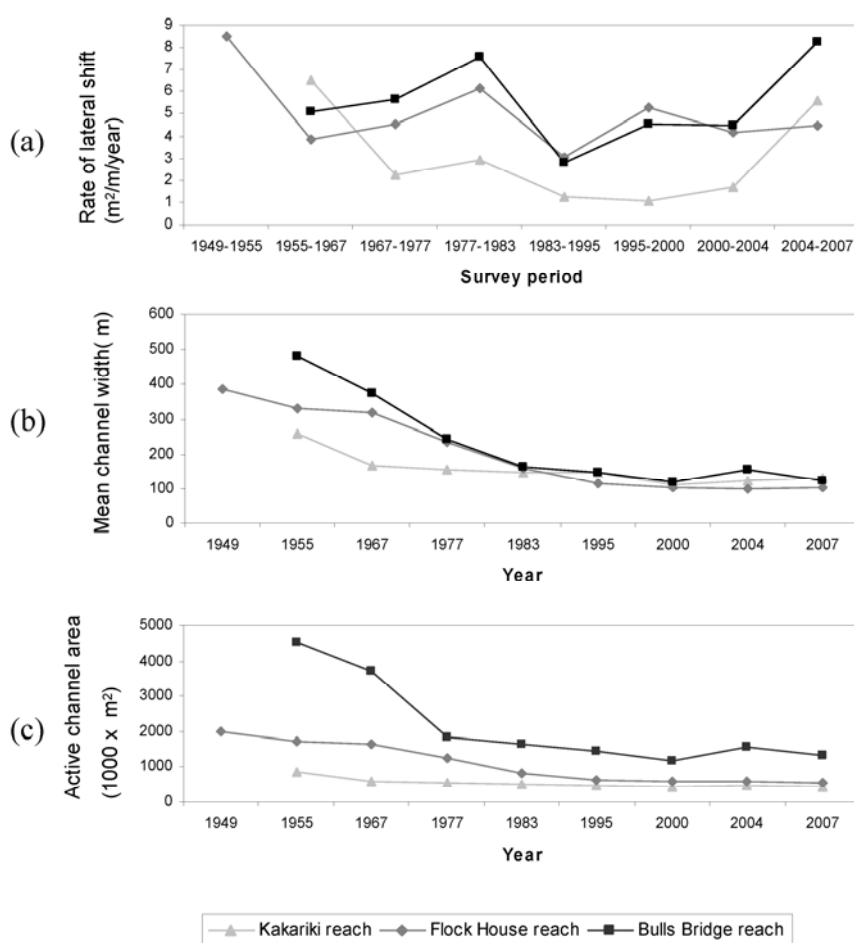


Figure 5. Changes in active channel parameters (a) rate of lateral shift (b) mean channel width and (c) active channel area, for the Kakariki, Flock House and bulls Bridges study reaches.

The rates of lateral channel shift calculated for each reach indicate that there has been movement of the channel midpoint and that the rate of this movement over time has been variable (Figure 5a). Although direct comparison of the rates of lateral shift is made difficult by the unequal number of years between records it does give some indication of channel stability over the study duration. The Flock House reach was subject to the greatest rates of channel midpoint migration during the period 1949-1955 with a rate of over $8 \text{ m}^2\text{m}^{-1}\text{year}^{-1}$ calculated (Figure 5a). The Bulls Bridge reach experienced the greatest rate of lateral shift during two periods, 1977-1983 and 2000-2004. For the Kakariki reach the rate of lateral shift was highest between 1955-1967 and 2004-2007. The results illustrate similarities in the way the Flock House and Bulls Bridge reaches have behaved over time, with the variation in the rates of lateral rate shift mirroring each other between 1955 and 2004 (Figure 5a).

Active channel area

Quantitative analysis of active channel composition change was carried out for each of the study reaches of the lower Rangitikei River (Figure 5c). What is immediately evident is a marked reduction in

the active channel area for all three reaches between 1949 and 1983. Analysis of channel modification revealed that in less than 30 years the active channel area contracted by 64% at Bulls and 68% at Flock House (Figure 5c). Since 1983 there have been relatively small changes in the active channel area. A small (25%) expansion of the Bulls Bridge active channel between 2000 and 2004, but by 2007 the extent of the active channel had reduced again. At Flock House after 1995 very little variation in the total area occupied by the active channel is evident (Figure 5c).

Change in active channel composition

Quantitative analysis of the active channel composition in the study reaches has the potential to highlight some aspects of the nature of channel change between 1949 and 2007 (Figure 6). These results show that between 1955 and 1983 there was a marked decline in the area of active gravel and semi-vegetated gravel in the reaches. In 1955 active gravel represented just over 50% of the total active channel area of the Bulls Bridge reach. By 1983 the area of active gravel had reduced by approximately 50%. The area of active gravel in the Bulls Bridge reach continued to decline by a further 30%. A small (5%) increase in the area of active gravel occurred in 2004. Overall since 1983 the relative proportion of the active gravel area has fluctuated only slightly, comprising between 80 and 87% of the total active channel area. In 1949 just over 60% of the total active channel area of the Flock House reach comprised active gravel (Figure 6b). By 1995 the area of active gravel accounted for 84% of the total active channel area. A similar increase in the relative proportion of active gravel area was also identified in the Kakariki reach (Figure 6c). In 1955 69% of the active channel comprised active gravel, 12 years later over 99% of the total active channel area was active gravel. Since then the extent of active gravel in the Kakariki reach has remained high at between 86% and 98% of the total active channel area. Changes in the relative proportion and area of semi-vegetated and vegetated gravel can also be identified in the three study reaches (Figure 6), with marked declines in all reaches.

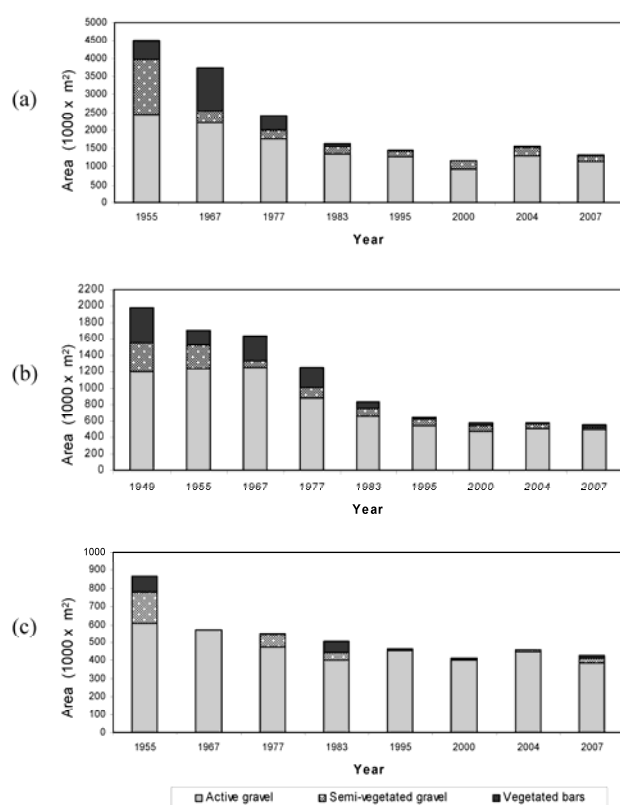


Figure 6. Changes in active channel composition showing active gravel area, semi-vegetated gravel and vegetated bars at: (a) Bulls Bridge, (b) Flock House, (c) Kakariki reaches.

Active channel geomorphology

GIS analysis of the active channel not only included the composition of the active channel but also differentiated between areas of wetted channel, lateral and mid-channel bars (Figure 7). Although the aerial photographs were taken during periods of low flow there will be some fluctuation in the relative proportion of bar type and wetted channel area. Despite these limitations some clear trends can be identified, with a reduction in the extent of lateral and mid-channel bars between 1955 and 1983 clearly visible. For example, in 1955 30% of the active channel area at Bulls Bridge comprised mid-channel bars, by 1983 this reduced to 5%.

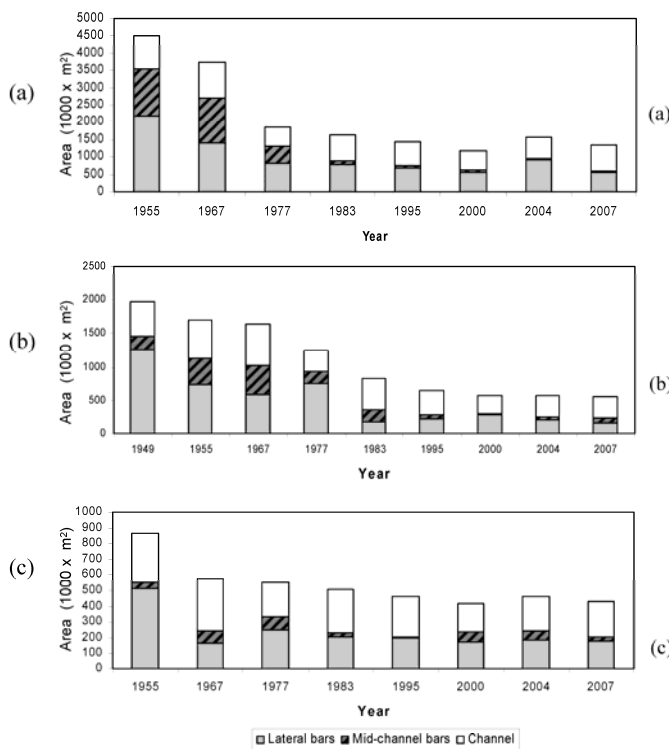


Figure 7. Changes in active channel geomorphology showing mid-channel and lateral bar area at: (a) Bulls Bridge, (b) Flock House, (c) Kakariki.

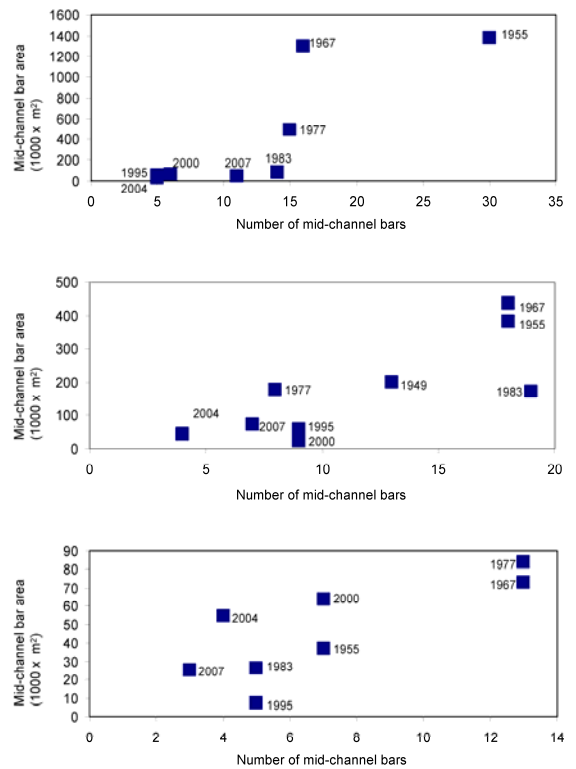


Figure 8. Changes in the number and area of mid-channel bars 1955 (1949 Flock House)-2007 at: (a) Bulls Bridge, (b) Flock House, (c) Kakariki.

Braiding and sinuosity

Figure 8 shows that not only has there been a reduction in the area associated with mid-channel bars between 1955 and 1983 but that the actual number of bars has also decreased. Lees and Werritty (1999) used an analysis of total medial bar area and number of bars to identify a trend from braided to single thread planform. This study uses a similar approach which identifies a reduction in braiding with fewer mid-channel bars detected within the study reaches and an associated reduction in the area of mid-channel bars between 1955 and 1983 (Figure 8). Whilst Bulls Bridge and Flock House show similar

trends (Figure 8a-b), results from Kakariki do not show a clear trend (Figure 8c), although there is some indication that the reach was more braided in 1967 and 1977. A braiding index summarises these changes (Figure 9a), showing a clear reduction in braiding over the period of study. Commensurate with this reduction in braiding is an overall increase in reach sinuosity, although the trend is not dramatic (Figure 9b).

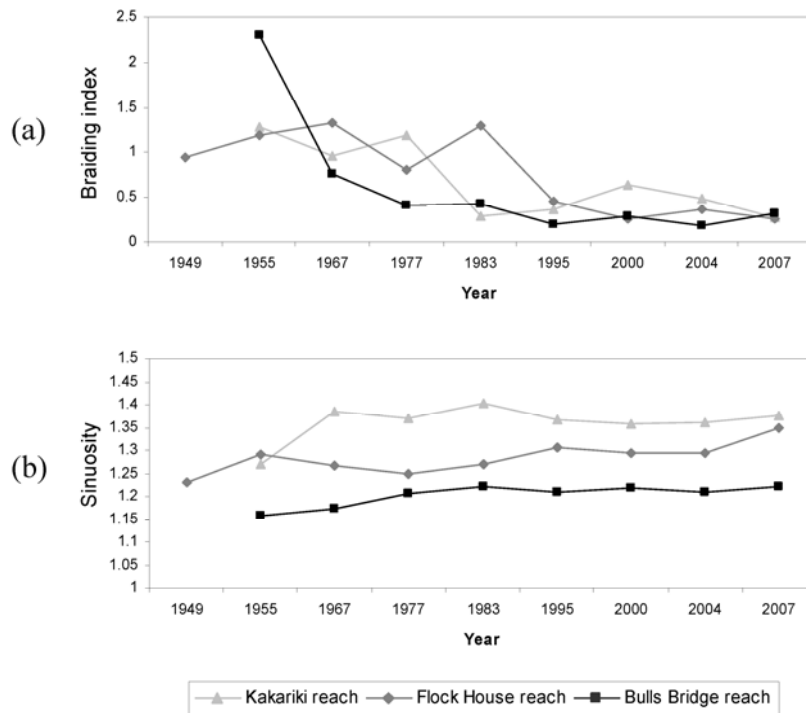


Figure 9. Changes in (a) braiding index and (b) sinuosity for the Bulls Bridge, Flock House and Kakariki reaches of the lower Rangitikei River 1955 (1949 Flock House)-2007.

Discussion

Analysis of channel planform and associated indices quantifying change in planform over time in the lower Rangitikei has highlighted significant change in form between 1949 and 2007, notably channel narrowing, and reduction in morphological complexity, lateral activity and extent of braiding. Closer examination of change in channel planform indices over the study period reveals that the rate of active channel modification has not been constant over the entire study period. The majority of changes in these indices occurred in the Bulls Bridge and Flock House reaches by 1983 (Figures 5-9). Since that time the active channel has remained relatively stable, with only small magnitude changes identified between 1983 and 2007. Evidence of channel change in the Kakariki reach suggests that most of the channel modification identified in the reach had occurred by 1967 and since that time there has only been relatively minor change in the active channel (Figures 5-9).

Numerous studies, including investigations into channel change in mainland Europe (Marston *et al.*, 1995; Bravard *et al.*, 1997; Liébault and Piégay, 2002, Liébault *et al.*, 2002) and the British Isles (McEwen, 1989; Gurnell, 1997; Winterbottom, 2000; Wishart *et al.*, 2008) have identified similar changes in gravel-bed river channel morphology. Essentially these rivers underwent a transition from a wide, unstable braided form to a narrower and more stable single thread channel. Channel change in these cases was conditioned by a number of factors including climatic changes and the onset of river engineering, with many of the potential factors coinciding making it difficult to differentiate between the individual effects of potential drivers of change. The issue to address in the Rangitikei is what is driving the clear and marked changes in channel character observed between 1949 and 2007? We suggest three potential principal causes.

1. Historical flow regime

Relatively small-scale alterations in the climate and flood regime can produce significant morphological adjustment in river channels (Rumsby and Macklin, 1994; Wishart *et al.*, 2008). The Mangaweka flow gauging site provides the longest continuous record of river flow for the Rangitikei River (Figure 10). Flow at Mangaweka comprises 79 to 88% of the flow at Kakariki during low flow periods (Horizons Regional Council, 2004) and so can be considered relatively representative of the general flow conditions occurring at the study reaches in the lower river. Figure 10 shows the flood peaks recorded at Mangaweka prior to 1970 in addition to the more recent continuous flow record. The data series shows no clear alteration in flood frequency or magnitude over the period of observation which would likely be responsible for river channel morphological change. It is also unlikely that the Moawhango dam in the upper catchment and associated flow diversion has contributed to channel change, since its influence is not detectable in the flow record at high flows and the effect on flood flow in the lower Rangitikei is estimated to be only a 0.4 percent reduction in flow (Horizons Regional Council, 2004). There is no evidence to suggest that there has been any change in the flood regime in the Rangitikei River from these records, although such changes have been identified in gravel-bed rivers in Scotland and northern England over a similar time period (Rumsby and Macklin, 1994; Werrity and Lees, 2001; Wishart *et al.* 2008). However there is no reason why New Zealand rivers should be in phase with British systems, in fact evidence suggests an anti-phase relationship (Macklin *et al.* 2009).

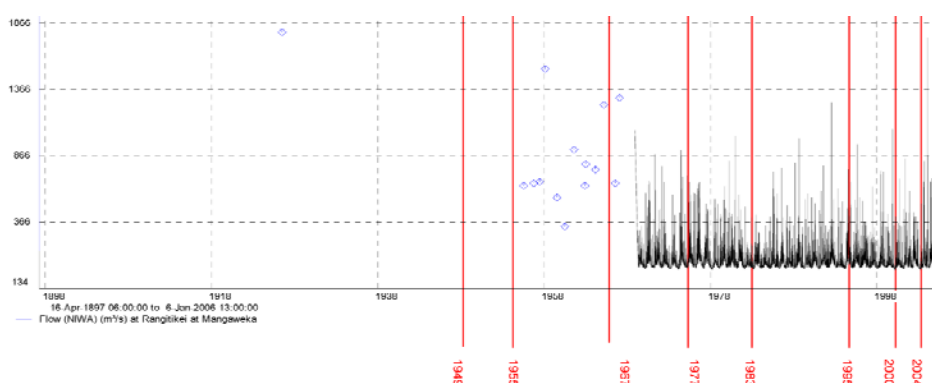
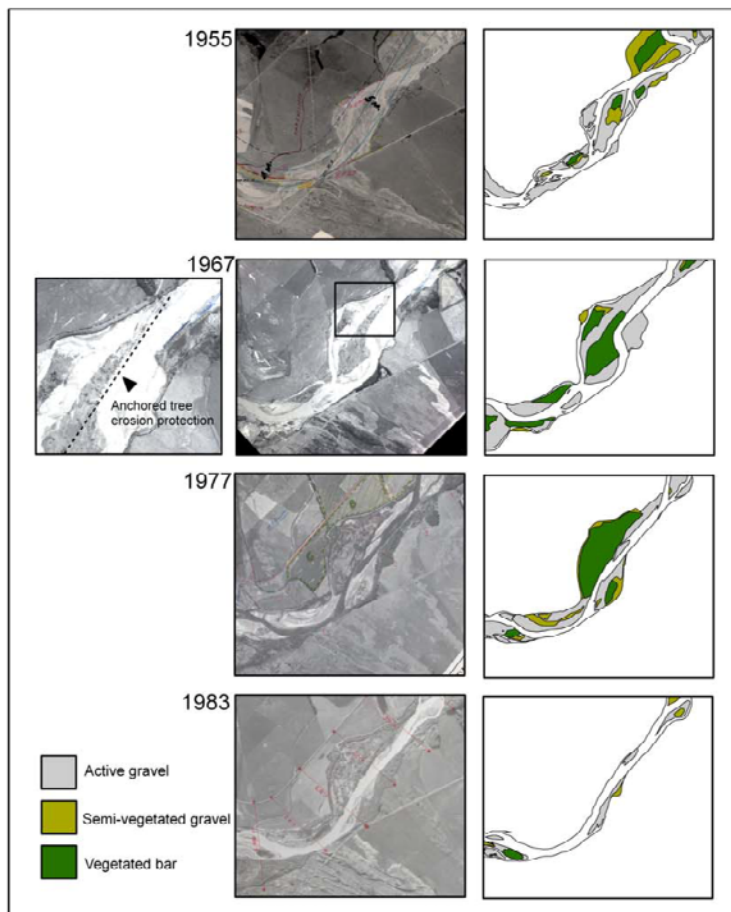


Figure 10. Flood hydrograph for the Rangitikei River gauged at Mangaweka, 16 April 1897 to 2006. Aerial photograph dates labelled (Courtesy of Brent Watson, Horizons Regional Council, Sept 2008).

2. Bank erosion protection

The Rangitikei River scheme commenced in the early 1950s with a programme of river control involving bank protection work using anchored trees and protective planting to stabilise banks. The stabilising effect of bank vegetation is well reported (e.g. McKenny *et al.*, 1995; Marston *et al.*, 1995; Gurnell, 1997; Abernethy and Rutherford, 1998). Observation of channel planform changes that have occurred in selected reaches of the lower Rangitikei suggest that bank protection measures implemented through the Rangitikei River Scheme have been particularly effective in controlling bank erosion. Figure 11 shows how a line of anchored trees placed in the active channel before 1967 has influenced channel form in this section of the Flock House reach. In 1955 this part of the channel was wide, multi-channelled and with a large mid-channel bar present. A line of anchored trees installed down the length of the mid-channel bar prior to 1967 effectively cut off the side channels from the main thalweg. Further vegetation stabilisation of the bar surface prevented reactivation of the abandoned channels, maintained a narrower single-thread planform and culminated in complete disconnection from the active channel by 1983. Closer inspection of aerial photographs and reconstructed planform maps



reveals the extensive role that the bank protection works played in modifying the active channel throughout the Flock House, Bulls Bridge and Kakariki reaches. Quantitative and qualitative evidence of channel change suggests that the early bank protection measures were particularly successful at reducing the active channel width and area, with the majority of the changes occurring prior to 1983 with relative stability since then. These findings are in agreement with research that has found that the development and encroachment of riparian vegetation, either through land use change or river engineering, has played a major role in promoting geomorphic change within river systems (Gurnell, 1997; Marston *et al.*, 1995; Liébault and Piégay, 2002).

Figure 11. The effect of anchored tree erosion protection on channel planform in the Flock House reach of the lower Rangitikei River, 1955 to 1983.

3. Sediment deficit

Total declared annual gravel extraction returns for the Rangitikei River have been between 120 000 and 240 000 m³ year⁻¹ from 1961 to 2000 (Horizons Regional Council, 2000), and between 77 000 and 179 000 m³ year⁻¹ since 2000 (pers. comm. Chris Veale, Horizons Regional Council, Sept 2008). These figures are believed to underestimate the actual amount of extraction for various reasons e.g. unreported extraction (Horizons Regional Council, 2000). With natural gravel replenishment rates of 20-30 000 m³ year⁻¹ estimated (Horizons Regional Council, 2000), it is clear that the amount of gravel extracted exceeds supply. Results of investigation by Horizons Regional Council confirmed initial concerns, raised by Rangitikei-Wanganui Catchment Board in 1979, that gravel extraction from the Rangitikei River has caused significant bed level degradation in a section of river from 4 km downstream of Bulls Bridge to 15 km upstream of the Kakariki Bridge (Horizons Regional Council, 2000). A zone of moderate aggradation, thought to be responsible for reduced stopbank capacity, was identified between 2.5 km and 15 km upstream (Horizons Regional Council, 2000). The wider more laterally active channel that existed prior to 1983 had more opportunity to rework sediments stored in the floodplain and channel through processes such as channel avulsion and cutoff development. Confinement of the active channel, most likely the result of bank protection measures, has decoupled channel and floodplain. This exacerbates sediment deficits already imposed by excess extraction, enhancing incision and isolating the floodplain from all but extreme flow inundations responsible for berm aggradation.

The impact of a major flood event: a robust system

In February 2004 the Rangitikei River catchment along with many other areas in the lower half of the North Island were subject to heavy rainfall as a consequence of an intense '150 year' storm. Rainfall in the Ruahine Ranges exceeded 200 mm in 24 hours at most sites (Meteorological Society, 2004). The hydrograph for the Rangitikei River gauged at Mangaweka recorded a maximum flow of 1756 m³ sec⁻¹ as a result of this rainfall (NIWA, 2008). Aerial photographs taken in 2004 record changes in active channel planform occurring in response to a low frequency high magnitude flood event. The Bulls Bridge reach alone showed any evidence of change in the extent of the active channel. Analysis of the planform in 2004 showed with a small (5%) increase in the area of active gravel (Figure 6a and 7a) corresponding with a slight increase in lateral bar area returning to pre-2004 extent by 2007 (Figure 7a). Mean active channel width increased by 30% as result of the flood but reduced by 20% before 2007 (Figure 4). These findings indicate that the high flood flows resulted in inundation and mobilisation of previously stable lateral bar surfaces, increasing the active channel boundaries temporarily. No increase in braiding index and only a slight increase in sinuosity due to bend extension was identified in the Bulls Bridge reach (Figure 9). The rate of lateral shift calculated for the Bulls Bridge and Kakariki reaches increased in the period of observation following the flood, suggesting a degree of post flood adjustment had occurred (Figure 5a). In contrast the Flock House and Kakariki reaches showed no evidence of expansion of the active channel area or morphological units within the active channel boundaries (Figures 5c and 6). Sinuosity increased slightly in the Kakariki reach and more strongly in the Flock House reach following the 2004 flood event (Figure 9b). Neither reach displayed any marked change in braiding index, number or area of mid-channel bars (Figure 8b, 8c and 9a).

Identification of the planform changes here suggests that the reaches responded to the flood event in slightly different ways, but all of which were robust, with minimal overall change detectable. Geomorphic response to flooding is conditioned by valley floor and channel configuration, priming discrete reaches and sensitising them to disturbance (Fuller, 2007). These results illustrate how limited, both spatially and temporally, the response of the lower Rangitikei River was to an extreme flood event. None of the channel changes recorded are approach the magnitude and extent of modifications identified between 1955 (1949 for the Flock House reach) and 1983. Such behaviour in response to a high magnitude event suggests these reaches in the lower Rangitikei River are robust, with a high capacity to absorb change, experiencing only minor adjustments as result of crossing intrinsic thresholds (Werritty and Leys, 2001). Despite a large flood event occurring during the period covered by the study, there is no evidence to suggest that the fluvial system had been forced toward a new process domain. This demonstrates that morphological stability can persist even in the face of an extreme flood event due to previous channel modification, either anthropogenic or natural, that has altered channel-floodplain interactions (Eaton and Lapointe, 2001).

The impact of river management changes

Management action recommended as a result of the 1983 review of the Rangitikei Scheme included widening the channel fairway to 500 m and the designation of a riparian zone, where some bank erosion would be acceptable. The Rangitikei Management Plan, adopted in 2000, recommended a reduction in gravel extraction from 15 km upstream and limitation on the use of rip rap within a 4-500 m meander zone (Horizons Regional Council, 2000). However, our analysis shows no evidence that these management changes have had an impact on channel planform in the study reaches.

Without a comprehensive analysis of the sediment budget or bed level changes occurring within the study reaches it is difficult to fully assess the morphological changes that have occurred in the lower Rangitikei River since 1949. However it is likely that continuing extraction and channel stability is contributing to channel degradation, a situation that is ultimately unsustainable. Channel incision has been shown to decouple channel and floodplain processes (Fryirs *et al.*, 2007). Management actions sympathetic to maintaining or encouraging channel floodplain connections are beneficial not only in terms of allowing the river to naturally adjust to changes in the sediment or flow regime, potentially avoiding catastrophic adjustment, but also improves riparian habitat and landscape diversity. To date such sympathetic action remains outstanding on the Rangitikei.

Ecological implications of channel planform change

The changes identified in the lower Rangitikei have significant implications for the composition and distribution of riparian and aquatic communities. In its broad, braided state, the river supported an extensive variety of habitats including pioneer communities in areas more frequently disturbed, more established vegetated communities, backwaters and various sized channels. By 1983 the active channel was predominantly single thread, narrow and exhibited significantly less morphological complexity. Biocomplexity in fluvial hydrosystems is the result of interactions between different processes operating at various scales, with differences in the nature and intensity of hydrological connectivity contributing to the spatial heterogeneity of riverine landscapes (Amros and Bornette, 2002). Contraction and

stabilisation of the lower Rangitikei River, and greater isolation from the floodplain, has been identified and indicates that extensive habitat homogenisation has occurred, potentially negatively impacting species diversity and abundance in the area, which is beyond the scope of this paper, but worthy of future investigation.

Conclusion

This study has utilised GIS analysis and quantified indices of channel change to examine active channel planform change occurring within three reaches of the lower Rangitikei River. Quantification of active channel changes permitted the identification of spatial and temporal patterns of channel modification between 1949/55 and 2007. The majority of channel changes occurred before 1983 with only relatively minor changes in all indices recorded subsequently. Statistically significant width reduction and channel stabilisation occurred between 1949/55 and 1983 in all three study reaches as the river metamorphosed from a multi-thread braided system to a single thread wandering pattern.

Although it is difficult to isolate causal mechanisms from the myriad of variables that have the potential to influence channel morphology, there is evidence to suggest that bank protection measures instigated under the Rangitikei River Scheme have had a considerable impact in terms of directly reducing the active channel width and area. It is also likely that gravel extraction has contributed to the observed channel changes, enhanced channel floodplain disconnection and exacerbated sediment deficits. No change in flow regime is detectable during the 50 year study period.

Concerns about channel degradation within the lower Rangitikei River have facilitated management actions, including recommendations to widen the channel fairway, designating an desirable erosion limit and moving gravel extraction from sites of degradation to areas experiencing aggradation. Quantitative analysis of the active channel planform shows no evidence that these management changes have had any immediate impact on channel planform to date, even with the occurrence of one of the largest floods on record in 2004.

The nature and magnitude of channel planform change in the lower Rangitikei River also has implications for the ecology of the lower Rangitikei River system. Limited connectivity of channel and floodplain and reduced heterogeneity of geomorphic features will affect the diversity and quantity of physical habitat along the river course for trout and other species.

Past management of the lower Rangitikei River has been reach-scale with an engineering-based approach focused on bank erosion mitigation and flood protection. This study has confirmed that the lower river has responded geomorphologically to these goals of river control. However questions as to the economic and ecological sustainability of this management style may encourage river managers to consider the benefits of promoting a self-adjusting fluvial system within a catchment-framed management approach.

This research has identified a number of key areas for future research. More work needs to be done in terms of identifying sediment sources and flux within the lower Rangitikei River and in the catchment as a whole. This study has acted as a first step in identifying and quantifying channel planform change in the lower Rangitikei River. Use of a sediment budgeting approach in the lower Rangitikei River would increase understanding of sediment transfer processes and the channel degradation issue, potentially identifying the trajectory of future change and informing river management practice. Future research is also required to assess the consequences of channel changes on ecosystem integrity and more specifically the availability of habitat for aquatic species.

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Quantification of channel planform change on the lower Rangitikei River, New Zealand, 1949-2007: response to management?

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