Interaction of ENSO-driven flood variability and anthropogenic changes in driving channel evolution: Corryong/Nariel Creek, Australia

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Acknowledgements
This work was undertaken as part of a Master's thesis by EAT, supervised by, and supported by a University of Melbourne Early Career Researcher grant to, PMM.

Anthony Wilson (NECMA) is thanked for providing background information. LiDAR data was made available by Rick Frisina of DEPI, Victoria. Hugh Smith, Justin Stout, Louisa Davis, Mei Yin Soh, Steph Kermode and Han She Lim helped with various aspects of this research.

Word count: 8299 words

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ABSTRACT *Understanding the relative contribution of climatic and anthropogenic drivers of channel change is important to inform river management, especially in the context of environmental change. This global debate is especially pertinent in Australia as catchments have been severely altered since recent European settlement, and there is also strong evidence of cyclical climate variability controlling environmental systems. Corryong/Nariel Creek is an ideal setting to further study the interaction between climate and anthropogenic changes on channel evolution as it has experienced both significant periods of flood and drought, controlled by the El Niño Southern Oscillation (ENSO), and extensive anthropogenic changes. Since European settlement the floodplain has been completely cleared, the riparian zone almost entirely invaded by willows, and every reach of the channel has experienced some form of direct channel modification. Through the combined analysis of channel evolution, climate changes and anthropogenic history of the river, it was found that both the ENSO-driven climate and anthropogenic drivers are significant, although at different scales of channel change. Significant straightening in response to land clearing in the early 20th century occurred before any records of direct channel modifications. Following this, most river management works were in response to instabilities created in the clearing period, or to instabilities created by flooding triggering a new phase of instability in reaches which had already undergone stabilisation works. Overall, human activities triggered channel instability via land clearing, and management works since then generally exacerbated erosion during high flows that are driven by climate fluctuations. This research raises the interesting question of whether rivers in Australia have become more responsive to the ENSO cycle since the clearing of catchment and riparian vegetation, or whether the past response to climate variability was different.*

KEY WORDS *Channel change; human impact; climate impact; ENSO, sinuosity, bank erosion*

Introduction

A persistent issue in fluvial geomorphology is the relative contribution of anthropogenic and natural controls on channel evolution. This is important to establish since it has wider river management implications in the context of global environment change (Macklin & Lewin 1997; Goudie 2006; Wohl 2011). The debate is a global one but is especially pertinent in Australia, as catchments have experienced significant anthropogenic modifications since European settlement in 1788, and yet there is also strong evidence of climate variability controlling environmental systems. Documenting post-European river channel changes and determining their causes allows prediction of the trajectory of future changes. By determining how rivers respond to both climate, and anthropogenic factors, appropriate management and restoration strategies can be adopted.

This paper uses Corryong Creek (known as Wheeler Creek in its headwaters, Nariel Creek in its upper reaches, and hereafter collectively referred to as Corryong Creek), to investigate the relative roles of anthropogenic and climatic drivers on channel evolution following European settlement. Corryong Creek is a tributary of the upper River Murray in southeast Australia, and is known to experience major channel instability issues that are likely to be due to a combination of extreme flood events, land clearing, exotic riparian willows, and historic river works. To achieve the aim, the geomorphological evolution following European settlement in 1838 up to 2010 was determined using a range of historic maps and documents, as well as aerial photography and remotely sensed imagery. This record of channel change was then analysed alongside climatic (rainfall and river discharge) records. Although Australian rivers are often considered unique (many being ephemeral and low-gradient), Corryong Creek is representative of rivers in higher energy settings as it is comparatively steep and has a relatively high energy gravel bed channel for its full length.

Impacts on Australian rivers

Geomorphic responses to climate drivers

Climate variation in southeast Australia is strongly linked to the El Niño Southern Oscillation (Allan 1988; Nicholls *et al*. 1996). Periods of sea surface cooling of the eastern and central Pacific Ocean (La Niña) result in a series of climate shifts leading to increased rainfall over Australia, while sea surface warming over the eastern and central Pacific (El Niño) leads to an increased probability of lower rainfall over Australia. The climate of southeast Australia was also recently linked to the Indian Ocean Dipole (Ummenhofer *et al*. 2009), although there currently is a debate on whether IOD is a manifestation of ENSO since both sea surface temperature fluctuations correspond to each other (Allan *et al*. 2001). This study distinguishes between ENSO and IOD years because some high rainfalls coincide with negative IOD years and not La Niña, but accepts the view that IOD is an aspect of ENSO. Irregular switches between El Niño and La Niña conditions, interspersed with periods of "neutral" conditions are thought to drive major changes in the climate of Australia (Meyers *et al*. 2007; Ummenhofer *et al*. 2009).

Globally, ENSO-driven hydrological variations have been demonstrated for a number of rivers (e.g. Richey *et al*. 1989; Amarasekera *et al*. 1997; Xue *et al*. 2011). In Australia, extreme rainfall and floods are linked to La Niña, and droughts are associated with El Niño (Adamson *et al*. 1987; Allan 1988; Power *et al*. 1999a; Micevski *et al*. 2006). Notable La Niña periods occurred in the 1920s, 1930s, 1950s and 1970s. Several known Australian droughts, including the Federation Drought (mid-1890s to mid-1900s), World War II Drought (late 1930s to late 1940s) and the Millennium Drought (mid-1990s to 2010), coincide with consecutive El Niño years (BoM 2008).

There is much evidence that many southeast Australian rivers are prone to cyclical channel changes, with channel enlargement during flood dominated periods, and channel narrowing during drought dominated periods (Nanson & Erskine 1988; Nanson *et al*. 2008; Rustomji *et al*. 2009). These alternating periods of higher and lower flood frequencies switch every 30 to 50 years, generating parallel periods of channel degradation and aggradation (Warner 1987). According to Warner (1987) and Erskine & Townley-Jones (2009), flood dominated regimes (FDRs) occurred in 1799–1820, 1863–1900, and 1949–1990; drought dominated regimes (DDRs) occurred from 1821–1862, 1901–1948, and 1991–2008. The presence and significance of alternating flood and drought regimes has been questioned based on its possible lack of regional applicability and geomorphic impact, along with a claimed lack of statistical evidence (Kirkup *et al*. 1998; Brooks & Brierley 2000). These changes are thought to be driven by longer-term climate fluctuations, and ENSO-driven river channel evolution has yet to be demonstrated for rivers in southeast Australia.

Geomorphic responses to anthropogenic activity

Since European settlement, the catchments of many southeast Australian rivers have been altered extensively through activities such as land clearing, willow (*Salix* spp.) planting and channel modification (Warner & Bird 1988; Rutherfurd 2000). In particular, catchment vegetation clearing has been attributed to increases in mean and peak discharge of most rural Australian streams (Brizga & Finlayson 1994; Brooks *et al*. 2003). Catchment clearing also increases sediment delivery to the river system (Brooks & Brierley 1997). Riparian zones were often cleared as part of floodplain clearing, or for cattle access. Not only did riparian clearing make banks more susceptible to erosion, it exacerbated the invasion of exotic willows, which were planted to stabilise banks. The channel narrowing effect of willows has, in some smaller channels, led to severe erosion where willow infested reaches are bypassed by cutoffs or avulsions (Brizga & Finlayson 1990; Pope *et al*. 2007; Erskine *et al*. 2012).

Channel modifications such as channelization, bank stabilisation and desnagging aimed to improve drainage, especially during floods. The long-term effects of channelization and bank stabilisation on

Australian rivers are not yet fully understood, nevertheless, there is evidence of engineering works causing river instability (Rankin 1982; Erskine 1990). The removal of large woody debris enhances flow velocities, increases sediment loads, degrades channel beds, and enlarges channels (Brooks & Brierley 2002; Brooks *et al*. 2003; Erskine & Webb 2003).

Study area: characteristics and land and water management history

Corryong Creek is a single channel gravel-bed tributary of the River Murray, approximately 115 km long with a catchment area of about 980 km^2 (Figure 1). The headwaters of the river are in the Victorian Alpine National Park, with the highest point at Mount Pinnibar (1772 m). There is one major tributary, Thowgla Creek, which joins the river downstream of the town of Corryong. This study investigates the river from the point the alluvial channel and associated floodplain begins (elevation 470 m) to the confluence with the Murray River (elevation 244 m), a 72 km length of the river (Figure 1). The catchment is underlain by Ordovician sandstone and schist, with Silurian granite intrusions forming upland areas within the catchment (Simpson *et al*. 2001). All upland and headwater reaches of the catchment are densely vegetated with native eucalypt forest, whilst the floodplain and lower slopes are cleared for agricultural use (see below).

The Corryong region was settled by Europeans in 1838. As with most rivers in the region, Corryong Creek has been altered extensively since then. Regional river managers and the local community believe that the amount of erosion recently experienced by the river is unnaturally high, exacerbated by past river management activities and perhaps by increasingly extreme flood events. Mass bank failures are significant problems to the local community as they remove valuable pasture, endanger livestock, damage infrastructure, disrupt farmland boundaries, and endanger the river ecosystem and its associated fishing tourism industry.

Originally, the catchment was densely vegetated by woodlands and forest (Miller 1934; DEPI 2012). Within a century of settlement, the entire floodplain was almost completely cleared (Mitchell 1981), with clearing continuing such that there is currently a cleared area of 201 km^2 (Barratt *et al*. 2007). Willows were introduced for stream stabilization, to mitigate the effects of riparian vegetation loss. According to newspaper reports, channel narrowing by willows contributed to flooding in Corryong as early as the 1920s (Albury Banner and Wodonga Express 1920; The Argus 1938), before willow planting became popular throughout Victoria from the 1950s to 1990s (Pope *et al*. 2006). Historic photos from the 1950s and 1960s document the severe channel obstruction and subsequent bank erosion caused by willows (Plates 1(a) to 1(d)). However, it appears that the erosion was attributed to large woody debris instead of the willows, as river works during the mid-20th century involved desnagging but not willow removal (Erskine & Webb 2003). Willow planting has now halted, and willows have been removed at a few reaches since the 1990s, but not extensively (Webster 2006). As a result, the channel is still either unvegetated or lined with willows and poplars instead of native vegetation, with the exception of one 200 m reach that has been revegetated with native eucalyptus trees.

The entire length of the river has been subject to stream works of some manner (Water Victoria 1989; Figures 2 and 3). Initial river engineering in the 1960s and 1970s, involving major channel straightening and realignment, were meant to increase the rate of drainage, but increased channel instability instead (Figure 2). Major channel straightening in the middle reaches led to avulsions through adjacent farmland after a large flood in 1972 (Webster 2006). Since the establishment of the Shire's River Improvement Trust (now the North East Catchment Management Authority, NECMA), attempts to radically modify channels have ceased. Projects now focus on regaining channel stability through rocking and tethered logs (Plates 1(e) to 1(g)). A few reaches have also received artificial gravel deposition by NECMA to decrease stream power. Stock trampling is still an issue as the majority of the river has been unfenced since the 2002/2003 drought (Webster 2006).

Several large floods are documented in the historic record, which led to mass bank erosion and infrastructure damage. These include a very large flood in 1917, a series of floods in the mid-1950s, and the recent major floods from September 2010 to January 2011. Local newspapers also reported floods in 1905, 1909, 1920, 1931 and 1941. A large bushfire in 1939 may have resulted in a short-lived increase in discharge during this period, followed by a longer-term reduction in runoff as vegetation was re-established. A response of this nature has been modelled for a more recent large bushfire in 2003 (Hill *et al*. 2008).

Methods

The earliest available data source is parish plans showing the position of the river, from 1882. These maps generally indicate the river with a reasonable degree of accuracy, since the parish plans are cadastral maps showing the boundaries of individual farms, and the river often acts as a property boundary. Comparison of the historical data sources with recent LiDAR data shows that meanders indicated in older data sources are present in the LiDAR data as meander scars on the floodplain (Figure 3). A further 13 historic sources were found, up to 2010, including later parish plans, aerial photos, a geological map, and a 2010 LiDAR survey of the river (Figure 4). The LiDAR data was collected as part of the Victorian State Government 'Index of Stream Condition' survey, and consists of a 2 km wide swath centred on the main channel, along the full length of the river. Figure 4 summarises the sources used, the years they were published or represent, and the approximate length of river each source covered. All data sources were scanned and then georeferenced using ArcGIS. Minor errors in the georeferencing of the older data sources are not significant, as most channel change since European settlement is due to meander cutoffs, channel straightening and widening (see below). Shifts in the channel centreline which might have affected measurement of meander migration rates are therefore not significant. Due to the decreasing resolution of data with age, the planform centreline and sinuosity (channel length divided by valley length) was the only consistent channel parameter measured throughout this time series. Average channel widths (channel surface area divided by channel length) and amount of sediment deposition for each reach (surface area of exposed sediment) were only measurable from the 1985 and 2004 aerial photos, and the 2010 imagery. Fluctuations of the area of exposed sediment could be due to either deposition of bars on the floodplain during floods, or an increase in vegetation cover, covering exposed gravel surfaces. Exposed sediment area was analysed in conjunction with channel width fluctuations and the climate and flood data to determine the geomorphic response to recent climate shifts.

In the 1985 and 2004 aerial photos, riparian vegetation extent was clearly visible. Since willows have already established along the riparian zone by this period, all riparian vegetation in aerial photos are assumed to be willows or poplars. The extent and continuity of riparian vegetation for each reach was scored using the habitat sub-index assessment method outlined by the Riparian Appraisal of Riparian Condition (Jansen *et al*. 2005). This index is useful as an indicator of willow impact because the variables involved in the scoring are geomorphologically relevant, including longitudinal continuity of riparian vegetation, width of riparian vegetation, and proximity to nearest patch of intact native vegetation (Jansen *et al*. 2005).

Changes in climate were determined using rainfall (1885 to 2013) and river flow records (1954 to 2013) obtained from Nariel Creek weather station and Stacey's Bridge gauging station (Figure 1). Post-1954, flood recurrence intervals were established using a Log Pearson III flood frequency analysis of instantaneous daily discharge data from May 1954 to February 2013. Prior to available flow data, flood events pre-1954 were interpreted from the rainfall record. These were confirmed using newspaper articles and historic photos depicting flood-induced bank erosion. When identifying periods of high flow, bushfire events were also noted since they have a hydrological effect of increasing discharge. A second gauging station exists downstream, close to the confluence with the River Murray at Towong (Figure 1). Although it has only been in operation since 1993, it provides additional insights into downstream changes in discharge, and the relative contribution of flows from the main stem of Corryong Creek and from Thowgla Creek, the major tributary.

To determine the significance of ENSO on Corryong Creek's hydrology, rainfall and flow anomalies (the deviation from the total rainfall/flow average) for each ENSO/IOD combination categories were gathered, as conducted by Ummenhofer *et al*. (2009), and tested statistically using ANOVAs. ENSO/IOD periods were defined using Meyers *et al*. (2007) and the Bureau of Meteorology website. The presence of cyclical flood regimes was tested by applying the statistical methods used by Riley (1981), Brooks & Brierley (2000) and Erskine & Townley-Jones (2009). A single factor analysis of variance (ANOVA) test determined significant differences between rainfalls of different climate regimes (Riley 1981; Brierley *et al*. 2005). To identify and analyse temporal changes in rainfall unique to Corryong, an intervention analysis was performed using the cumulative sum technique (CUSUM), which determines the yearly rainfall deviation from the total rainfall mean of the entire time series. This was followed by a Wilcoxon Rank Sum test (Erskine & Townley-Jones 2009). The confidence level for all ANOVAs is 95%.

For analysis of channel changes, and presentation of results, the study reach was divided into four zones (Zones A to D) and further divided into 24 reaches (numbered 1 to 24 as the channel progresses downstream). There are 3 reaches in Zone A, 9 reaches in Zone B, 8 reaches in Zone C and 4 reaches in Zone D. Zone boundaries were defined at major confluences and at the transitions between partially-confined and unconfined valley settings to account for the geomorphic effects of discharge volume and valley confinement. Zone A, which has a discontinuous floodplain, ends at the confluence of Corryong Creek and Simpsons Creek. The end of Zone B marks the end of the discontinuous floodplain and the large widening of the valley downstream. Zone C continues just upstream of the confluence of Corryong and Thowgla Creek, from which Zone D extends to the River Murray. Although some reaches in Zones C and D are adjacent to the valley side, there is practically no lateral confinement as the length of connection is very small, extending no more than 200m.

Results

Channel changes: sinuosity

Since the 1880s, Corryong Creek has become significantly straighter throughout its length (Figures 6 and 7). The overall average sinuosity in 1882 was 2.01, whilst in 2010 it was 1.47, a 27% reduction. Furthermore, although the river has predominantly been a single channel the earliest mapping shows several anabranches that are now absent (e.g. Reaches 2, 6, 15, and 22; Figures 6 and 7). NECMA records indicate that minor avulsions occurred during the 1993 and 2010 floods, but engineering works kept the channel in its original course. Catchment-wide, there is a consistent pattern in sinuosity change over time with three distinct phases. From the early to mid-20th century there was a significant decline in sinuosity. This is followed by further decrease at a lower rate from the mid-20th century, and from the 1990s to 2010, there was a slight sinuosity increase.

On average, Zone A (Figure 5(a)) had a relatively constant sinuosity from the 1920s to 2010 (between 1.13 and 1.19; Figure 6(a)), as it is mostly partially-confined and has limited lateral freedom for channel movement. The only unconfined reach in Zone A (Reach 2) experienced significant straightening, especially before the 1950s. From the 1920s to 1950s Reach 2's sinuosity decreased from 1.40 to 1.26 (-0.14), whilst from 1950s to the 1990s sinuosity decreased from 1.26 to 1.21 (-0.05) (Figure 6(b)). Unlike the catchment-wide trend, sinuosity continued to decrease from the 1990s to 2010 (1.21 to 1.14; -0.07).

The degree of straightening increases downstream as the channel progressively becomes unconfined. The catchment-wide sinuosity trends outlined above dominate Zones B and C (Figure 5(b), 6(c)). In Zone B, from the 1880s to 1920s the sinuosity decreased from 2.15 to 1.74 (-0.41) whilst the change from the 1920s to 1990s was 1.74 to 1.38 (0.36) (Figure 6(a)). Sinuosity increased slightly from the 1990s to 2010 (1.38 to 1.43; +0.05). In Zone C, the sinuosity decreased from 1.88 to 1.50 (-0.38) in the 1920s to 1940s and from 1.50 to 1.37 (-0.13) in 1940s to 1990s. Sinuosity increased from the 1990s to 2010 (1.37 to 1.40; +0.03). Significant river realignment work was conducted in both Zones B and C. In addition to channel straightening, channels that ran some distance away from the valley side were pushed against the valley wall, and meanders away from the valley wall were cut off. Although the historic maps can only indicate that the works occurred sometime between the 1940s and 1980s, they are most likely from the 1960s and 1970s given the known management history.

In Zone D, there was a decrease in sinuosity from the 1920s to 1970s (2.05 to 1.97; -0.08) and a further decrease from the 1970s to 1990s (1.97 to 1.86; -0.11). This was followed by an increase from the 1990s to 2010 (1.86 to 1.94; +0.08) (Figure 6(a)). The pattern of straightening by in Zone D (unconfined floodplain) was different to that in upstream Zones (partly confined floodplain). By the 1940s, meanders had become larger in size and fewer in number (Figure 5(d)). This type of meander evolution represents a significant change in pattern, but is not reflected in changes in sinuosity, as total change in channel length is relatively minor.

Channel changes: width, exposed sediment and vegetation

Measurement of channel width and area of exposed sediment was possible from the 1985, 2004 and 2010 aerial photos and LiDAR imagery (Figure 7). Over this period, the greatest variability occurred in Zones C and D. Between 1985 and 2003, average channel width increased (2 m in Zone C, and 1 m in Zone D) whilst between 2003 and 2010, average channel width reduced by 1 m in Zone C and 2 m in Zone D. A large area of exposed sediment was present in 1985 which decreased in the 2003 photograph (a 70% decrease in Zone C and a 58% decrease in Zone D) and increased again between 2003 and 2010 (a 60% increase in exposed sediment in Zone D). These observations indicate that channel width and exposed sediment area fluctuate together. When the channel was wider there was a decrease in exposed sediment, and when the channel was narrower there was an increase in exposed sediment (Figure 7).

Between 1985 and 2004, there was a slight overall increase in riparian habitat continuity, which remained largely unchanged up to 2010 (Figure 8). According to field observations, willows appeared to intensify bank erosion at narrowed reaches due to willow encroachment into the channel, but had little apparent impact in wider reaches. Where channel narrowing by willows is especially significant, avulsions and cutoffs have occurred during major floods.

Climatic variability

Figure 9 depicts Corryong Creek's annual rainfall anomalies from 1885 to 2010, with the flood events and the "wet" and "dry" ENSO/IOD years identified. Figure 10(a) shows discharge anomalies using data from the Stacey's Bridge gauge from 1954 onward. There is a very poor relationship between rainfall amount and the size of floods at the daily level, making rainfall-runoff modelling, or extrapolation from the rainfall record difficult. For instance, in 2010, the highest flow at Stacey's Bridge (109 m^3s^{-1}) was produced by daily rainfall of 83.2 mm, whilst later daily rainfalls (on a wetter catchment) of 90.4 and 88 mm produced peak discharges at Stacey's Bridge of 28 and 42 m^3s^{-1} (5- and 10-year floods) respectively. There is therefore considerable uncertainty regarding the size of pre-1954 floods. Based on newspaper reports and comparison with the rainfall data, the largest flood occurred in 1917 (La Niña and negative IOD year). The second largest flood is likely to have been in September 2010 (La Niña year), a 100-year flood. There are clusters of high rainfall and flood events in the 1950s, 1970s, 1980s and the 1990s (Figure 9). Bushfires have an effect on flow, given that the 5-year flood in 2003 coincided with a major bushfire but had below average rainfall (Figure 9). The 1905 flood also coincided with a bushfire. In 1939, the Black Friday bushfires on January 13 were followed by 94 and 78.5 mm of rainfall on February 27 and 28.

The influence of ENSO on Corryong Creek's hydrology is very strong. All major flood events and above average rainfalls and flows were during La Niña and/or negative IOD years. Periods of below average rainfall and discharge occur during "dry" years (El Niño and/or positive IOD; Figure 10). ANOVA testing comparing the monthly rainfall of "wet", neutral and "dry" years produced a very significant p-value (2.07×10^{-272}). Overall, monthly rainfall was 7.7 mm above average for "wet" years, 1.8 mm below average for neutral years, and 12.2 mm below average for "dry" years. Likewise, ANOVA testing comparing the annual maximum instantaneous flow of "wet", neutral and "dry" years also produced a very significant p-value (6.89×10^{-6}). On average, the annual maximum instantaneous flow was 16.0 m^3sec^{-1} above average for "wet" years, 3.1 m^3sec^{-1} below average for neutral years, and 17.9 m^3sec^{-1} below average for "dry" years.

The multidecadal flood regimes defined for other catchments in southeast Australia (Erskine and Townley-Jones 2009) are not applicable to Corryong Creek. An ANOVA test comparing the average annual rainfalls of each regime produced an insignificant p-value of 0.154 (Table 1). Repeating the methodology to determine a flood regime unique to Corryong's rainfall still does not reveal multidecadal climate fluctuations. However, through this process, an upward shift in average annual rainfall after the mid-20th century was detected. A Wilcoxon Rank Sum test (Table 2) shows that there is a significant difference in rainfall between 1885 and 1950, and 1951 and 2000 (p-value of 0.006). There is also more variability in annual rainfall after 1950, as depicted by its higher standard deviation

(Table 2). An overall increase in annual rainfall and the increased frequency of dry and wet extremes through the 20th century has also been observed in other areas of Australia (Nicholls & Lavery 1992).

Interpretation

Since European settlement, Corryong Creek has had a complex geomorphological history. There has been a reduction in catchment vegetation cover, the introduction of willows to the riparian zone, changes in the approach to river management, changes in rainfall pattern coupled with ENSO-driven flood and drought events, and bushfires. Collectively, these variables have resulted in Corryong Creek evolving from a highly sinuous river with several anabranching reaches, into a low sinuosity single-channel river. Given that both climatic and anthropogenic factors have been identified in the evolution of Corryong Creek, the question remains, what is the relative importance of these two drivers of channel change in this catchment? This can be answered by examining the channel changes over time, relative to the changes in the drivers of channel change.

In terms of channel planform, there was an overall pattern of channel straightening between 1882 and 2010 (Figure 3). Within this period, three major phases of channel change are apparent: (i) a phase of rapid catchment vegetation clearance, accompanied by a significant decline in sinuosity from the late 19th to mid-20th century; (ii) a relatively lesser decrease from the 1960s to the 1990s; and (iii) a slight increase from the 1990s to 2010 (Figure 6).

The late 19th to mid-20th century was characterised by a large reduction in channel sinuosity. This coincided with the near-complete clearing of the floodplain and riparian zone following European settlement to the early 20th century. In the absence of any record of direct anthropogenic channel changes in the early 20th century (the earliest record of significant channel modification was in the 1960s), it is more likely that the rapid reduction in catchment land cover, coupled with intermittent flooding, are responsible for these channel changes. Clearing may have led to larger, flashier floods that increased erosion rates during high flows and reworked the river into a straighter channel. This is consistent with newspaper reports of significant flood damage, and photos showing significant bank erosion during this period (Figures 2 and 10). In addition to the major 1917 flood and above average rainfall occurring during wet ENSO/IOD years, the fact that flooding was also reported during years of below average to average rainfall (1905, 1909, 1921, 1931 and 1941) may be indicative of a higher sensitivity to climatic variations as a result of catchment clearing (Madej 1995).

From the 1960s onward, reports of significant channel instability, such as mass bank erosion and avulsions, continued. In response, extensive river engineering works were conducted to control the river, through severe channelization, willow planting and desnagging. Most notably, the entire channel of Zone B was greatly modified as it was purposefully straightened and realigned against the valley wall to increase flood celerity and maximise the area of grazing pasture (Figure 5(b)). This phase of intense management practices spanned from the 1960s to the 1990s. It is difficult to quantify the relative roles of natural and anthropogenic channel change in this period as the response to ongoing natural erosion was to increase the extent of engineering works along the channel. However, the extent of the channel straightening, realignment and bank battering was almost certainly greater than would have been generated by natural erosion alone during this period. Also, it is likely that river engineering created a positive feedback loop of creating further instability, as was the case for many catchments in Australia (Rutherfurd 2000).

However, the sinuosity decrease during the middle 20th Century was smaller compared to that in the earlier part of the century. Corryong Creek's most significant change in form was largely the result of floods enhanced by catchment clearing, rather than later direct channel modification. However, this inference cannot be extended to suggest that catchment clearing, as a general rule, has more influence on channel change than channel modification. This is because the relative level of impact is largely due to the sequencing of these factors. Because the channel was already significantly straightened by the 1960s, further straightening (either through artificial straightening or otherwise by floods) could only be relatively minor. Also, it was during the mid-20th century that willows established a stronghold on the riparian zone: in most reaches (except steep, confined reaches) they decreased the channel's capacity for change in terms of planform. Overall though, these findings are a useful statement of the potential for catchment clearing to affect channel form more than direct channel modification, given the circumstances of succession and interrelated factors such as willow spread.

The large flood events driving major periods of channel erosion appear to be controlled by ENSO, since all high flows coincide with La Niña and/or negative IOD (Figure 9 and 11). Several decadal scale flood and drought periods are apparent, reflecting the dominance of either wet or dry ENSO years. In the 1950s, newspapers reported particularly significant levels of erosion that were likely to be due to the combination of large and small floods clustered within this decade, along with a bushfire in 1952. It is evident that in addition to magnitude, the close succession of high flows also affected flood impact. The 1960s was dominated by below average flow, dictated by El Niño and positive IOD. The series of floods in the 1970s also led to significant erosion (Webster 2006). Another drought period mostly dominated by below average flows occurred in the 1980s.

The final stage of channel planform change is from the 1990s to 2010, when there was a slight increase in channel sinuosity. This reflects the shift towards more sympathetic river management techniques. As channel straightening and realignment works halted from the 1970s onward, the river has had the freedom to reconfigure itself into a more sinuous form. Assuming that the 1882 mapping is close to the pre-disturbance morphology, the recent increase in sinuosity indicates that the channel is, to some extent, returning to its pre-disturbance conditions. In addition, despite the prohibition on willow planting, willows still dominate the riparian zone and there is no sign of a reduction in spread (Figure 8). Severe decadal scale fluctuations in ENSO-driven flood occurred throughout the 1990s and 2000s, with floods (driven by La Niña and negative IOD) dominating the 1990s and a significant drought in the 2000s (driven by El Niño and positive IOD), followed by a return to La Niña conditions in 2010.

Alongside the changes in channel planform outlined above, the channel cross-section has also been affected (Figure 7). However, in contrast to the changes in channel planform, which with the exception of the most recent two decades follow an overall trend toward straightening, the cross-sectional changes were high variable. The data available since 1985provides information on channel width and exposed sediment, but not much can be said about pre-disturbance channel depths. In general, cross-section changes correspond strongly with climatic fluctuations. In 1985, the large surface area of exposed sediment was due to a significant portion of the floodplain being stripped of grass. Frequent flooding occurred in the 1970s, ending with a 10-year flood in 1981. The 1980s were mostly dominated by below average flows, although there is no aerial photography available from the late 1980s or early1990s to assess the impact of this low flow period on channel morphology. Frequent flooding from 1993 onwards and bushfire-induced high flows in 2003 resulted in a wide channel in 2004. There was a decrease in exposed sediment in 2004 relative to 1985, indicating that vegetation establishment was relatively rapid following the 1993 and 1998 floods. The significant drought in the 2000s, however, caused the significant channel narrowing observed in 2010. There was also a slight increase in exposed sediment, due to the deposition of sediment in bars.

The extent specific reaches widened or narrowed also varied spatially. Despite the fairly low impact of engineering works on sinuosity, there were significant changes to the channel cross-section at a local scale. This was most evident at reaches that have been historically straightened and/or realigned (including Reaches 7, 10 and 13), where diversion issues, significant channel deepening, channel widening from gravel accumulation, and high rates of channel movement occurred.

Discussion and Conclusions

This study set out to investigate the relative roles of anthropogenic and climatic drivers on channel evolution following European settlement of an upland catchment in southeast Australia. Two channel change parameters were measured: channel planform and channel width. Channel planform changes require more time and energy compared to the cross-section scale changes. Changes in planform and channel width over time and space were compared to trends in land clearing, climate, historic river works, and willow spread. Different scales of channel change were not collectively driven by either anthropogenic or climatic variables. Identifying the most important driver of channel change depends upon both the spatial scale and the timescale of interest

In terms of channel planform, most of the straightening of Corryong/Nariel Creek occurred in the early 20th century, which coincided with significant catchment and riparian land clearing, but not with the period of deliberate channel modifications that dominated the second half of the 20^{th} century. The catchment has been dominated by ENSO-driven rainfall variations throughout the study period. Flooding during La Niña years would have been enhanced by catchment clearing in the early 20th century, leading to channel destabilisation and the large-scale bank erosion and catastrophic widening documented in photographs from the 1930s and 1940s. In turn, the widening led to a massive reduction in sinuosity as larger meanders were cut off and smaller meanders incorporated into the dimensions of the newly enlarged channel. The lower rate of sinuosity decrease measured during the second half of the 20th century, despite extensive channel straightening and realignment works during this period, was due to a combination of several factors. Firstly, because of the large reduction in sinuosity that had already occurred, the potential for further straightening (deliberate or otherwise) was limited. Secondly, willows had now invaded almost the full length of the channel. Whilst the willows caused local cutoffs and avulsions, they acted to stabilise many reaches. The most recent phase of channel evolution, from the 1990s up to the major flood in 2010, coincided with the era of modern, sympathetic river management techniques (Rutherfurd 2000; Spink *et al*. 2009). Since, channel clearing and straightening are now not widely used, the river has an increased capacity to reorient itself towards its more naturally meandering planform. Consequently, the minor increase in sinuosity, and the fluctuations in channel width over this period are closely tied to the wet and dry phases of the ENSO cycle.

These findings are consistent with studies on the geomorphological histories of other southeast Australian rivers. In the past 150 years, most rural streams have experienced significant erosion. In addition to bank erosion expanding the channel cross-section, such as at the Nepean River (Hubble & Rutherfurd 2010), Cann River (Brooks *et al*. 2003) and Bega River (Brooks & Brierley 1997, 2000), channels have also evolved towards a straighter planform, such as at Gilmore Creek (Page *et al*. 2007).

Analysis of the cross-sectional channel change suggests channel evolution is at least partly controlled by ENSO-driven climate variation. There is a strong ENSO signal in the hydrology of Corryong Creek evident by the interdecadal to decadal clustering of floods. However, there was no statistical evidence for multidecadal flood regimes, which is also the case for the Bega River (Brooks & Brierley 2000). The channel cross-section fluctuations appear to be driven by the decadal-scale ENSO-driven hydrological fluctuations. Since 1985, channel widening occurred during the La Niña-dominated periods, and channel narrowing during the El Niño-dominated periods. The relationship between channel width fluctuations and the ENSO cycle are not completely clear at present, due to the limited availability of aerial photography for key periods since 1985. More frequently gathered and high-resolution data in the coming decades would be able to further validate this relationship. An interesting question for future research is whether rivers in Australia have become more responsive to the ENSO cycle following the clearing of catchment and riparian vegetation, with the increased capacity for channel width changes this implies, or whether in the past the response to climate variability was manifested differently.

As illustrated by all of these findings, different variables control different scales of channel change. This is because each has a different potential alter erosion rates. For instance, catchment clearing is expansive, usually not reversed, and able to significantly alter catchment hydrology (Siriwardena *et al*. 2006), thus, it has the capacity to affect both channel shape and planform over large areas. On the other hand, more temporally periodic and localised variables are likely to only impact the cross-section and are less likely to affect the reach-scale planform. Channel straightening is an exception, as it directly affects planform sinuosity. However, its impact on sinuosity depends on the scale of straightening, and at the level conducted at Corryong Creek sinuosity changes due to deliberate engineering works are secondary to the effect of catchment land clearing.

Acknowledgements

This work was undertaken as part of a Master's thesis by EAT, supervised by, and supported by a University of Melbourne Early Career Researcher grant to, PMM. Anthony Wilson (NECMA) is thanked for providing background information. LiDAR data was made available by Rick Frisina of DEPI, Victoria. Hugh Smith, Justin Stout, Louisa Davis, Mei Yin Soh, Steph Kermode and Han She Lim helped with various aspects of this research.

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Tables

TABLE 1. ANOVA test results comparing the monthly rainfall measurements to the five flood regimes defined by Erskine and Townley-Jones (2009).

Groups	Count	Sum	Average	Variance
FDR (1863-1900)	197	17314.8	87.9	2904.3
DDR (1901-1948)	575	47602.3	82.8	3354.7
FDR (1949-1990)	488	44061.3	90.3	3911.5
DDR (1991-2008)	216	18302.2	84.7	3325.5
FDR (2009-2013)	49	4839.1	98.8	3801.4

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	23327.13	4	5831.8	1.7	0.154	2.38
Within Groups	5297203	1520	3485.0			
Total	5320530	1524				

TABLE 2. Wilcoxon Rank Sum test results, comparing annual rainfall (mm/year) between the first and second half of the 20th Century.

Years	1895-1949	1950-2000
Standard deviation	228.021	281.444
Sample size	54	48
Sum of rankings	2404	2849
U statistic	1673	
Z-score	2.528	
Z-critical	-1.960	
Right-tailed p-value	0.006	
Two-tailed p-value	0.0115	

Figure and Plate Captions

FIGURE 1. Map of Corryong and Nariel Creek, indicating the major tributaries, Zones A to D, the location of Nariel Creek weather station, and the flow gauges at Stacey's Bridge and Towong.

PLATE 1. Historic photos of Corryong Creek. (a) Mass bank erosion; (b) riparian willows; (c) mass bank erosion and sediment release; (d) willow encroachment leading to local water level increase; (e) bank tethering with logs; (f) bank tethering with logs; (g) bank stabilisation with rocks.

FIGURE 2. Channel management activities on Corryong Creek. Each square represents one instance of channel modification, along approximately 1 km of reach (some works are at-a-point, others are more extensive). Modified from Water Victoria (1989).

FIGURE 3. Examples of data sources and quality of channel change information provided (Reach 15, Zone C). The arrows indicate the visibility of past morphology as scars. The tributary mapped in the parish plan (a) matches the scar in the LiDAR (d).

FIGURE 4. Sources of data used to reconstruct the evolution of Corryong Creek's geomorphology, and their spatial extent across the four Zones.

FIGURE 5. Selected reaches of Corryong Creek, showing historic channel centrelines superimposed over the 2010 LiDAR data.

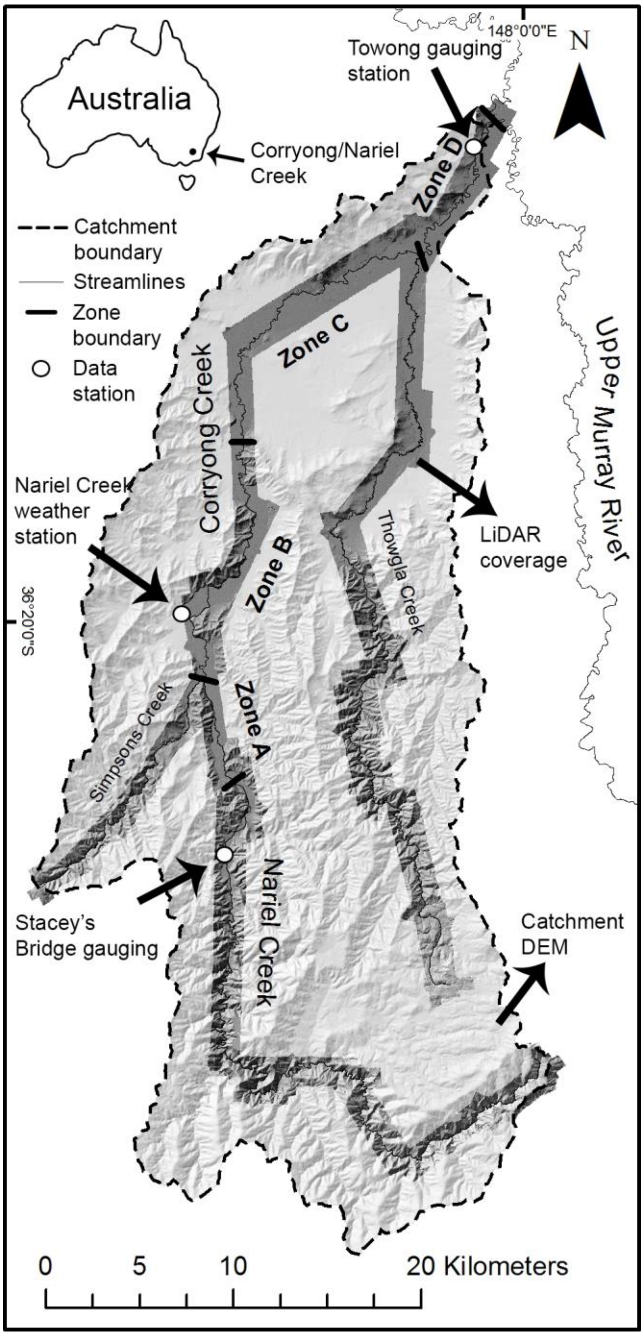
FIGURE 6. (a) The change in sinuosity for each Zone from 1882 to 2010; (b) sinuosity changes for Reach 2, the only unconfined reach in Zone A.

FIGURE 7. (a) The change in channel width from 1985 to 2010; (b) exposed sediment changes from 1985 to 2010.

FIGURE 8. The change in riparian (willow) condition and extent between 1985 and 2004.

FIGURE 9. Annual rainfall anomalies (the deviation from the mean of the total dataset of 1041 mm) from 1885 to 2010. Also shown are the ENSO/IOD year classifications, and flood events identified from various sources.

FIGURE 10. Maximum flow anomalies (the deviation from the mean of the total dataset of 2385 ML/day). Also shown are the ENSO/IOD year classifications (a). (b) shows the mean monthly rainfall anomalies for years of different ENSO/IOD categories (1885 to February 2013). Error bars indicate the 90% confidence interval and n denotes the number of years in each category.



Australia
Corryong/Nariel Creek
148°0'0"E
N
Towong gauging station
Catchment boundary
Streamlines
Zone boundary
Data station
Zone D
Zone C
Zone B
Zone A
Corryong Creek
Nariel Creek weather station
Upper Murray River
LiDAR coverage
Thowgla Creek
36°20'0"S
Simpsons Creek
Nariel Creek
Stacey's Bridge gauging
Catchment DEM
0 5 10 20 Kilometers

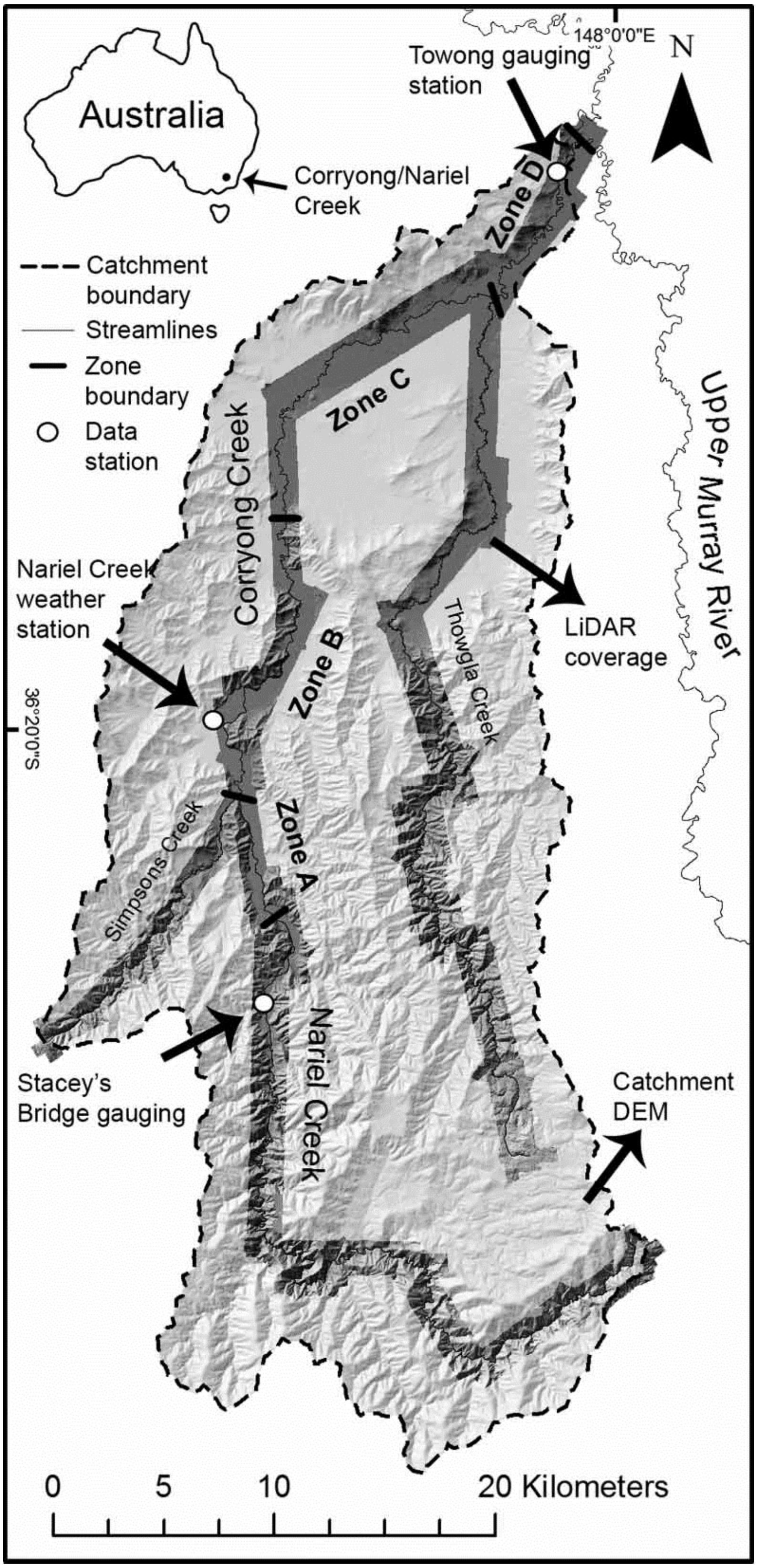

148°0'0"E
N
Towong gauging station
Australia
Corryong/Nariel Creek
Catchment boundary
Streamlines
Zone boundary
Data station
Zone D
Zone C
Corryong Creek
Upper Murray River
Nariel Creek weather station
Zone B
Thowgla Creek
LiDAR coverage
36°20'0"S
Simpsons Creek
Zone A
Stacey's Bridge gauging
Nariel Creek
Catchment DEM
0
5
10
20 Kilometers

Figure 1.

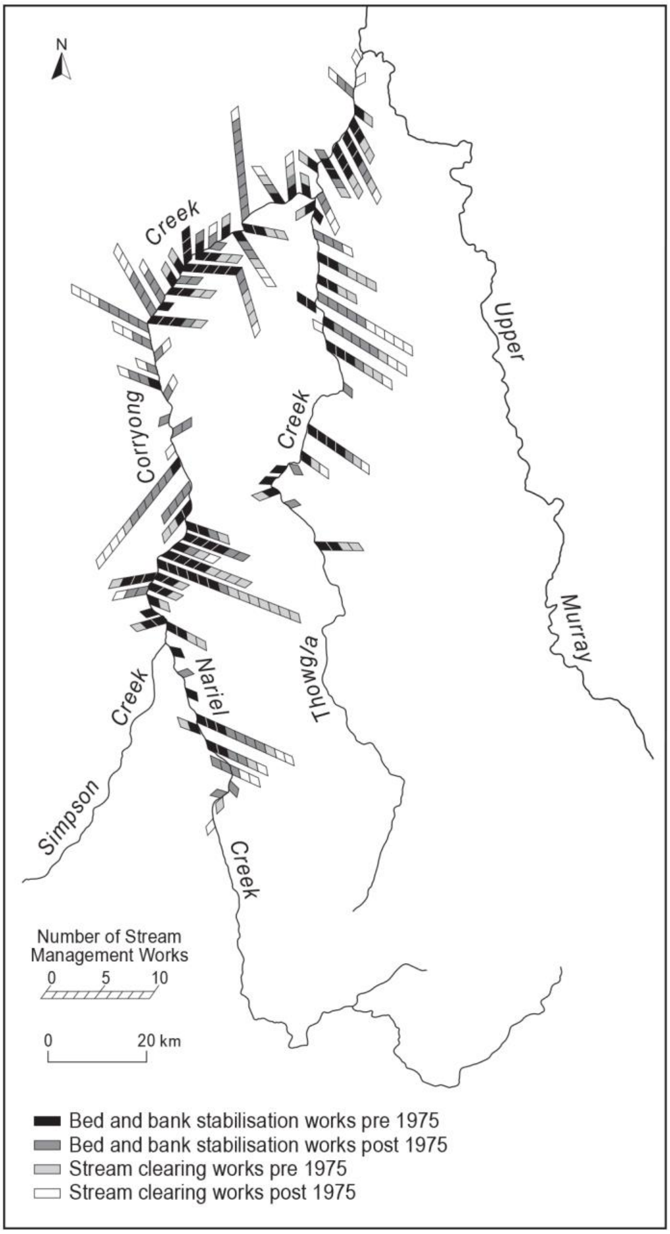

N
Upper
Murray
Creek
Corryong
Creek
Thowgla
Nariel
Creek
Simpson
Creek
Creek
Number of Stream
Management Works
0 5 10
0 20 km
Bed and bank stabilisation works pre 1975
Bed and bank stabilisation works post 1975
Stream clearing works pre 1975
Stream clearing works post 1975

Figure 2.

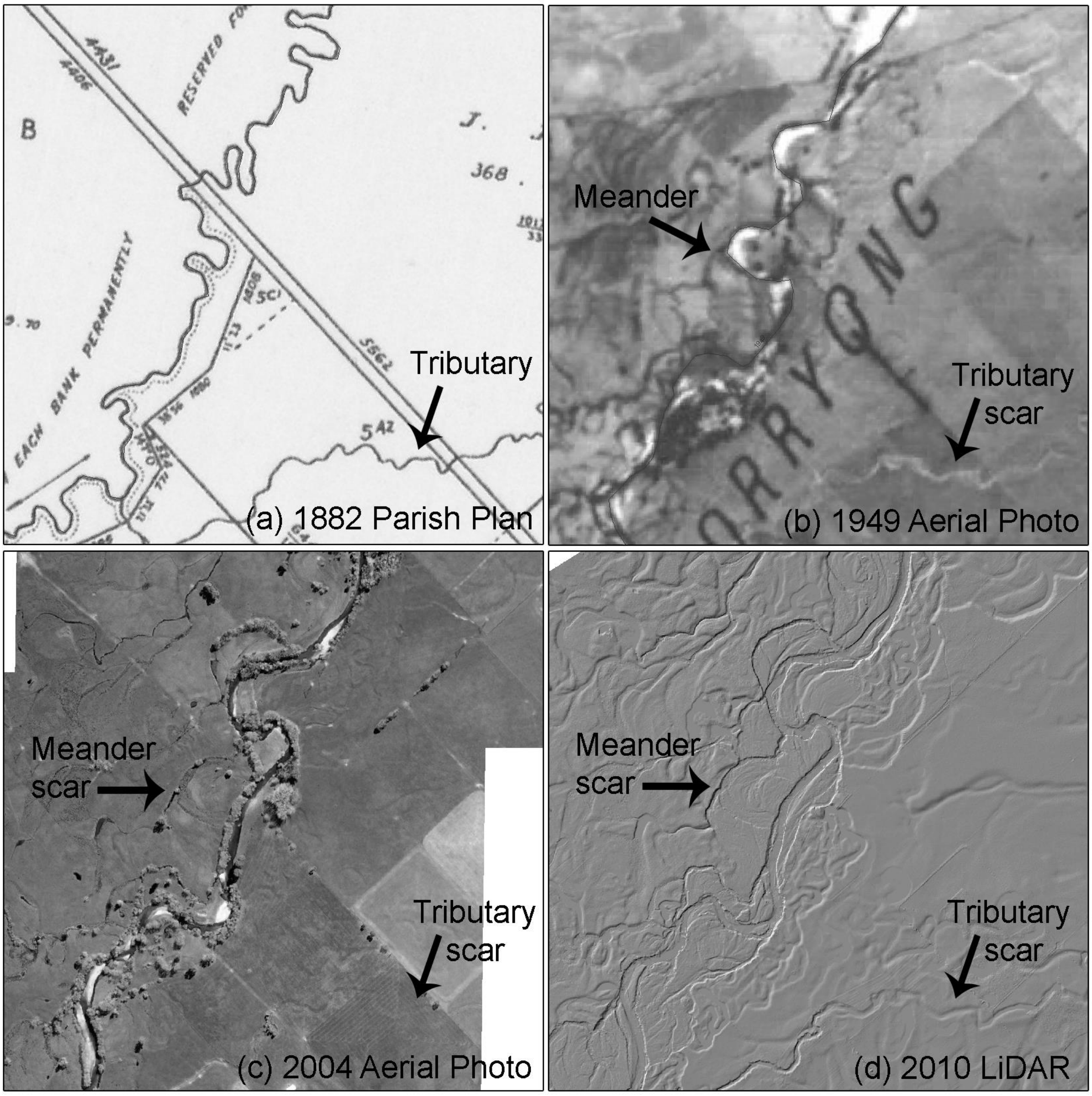
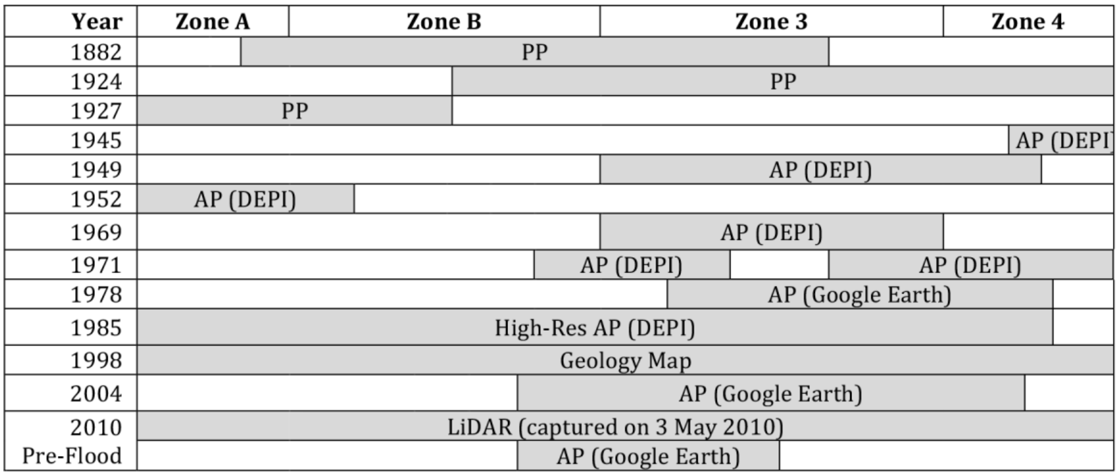
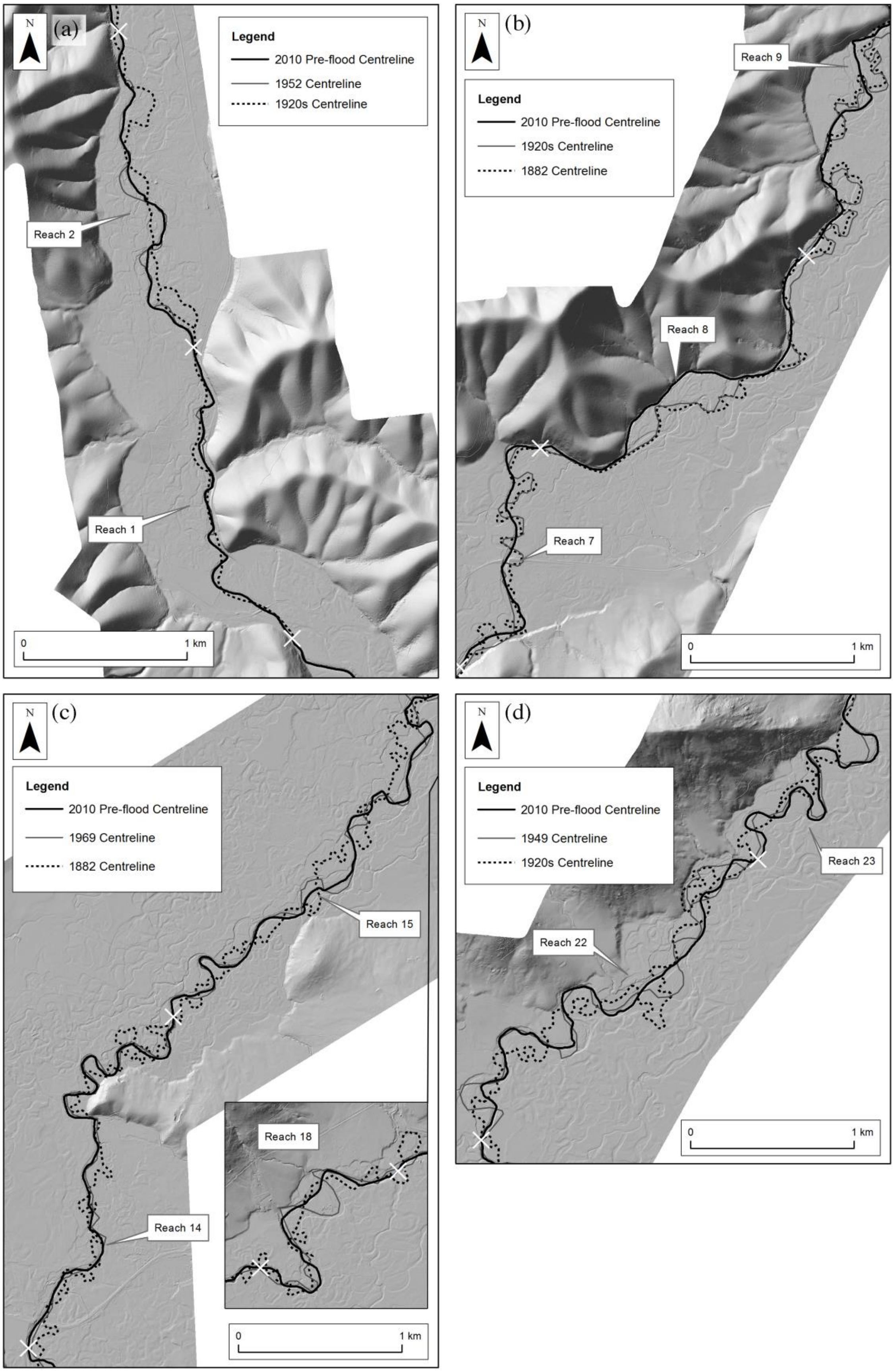

Tributary
(a) 1882 Parish Plan
Meander
Tributary
scar
(b) 1949 Aerial Photo
Meander
scar
Tributary
scar
(c) 2004 Aerial Photo
Meander
scar
Tributary
scar
(d) 2010 LiDAR

Figure 3.



PP – Parish Plan; AP (DEPI) – Aerial Photos from DEPI; AP (Google Earth) – Google Earth Imagery; High-Res AP – High-Resolution Aerial Photos

Figure 4.



(a)
N
Legend
2010 Pre-flood Centreline
1952 Centreline
1920s Centreline
Reach 2
Reach 1
0
1 km
(b)
N
Legend
2010 Pre-flood Centreline
1920s Centreline
1882 Centreline
Reach 9
Reach 8
Reach 7
0
1 km
(c)
N
Legend
2010 Pre-flood Centreline
1969 Centreline
1882 Centreline
Reach 15
Reach 18
Reach 14
0
1 km
(d)
N
Legend
2010 Pre-flood Centreline
1949 Centreline
1920s Centreline
Reach 23
Reach 22
0
1 km

Figure 5.

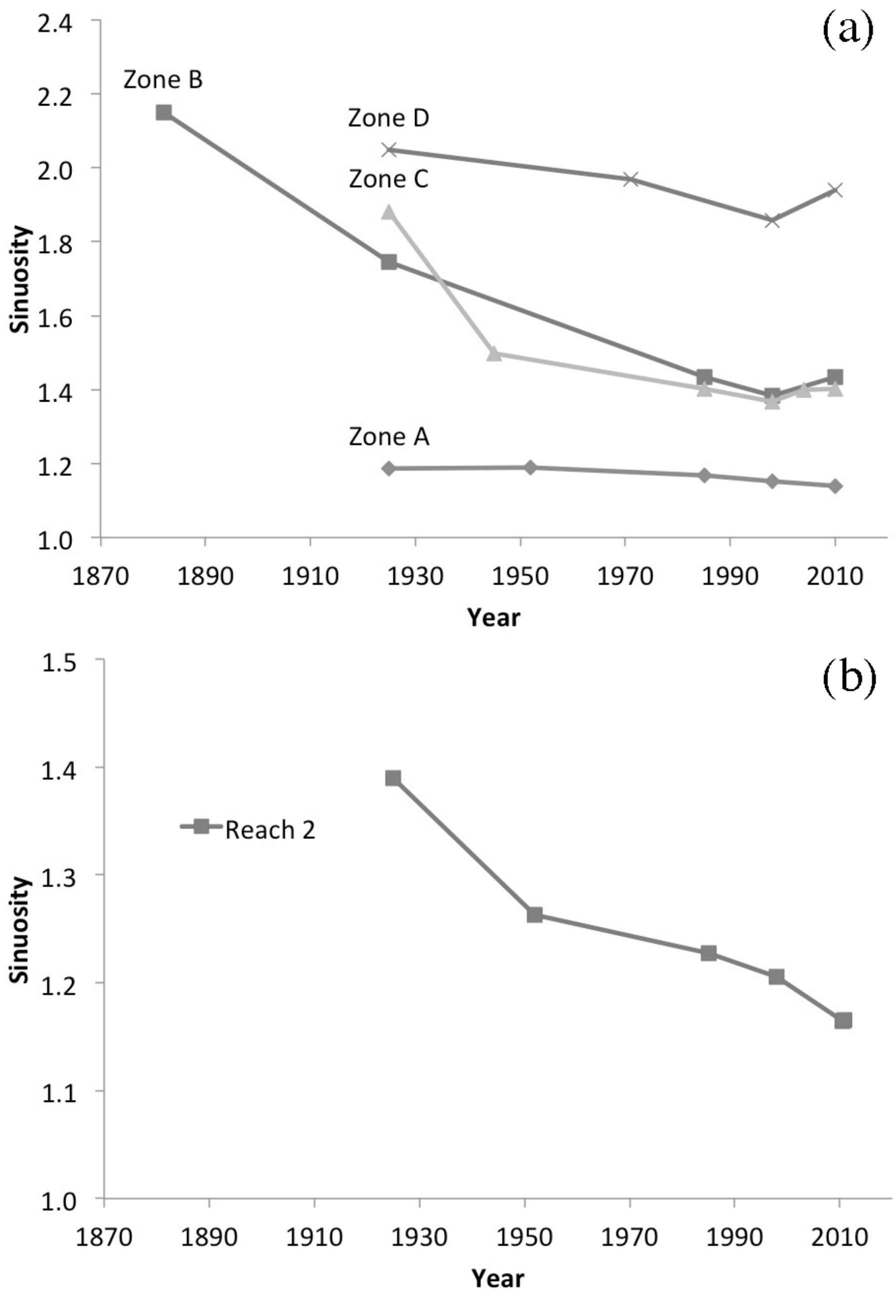
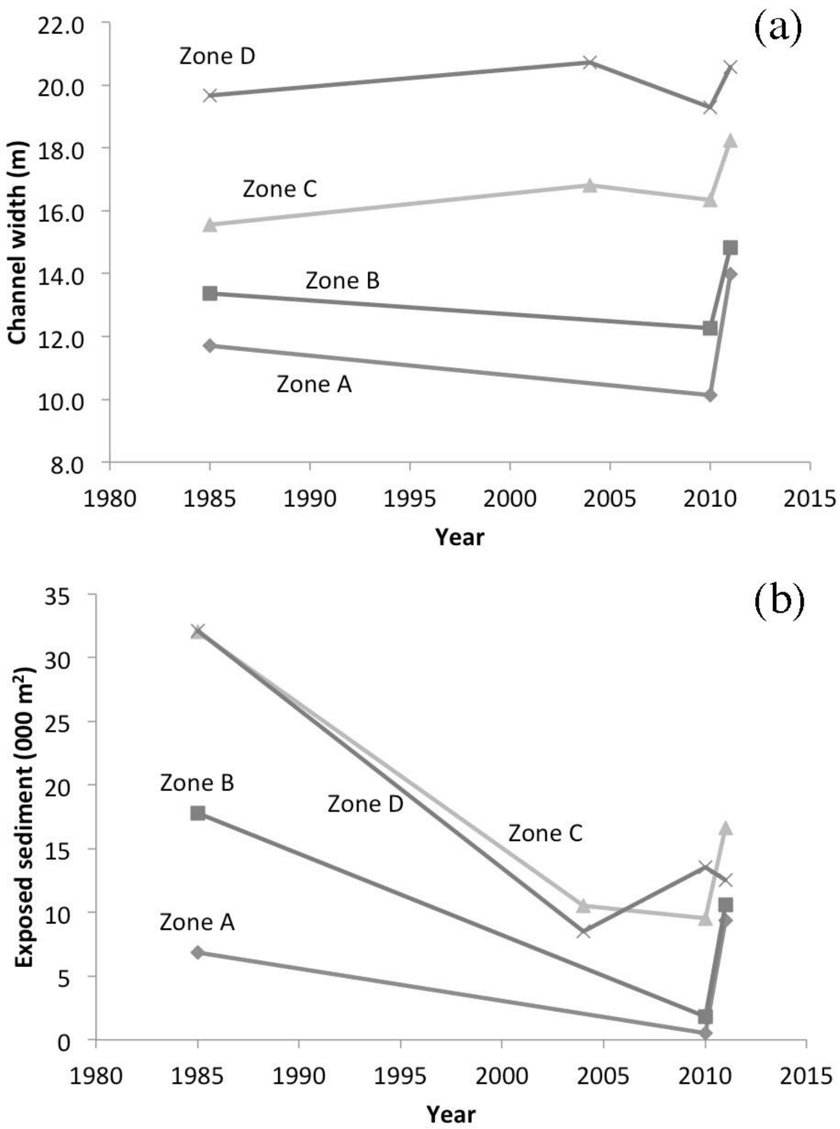

(a)
Zone B
Zone D
Zone C
Zone A
Sinuosity
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
1870
1890
1910
1930
1950
1970
1990
2010
Year
(b)
Reach 2
Sinuosity
1.5
1.4
1.3
1.2
1.1
1.0
1870
1890
1910
1930
1950
1970
1990
2010
Year

Figure 6.


(a)
Zone D
Zone C
Zone B
Zone A
Channel width (m)
22.0
20.0
18.0
16.0
14.0
12.0
10.0
8.0
1980
1985
1990
1995
2000
2005
2010
2015
Year
(b)
Zone B
Zone D
Zone C
Zone A
Exposed sediment (000 m²)
35
30
25
20
15
10
5
0
1980
1985
1990
1995
2000
2005
2010
2015
Year
Figure 7.

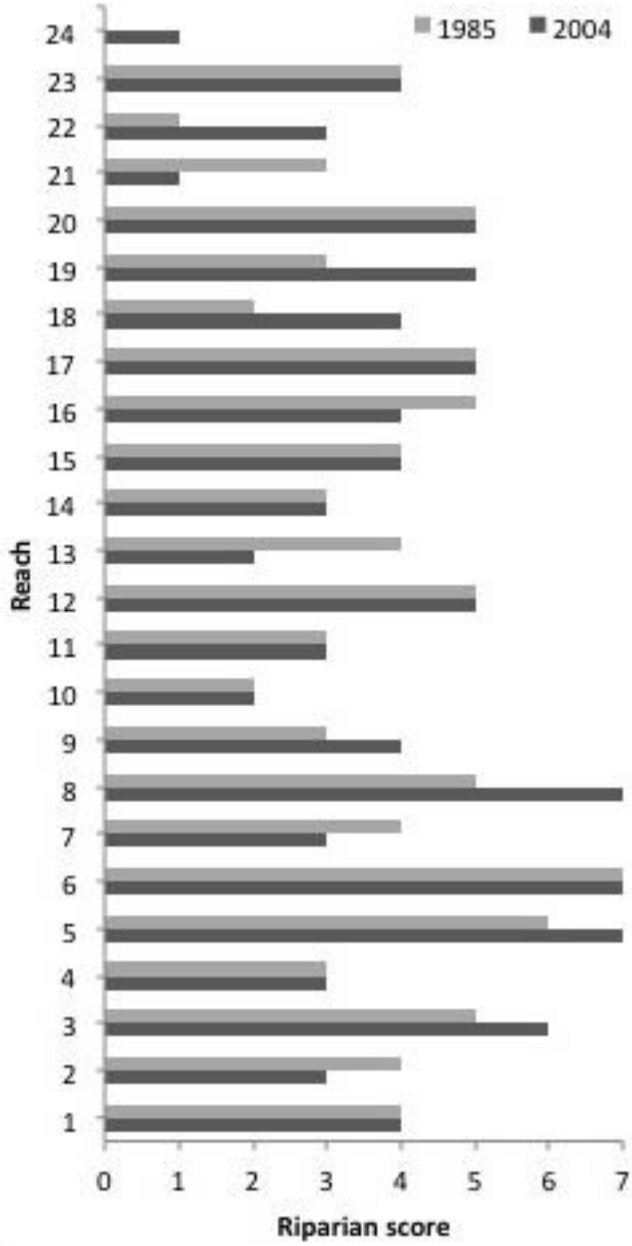
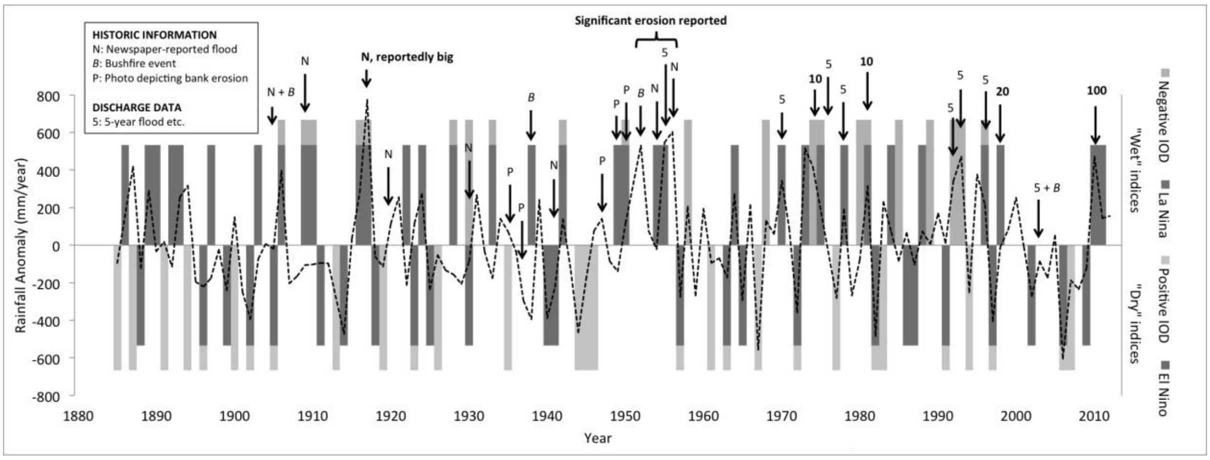
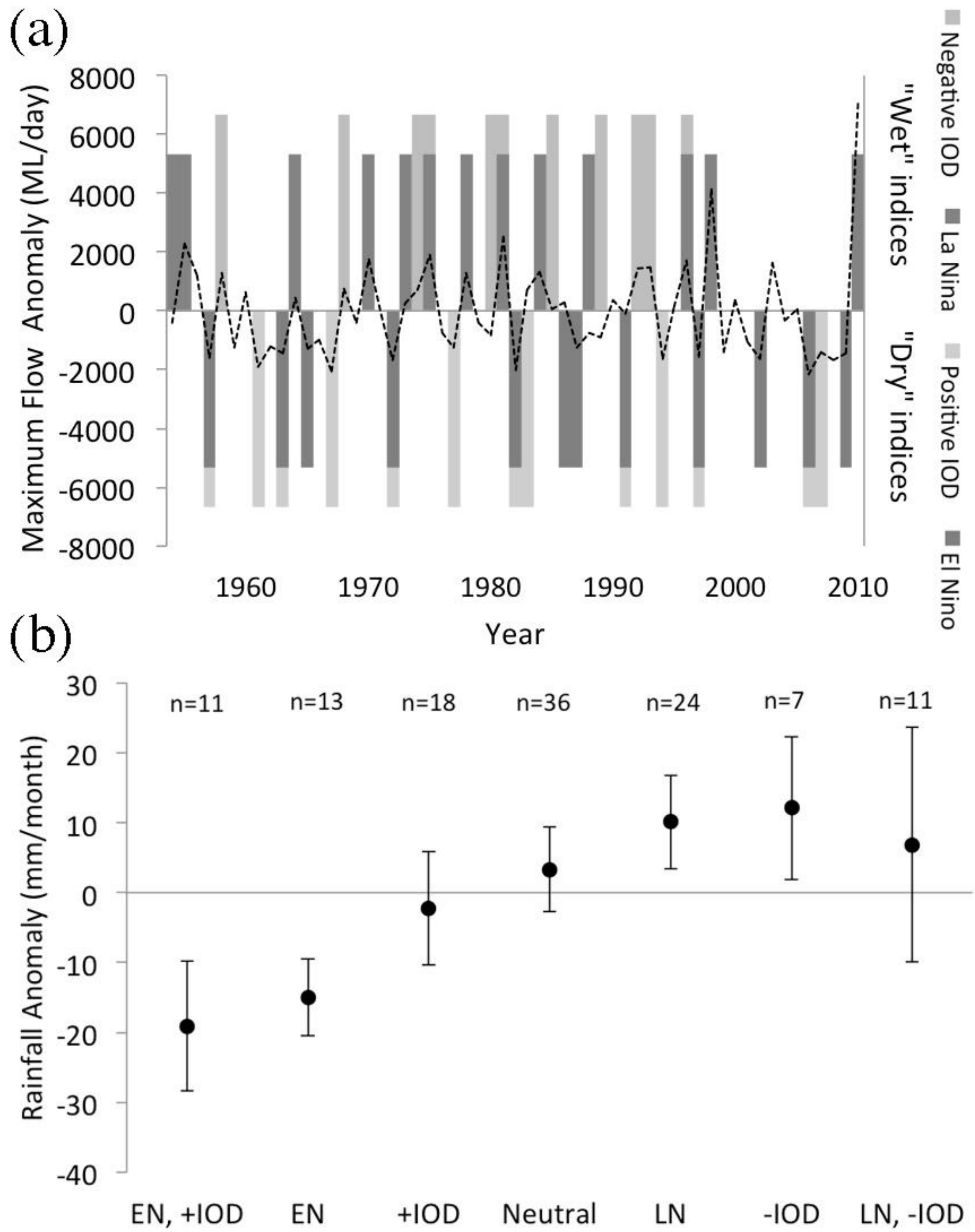

1985
2004
Reach
24
23
22
21
20
19
18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
1
2
3
4
5
6
7
Riparian score

Figure 8.



HISTORIC INFORMATION
N: Newspaper-reported flood
B: Bushfire event
P: Photo depicting bank erosion
DISCHARGE DATA
5: 5-year flood etc.
Significant erosion reported
N, reportedly big
N + B
Rainfall Anomaly (mm/year)
Year
Negative IOD
La Nina
Positive IOD
El Nino
"Wet" indices
"Dry" indices

Figure 9.



(a)
Maximum Flow Anomaly (ML/day)
8000
6000
4000
2000
0
-2000
-4000
-6000
-8000
1960
1970
1980
1990
2000
2010
Year
"Wet" indices
"Dry" indices
Negative IOD
La Nina
Positive IOD
El Nino
(b)
Rainfall Anomaly (mm/month)
30
20
10
0
-10
-20
-30
-40
n=11
n=13
n=18
n=36
n=24
n=7
n=11
EN, +IOD
EN
+IOD
Neutral
LN
-IOD
LN, -IOD

Figure 10.

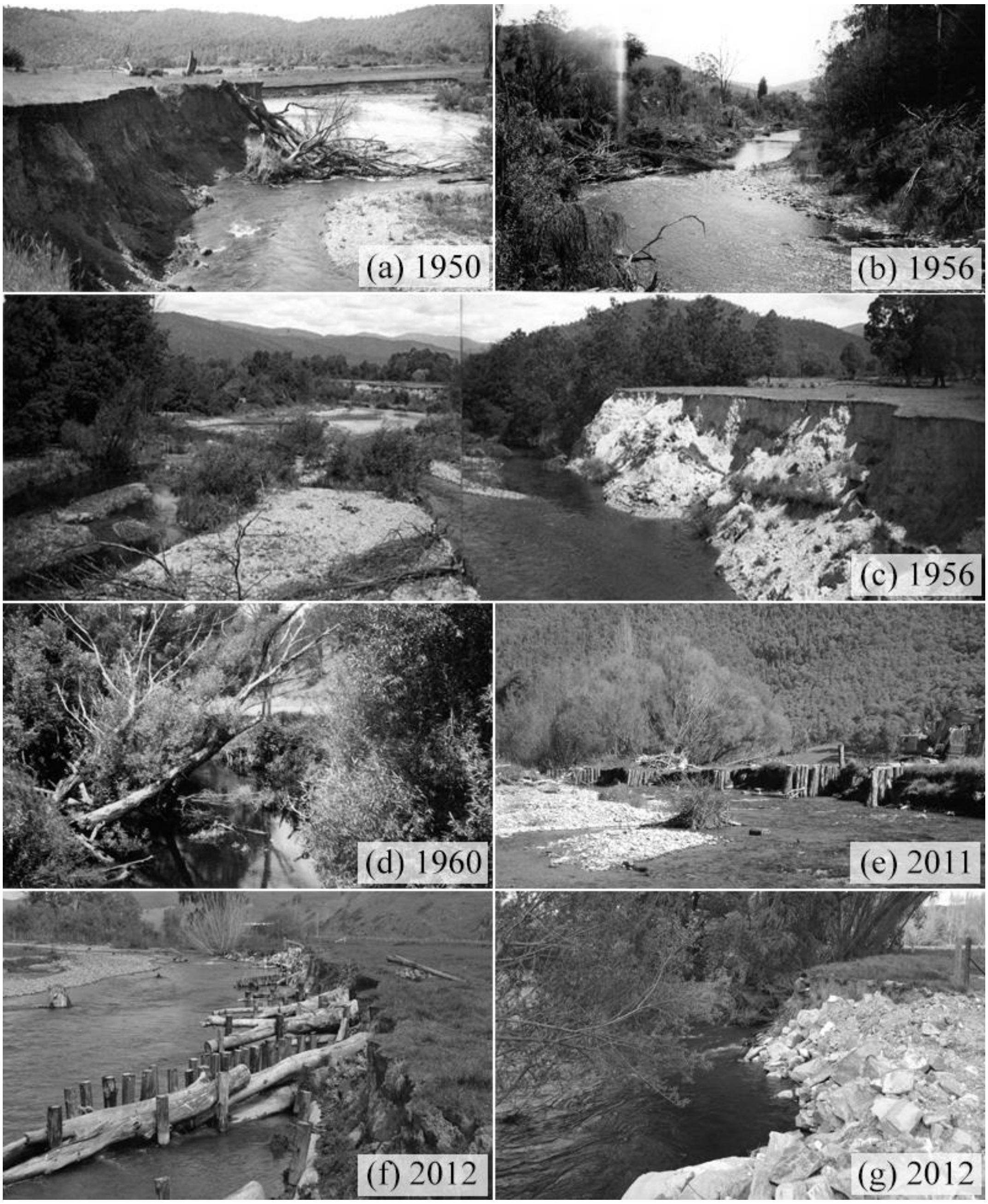


Plate 1.