The Evolution of Corryong/Nariel Creek since European Settlement: Implications for On-going Management Prioritisation

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Key Points

- Channel change and erosion rates of Corryong Creek were measured using historic maps and aerial photographs, from 1882 to 2011.
- Climatic and anthropogenic histories were also gathered and analysed collectively with channel change data, in order to understand the dynamics of the fluvial system.
- Channel change trends are linked to ENSO fluctuations (bank erosion during La Niña, bank deposition during El Niño). Anthropogenic activities also significantly intensified erosion rates.
- Based on our results, recommendations on priority are made for the aims and actions of river management. Essentially, we recommend that 1) reducing community vulnerability by promoting community adaptation be addressed first, and then 2) mitigating erosion risk.

Abstract

Geomorphological stability is a useful starting point to inform river management priorities, as it is critical to other river health parameters such as ecology and water quality. A key debate in channel stability is the relationship between climate and human activity. Corryong Creek is an ideal setting to study the interaction between climate and anthropogenic changes on channel evolution as it has experienced significant levels of both. Catastrophic floods have been induced by high rainfall, the floodplain has been completely cleared, the riparian zone is almost entirely invaded by willows, and every reach of the channel has experienced some form of channel modification. The impacts of both climatic and anthropogenic factors are visible in our channel change data, although at different spatiotemporal scales. Higher flows during La Niña resulted in channel widening while lower flows during El Niño resulted in channel narrowing. In addition, land clearing had caused the river to evolve into a higher-energy, straighter channel, while spatially variable and temporally irregular factors such as river engineering, willow density and stock trampling tended to intensify erosion on a reach scale. As our analysis shows that periodic increases in erosion during La Niña are expected, the local community needs to first accept and adapt to some level of channel erosion in order to avoid catastrophic damage during floods. As the second priority, since the reversibility of these factors are limited, erosion risk can be mitigated through strengthening willow management, limiting river engineering, practicing bushfire management, and fencing the riparian zone.

Keywords

Bank erosion, sinuosity, channel change, climate influence, anthropogenic influence, systems thinking

Introduction

River management needs to be informed by a holistic understanding of the fluvial system in question. This can only be done by considering both present and past conditions of the river environment, and by doing so, the appropriate management techniques will arise (Schumm & Lichty, 1965; Wasson, 1994; Lane & Richards, 1997; Rustomji et al., 2009). This is the case with determining the dynamics between anthropogenic and climatic controls on river channel change, a question that has wide river management implications in the context of global environmental change (Macklin & Lewin, 1997; Goudie, 2006; Wohl, 2011). While erosion and channel movement naturally occurs to maintain channel stability, there is evidence of human activity intensifying erosion rates (Rutherfurd, 2000).

This debate is especially pertinent in Australia. In various catchments in southeast Australia, factors such as land clearing, exotic willow invasions and direct channel modification are known causes of increased erosion rates (Rutherfurd, 2000). It has also been suggested that many southeast Australian channels are prone to a climate-driven cyclic pattern of channel change: channel enlargement during periods of large infrequent flows, followed by channel narrowing during periods of smaller and more frequent flow events (Nanson & Erskine, 1988; Nanson et al., 2008; Rustomji et al., 2009). Flood regime theory suggests that the climate in southeastern Australia is dominated by alternating periods of higher and lower flood frequencies every 30 to 50 years (Warner, 1987; Erskine & Townley-Jones, 2009). It is also possible for the ENSO-driven climate variation of southeast Australia (Nicholls et al., 1996; Ummenhofer et al., 2009), and its recent link to the Indian Ocean Dipole or IOD (which is debated to be a manifestation of ENSO; Allan et al., 2001) to be visible in channel change.

The question now lies in how river management should respond. Geomorphological stability is a useful starting point, as it is critical to other river health parameters such as ecology and water quality (Brierley et al., 2002; Robinson et al., 2002). Determining the drivers of erosion, their dynamics, the scale of their impact and the extent that they can be managed would help with prioritising management actions, which is often difficult because of the differing concerns of stakeholders and conflicting river health factors.

Corryong/Nariel Creek

Corryong Creek, referred to as Nariel Creek in its upper reaches, is a gravel-bed tributary of the River Murray approximately 115 km long and its catchment about 980 km^2. Since European settlement, the catchment has been altered extensively through land clearing, willow planting, channel straightening and channel realignment. Regional river managers and locals believe that the amount of erosion recently experienced by the river is unnaturally high, exacerbated by past river management activities. Mass bank failures and avulsions are significant problems to the local community as it removes valuable pasture, endangers livestock, damages infrastructure, disrupts farmland boundaries, and endangers 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), while it is presently completely so (Barrat et al., 2007). Willows were introduced for stream stabilization, to mitigate the effects of riparian vegetation loss. According to newspaper reports, it is likely that 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. 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 management only began in Australia in the 1990s (Pope et al., 2006). Along Corryong, willows have been removed at a few reaches, but not extensively (Webster, 2006). As a result, the channel is still almost completely lined with willows instead of native vegetation.

The entire length of the river has been subject to stream management works of some manner (Water Victoria, 1989). Initial river engineering in the 1960s and 1970s involved major channel straightening and realignment that were meant to increase the rate of drainage (Figure 1). Unfortunately, channel instability increased and a large flood in 1972 led to avulsions through farmland. Farmers responded by fencing the channel and planting willows (Webster, 2006). Gravel was also excavated from banks to build roads during this period, leaving banks exposed and unstable (Webster, 2006). Since the establishment of the Shire's River Improvement Trust (now the North East Catchment Management Authority), attempts to radically modify channels have ceased. Projects now focus on regaining channel stability through rocking and tethered logs (Figure 1). Gravel has also been artificially deposited in a few reaches as a form of grade control to decrease stream power. However, the channel is still believed to be unstable due to observations of channel widening from gravel accumulation (or channel deepening in reaches laterally restricted by willows), and high rates of channel movement at reaches that have been historically straightened and/or realigned. Stock trampling is another issue as the majority of the river has been unfenced since the 2002/2003 drought (Webster, 2006).

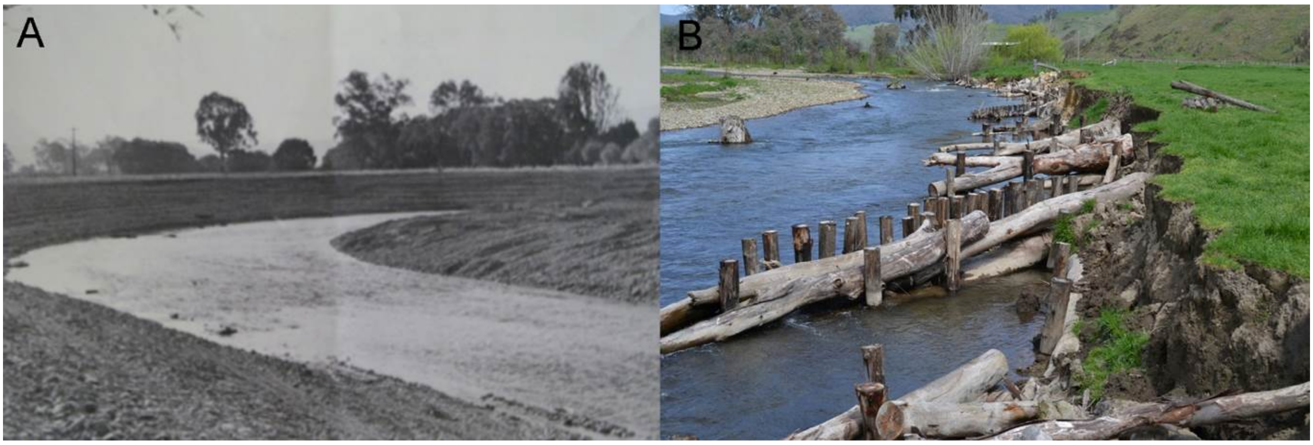

Figure 1. Different sections of the same reach in A) 1956 and B) 2012. Earlier river management works involved severe channel straightening and realignment. It is presumed that these works have caused the channel instability issues still currently faced, leading to more stabilising works being implemented since.

Relatively less is known of Corryong Creek's relationship with climate, except that several well-known floods have led to mass bank erosion and infrastructure damage. These include a very large flood in 1917, a series of floods in the 1950s, and the recent major floods from September 2010 to January 2011. It is also possible that Corryong Creek's discharge to be controlled by ENSO, since the River Murray has been found to be so (Simpson et al., 1993).

By analysing the spatiotemporal trends of channel change, anthropogenic factors and climate, one can reveal the system's dynamics. First, by measuring and analysing channel form over time, periods of higher and lower erosional activity can be identified, reflecting fluctuations in system inputs that either increase or decrease stream power. The variables that control the system inputs themselves are more prominent or only began at certain points of time. Therefore, with the histories of river management, willow growth and climate established, it is possible to observe which human influence or climate event is likely to have triggered overall channel erosion or deposition. Reach-scaled comparisons can also reveal the interaction between spatially variable triggers (e.g. river works) and channel change. With the anthropogenic history already known, the histories of channel evolution and climate now need to be measured and analysed.

Reconstructing channel change history

Measurements were made from the point alluvial channel began to the confluence with the Murray River (Figure 2). The study reach was divided into four zones (Zones A to D). Zone boundaries were defined at major confluences and at the margin 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 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. Using ArcGIS, 14 channel forms spanning 1883 to 2011 were digitised from parish plans, aerial photos, a geological map, and LiDAR (Figure 2). Due to the decreasing resolution of data with age, the planform centreline (and therefore sinuosity) was the consistent channel parameter measured throughout this time series. Average channel widths and area of exposed sediment for each reach were measured for 1985, 2004, 2010 and 2011. Seasonal changes in the riparian boundary are considered insignificant because all except the 2004 (August) data were taken in the summer, and there is evidence of concurrent channel widening and decreasing exposed sediment due to vegetation encroachment. Based on channel behaviour since the 2010 flood, reductions in exposed sediment extent are interpreted as being due to vegetation encroachment, whilst increases in extent are interpreted as being primarily due to deposition of new sediment, rather than removal of vegetation.

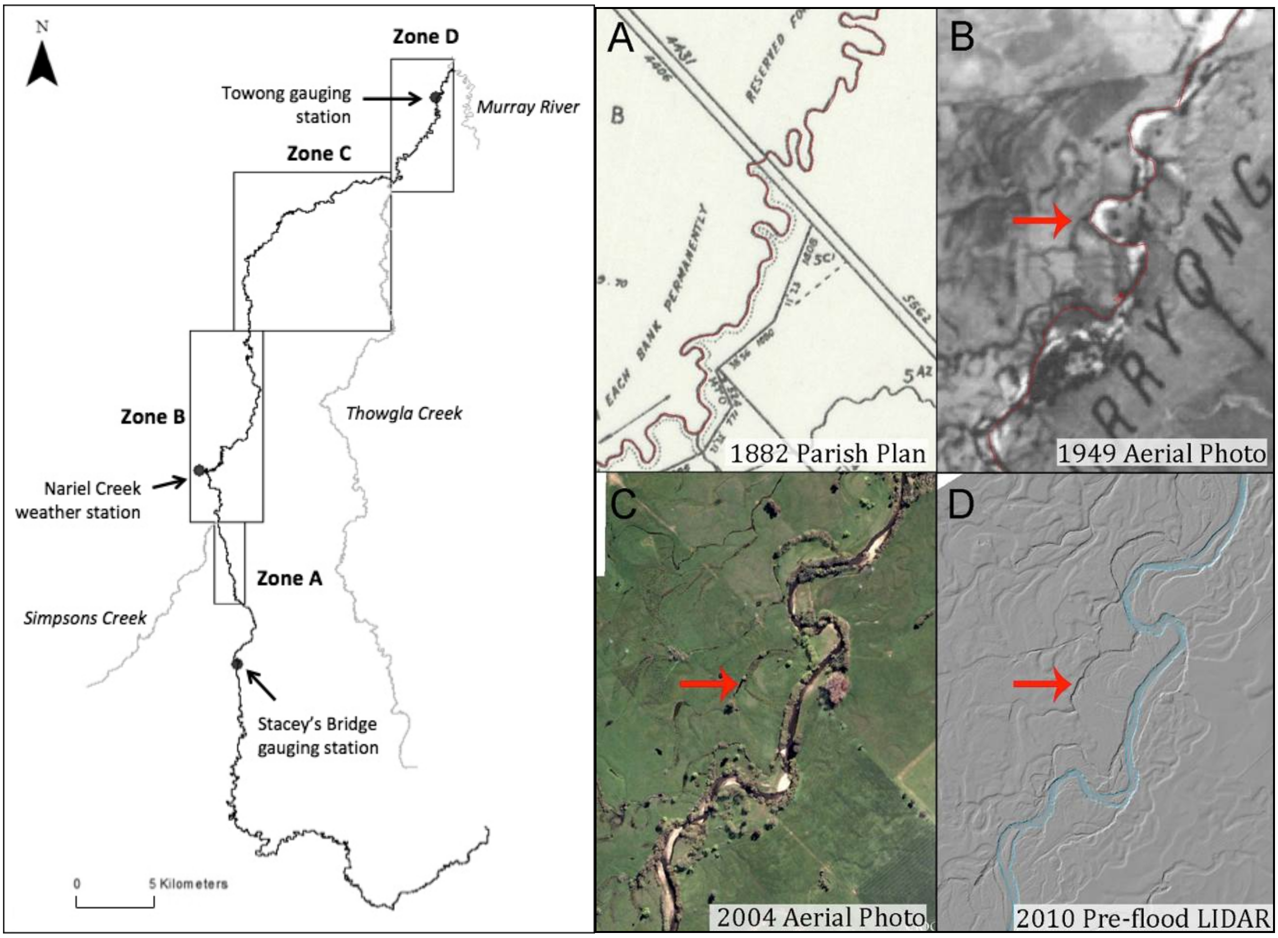

Figure 2. Map of Corryong Creek (left), depicting the separate Zones, the Nariel Creek weather station and Stacey's Bridge gauging station. Panels A to D show the same reach captured by different sources. The red arrows point out a meander that was once present but the scar of which still remains.

Changes in climate were determined using rainfall (1884 to 2013) and river flow records (1954 to 2013) obtained from Nariel Creek weather station and Stacey's Bridge gauging station (Figure 2). Post-1954, flood recurrence intervals were established using a Log Pearson III flood frequency analysis of maximum instantaneous daily discharge data. When identifying periods of high flow, bushfire events were also noted since they have a hydrological effect of increasing discharge. Newspapers and DEPI photos confirmed major floods. 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). This was followed by a Wilcoxon Rank Sum test (Erskine & Townley-Jones, 2009). ENSO and IOD periods were defined using Meyers et al. (2007) and the Bureau of Meteorology. Rainfall and flow anomalies for each ENSO/IOD combination categories were gathered, as conducted by Ummenhofer et al. (2009), and tested statistically using ANOVAs.

Results

Since the 1880s, Corryong Creek has become significantly straighter throughout its length (Figure 3). The overall average sinuosity of 1.47 in 2011 is 26% lower than the 2.01 in 1882. There are three general stages to sinuosity change observed (Figure 4). From the early to mid-20th century, there is a large decrease in sinuosity. From then to the mid-1990s, there is also a decrease in sinuosity, although at a lower rate. This is followed by a slight increase in sinuosity from the mid-1990s to the present.

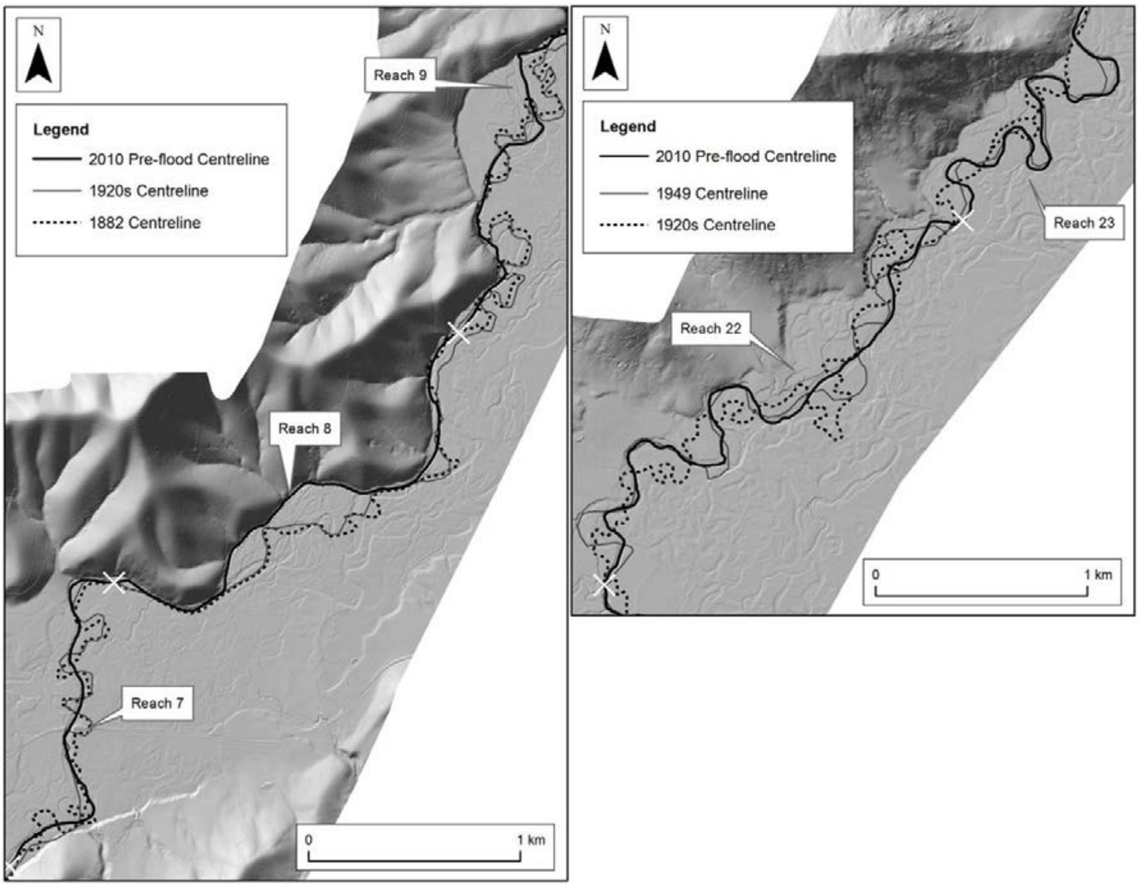

Figure 3. Examples of channel straightening. The planforms are superimposed over the LiDAR data captured in 2010.

Measurements of channel width and sediment deposition from 1985 provide further insight to channel change patterns. First, there is a large total area of exposed sediment measured in 1985, indicating a recent release of sediment and deposition into the system. Relative to the channel in 1985, there is an overall increase in channel width in 2004. This indicates significant erosive activity at least during and perhaps before 2004. The decrease in exposed sediment in 2004 is due to vegetation encroachment of the exposed sediment from 1985. Comparatively to 2004, channel width decreased in 2010 (pre-flood) as sediment was deposited along the banks of the channel (with little evidence of vegetation removal by erosion), mostly at the end of the channel. This is shown by the increase in exposed sediment area in Zone D. Thus, depositional processes were more dominant around this period. Almost immediately after the 100-year flood in 2010, there was large-scale channel widening. The increase in exposed sediment was due to deposition of new sediment and the removal of vegetation by overflow.

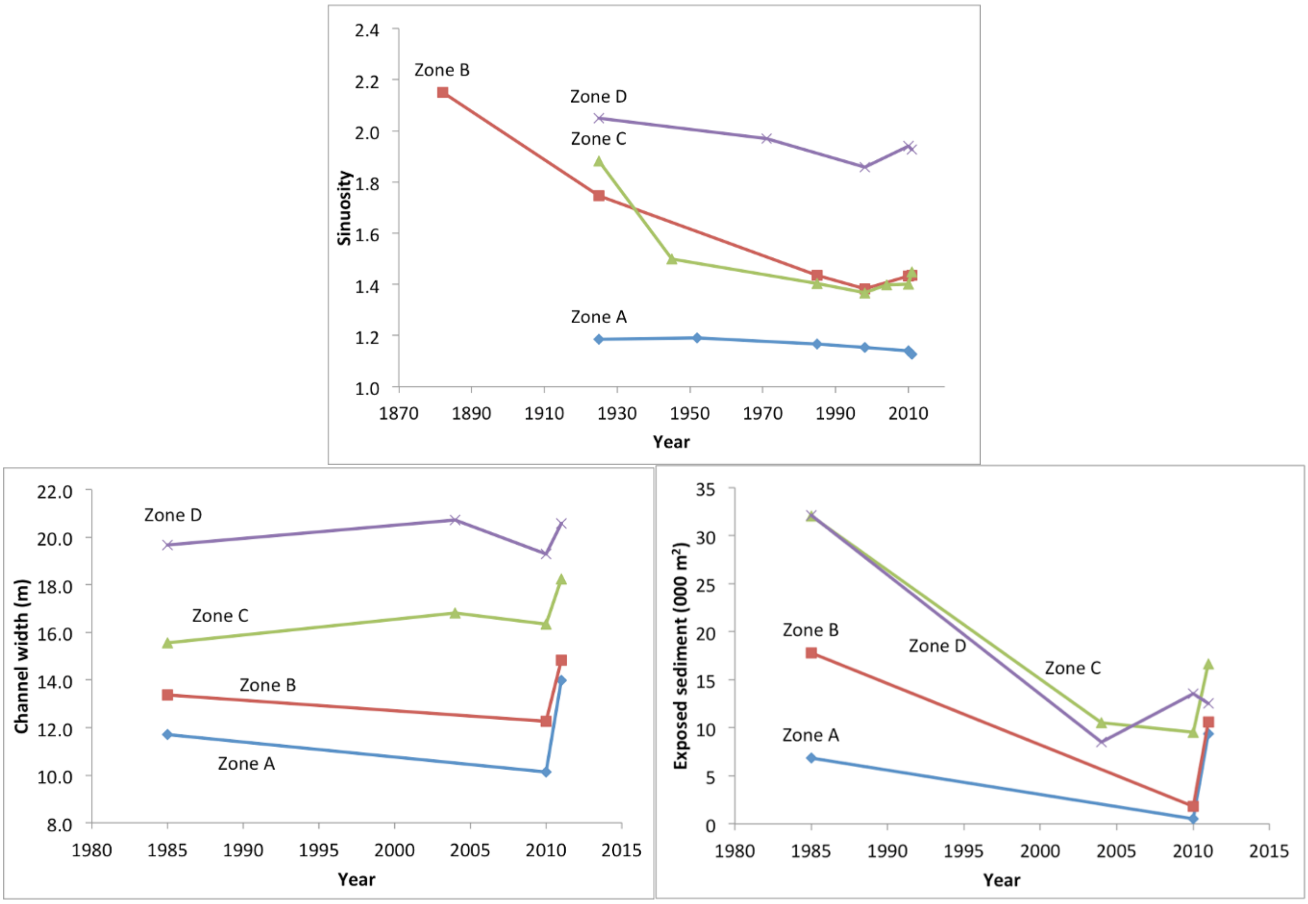

Figure 4. Sinuosity, channel width and sediment deposition measurements categorised by Zone.

The multidecadal flood regimes defined for other catchments in southeast Australia (Erskine & Townley-Jones, 2009) are not applicable to Corryong Creek (Figure 5) – an ANOVA test comparing the average annual rainfalls of each regime produced an insignificant p-value at a 95% confidence level. Repeating the methodology (using a CUSUM analysis, which determines the yearly rainfall variation from the rainfall mean of the entire time series) to determine a flood regime unique to Corryong's rainfall still does not reveal multidecadal climate fluctuations. However, the influence of ENSO/IOD is statistically strong in the rainfall and flow data. Above average rainfalls and flow typically occur during years of La Nina and/or negative IOD; below average rainfalls and flow occur during years of El Niño and/or positive IOD (Figure 6).

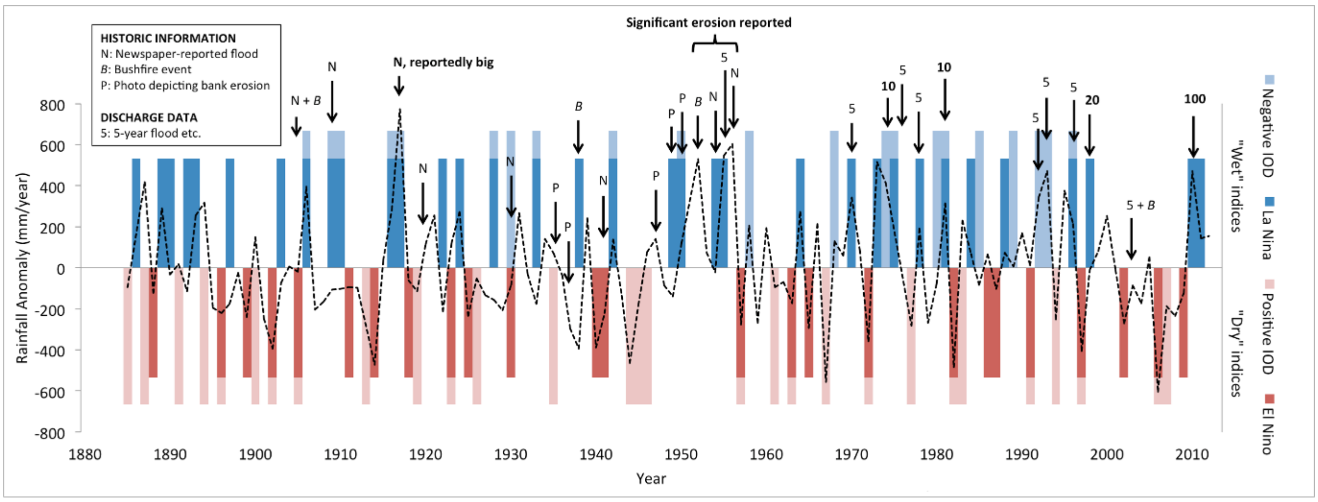

Figure 5. Annual rainfall anomalies (deviating from the overall average). Also shown are ENSO classifications, major flood and fire events from 1885 to 2012.

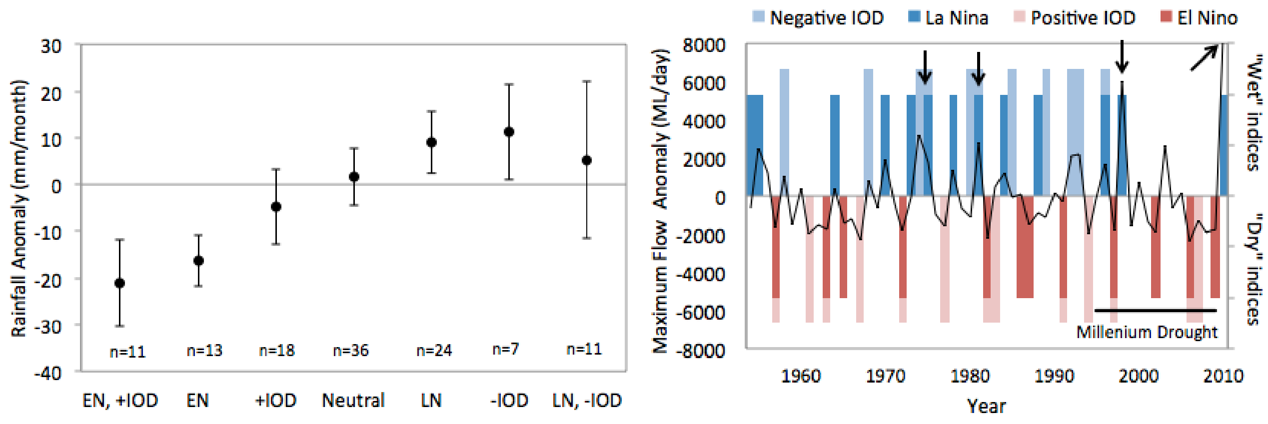

Figure 6. Mean monthly rainfall anomalies (left) and maximum flow anomalies (right) for years of different ENSO/IOD categories. Error bars (left) indicate the 90% confidence interval while the arrows (right) depict the two 10-year floods in 1974 and 1981, the 20-year flood in 1998, and the 100-year flood in late 2010.

Discussion

There are three stages to Corryong Creek's geomorphological history. The late 19th to mid-20th century is characterised by a large fall in channel sinuosity. This coincides with and is hence attributed to the near-complete clearing of the floodplain from settlement to the early 20th century. Therefore, most of the overall channel change is not due to extensive channel modification works, as it may have been expected, since they only began in the 1960s. It is likely that clearing led to larger, flashier floods that increased erosion rates during high flows and reworked the river into a higher energy, straighter channel.

From the mid-20th century to the 1990s, the channel exhibited instability issues involving mass bank erosion and avulsions, which would largely stem from the vegetation clearing. In response, there were repeated attempts to straighten the channel. This period is characterised by a lesser decrease in sinuosity relative to the earlier part of the century. There are several possible reasons. Since the channel was already significantly straightened, further straightening (deliberate or otherwise) could only be minor. It is also during the mid-20th century when willows established a stronghold on the riparian zone – they could have decreased channel capacity for change (at least in terms of planform, since willows were observed to intensify bank erosion at narrowed reaches). Since the 1990s, there has been a slight increase in channel sinuosity. This parallels the more sympathetic river management techniques that have taken over to allow the channel to achieve its more stable, sinuous state.

In terms of climate, there is evidence of more bank erosion during La Niña and more bank deposition during El Niño. The major 1917 flood occurred during a La Niña year. Significant levels of erosion were also reported in the 1950s, which was a decade dominated by La Niña and high rainfall. The large amount of sediment found exposed in 1985 was probably released by the series of floods throughout the 1970s, which includes two 10-year floods in 1974 and 1981, both of which were La Niña years. The influence of bushfires is also apparent, where channel widening found in 2004 occurred after a major bushfire in 2003 upstream of the study reach. A 20-year flood, another La Niña year, had also recently occurred in 1998. Then, in 2010 (pre-flood), channel width had decreased, demonstrating the dominance of sediment deposition during low flows caused by the El Niño years of the Millennium Drought. The drought ended with the 100-year flood in 2010 (La Niña), resulting in mass channel widening and release of sediment. Since there is a strong ENSO signal in Corryong Creek's hydrology, and since our findings show that channel change is likewise responsive to ENSO fluctuations, it is possible to predict flooding and erosion using ENSO (longer-term flood regime cycles were not found).

Our findings ultimately show that different variables lead to different scales of channel change, summarised in Figure 7. Flood events do not appear to affect sinuosity significantly – after the 100-year flood in 2010, the planform remained almost exactly the same yet there was severe channel widening and release of sediment. This is likely to be due to the persistence and scale of these variables (Knighton, 1998). For instance, catchment clearing is expansive, not easily reversed, and able to alter catchment hydrology greatly (Siriwardena et al., 2006) – thus, it has the tenacity to affect planform. On the other hand, more periodic and spatially inconsistent variables, such as river engineering, willow density and stock trampling, tend to only impact the cross-section.

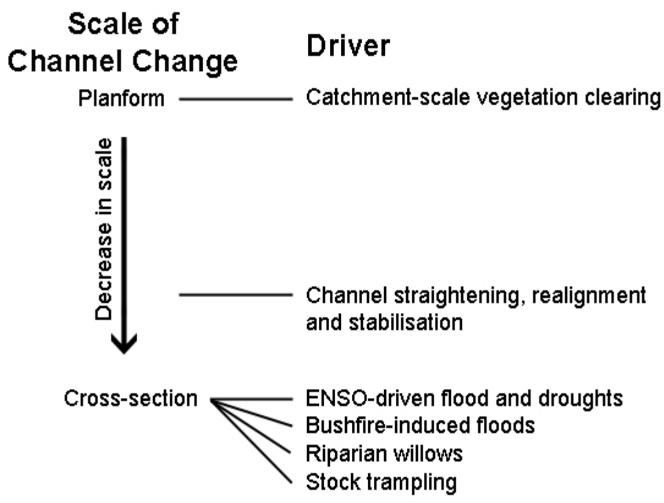

Figure 7. The type of channel change and its driving factors, as evidenced by Corryong Creek.

Implications for on-going management

Assuming that the earliest image of Corryong Creek in 1882 is close to its pre-disturbance morphology, then the recent increase in sinuosity indicates that the river's stability is improving, at least in a geomorphological sense. As channel straightening and realignment works halted from the 1970s onward, the river has had the freedom to reconfigure to a more sinuous natural form. This explains the local community's conflicting impression that the channel is erosive and unpredictable, since there was an increase in channel migration in recent memory. The mass bank erosion that resulted from the recent 100-year flood in 2010 and 20-year flood in 1998 would have contributed to this perception. Therefore, the present approach to river management (bank stabilisation and gravel deposition only at selected banks, with no channel straightening and realignment) can continue. However, these forms of channel engineering should proceed with caution, as they only address the symptoms of channel erosion rather than the cause (i.e. the drivers in Figure 7; Spink et al., 2009).

To address the community's concerns with erosion and damage, we recommend that 1) reducing community vulnerability and 2) mitigating erosion risk should be the primary aims of managing Corryong Creek and similar catchments (Table 1). These are not new ideas for river management in the region – the frameworks of most of the management actions we identify are already in place or planned (e.g. see http://www.necma.vic.gov.au/). Nevertheless, as with all multivariate environmental problems, prioritisation of action is often the issue (Brierley et al., 2002) – this is where our findings could be of benefit (Table 1).

Table 1. Recommended prioritisation of river management aims and actions.

Primary aim	Secondary aim	Examples of actions
1. Reduce community vulnerability	1. Increase awareness of channel stability issues	1. A forum for regular discussion on river management. 2. Education to make all stakeholders aware that: a. Some level of channel migration and bank erosion is inevitable and necessary. Otherwise, floods will create catastrophic damage. b. Climate-driven high flow events are unavoidable. c. River engineering, willows, stock trampling and bushfires increase damage risk.
	2. Encourage community participation and cooperation	1. An incentive program for landholders to conduct environmental restoration works e.g. the Oven's River Tender program.
	3. Avoid infrastructure damage	1. Wherever possible, relocate all structures away from the flood zone. 1. Otherwise, stabilise banks with the understanding of potential risks.

	4. Protect local farming and recreational fishing industries	1. Fencing to keep stock away from unsafe areas during high flows. 2. Recreational fishing management to avoid disruption.
	5. Improve flood prediction	2. Develop ENSO-based flood modelling. 2. Relay predictions to the community.
2. Mitigating erosion risk	1. Avoid further channel instability	1. Limit channel straightening, realignment and excessive bank stabilisation. 2. Strengthen willow removal works and revegetate with native vegetation. 3. Fence the riparian zone to avoid stock trampling.
	2. Reduce the impact of bushfire-induced floods	1. Bushfire risk management.

Reducing community vulnerability should be considered first because our evidence points to the inevitability of increases in erosion during La Niña. Our results show Corryong Creek's morphology to be responsive to changes in hydrology, which in turn is strongly influenced by ENSO. Furthermore, natural levels of erosion are necessary to avoid catastrophic flood damage such as from the 2010 floods. The duration and extent of channel erosion, as with flood impact (Costa & O'Connor, 1995), may depend on both the magnitude and frequency of high rainfall instigated by La Niña. Since ENSO cycles fluctuate every two to five years, these periods may be around the inter-decadal to decadal scale. The La Niña-dominated decade of the 1950s and the El Niño-dominated 2000s are examples of ENSO clusters that have resulted in significant channel erosion and deposition respectively. If increases in erosion during La Niña cannot be avoided, then river management must reduce community vulnerability by promoting lifestyle adaptation (Thomalla et al., 2006). Adopting the erodible corridor concept may also be a consideration (Piégay et al., 2005).

In addition, anthropogenic activity has been found to enhance overall erosion rates (i.e. through catchment clearing), and intensify erosion at local reach scales (i.e. through channel engineering, willows and stock trampling). Most of these variables are theoretically changeable (with the exception of catchment clearing since the entire floodplain is used as cattle pasture), but can only affect erosion rates to a limited extent. This is why mitigating erosion risk is prioritised second. In terms of avoiding further channel instability, limiting river engineering works should be first considered because of its larger potential to induce further instability, as it directly straightens the channel. Willow management should then be addressed as willows may intensify erosion rates at a reach scale. Fencing would also protect banks from weakening under stock trampling. Lastly, as bushfires has contributed to flooding, bushfire risk management is also important.

Conclusion

Periodic high levels of bank erosion are to be expected since they are driven by the high rainfalls of La Niña years. In addition, it was found that anthropogenic influences have intensified erosion rates, although their reversibility is limited. Therefore, we recommend that first the local community needs to accept and adapt to some level of channel erosion in order to avoid catastrophic damage during floods. The second priority should then be to mitigate erosion risk by strengthening willow management, limiting river engineering, practicing bushfire management, and fencing the riparian zone. These recommendations are made possible by a systems understanding of Corryong Creek's multivariate geomorphological history.

Acknowledgments

This work was supported by a University of Melbourne Early Career Researcher grant to PMM. Anthony Wilson (North East Catchment Management Authority) is thanked for providing background information. LiDAR data was made available by Rick Frisina of the Victorian Department of Environment and Primary Industries. Hugh Smith, Justin Stout, Louisa Davis and Mei Yin Soh helped with fieldwork and GIS analysis.

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