Taming the Hungry Beast: the effectiveness of engineered log jams in an incising gravel-bed river

James S. Daley
University of Wollongong

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Taming the Hungry Beast: the effectiveness of engineered log jams in an incising gravel-bed river

Abstract
A recent focus in river management has encouraged the reintroduction of large woody debris (LWD) into streams, implementing geomorphic and ecological principles to rehabilitate stream channels. Practice has outpaced scientific assessment, with few scientifically constrained LWD reintroduction programmes in Australia. No assessment has yet been undertaken regarding the effectiveness of LWD in constraining active channel destabilisation. This study assessed the geomorphic responses to the construction of engineered log jams (ELJs) in a 3 km reach of the lower Wilson River on the mid-north coast of New South Wales (NSW). ELJ construction was undertaken to prevent further bed incision and bank erosion associated with upstream migrating channel destabilisation. Eight floods of geomorphic significance have occurred since ELJ structures have been installed including the flood of record in February 2009, with a 48 year recurrence interval (1845 m$^3$s$^{-1}$). A comparison of repeated surveys throughout the period of remediation, from 2004 to 2012, was conducted in a capacity available to most river management authorities. Reach and sub-reach changes were assessed using ANOVA statistics and GIS analysis, as was pool-riffle wavelength and amplitude. ELJ structures have largely performed to design objectives and have predominantly remained stable under recent high energy conditions, though some structures are under considerable risk of failure. Despite these risks, no detectable changes occurred in the magnitude of bed variability, pool-riffle amplitude or pool-riffle wavelength. Riffle elevations however have increased in many areas throughout the reach and further bed incision has not occurred. This study demonstrates ELJs can provide a successful mechanism to managing active channel destabilisation, though this must be framed within the context of long term riparian rehabilitation.

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Taming the Hungry Beast: the effectiveness of engineered log jams in an incising gravel-bed river

James S. Daley

A research report submitted in partial fulfilment of the requirements for the award of the degree of Bachelor of Environmental Science (Honours)

October 2012
The information in this thesis is entirely the result of investigations conducted by the author, unless otherwise acknowledged, and has not been submitted in part, or otherwise, for any other degree or qualification.

James Daley
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To my father and brother, thank you for the unpaid time and labour you both donated. It must have been difficult to endure paddling the canoe around the scenic Wilson River, and I appreciate your contributions. I can’t wait to get back out into the field with you.

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To all the additional friends and family who have been there but have not got a special mention, thanks to you too, and thank you for understanding.
ABSTRACT

A recent focus in river management has encouraged the reintroduction of large woody debris (LWD) into streams, implementing geomorphic and ecological principles to rehabilitate stream channels. Practice has outpaced scientific assessment, with few scientifically constrained LWD reintroduction programmes in Australia. No assessment has yet been undertaken regarding the effectiveness of LWD in constraining active channel destabilisation. This study assessed the geomorphic responses to the construction of engineered log jams (ELJs) in a 3 km reach of the lower Wilson River on the mid-north coast of New South Wales (NSW). ELJ construction was undertaken to prevent further bed incision and bank erosion associated with upstream migrating channel destabilisation. Eight floods of geomorphic significance have occurred since ELJ structures have been installed including the flood of record in February 2009, with a 48 year recurrence interval (1845 m³s⁻¹). A comparison of repeated surveys throughout the period of remediation, from 2004 to 2012, was conducted in a capacity available to most river management authorities. Reach and sub-reach changes were assessed using ANOVA statistics and GIS analysis, as was pool-riffle wavelength and amplitude. ELJ structures have largely performed to design objectives and have predominantly remained stable under recent high energy conditions, though some structures are under considerable risk of failure. Despite these risks, no detectable changes occurred in the magnitude of bed variability, pool-riffle amplitude or pool-riffle wavelength. Riffle elevations however have increased in many areas throughout the reach and further bed incision has not occurred. This study demonstrates ELJs can provide a successful mechanism to managing active channel destabilisation, though this must be framed within the context of long term riparian rehabilitation.
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<th>Description</th>
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<tbody>
<tr>
<td>WD</td>
<td>Woody Debris</td>
</tr>
<tr>
<td>LWD</td>
<td>Large Woody Debris</td>
</tr>
<tr>
<td>ELJ</td>
<td>Engineered Log Jam</td>
</tr>
<tr>
<td>DFJ</td>
<td>Deflector Jam</td>
</tr>
<tr>
<td>ELS</td>
<td>Elevated Log Sill</td>
</tr>
<tr>
<td>RG</td>
<td>Rock Girdle</td>
</tr>
<tr>
<td>NSW</td>
<td>New South Wales</td>
</tr>
<tr>
<td>PMHC</td>
<td>Port Macquarie-Hastings Council</td>
</tr>
<tr>
<td>PTH</td>
<td>Pear Tree Hole, Rolland's Plains NSW</td>
</tr>
<tr>
<td>POT</td>
<td>Peak-Over Threshold</td>
</tr>
<tr>
<td>ARI</td>
<td>Annual Recurrence Interval</td>
</tr>
<tr>
<td>ENSO</td>
<td>El Nino Southern Oscillation</td>
</tr>
<tr>
<td>SOI</td>
<td>Southern Oscillation Index</td>
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1. INTRODUCTION

1.1 Introduction

Extensive modification and degradation of south-eastern Australian streams has occurred since the arrival of Europeans, particularly within the last century (Rutherfurd et al. 2000). Practices include extensive catchment clearing and grazing, flow regulation, flow and gravel extraction, artificial channel reorientation and the removal of vast quantities of in-channel and riparian vegetation (Lester and Boulton 2008). These rapid, human-induced disturbances have resulted in large-scale changes to geomorphic processes and significantly impaired biota. Until the 1990’s, the manifest focus of river managers was on asset-protection, with river engineering works treating the symptom rather than the cause. Insufficient understanding of fluvial processes often resulted in the generation of a new set of problems whilst trying to impede prior ones (Spink et al. 2009).

In an attempt to improve flood conveyance and drainage, continuous desnagging programmes, the active removal of large woody debris (LWD) from streams, ran for up to 150 years (Reinfelds et al. 1995; Brooks et al. 2003; Hoyle et al. 2008). The enthusiasm for LWD removal led to the systematic extraction of the near entirety of wood load in some systems, particularly in south-eastern Australia (Gippel et al. 1992). As a result, the state of many lowland streams throughout south-eastern Australia is severely impaired, with increased channel size and transport capacity (Brooks and Brierley 1997; Brierley et al. 1999; Spink et al. 2009; Hubble and Rutherfurd 2010). From an economic perspective, large areas of productive land were lost to channel expansion and as such, river ‘improvement’ shifted to bank protection and engineered revetment (Spink et al. 2009). LWD was again seen as the problem, perceived as a major cause of bank erosion. Over 8000 pieces of LWD were removed from the Williams River, NSW, between 1954 and 1991 (Erskine 1998; Brooks et al. 2004), while continuous desnagging in the Latrobe River coincided with up to a metre of bed-level incision (Reinfelds et al. 1995). Rapid erosion and downstream aggradation has led to profound homogenisation of channel morphology and habitat diversity, and hence reduced biotic diversity and abundance such as on the Cann River, Victoria (Brooks et al. 2003).

Over the past two decades, stream management attitudes and practices have shifted to a more holistic, natural-systems approach. Major efforts are now being made in restoring the ecological health of our rivers, often at considerable cost. River restoration has become a multi-billion dollar global industry, with annual expenditure in Australia exceeding AU$100 million (Price et
Management strategies commonly involve reinstating vegetation to the fluvial system, either through riparian management (Brooks and Lake 2007) or "resnagging" channels (Erskine and Webb 2003). Conventional hard-engineering structures, such as rock toe revetment, are often unrepresentative of natural stream characteristics, whilst providing only limited ecological services to river management. These structures are focused on asset-protection and lack the dynamic geomorphic and ecological roles of LWD. In natural channels, LWD has an essential role in hydraulic processes and grade control, inducing local scour and channel complexity, providing natural bank protection and habitat for stream fauna. An appreciation of this critical role is manifesting with greater application in management practices integrating the reintroduction of wood to emulate natural river systems.

LWD consists of in-stream woody material with a minimum diameter of 0.1 metres, such as logs, fallen trees and large branches. The characteristics of log structures have led to a number of interchangeable terms to describe LWD in the scientific literature. These include snags, log jams, coarse woody debris (CWD), structural woody habitat (SWH) and coarse-particulate organic matter (CPOM). For the purpose of this thesis, the term LWD will be used. In forested channels, this wood is generally sourced from the riparian zone. Considering the magnitude of lost riparian vegetation in agricultural and urban landscapes, it is unlikely that the wood loading in most disturbed streams will naturally recover in the foreseeable future, despite considerable efforts in riparian management. The artificial reintroduction of LWD provides an initial alternative to achieving the biophysical services provided by natural wood accumulations until natural recruitment can occur (Erskine and Webb 2003). However, throughout Australia and the world a lack of detailed understanding of the mechanics of LWD and effective design principles have resulted in the failure of many wood reintroduction projects (Abbe et al. 2003). Engineered log jams (ELJs) are artificially designed and installed LWD accumulations that approximate natural log jams to achieve specific goals (Abbe and Montgomery 1996), overcoming the potential social hazards of unrestrained, mobilised LWD. Though largely established in North America, ELJs have been demonstrated to achieve bank revetment, bed stabilisation (Abbe et al. 2003; Montgomery and Abbe 2006), increased geomorphic complexity (Montgomery et al. 2003) and produce fish habitat (Pess et al. 2007) in disturbed, incised channels. These structures have been modelled off natural LWD accumulations in forested systems to strategically fulfill the hydraulic and ecological functions they serve. Considering the hydrologic distinction of Australian river systems, where highly variable discharge and low sediment supplies are the norm, and the relative characteristics of native vegetation, dense hardwoods with unique branching systems, the patterns and effects of LWD accumulations potentially differ from their Northern Hemisphere counterpart.
The scientific assessment of geomorphic rehabilitation practices remains considerably deficient in Australia, making the determination of restoration requirements and specific rehabilitation strategic designs particularly fraught. The assessment of wood rehabilitation strategies often focus on goals of improving habitat stability and geomorphic complexity (Bond and Lake 2003; Brooks et al. 2006a). Other governing considerations aside, these goals encourage the return of a functioning aquatic ecosystem (Palmer et al. 2010). For many other streams, however, erosional processes and the deterioration of stream ecosystems is still ongoing. In such river systems, the infancy of disturbance regimes suggest that, left unchecked, these rivers will likely progress to a similarly degraded-channel state as seen in many parts of south-eastern Australia. Achieving meaningful stabilisation success in these river reaches, preferentially with guided principles in rehabilitation, is an essential priority of river management. The challenge in degrading channels lies in creating stable remedial measures in an unstable river system. Arresting active bed incision prior to achieving other rehabilitation goals is necessary prevent potential undermining and failure.

Figure 1 Mass failure at Pear Tree Hole on the Wilson River, February 2009. Bank erosion has been a persistent management problem on the Wilson River.
1.2 Aims and Objectives

The reintroduction of LWD into streams has been a recent development of Australian stream management, with a detailed practitioner’s guide developed as late as 2006 (Brooks et al. 2006b). Though the important role of wood in hydraulic, geomorphic and ecological processes has been recognised, the best-practice method of reintroduction remains a point of debate, specifically the type, range and design of structures (Abbe et al. 2003; Erskine et al. 2012). The efficacy of reintroducing LWD into Australian streams has had limited scientific assessment, with the general focus of current literature providing insight into the rehabilitation of already degraded systems (Brooks et al. 2004). Studies have had a measured focus on reinstating morphological heterogeneity (Brooks et al. 2006a) and re-establishing natural species populations (Bond et al. 2006; Coleman 2006; Howell et al. 2012) to promote the return to a more natural functioning system. Experimental reintroduction of wood on the Williams River, NSW, found that bed stability improved across the treatment site throughout the study period, with an increased sediment retention of 40m$^3$ for every 1000m$^2$ of channel (Brooks et al. 2006a). However, the effectiveness of ELJs in streams experiencing active knickpoint erosion and deterioration of the channel bed and banks under Australian conditions has had little scientific attention. Fifteen months after construction and several flood events, ELJs installed in a degrading reach of the Orara River, NSW, had successfully prevented further bank erosion (Broderick and Blake 2001). Beyond this limited study, little attention has been granted to assessing LWD in erosion control in destabilising river systems. The pertinent question remains, can ELJs be used to re-stabilise actively degrading streams?

The Wilson River is a gravel-bed stream that has experience large-scale changes in morphology following European settlement. Direct impacts from commercial gravel extraction operating from 1966 to 1995 resulted in the removal of over 600 000m$^3$ of gravel and the upstream migration of an active erosional front (knickzone). The Wilson River was found to have the most consistently high biotic integrity and habitat attributes of rivers in stress within NSW (Harris and Gehrke 1997), and upstream of the knickzone the river maintains significant habitat value. Priority for rehabilitation focused on protecting these relatively intact reaches through stabilisation of the knickzone using ELJs. Following a geomorphological assessment of the lower reach of the Wilson River, several stages of wood reintroduction occurred within the study reach. In order to preserve the intact reaches the goal of this LWD rehabilitation strategy was to:
• prevent further bed incision
• minimise active bank erosion
• a reduction of hydraulic grade
• a reduction of bedload transport capacity
• reinstatement and protection of riparian vegetation

This study is intended to provide an assessment of the effectiveness of ELJs in managing an actively destabilising stream and the rehabilitation of an over-steepened reach by assessing the performance of ELJs in a geomorphic erosion control plan after experiencing a range of flood events. Specifically, this study will:

1) Quantify the distance and rate of bank erosion in the channel-widened sections of the study reach;
2) Compare the observed geomorphic changes in the downstream profile following the installation of ELJs, to determine whether channel incision is an ongoing process;
3) Assess whether the rehabilitation strategy implemented by Port Macquarie-Hastings Council and the Northern Rivers Catchment Management Authority has been successful in achieving its project goals and provide site-specific recommendations for the future management of the study reach; and
4) Provide an evaluation of the use of ELJs in rehabilitation programmes with goals to stabilise active processes of degradation;

1.3 Thesis Outline

This thesis is structured with the following chapter providing a review of the current literature and understanding of the causes and processes of degradation in south-eastern Australia and the role of wood in stream management. Chapter three provides an overview of the study area and specific post-European land use history. Chapter four describes the methods used to collect field data and integrate with previous data sets for various analyses and assessments. Chapter five presents the results of the analyses in relation to channel changes, bed-level dynamics and morphodynamics, and assessment of the ELJ-associated scour. This is followed by a discussion of the relevance of these results in relation to the broader literature and their implications (Chapter six), which further provides limitations to this study. Finally, Chapter seven provides recommendations for the future management of the Wilson River and identifies broader conclusions of this study.
2. LITERATURE REVIEW

The purpose of this chapter is to briefly review the studies of past practices in relation to stream management in south-eastern Australia, and establish the relevance of this study in the wider context of the literature. A summary of degradation cause and response is provided with both Australian and international foci followed by an outline of the reasons for the management of LWD in rivers.

2.1 History and pattern of post-European disturbance to south-eastern Australian streams

Post-European settlement and agricultural development has led to catastrophic biophysical degradation of many coastal streams in south-eastern Australia, with over 80% of Australian river reaches affected by catchment disturbance and 85% considered significantly modified (Land and Water Australia 2002). In southeast Australia extensive grazing and cropping industries have significantly altered hydrological regimes (Lester and Boulton 2008).

Channel instability commonly occurs with an episodic series of large magnitude flood events (Nanson 1986; Erskine 1994; Doyle 2003). However, the principal processes influencing channel instability have remained contentious, with studies exemplifying degradation as a lagged response to systematic changes in catchment processes associated with modern anthropogenic activity (Brierley et al. 1999; Brooks 1999; Brooks and Brierley 2004). Though climatic controls invariably provide significant mechanisms for channel degradation, it is clear that post-European agricultural activities and disturbance has significantly altered fluvial dynamics in Australia, preconditioning rivers to erosion susceptibility (Hoyle et al. 2008; Hubble and Rutherford 2010). Throughout the mid to late Holocene, coastal south-east Australian rivers have experienced a defined period of relative geomorphic stability (Nanson and Doyle 1999). Pre-European conditions have been described for several major coastal streams along the south-east Australian coast (Wasson et al. 1998; Brierley et al. 1999; Doyle 2003; Hoyle et al. 2008), relying on explorers and settler's documentary notes, diaries, parish maps and sedimentological analyses. Though catchment characteristics are spatially variable and idiosyncratic by nature, at the time of European settlement lowland streams were generally found to have low capacity channels with well developed pool-riffle units or discontinuous channels with extensive swamplands. Vegetated floodplains were dominated by open eucalypt
forests to sub-tropical rainforest. The Thurra River in East Gippsland, Victoria provides a rare contemporary example of pre-disturbance condition (Brooks 1999; Brooks and Brierley 2002) with little modern human impact. The river features a narrow channel with a high woody debris load, regular bankfull exceedance, dense riparian margins and significant bed form complexity (Figure 3).

Post-European settlement, particularly in the last century, has resulted in a pattern of rapid channel metamorphosis (Figure 2) with increased hydraulic velocities, channel incision and widening, losses of geomorphic heterogeneity and biodiversity, and reduced water quality across many coastal river systems. This pattern of degradation has had a multitude of associated social, economic and environmental impacts (Erskine 1999). Both direct and indirect human impacts have altered the conditions of Australian rivers, increasing the effectiveness of flood events (Table 1). The timing and pattern of response is not uniform across the region, dependent on the type and extent of human disturbance, the resilience of catchments and river systems and climatic forcing throughout this period (Brooks and Brierley 1997). A lack of detailed records and variable land use practices makes synthesising disturbance histories difficult; however, it is possible to provide a generalised account of the disturbance history for the region based on socio-geomorphic factors and common themes in agricultural practices.

<table>
<thead>
<tr>
<th>Causes of degradation</th>
<th>Direct channel change</th>
<th>Indirect catchment change</th>
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<tbody>
<tr>
<td></td>
<td>Clearance of riparian vegetation</td>
<td>Land use changes</td>
</tr>
<tr>
<td></td>
<td>Removal of LWD</td>
<td>• Forest clearance</td>
</tr>
<tr>
<td>Decreased erosional resistance</td>
<td></td>
<td>• Agricultural activity</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cattle grazing</td>
</tr>
<tr>
<td>Increased erosional force</td>
<td>River Regulation and water storage</td>
<td>Changes to ground cover (increased runoff and discharge)</td>
</tr>
<tr>
<td></td>
<td>• Dams and reservoirs</td>
<td>• Creation of agricultural drains and irrigation channels</td>
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<td></td>
<td>Channel modifications</td>
<td>• Urbanisation and building/infrastructure construction</td>
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<td></td>
<td>• River engineering</td>
<td>Mining activity</td>
</tr>
<tr>
<td></td>
<td>• Channelisation and channel realignment</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Sediment extraction and dredging</td>
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</table>
| European colonisation generally began in the early to mid nineteenth century as transient cedar-cutters and pastoralists selectively cleared the floodplain. This is unlikely in many areas to have caused significant hydrological changes within the heavily forested coastal catchments. Extensive deforestation and wetland drainage occurred throughout the latter half of the nineteenth century, with metamorphosis occurring within several decades of vegetation
clearance (Brierley *et al.* 1999). Vegetation cover provides a major control on hydrologic conditions, limiting hillslope sediment transport and storm water runoff. The removal of natural vegetation increases the potential impact of climatic events (Knighton 1998). Experiments by Goudie (1993) found catchment clearance in the Australian Highlands resulted in over 500% increases of peak flow during high discharge events, while Cohen (2003) reported a five-fold increase in post-European channel capacity in the Bellinger catchment.

Between the late nineteenth and early twentieth century, the Bega river channel had experienced a three-fold increase in channel width and up to 2m of sediment accumulation though little change was detected in the following half century. Similar trends in degradation have been found in the Nambucca catchment during a period of extensive land clearing coupled with a flood-dominated regime (Doyle 2003). However, the advent of modern intensive farming and grazing practices of the twentieth century significantly altered the land. Industrialisation of farming practices and machinery provided a mechanism for greater agricultural production and the development of an appreciable export industry to the United Kingdom (Muller 1984; Telfer and Miller 2001). Consequentially, the extent of channel modification increased as river training and improvement programmes were conducted by authorities in most agricultural streams, with a concerted focus on asset protection (Reinfelds *et al.* 1995; Erskine and Webb 2003). Coastal streams have been impaired by common practices of riparian vegetation clearance, channelisation, regulation, desnagging, aggregate extraction and grazing.

These practices were often undertaken in combination with each other, with effects of channel metamorphosis usually not limited to an individual factor. For example, land and riparian clearing provides cattle with the ability to graze in and along streams. Both of these practices provide a mechanism for destabilising banks and exacerbate erosional processes. Riparian vegetation provides an important control on channel morphology, with direct relationships to channel geometry and bank strength, reducing bank shear stress and flow velocity. The removal of riparian vegetation has been a widespread practice (Erskine and Webb 2003; Webb and Erskine 2003; Lester and Boulton 2008; Lester and Wright 2009), with agricultural activities encroaching right to the stream bank and little-to-no compelling reason for farmers to leave banks vegetated. Once removed, little control existed to hinder processes of channel metamorphosis. The introduction of ungulate species, particularly cattle, promoted further instability with intensive grazing damaging fragile bank soils while hindering and consuming new-growth vegetation and reducing water quality (Trimble 1994; Bell and Priestley 1999). A lack of structural control exacerbated bank instability as stream power and sediment transport capacity increased. Destabilised banks provided a greater supply of sediment, resulting in the
formation of sediment slugs and a loss of in-stream complexity. The removal of riparian vegetation has also resulted in a loss of source material for in-stream woody debris and organic particulate matter (Lester and Boulton 2008). This was actively encouraged under the auspice of preventative desnagging (Erskine and Webb 2003).

Government-initiated desnagging operations were conducted from the late nineteenth century under The Irrigation Act (1886) and later continued under The River Improvement Act (1948) up until 1995 (Erskine and Webb 2003). The goals of desnagging were to improve navigability (Gippel et al. 1992) and flood mitigation through increased channel flow capacity and reduce flow velocities. It was perceived that snags increased flow velocity, bank erosion, the magnitude and duration of floods and impaired fish passage (Gippel et al. 1996a; Erskine and Webb 2003; Lester and Wright 2009). By removing LWD, it was believed that local flood waters would be lower and floodplain drainage would occur more rapidly. Combined impacts of riparian and LWD removal have been directly linked to increased flow velocity, with 20% increases reported along the Glenelg River following snag removal (Erskine 1994). Other significant environment impacts include bed instability and incision, morphological homogenisation (Figure 3) and a loss of physical habitat (Reinfelds et al. 1995; Erskine and Webb 2003; Brooks et al. 2004), with resulting reductions in ecological function, and declining density and diversity of freshwater organisms (Brooks and Brierley 2004; Lester and Boulton 2008).

Further degradation has been caused through 'river training' or channelisation as a flood mitigation strategy and aggregate extraction. Channelisation has involved creating artificial meander cut-offs and channel straightening, and in some cases constraining stream courses through concrete-lined artificial channels and constructing drains for wetland reclamation. These operations produced reductions in stream length and roughness and increasing flow velocity, causing further channel instability (Reinfelds et al. 1995). Extraction industries have also removed substantial amounts of aggregate from rivers generally for construction and industrial purposes and was until recently conducted under the guise of preventing bank erosion (Resource Planning Pty Ltd 1990). However, excessive aggregate removal and mining has produced the opposite effect, initiating bed degradation, bank erosion, channel instability and channel widening (Erskine et al. 1985).

Lowland rivers in south-eastern Australia are now up to 25% straighter (Reinfelds et al. 1995) with larger channel capacities, influencing floodplain inundation frequency, channel dynamics and stream ecology. The specific changes occurring on the Wilson River will be explored in the following chapters.
2.2 Processes of bed level incision and bank erosion in alluvial streams

Fluvial systems seek to exist in an equilibrium state with the dominant hydrological and sedimentological regimes (Schumm et al. 1984; Knighton 1998). Changes in these conditions often equate to a progressive adjustment of the river to maintain efficiency, most commonly through degradation or aggradation. These responses have been recognised throughout southeastern Australia (Brooks and Brierley 1997; Brierley et al. 1999; Hoyle et al. 2008) and throughout many of the world's alluvial rivers (Schumm et al. 1984; Schumm 1994; Simon and Rinaldi 2006). Bed level incision and bank erosion are the most important mechanisms of channel geometry adjustment in incised alluvial streams. They represent common disturbance responses occurring from numerous human-related and natural impacts (Schumm 1999), or very often the combined effect of multiple impacts. Despite these relational disturbances, the overall mechanism of degradation is the excess sediment transport capacity relative to sediment availability (Simon and Darby 1999), usually resulting in similar morphological effects across physiographic environments. Downstream aggradation ensues, often as a sediment slug to produce a homogenised highly altered channel (Brierley et al. 1999). The cause of degradation may form through increased erosional forces with, relative excess of flow energy, stream power or shear stress, or through decreased erosional resistance such as a reduction in bank cohesion (Table 1). Degradation is different to scour, which is generally short-term, localised bed-level variability in response to peak discharge events. Bed scour is usually limited in magnitude and spatial extent, involving the formation of pools by eddying in the rising stage of a flood or storm flow (Knighton 1998). Degradation is the systematic downcutting of a channel over a significant spatial and temporal scale, affecting a reach extent up to entire stream networks (Simon and Darby 1999).

Lane (1955) represents channel stability as a relationship of stream power proportionality,

\[ Q_S \propto Q_s d_{50} \]

where \( Q \) is channel-forming discharge (m³s⁻¹), \( S \) is channel slope, \( Q_s \) is bed material discharge (m²s⁻¹) and \( d_{50} \) is the median grain size of the bed material (m). An imbalance in the above equation will result in a proportional adjustment of parameters. For example, an increase in discharge or channel gradient will respond at a given location in a proportional increase in fluvial entrainment (material discharge), with the channel acting as sediment conveyor belt and a resultant downstream translation of bed material. Though a simplification of the complexity of channel erosion, this exemplifies the process-response mechanics of degradation and how the exceedance of geomorphic thresholds can effectively initiate channel incision (Schumm et al.)
In an incised stream, bed material is generally non-uniform, cohesionless sands to gravel (Knighton 1998). The movement of material depends not only on variables of hydraulic, velocity, shear and stream power thresholds, but is strongly reliant on the physical properties of the bed material (Schumm et al. 1984).

Once incision has commenced, the process can migrate upstream as with channelisation (Brookes 1985), or downstream as with flow regulation (Brierley and Fryirs 2005). As an abrupt change in elevation or slope, a knickpoint marks the point of incision. This can occur as a broader, steeper section along the longitudinal profile of a stream, termed a "knickzone", as on the Wilson River where the degrading processes are distributed along a reach (Schumm et al. 1984). Knickpoints and knickzones can produce higher, steeper banks lacking vertical stability. This can reduce the erosional resistance of the channel boundary making it susceptible to mass failure and bank retreat.

Figure 2 Evolution of an incised river channel from initial incision and bed degradation (a, b) and unstable, widening banks (c, d) to unstable banks and aggradation (d) and eventual relative stability in new state (e). (source Schumm 1994)
In its attempt to establish an equilibrium state with hydrologic and sedimentological conditions, it is unlikely that erosion in an incising channel will naturally cease until it has progressed through a sequence of incised channel evolution (Schumm et al. 1984; Schumm 1999). When incision is initialised, channels rapidly deepen to a maximum depth (Figure 2), and lateral erosion occurs. Channel widening ensues and discharge increases as the channel constrains a larger volume of water. Incised channels may be unable to dissipate energy over the floodplain during peak flows, reducing the occurrence overbank flooding. Higher shear stress and sediment transport capacity can exacerbate the geomorphic effectiveness of floods, while the loss of floodplain connectivity overbank flooding can have detrimental environmental and societal impacts (Bravard et al. 1999). As the degradation migrates upstream, aggradation occurs and eventually the system restabilises, with recovery to a new equilibrium state. This final stage is hypothetical and has not been observed in southeast Australian fluvial systems (Erskine 1999). These processes of degradation have occurred naturally throughout geological history, though the interference of human activity has significantly increased the rate at which these processes occur.

Though the process of knickpoint initiation and recession is discussed quite widely discussed throughout the literature (Schumm et al. 1984; Schumm 1999; Zhang et al. 2011; Foster and Kelsey 2012), the topic of knickpoint dissipation is notably lacking. There is either little regard or little understanding of the process requirements to arrest a migrating knickpoint, whether through long-profile readjustment or the magnitude of resistance to abate further recession. Though artificial grade control is commonly implemented, little scientific foundation and evaluation underpins the practice (Shields Jr 2009). Artificial steps mimicking natural morphological architecture have been found to provide appreciable flood control and ecological functionality in comparison to hard concrete dams (Comiti et al. 2009), though assessment of knickpoint arrest has not been a goal of these scientific assessments. Do channels require significant bedrock steps to halt knickpoint recession? Does rock revetment and channelisation in an alluvial setting provide a geomorphic and ecological solution? Can a log-filled reach provide significant roughness and sediment storage control to prevent ongoing knickpoint recession?
2.3 The role of wood in streams and stream management

Over the past two decades the beneficial value of riparian vegetation and in-stream woody debris has had a growing recognition in river rehabilitation and management practices. Prior to this, active removal of LWD and riparian vegetation was promoted under the guise of ‘river improvement’ (Erskine and Webb 2003). The rationale for vegetation removal is discussed above but the reason for this paradigm shift in management practice is largely due to the considerable amount of research demonstrating the importance of geomorphic (Abbe and Montgomery 1996; Abbe et al. 2003; Erskine and Webb 2003), ecological (O'Connor 1992; Bond and Lake 2003; Bond et al. 2006; Scealy et al. 2007) and hydraulic (Keller and Swanson 1979; Gippel et al. 1996a) values offered to the fluvial system.

2.3.1 Wood and fluvial geomorphology

Wood influences the geomorphology of fluvial systems at various spatial scales from controlling physical features, such as bedform and channel complexity (Keller and Swanson 1979; Keller and Macdonald 1995; Abbe and Montgomery 1996), to influencing the geomorphologic character of a river (Montgomery et al. 2003). LWD affects important biogeochemical processes including carbon, nitrogen and phosphorus cycles and has the potential to provide hyporheic connectivity and exchange (Brooks et al. 2006b). The density and branching structure of Australian hardwoods tend to promote the development of in situ LWD proximal to the source of introduction (Lloyd et al. 1991). These pieces become retention mechanisms for LWD structures (log jams) as transported LWD and sediment are trapped and accumulated within the structure. Accumulations that occupy more than 10% of a channel cross section exert significant local control on stream stability and enhances channel heterogeneity (Gippel et al. 1996a). Once embedded in the channel, LWD can stabilise as channel hardpoints (Abbe and Montgomery 2003) and in some settings can last for thousands of years (Nanson et al. 1995) found that buried logs can have residence times of thousands of years. The degree to which individual accumulations affect hydraulics and morphology depend on the size of the channel, size of the LWD and orientation to flow.

LWD obstructing flow can initiate the formation of scour pools, bars and islands (Abbe and Montgomery 1996). This can lead to elevated sediment storage and/or scour-producing vortex flows, providing a major control on pool development in some streams (Brooks and Brierley 2002). LWD stabilising in the centre of the channel can deflect a significant percentage of the
flow into banks, facilitating localised channel expansion of up to 230% and the development of meander cutoffs (Keller and Swanson 1979; Gippel et al. 1996b). The magnitude of the impacts can be large, with complete domination on channel form and processes (Figure 3). LWD with high channel blockage ratios can create backwater effects (upstream elevation of the water surface) increasing sediment storage and the potential for avulsion by promoting flow to secondary channels and across floodplains. In 1971, rapid avulsion to a flood chute occurred on Wildcat Creek in Indiana, USA, after a large snag developed in the primary channel (Keller and Swanson 1979).

Stable log jams that form on the concave bank of a meander bend, meander jams (Abbe 2000), provide another mechanism for channel avulsion. Generally located on the outer, downstream bank, these accumulations provide revetment to bank erosion and reduce the radius of curvature of meanders, creating tighter bends (Abbe 2000; Abbe and Montgomery 2003). Observations on the Queets River, Washington, showed that curvature on alluvial channel bends with meander jams had significantly lower radii than meanders lacking stable woody debris (Abbe and Montgomery 2003). Compression of the bend increases super-elevation of the water surface against the concave bank due to the interaction of centrifugal force acting on the water, enhancing the potential for overbank flows and cutoff initiation.

Comparative geomorphic observations in paired catchments in Victoria, Australia, exemplify the magnitude of the role of wood in the fluvial environment (Figure 3). Over the last century, extensive vegetation clearance from the channel and floodplain of the Cann River resulted in a 700% increase in channel capacity, a steepening of channel gradient by 250%, bankfull velocity increased by 6.1 times and a 45-fold increase in bankfull discharge was observed (Brooks 1999; Brooks et al. 2003). Peak instantaneous sediment transport increased 1000-fold, with a significantly greater calibre of sediment transported downstream. This has occurred despite no comparable changes to the geomorphic and hydrological equivalent, neighbouring Thurra River (Brooks et al. 2003). The removal of wood provides the only practicable possibility for the rapid degradation experienced along the Cann River (Figure 3).
Riparian vegetation also directly contributes to channel complexity as the primary source of wood in streams, particularly with *Eucaluptus* species in Australia (Lloyd *et al.* 1991). Trees collapse into stream channels, through a variety of processes, and either remains *in situ* or is transported downstream. In forested areas, effective resistance to mass bank failure is provided through riparian root reinforcement (Docker and Hubble 2008; Hubble *et al.* 2010). Abernethy and Rutherford (1999) found that riparian corridors of Swamp Paperbark and River Red Gum increase bank stability, with 132% and 175% respective increases in factor of safety. The influential role on channel geometry can restrain channel migration and have more spatially significant geomorphic and biogeographic effects through constricting channel capacity, causing increased floodplain inundation, sedimentation and long-term development (Brooks and Brierley 2002). Streams with dense riparian vegetation have a tendency to be narrower and deeper than relative exiguous counterparts (Brooks *et al.* 2003).

### 2.3.2 Wood and stream ecology

Logs provide important controls on channel stability and complexity, creating physical habitat for a range of aquatic biota, including fungi, macroinvertebrates, fish and aquatic reptiles and are incumbent aspects of aquatic food webs (Lovett and Price 2007). The bedform complexity created by wood facilitates habitat diversity for fish and other animals (Bond and Lake 2003; Howson *et al.* 2012), while the physical presence of wood provides substrate and habitat for algal growth and macroinvertebrate colonisation, particularly in soft-bottomed or sanded streams limited in stable surfaces (Bond *et al.* 2006; Scealy *et al.* 2007). Vegetation ranging in size from leaf litter to large snags provides diverse ecological services to aquatic assemblages.
Wood substrate provides a major surface for algal colonisation, with high level primary production of invertebrate abundance and richness (O’Connor 1992; Bond et al. 2006). Algae communities provide additional habitat for other macroinvertebrates and stream insects. Macroinvertebrate biomass associated with LWD constitutes 50% of total present along the streambed (O’Connor 1992). Higher trophic levels such as fish can be attracted by an abundance of resources (Howson et al. 2012), creating ecological hot spots (Bond et al. 2006).

High LWD densities positive correlate with the distribution and abundance of fish (Crook and Robertson 1999) and more diverse, stable species assemblages (Howson et al. 2012). Native Australian fish species, such as the river blackfish *Gadopsis marmoratus* rely on woody debris for micro-scale habitats (Koehn et al. 1994; Bond and Lake 2003). LWD provide structures for predator avoidance, spatial reference, territory boundaries and oviposition (Merrick and Schmida 1984; Harris and SJ 1996). Further, woody habitats and associated macro-scale geomorphic structures are valuable refugia for riverine fish to avoid and survive catastrophic events, such as high flow velocities during floods (Fausch 1993) or extreme low flows during droughts (Bond and Lake 2005). Comparable ecological values are likely provided to other Australian aquatic fauna including turtles, terrapins and platypus (Coleman 2006). The management of wood in streams is critical to the stability of ecological health, with the reintroduction of woody debris and riparian vegetation now a common approach in river rehabilitation programmes. A fundamental imperative to 'restore' and reverse the catastrophic biophysical impacts to streams in south-eastern Australia has enhanced the need for successful remediation of geomorphic functions.

### 2.3.3 Reintroducing wood to rivers

Few examples of LWD introductions have involved rigorous scientific evaluation and the practice has far outpaced the scientific justification. The development of thorough guidelines is still necessary (Abbe et al. 2003; Brooks et al. 2006b), with experimental designs in wood reintroduction rapidly developing over the last 15 years. The need for detailed understanding of the hydraulics, afflux and erosion associated with the addition of LWD, flume and field experiments have focussed on single piece and multi piece introduction (Gippel et al. 1996b; Gerhard and Reich 2000). Gerhard and Reich (2000) further provide an assessment of LWD as a bank revetment mechanism, where small 5-member stacks were dug into the banks of an agricultural stream with the goal of increasing low-flow sinuosity and channel heterogeneity. In a similar study Lester and Wright (2009) used simple structural designs of single piece and
multi piece ‘clumps’ to assess affects on flooding and flow velocity, finding negligible associations with LWD. Justification for this design, despite postdating the development of ELJ technology (Brooks et al. 2006b), was in the simple applicability to local landholders. The use of cylindrical cut logs in these studies, however, are not necessarily representative of ‘natural’ LWD accumulations and optimal reintroduction techniques.

The most significant developments in reintroducing LWD have come from North America where it has been guided by concerns of depleted Salmonoid fisheries (REF). Understanding of Salmonoid life history and habitat requirements initially highlighted the necessity of wood in rivers. Detailed observations of pristine rivers in Washington, USA, led to the development of a classification scheme for LWD accumulations and their subsequent influence on fluvial processes (Abbe and Montgomery 1996; Abbe 2000). This included boundary and hydraulic effects, structural orientation, channel location and substructure classification of LWD members. Natural LWD has been observed to often retain their root wad, significantly influencing hydraulic behaviour and stability (Abbe and Montgomery 1996). LWD with intact root wads are more likely to form stable hard points and accumulate within the channel due to the added difficulties in transport. Generally, logs will orientate parallel to flow with root wads facing upstream and trunk downstream, inclined 10-30° (Abbe 2000). Orientated vertical to the bed, root wads act as an anchor to LWD, with a concentration of mass associated with the ability to support the tree’s weight and a high comparative density of retained alluvium in the root mass. These structures further alter flow, friction and resistance forces. Through this scheme, engineered log jam (ELJ) structures were developed to emulate the complexity of natural fluvial accumulations, provide the suite of services provided by natural LWD and effectively address specific engineering requirements. The inclusion of logs with intact root wads has been an essential element to ELJ technology (Abbe et al. 1997).

ELJs refer to a group of in-channel hydraulic structures designed for flow manipulation and channel stability. Reintroduction goals using ELJs include bed and bank erosion control, channel realignment, infrastructure protection and biological habitat. Based on civil engineering approaches to infrastructure design, the technology has now been experimentally manipulated in several successful river management and rehabilitation programmes in the USA (Abbe et al. 1997; Drury et al. 1999), providing a factor of safety, quality control and quality assurance relative to traditional engineering efforts at a significantly lower cost than alternative river management solutions (Drury et al. 1999). Designed to meet equivalent objectives, LWD bank revetment construction on the Cowlitz River, Washington, was 1% of the cost of a comparative project using rock rip-rap (Abbe et al. 1997). ELJ installation provides an intermediate
management approach within the generally extensive timeframes necessary for natural recruitment processes to be reinstated through riparian revegetation.

In response to dramatic erosion and degradation throughout the Nambucca catchment in northern NSW, rehabilitation was undertaken by local landcare groups between 1995-96 in a number of tributaries (Doyle 2003). This rehabilitation strategy utilised predominately log sills and timber pin groynes alongside rock ramps and revegetation (Doyle 2003). Though different designs exist, log sills are aligned perpendicular to flow to act as grade control structures by providing a local step-profile to dissipate energy and provide bed stability (Brooks et al. 2006b; Department of Sustainability and Environment 2007). Pin groynes, also known as pile fields and pile groynes, are low permeable fences constructed in the stream bed to protect an eroding bank and induce aggradation (Department of Sustainability and Environment 2007).

In many instances, the log sill structures of the Nambucca have failed after being undercut or outflanked (Doyle 2003). Fifty five log sills were emplaced in already degraded reaches, of which only 14 remained as successful structures (Doyle 2003). Likewise, the use of pin groynes along the Nambucca has been met with varying success. Though the Nambucca provides examples of both success and failure in the reintroduction of wood, subsequent generations of LWD introductions have benefited from the experimental nature of such strategies, with detailed construction guidelines improving on theoretical and practical errors (Hardie 2007).

Along the NSW mid-north coast, other community-based rehabilitation projects installed ELJs in the Clarence River Catchment. Installed late 1999-2000, the projects incorporated then emerging theories of LWD and ELJ to create several remediation structures (Broderick and Blake 2001). These included elevated log sills (ELS), root ball groynes, log jams, pin groynes and log and brush groynes. An aspect of log sill designs that had developed from the Nambucca River rehabilitation works was to elevate logs above the bed and provide radial pin abutments to prevent outflanking (Figure 4). By raising the ELS above the bed, fish passage is provided during low flow, and the possibility of being drowned out during floods is reduced, promoting deposition in bed-mobilising events (Brooks et al. 2006b). Root ball groynes were constructed as flow deflectors to provide bank protection (Figure 6). Though designs lacked scientific assessment, their development by the NSW Northern Rivers CMA has provided a basis for successful biophysical rehabilitation. Observations have demonstrated the structures have generally performed as planned, though structural failure has not been eliminated. These designs have been utilised along the Wilson River in recent years (see chapter 3 and Appendix A), with failure and outflanking during a 50 year recurrence interval flood in February 2009. Lessons from these experimental introductions, as with the Nambucca, highlight the necessity of
comprehensive approach with a site specific understanding of fluvial, geomorphic and disturbance processes.

Figure 4 (A) A naturally recruited log at low flow on the Wilson River demonstrating the tendency of logs to form log steps; and (B) an elevated log sill on the Wilson River under high flow conditions

LWD reintroduction on the Williams River, NSW, was conducted to specifically evaluate the effectiveness of ELJs in the rehabilitation of a degraded river reach. Initiated in 2000, 20 ELJs were constructed over a 1km reach with the goal of improving channel stability and recreating channel complexity (Brooks et al. 2004). ELJ designs were derived from North American models
(Abbe et al. 1997; Abbe 2000) and have been described in Table 2. These were all constructed using only native hardwood trees and local alluvium as ballast, with no anchoring cable or rock revetment. Within five years, the structures had experienced ten floods above the mean annual flood, five of which were considered geomorphically effective; capable of mobilising the bed. Contiguous surveying provided detailed geomorphic and ecological adjustments throughout the evaluation period and have provided promising results. The test reach has demonstrated the effective potential of reach-scale LWD introductions, with measured increases habitat complexity, sediment storage and fish abundance (Brooks et al. 2006a). Comparison with a disturbed control reach has indicated changes have been associated with LWD additions as no significant changes have occurred in this control reach despite experiencing equivalent hydrologic activity.

The scale of the Williams River project represents the most comprehensive LWD rehabilitation effort undertaken in Australia, and only project established to provide a scientific foundation for Australian LWD reintroduction. The authors have suggested far greater resources will be required to effectively reverse the broad scope of degradation throughout south-eastern Australian streams (Brooks et al. 2006a), though these early trials suggest that ELJs have the potential to provide initial recovery mechanisms to long term rehabilitation objectives.

<table>
<thead>
<tr>
<th>Log structure type</th>
<th>Primary characteristics</th>
<th>Functional attributes</th>
</tr>
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<tbody>
<tr>
<td>Deflector Jams (DFJs)</td>
<td>Large multiple log jam structures built into eroding banks (typically 50 or more logs with root wads); suitable for banks subject to mass failure</td>
<td>Bank erosion control structures; redirection of thalweg towards channel centre (away from eroding bank toe); pool scour induction - adjacent to upstream streamward edge of structure; complex habitat within structure itself</td>
</tr>
<tr>
<td>Bar Apex Jams (BAJs)</td>
<td>Multiple log jam structures - typically 10–30 logs, built into the upstream apex of an existing bar or island</td>
<td>Bar stabilisation structures; induction of bar/island deposition; complex habitat</td>
</tr>
<tr>
<td>Bank Revetment Structures (BRVTs)</td>
<td>Small structures consisting of several stacked logs (±root wads) parallel to flow at bank toe; generally only for low banks not subject to mass failure</td>
<td>Fluvial erosion control structures; ideal for re-creation of bank undercut habitat</td>
</tr>
<tr>
<td>Log Sills (LSs)</td>
<td>Small stacked log accumulations (generally pyramidal in section) generally buried into bed perpendicular to flow — ideally with DFJ or BAI abutments on either side</td>
<td>Bed control structures; induction of step-pool type morphology; re-creation of hyporheic exchange functioning</td>
</tr>
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3. REGIONAL SETTING

The Wilson River is a major northern tributary of the Hastings River along the mid-north coast of NSW, Australia (Figure 5) with a catchment area of approximately 500 km² at the Avenal stream flow gauge (Stn 207014) before its confluence with the Maria River (Figure 5). The study reach comprises approximately three kilometres of the channel (Figure 5) and is characterised by a bedrock-controlled discontinuous floodplain river style (Brierley and Fryirs 2005). Without implementing the detailed technique of Thompson et al. (2006), the study reach conforms to the classification of a pool-riffle channel. Above the study reach, the Wilson has multiple channels whilst downstream of study reach it has become a single thread channel, with a fivefold increase in bankfull width and an 8.5% reduction in channel length.

3.3 A brief history of settlement and land use

3.1.1 Landuse in the Wilson River Catchment

The Wilson River has experienced a comparable European settlement history to many coastal rivers south-eastern Australia. The Hastings catchment was officially discovered by Surveyor-General John Oxley in 1818 with a penal settlement established at the mouth of the Hastings River in 1821 with the arrival of Commandant Captain Francis Allman (Gray 1966). Captain Allman pioneered sugar cane cultivation in Australia and as the crop grew and spread, agriculture along the Hastings allowed further settlement.

The first European arrivals to Rollands Plains were most probably cedar-cutting convict gangs, selectively logging some of the largest Red Cedar trees, Toona ciliata, from the floodplain. At this time, free settlers were not permitted beyond the boundaries of the nineteen counties to the Manning River (Cooper 2012). ‘Cedar cutters’ were the first European inhabitants to occupy other major river valleys of the region, including the Macleay and Nambucca Rivers (Townsend 1993). Little attempt would have been made to clear the land as these transients were only interested in extracting the highly prized timber for export to Sydney. Once stocks depleted, however, agriculture would have soon followed. Establishing when settlement first began along the Wilson River is difficult, but by 1832 an Agricultural Station was established at Telegraph Point and another convict agricultural establishment at Rollands Plains (Raymond 1832).
Figure 5 Locality map of the Wilson River study reach with in-channel geomorphic units.
Severe frosts in 1828 prevented ongoing success of sugar cane crops and wheat production was attempted though, quickly, it too failed due to the humid climate (Cooper 2012). By the 1830s, the district was opened to free settlers with the Rollands Plains establishment as the northerly extent of the eastern mailman’s route in 1832 (Raymond 1832). As a regional centre with “extensive buildings”, Rollands Plains presented a resting place for travellers heading north to the Macleay River. By this time, corn and tobacco crops were the main produce, alongside pastoral and subsistence farming. In 1845, the convict establishment at Rollands Plains had been closed down and the area was mainly established by pastoralists. A dray road across the Marlo Merrican range underwent construction in the early 1860s to allow farmers to transport goods from Upper Rollands Plains to Kempsey (The Sydney Morning Herald, 23/02/1860). The route was dangerous and poorly designed, and after floods in 1862 washed away two bridges the project remained incomplete and impassable (The Maitland Mercury, 12/03/1863). Throughout the 1860s- and -70s, a flood-dominated period resulted in subsequent loss of crops (Cooper 2012). A revival of the sugar cane industry emerged in the nearby township of Wauchope, though again this had collapsed by 1878 (Cooper 2012). In the small community, little to no development occurred throughout the Hastings until the early-mid twentieth century.

Agriculture gradually shifted to dairying, with dairy cattle, pigs and fodder crops providing the dominant land use along the Wilson River (Cooper 2012) and continued through the early 1900s. A lack of refrigeration meant that dairy production was in cream from butter, with a butter factory established in Wauchope in 1893 and another in Port Macquarie in 1897. A new factory was established in 1917 after railway construction in Wauchope, with another butter factory opened at Telegraph Point for the Wilson River farmers (Cooper 2012). This allowed for much more expedient transport of food exports to the Sydney market.

Development thrived during the Second World War as the region became the centre of dairy production. The United Kingdom relied heavily on Australian and New Zealand agricultural exports to support high food demands (Muller 1984). This period represents the environmental nadir of the area as increased demand coincided with the advent of industrial agriculture. Land use intensified as production expanded across the alluvial flats. Dairy cattle and pigs were run right into streams with increased production (Telfer and Miller 2001), with piggeries established along channel banks (Preen, T pers. comm. 2012). The land was intensively ploughed where crops were grown, with chemical pesticides and fertilisers developed and used extensively. Bulk refrigeration was distributed to dairy farmers along the Wilson River by the Hastings District Dairy Co-op, allowing further increases in production as the area gradually shifted from butter to milk production. In 1955-56 approximately 4.6 million gallons (18 million
Kg) and 1.7 million gallons (6.8 million Kg) of milk were supplied to the Co-op and Milk Board, respectively (Cooper 2012). By 1965-66, supplies increased by 17% and 76% to these organisations.

In the late 1960s and early 1970s, the dairy industry began to decline as the United Kingdom increased trading with the European Union (Telfer and Miller 2001) and the Australian butter export market collapsed in 1973 when the UK became a member of the European Union. Economical pressures saw a shift to beef production and forestry in Rollands Plains, with a de-intensification of land use practices. In the 1979 aerial imagery, a Poplar industry had developed to serve in the manufacture of matchsticks (Figure 16) which was maintained until the early twenty-first century. Hobby-farming and beef cattle are currently the main land use practices in the Wilson River Catchment, with some dairy and corn fodder production in the foothills of the valleys.

3.1.2 Aggregate extraction

Extractive industries began operating on the lower Wilson River in 1965-66, though local gravel extraction had been unofficially undertaken from as early as the 1920s (Cohen and Telfer 2006). A historical analysis of aerial imagery indicates that gravel bars did not proliferate along the Wilson River until the 1950s to 1960s, making gravel extraction accessible and economically viable. Significant expansion of the industry occurred during the 1970s and continued to operate up to 1995 (Royalty Branch of the Department of Mineral Resources, after Cohen and Telfer 2006). Conservative estimates indicate 1.045 million tonnes, or 614,740 m³, of material was extracted over 29 years. This is likely to be an underestimate of the actual amount extracted as records remain incomplete and do not account for unofficial gravel extraction (Cohen and Telfer 2006).

These records are indicative of heavy extraction along the river and it is highly likely extraction rates far exceeded sediment recharge rates. Guidelines for river protection and sustainable yields were nonexistent and in the early 1990s gravel extraction was justified as a strategy for increasing bank stability (Resource Planning Pty Ltd 1990). Bed-level lowering of up to 1.5 metres has occurred in the vicinity of gravel extraction though it was perceived that “the benefits of extraction for bank stability outweigh the possible detrimental effects of bed lowering” (Resource Planning Pty Ltd 1990).
3.1.3 History of rehabilitation works

The Wilson River has experienced significant changes in channel morphology since the arrival of Europeans. These changes are related to the settlement and land use history that has occurred throughout the catchment over the last 200 years and in the last two decades numerous rehabilitation projects have been implemented to stabilise the Wilson River (Appendix A). These works have been guided by a variety of catchment-style geomorphic, fluvial and Departmental Rivercare assessments. Rehabilitation has included channel realignment, rock revetment and bench construction, rock ramp bed controls, brush fencing and stock exclusion fencing. More recently, root ball installation (Broderick and Menzies, 1999) and revegetation plans have been implemented with a dominant focus on bank protection downstream of the zone of incision recognised by Cohen and Brierley (1999).

After identification of this knickzone, in September 2001 four rock girdles (RGs) were constructed at the upstream extent of the study reach (Figure 5) as a bed stabilisation attempt. Subsequent bank protection of rock toe revetment, bank battering and revegetation downstream to Scotts Plains Road (Figure 5). Repeated outflanking at the Scotts Plains Road crossing initiated the addition of a large amount of rock to form channel-spanning rock ramp. A 2006 re-survey of the site and assessment of remediation projects determined bed-level incision was ongoing, with bank erosion persisting as a major issue along the lower Wilson River (Cohen and Telfer 2006). In late 2007, Stage 1 works were undertaken within the incising sub-reach (Figure 5) involving the construction of three elevated log sills (ELSs), pile fields and root balls. After a series of floods in 2009 several hectares of floodplain was eroded at Pear Tree Hole (PTH) downstream of the knickzone (Figure 5). This spurred the construction of eight engineered log jams (ELJs), two pile fields each involving rows of 0.3 m diameter pins, channel realignment, rock wall emplacement and native-species revegetation in January 2010 (Stage 2 works).

Detailed post construction specifications for these works are unavailable. Specifications for the Stage 2 works at Pear Tree Hole are limited, with insufficient details of the logs used to accurately undertake force-stability analyses. The subsequent log stability assessments (after Shields et al. 2000) are unlikely to effectively predict the stability of the Wilson River ELJs, however, summary details can be found in Appendix B. All analyses used a dry weight wood density of 0.8 kg.m⁻³ and an assumed stream velocity of 6 m/sec.
Figure 6 (A) Location of Stage 2 works at Pear Tree Hole; (B) ELJ Deflector Groyne 1 (ELJ1) as constructed; and (C) ELJ Deflector Groyne 4 (ELJ4) and after three bed mobilising floods. Note partial undermining of the structure on the proximal side (left of image). ELJ1 failed after these floods.
3.2 Geological setting

Extending inland to the Great Dividing Range, the Wilson River catchment lies within the Lachlan Fold Belt. The catchment is dominated by early Carboniferous Boonanghi and mid Carboniferous Byabarra Beds comprising mudstone, lithic sandstone and conglomerate (Hastings 1:100 000 Geological Series Sheet). The intrusive upper Permian Gundle Granite can be found in the mid to upper catchment, and its boundary with the Byabarra Beds represents a major break in slope and the beginning of floodplain development (Cohen and Telfer 2006). The study reach is located within Holocene floodplain sediments underlain by lithic Byabarra Beds, with bedrock outcropping at several locations within the study reach (Figure 5).

The study reach is a coarse gravel bed river setting, consisting of coarse gravel with distinct surface armouring of small to large cobbles. The surface grain size displays a uni-modal, normal distribution with an average median grain size of 68 mm and $D_{\text{max}}$ of 207 mm (Table 3). A hydrogeomorphic assessment conducted in 2006 established complete mobilisation of the entire grain-size fraction in study reach above a discharge threshold of 394 m$^3$s$^{-1}$ (Cohen and Telfer 2006). This is in agreement with field observations following the 2012 floods.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$D_{5}$</td>
<td>9</td>
<td>26</td>
<td>29</td>
<td>28</td>
<td>23</td>
</tr>
<tr>
<td>$D_{16}$</td>
<td>28</td>
<td>35</td>
<td>38</td>
<td>37</td>
<td>35</td>
</tr>
<tr>
<td>$D_{35}$</td>
<td>42</td>
<td>53</td>
<td>54</td>
<td>52</td>
<td>50</td>
</tr>
<tr>
<td>$D_{50}$</td>
<td>57</td>
<td>77</td>
<td>70</td>
<td>66</td>
<td>68</td>
</tr>
<tr>
<td>$D_{84}$</td>
<td>109</td>
<td>115</td>
<td>104</td>
<td>107</td>
<td>109</td>
</tr>
<tr>
<td>$D_{95}$</td>
<td>141</td>
<td>128</td>
<td>127</td>
<td>144</td>
<td>135</td>
</tr>
<tr>
<td>$D_{\text{max}}$</td>
<td>231</td>
<td>157</td>
<td>226</td>
<td>215</td>
<td>207</td>
</tr>
</tbody>
</table>
3.3 Climate and Hydrology

It is beyond the scope of this project to undertake a detailed assessment of the climatic and hydrologic conditions of the Wilson River. However, this section provides a brief summary of the pertinent hydrologic trends affecting the instability and rehabilitation foci of the Wilson River. Climate has been assessed using three rainfall stations throughout the catchment and a high-quality long-term rainfall station at Port Macquarie (Table 5). Port Macquarie has been recognised as the only high-quality long term rainfall station of these four (Lavery et al. 1991). Regression analyses were performed for each Wilson River stations to determine correlation of datasets. Though spatial variability in rainfall characteristics and individual storm cells will create explicit differences between stations, statistical analyses of variance (ANOVA) indicate all datasets are highly correlated with Port Macquarie rainfall data (Table 4).

<table>
<thead>
<tr>
<th>Station No.</th>
<th>Station Name</th>
<th>DF</th>
<th>F Ratio</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>60031</td>
<td>Telegraph Point (Farrawells Road)</td>
<td>1</td>
<td>55057.53</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>60052</td>
<td>Upper Rollands Plains (Greenacres)</td>
<td>1</td>
<td>10321.23</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>60071</td>
<td>Rollands Plains</td>
<td>1</td>
<td>11864.76</td>
<td>&lt;0.001</td>
</tr>
</tbody>
</table>

Figure 7 Total annual rainfall with a 10-year moving average for the Wilson River Catchment (grey line). Dashed line represents the long term average annual rainfall for the catchment.
As with other east coast Australian catchments, rainfall throughout the Wilson River experiences considerable inter-annual variability (Figure 7). Table 5 summarizes the monthly average rainfall for the Wilson River Catchment. On average, February and March are the wettest months of the year across all stations, whereas August to September are the driest. Large rainfall events that correlate with peak over threshold (POT) floods (394 m³s⁻¹) are commonly associated with sub-tropical low pressure systems over the east coast of Australia. These systems prevail in summer months following a southerly shift in the Intertropical Convergence Zone (ITCZ). Synoptics for these events can be found in Appendix C.
The analysis of mass residual curves for rainfall at key gauging stations (Figure 8) indicates several cyclic rainfall epochs within the long term period. This analysis plots the cumulative deviation from a reference point to determine arithmetic trends within the data set, such as rainfall (Kraus 1956, Riley 1988) and streamflow (Smith 1995). Two distinct rainfall regimes are apparent, with consistently wetter, above average precipitation indicated by a positive gradient in the mass residual curve (Figure 8) and periods of generally drier, below average precipitation indicated by a negative gradient. Within these regimes, periods of average precipitation are represented by a lack of positive or negative trends. These regimes appear to last for between one to several decades and correlate with secular climatic trends for south-eastern Australia (Erskine and Warner 1988; Nicholls and Lavery 1992; Kirkup et al. 2001).

The division between these periods has been selected by the highest/lowest percentage cumulative mean departure and correspond for available stations (Figure 8). These rainfall trends do not occur in a systematic cycle. These trends are summarised in Table 6 and include:

- From 1886 to 1900 above average rainfall occurred
- The period from 1901 to 1920 was drier than the two preceding periods and below average rainfall occurred, followed by relatively average levels of rainfall occurred between 1920 and 1938, and another decade of below average rainfall
- From 1948 to 1978 rainfall was above average as with most of coastal NSW
- In 1990, drier than average conditions occurred and prevailed to the late 2000s
- From 2008, rainfall has been consistently above average and may indicate the break to another wet period
Prior to 1886, there was relatively average rainfall. Anecdotal evidence indicates major floods occurring in the late 1850s to 1860s (1862 floods), and may indicate a wet period through to the early 1870s (Cooper 2012). In September 1857, a flood large enough to inundate the floodplains with up to two feet of water has been documented (The Maitland Mercury & Hunter River General Advertiser NSW, 05/07/1857). However, a lack of complete rainfall or discharge records prevents further details on this wet period being established. Between wet/dry periods, a recognisable shift in average annual rainfall characteristics occurs. Average annual rainfall during the drier periods is approximately 550 mm yr\(^{-1}\) lower than during the wet periods. For the long term station records average rainfall is around 1300 mm yr\(^{-1}\) at Telegraph Point to 1500 mm yr\(^{-1}\) at Port Macquarie. There is a rainfall gradient of 1000 mm yr\(^{-1}\) to 1250 mm yr\(^{-1}\) during dry periods, respectively. During wet periods, average annual rainfall exceeds 1500 mm yr\(^{-1}\) at Telegraph Point and 1700 mm yr\(^{-1}\) at Port Macquarie (Table 6). These average trends are supported by the short term records of Rollands Plains and Upper Rollands Plains stations.

Previous studies (Cohen and Telfer) have determined the period of above average rainfall experienced from 1948 continued until 1990 in the greater Hastings Catchment, whereas in other areas of the state the break point to has been identified as 1978/79. However, a thorough assessment of the rainfall across the three open stations in this study reveals precipitation appeared to return to average rainfall conditions from 1979, lasting until this 1990 break. From this point through to the mid-late 2000s, pronounced levels of below average rainfall have been recorded.

Table 6 Historical rainfall trends

<table>
<thead>
<tr>
<th>Dry Periods</th>
<th>Average Periods</th>
<th>Wet Periods</th>
</tr>
</thead>
<tbody>
<tr>
<td>1900 – 1920</td>
<td>1874? – 1886</td>
<td>1862 – 1874?</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2008 &gt;</td>
</tr>
</tbody>
</table>

Average annual rainfall variation (mm yr\(^{-1}\))

| 1000 - 1250 | 1300 - 1500 | 1500 - 1700 |

Discharge has been assessed using hourly discharge data from the Wilson River Avenal stream gauge (Stn 207014) obtained from NSW hydrologic agencies (Figure 5b). The Avenal streamflow gauge has been operating since 1984 with near continuous data (108 days of missing record; 82 = 0 mm; 20 days >0 mm rainfall; 5 days >15 mm rainfall; 1 day >50 mm rainfall).
rainfall). The gauge is downstream of the confluence of Bril Bril Creek tributary before the confluence of the Wilson River and Maria River and above the tidal extent of the Wilson River. Although discharge values are not truly representative of the study reach, it is certainly reflective of the streamflow conditions. Unfortunately, no long term record of stream flow exists for the Wilson River catchment. Although rainfall cannot accurately define discharge or flood events, it will be used here as a surrogate to complement hydrologic activity.

Peak instantaneous discharge was considered preferential to daily average flow due to narrow flood peaks and significantly underestimated values obtained by daily averaging. Hourly discharge rate in megalitres was converted to cubic metres per second (m³.s⁻¹) using a conversion of

\[ m^3 s^{-1} = \frac{ML}{86.4} \]

Flood frequency analyses were performed using FLIKE 4.50 (Kuczera 2001) for probability modelling of the annual-maximum and peak-over-threshold, or partial, flood series. A discharge-threshold for the partial series was established at 394 m³.s⁻¹ as it is the flow necessary for entire bed fraction (>D₉₅) mobilisation (Cohen and Telfer 2006). Independence of flood events was determined using a method adapted by Potter and Pilgrim (1971) for eastern NSW. An inter-flood period of three calendar days between the lee (falling limb) and stoss (rising limb) of separate flood events was stipulated, resulting in the number of independent flood events broadly equal to the number of years of record. Though the log-Pearson III frequency distribution is the most widely accepted statistical distribution model in Australia for flood frequency analysis (Ladson 2000; Engineers Australia 2001), the Generalised Pareto distribution has been shown to provide the most suitable approximation of flood modelling in eastern Australia (Vogel et al. 1993; Rustomji 2009). For this reason, a Bayesian analysis using the Generalised Pareto frequency distribution was performed on both the annual maximum and partial flood series. Comparative flood frequency results can be found in Appendix C using daily-average-flow, hourly flow and log-Pearson III, Generalised Extreme Value and Generalised Pareto distributions.
The mean daily discharge throughout the 28 years of operation is 7.0 m$^3$s$^{-1}$ and a mean annual discharge of 2480 m$^3$s$^{-1}$. Table 7 provides probabilistic peak flow estimates for floods of given ARI magnitude. Using this flood frequency analysis, it is expected that a flood of geomorphic significance (a flood capable of mobilising the entire bed fraction; >394 m$^3$s$^{-1}$) will have a return interval between 1.25-1.5 years. The flood of record occurred in February 2009 with a peak instantaneous discharge of 1845 m$^3$s$^{-1}$ (Figure 9). This equated to a 48-year annual recurrence interval (ARI) flood event. From the peak-over-threshold (POT) analysis, the last five years has experienced a dramatic increase in flood activity in comparison to the rest of the streamflow record (Figure 9b). Not only has the flood of record occurred within this period, but four of the ten largest peak events recorded since 1984 have occurred within this time. In total, ten

Figure 9 Flood history analyses for the Wilson River at Avenal (Stn 207014) using the (A) annual series and (B) peak over threshold series displaying peak instantaneous discharge for independent floods above the one year ARI. (C) Southern Oscillation Index for the period of gauging. Negative values indicate El Niño periods (red) with La Nina events (blue) indicated by positive values; note the correlation of flood activity and SOI value. Recurrence intervals are based on the Generalised Pareto distribution flood frequency analysis.
independent POT floods have occurred since September 2007, with an additional twelve above the annual recurrence interval estimate. A comparable period of flood activity occurred within a 1988 – 1990 period, in which seven POT floods occurred over a 24-month period.

Table 7 Estimate of peak flood discharge (m³ s⁻¹) using Generalised Pareto flood frequency analysis

<table>
<thead>
<tr>
<th>ARI (yrs)</th>
<th>Expected Parameter quantile</th>
<th>Monte Carlo 90% quantile probability limits</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>116</td>
<td>99</td>
</tr>
<tr>
<td>2</td>
<td>708</td>
<td>624</td>
</tr>
<tr>
<td>5</td>
<td>1285</td>
<td>1166</td>
</tr>
<tr>
<td>10</td>
<td>1552</td>
<td>1410</td>
</tr>
<tr>
<td>20</td>
<td>1727</td>
<td>1586</td>
</tr>
<tr>
<td>50</td>
<td>1870</td>
<td>1716</td>
</tr>
<tr>
<td>100</td>
<td>1936</td>
<td>1777</td>
</tr>
</tbody>
</table>

Both of these periods of high flood activity correlate with positive southern oscillation index (SOI) values. Additionally, negative SOI values correlate with a reduction in flood activity (Figure 8). The El Niño-Southern Oscillation provides the most important climatic driver for rainfall and flood conditions along the east coast of Australia (Meinke et al. 2005).

Since the construction of the elevated log sills (ELSs) ten floods exceeding complete bed material entrainment have occurred (Figure 11 - F1-F10), with three of these floods experienced since construction of bank protection ELJs. It is generally considered that geomorphically effective floods have a discharge capable of mobilising the median particle size (Ackers and White 1973). However, considering the quantity of floods above entire bed-fraction
(grain size >D₉₅) entrainment in the post construction period, this discharge has been used as a critical threshold. A growing appreciation in hydrogeomorphic studies is the use of time over threshold rather than the peak above this threshold (Brooks et al. 2004; Brooks et al. 2006a). This is relatively understood that once a critical threshold is exceeded, the bed material remains mobilised for the duration above this level and will have a corresponding impact on the channel.

On this basis, the Wilson River has experienced a period of geomorphic effectiveness since the construction of remedial ELJ works. The June 2009 and December 2010 were negligible, with duration above threshold seven hours and two hours, respectively (Figure 11). The other floods range from 13 hours to 45 hours. The most geomorphically effective floods occurred in May 2009 (F4, hours > Qcrit = 45) and June 2008 (F8, hours > Qcrit = 40). Considering this analysis, despite the May 2009 having a flood peak almost half that of the flood-of-record in February of the same year (F2 hours > Qcrit = 31), it was potentially as geomorphically important as this earlier event with bed entrainment occurring for an additional 14 hours.
Figure 11 Flood hydrograph from Avenal (Stn 207014) post-construction floods referred to in the text (F1-10). The estimated reach-averaged critical threshold for bed mobilization is superimposed on each plot (dashed line). Shown on each graph is the number of hours flow exceeded the threshold.
4. METHODS

4.1 Field survey

The digital elevation model (DEM) for this study was created from measurements collected using a combination of real time kinematic (RTK) survey equipment (integrated Trimble® R7 and R8 GNSS System) and a total station (Trimble® S3). Survey measurements were collected using GDA94 MGA Zone 56 in the horizontal plane and AHD71 as the height datum. A base station was established on a state survey marker located at PTH and differentially-derived temporary benchmarks were used to move across the study region. Use of a base station allowed for real-time corrections of points measured with the GPS system, enabling the production of a sub-decimetre dataset. The total station was used to obtain values for deep water sites and where dense riparian canopy prevented accurate measurements. Measurements were obtained over two surveying periods in February and April 2012. No hydraulically significant flows were recorded between survey periods, and it is therefore assumed that no significant geomorphic changes occurred within this time. A topographic survey of the longitudinal channel profile, following the thalweg, was conducted through the three kilometre reach between the most upstream stabilisation structure, rock girdle 1, and Scott's Plains Crossing (Figure 5). Relevant features and channel morphology were recorded, including the locations of scour pools, riffles, bars, bank-full flow separation lines identified by flood debris, high bank, water level, rehabilitation structures and flood debris. Field observations and digital photographs were taken throughout the field trip.

Bed material data was collected using the Wolman method (Wolman 1954). Three transects of 30m was conducted on bars adjacent to prominent meander bends, with the B-axis of a hundred randomly selected particles measured along each transect. Particle size probability distribution was plotted as an average of the three transects. These were supplemented by additional bedload data from Cohen and Telfer (2006).

4.1.1 Background on previous time series

Previous survey data has been collected through the study area as part of an ongoing assessment program by PMHC for the rehabilitation works. These surveys include;
- March 2004  A limited post-construction thalweg survey of rock girdle structures
- May 2006  A thalweg survey of the lower Wilson River, from the confluence of the Marlo-Merrican Creek tributary to Avenal
- April 2008  Limited Post-construction thalweg survey of the 'Wilson knickzone' (Cohen and Telfer 2006)
- September 2008  Post-flood survey of the 'Wilson knickzone' (Cohen and Telfer 2006) and pre-construction survey of PTH for structural designs
- August 2009  Pre-construction survey of PTH after 2009 floods and associated significant readjustment of bank margins
- March 2011  Post-construction survey of riffle crests through the 'Wilson knickzone' (Cohen and Telfer 2006)

4.3 Spatial analyses

ArcGIS 10 (ESRI 2010) was used to integrate the point data from field surveys. Data points were downloaded as CSV files from individual survey periods, and the accuracy of each point was visually assessed against a threshold value (100 mm). Data that exceeded this value were excluded, creating a highly accurate dataset. A time series comparison of bed level was conducted using thalweg survey data. Points were manually selected to construct a longitudinal profile and plotted against profiles from previous years. Differences between morphologic features (riffle location, riffle height, pool depth) were recognised by creating a time-series comparison of longitudinal profiles. Where time-series changes in features occurred, spatial analysis using ArcGIS determined the real difference between time series as opposed to apparent changes from long profile readjustment associated with lateral migration and channel length.

Aerial photographs were collected for the years 1943, 1965, 1969, 1989 along with orthorectified imagery from 1997, 2003, 2005, and 2009 to determine historical planform changes and bank migration rates. This resource collection represents the readily available aerial imagery for the study reach. A previous study of historical changes on the Wilson River (Cohen and Telfer 2006) utilised parish maps to determine sub-reach changes and cut-offs occurring prior to 1943. Although available for use, these maps were excluded due to their lack of
sufficient detail and scale, as evaluated for this research project. Imagery was georeferenced to the 2009 ortho-rectified aerial imagery using a dataset of historical landmarks as ground control points and a second-order polynomial transformation. Ground control points were predominantly focused around the study reach and channel rather than across the extent of the aerial photographs. Calculated root mean square errors (Table 8) are representative of the maximum error between ground control points. The real spatial error of channel bank position is constrained within these errors, but cannot be more accurately determined. High-bank channel margins were digitised from images for both the left and right bank. It was assumed that no change in bank position occurred where vegetation encroachment and bar stabilisation was apparent in later years, as these represent in-channel features rather than a re-established high-bank. A 2012 high-bank channel margin was digitised using field surveyed GPS points.

<table>
<thead>
<tr>
<th>Year of imagery</th>
<th>RMSE (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1943</td>
<td>2.029</td>
</tr>
<tr>
<td>1965</td>
<td>3.439</td>
</tr>
<tr>
<td>1969</td>
<td>3.582</td>
</tr>
<tr>
<td>1979</td>
<td>2.793</td>
</tr>
<tr>
<td>1989</td>
<td>2.825</td>
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<tr>
<td>1997</td>
<td>3.027</td>
</tr>
<tr>
<td>2003</td>
<td>2.166</td>
</tr>
<tr>
<td>2005</td>
<td>1.751</td>
</tr>
</tbody>
</table>

USGS-developed Digital Shoreline Analysis System, DSAS 4.2, was used to quantify spatial variations in bank position using Net Shoreline Movement Statistics. DSAS 4.2 is an ArcMap extension that calculates change statistics for multiple historical boundary positions by applying a cast from a baseline polyline between a vertex-start and vertex-end. Transects are placed at regular intervals from the cast and measurements of the distance from the baseline boundary to other boundaries along each transect can be derived. Developed for coastal and shoreline research, the software is capable of producing change statistics for any boundary with discernable time-series changes and is suitable measuring channel migration (Thieler et al. 2009). After digitisation of channel margins, three distinct zones of lateral migration were visually apparent within the study reach and analysed individually (Figure 12B). A transect feature class with a 4m transect spacing was cast across each migration zone from the 1943 baseline margin (Figure 12A). A smoothed baseline cast of twenty metres was used to orient
transects perpendicular to bend curvature rather than to the exact polyline angle at the baseline point (Figure 12B). Once the transect feature classes were created, change statistics were computed between sequential time series to determine the distance of channel migration. Change detection was only considered true if migration exceeded the combined RMS error of both time series (Table 8).

Bank migration has been plotted as an averaged distance for each zone between time series, reported as an end point migration (total migration within a given period) and normalised to an annual rate of erosion. Normalisation assumes a time-dependent standard process of progressive entrainment without accounting for mass failure, which has been shown to be a significant bank erosion process on the Wilson River. Averaging migration data to an annual rate, however, is the only feasible technique to account for differences in time periods between aerial imagery.

![Figure 12 Diagrammatic representation of DSAS transect calculation (Himmelstoss 2009) (A) and location of transect envelopes through study area (B)](image)

### 4.4 Statistical analyses on topographic data

#### 4.4.1 Time-series modelling

The reach was divided into five visually amenable sub-reaches on the basis of characteristic differences in bed and bank stability (Table 9). Normality of the data was verified by inspecting plots of studentised residuals. Data was explored using Two-Way ANOVA to assess the
interaction between sub-reach treatment and survey periods, and the individual significance of these parameters. Through this experimental design it was possible to ascertain whether variance and the magnitude of variance were operating at intra-reach scale. Results are presented with relevant test statistic (f) and probability (p).

<table>
<thead>
<tr>
<th>Sub-reach</th>
<th>Chainage</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>360 - 640</td>
<td>Above zone of remediation works; bed and banks stable</td>
</tr>
<tr>
<td>II</td>
<td>640 - 940</td>
<td>Primary zone of remediation works and ‘knickzone’ to vegetative constriction meander bend; bed unstable; laterally stable</td>
</tr>
<tr>
<td>III</td>
<td>940 - 1480</td>
<td>Below zone of remediation works, bed unstable; dominant lateral stability</td>
</tr>
<tr>
<td>IV</td>
<td>1480 - 2200</td>
<td>Bed unstable, banks laterally unstable; to below ELJs</td>
</tr>
<tr>
<td>V</td>
<td>2200 - 2800</td>
<td>Bedrock pool to Scott’s Plain Road Crossing</td>
</tr>
</tbody>
</table>

4.4.2 Pool-riffle morphodynamics

Pool-riffle morphodynamics were measure from time-series surveys (see part 4.1) of comparable point resolution. Wavelength was measured as thalweg distance between riffle crests (Figure 13) and amplitude defined as half the residual pool depth; the difference between the pool bottom and downstream riffle crest (Lisle and Hilton 1992; Tonina and Buffington 2007). Pool-riffle amplitude was determined for individual waves, or pool-riffle sequence, to avoid bias of the trending process and assumed local relationships between pools and riffles. These dynamics were individually explored using ANOVA.

Figure 13 Longitudinal interpretation of a pool showing morphodynamic measurements related to wavelength and amplitude characteristics (modified from Lisle and Hilton 1992)
4.4.3 Scour predictions and comparison

Observed scour utilised pre-construction (August 2009) and post-construction (April 2012) survey data for two key ELJs at PTH; ELJ4 and ELJ5. Three-dimensional DEMs were created for both surveys utilising inverse distance weighted (IDW) interpolation in ArcGIS 10. The 2009 elevation surface was deducted from the 2012 surface using the raster math function to create a 2m-grid change detection map. A high resolution surface of the post-construction scour associated with the mega-deflector ELJ4 was created from detailed survey point data.

Empirical scour predictions for the above-mentioned ELJs were derived using the Farraday and Charlton method (Farraday and Charlton 1983) for gravel-bed channels. Design flow velocities were derived from tractive stress calculations by ELJ construction design notes and several estimates of Manning’s roughness co-efficient (Chow 1959) with two measured values of gradient, surveyed bed-level slope and peak flow water level using flood level debris. Critical scour depth multipliers were used from ELJ orientation to flow (Rutherfurd et al. 2000). This was compared with maximum observed scour depth values.
5. RESULTS

The Wilson River, like many other coastal river systems has undergone dramatic geomorphic changes throughout the twentieth century which is still ongoing. Section 5.1 presents the analysis of the historical channel changes, whilst Section 5.2 and 5.3 present results that assess the effectiveness of the rehabilitation that has been occurring since 2006.

5.1 Planform changes, bank erosion rates and knickpoint migration on the Wilson River

Ortho-rectified and georeferenced aerial photographs were used to determine the position of the destabilising front – ‘the knickzone’, following on from Cohen and Telfer (2006) who examined geomorphic changes on the Wilson River from 1943 to 2006. This assessment determined the position of the knickzone as the boundary between stable upstream reaches and actively eroding downstream reaches, where active bar formation was an obvious indicator of destabilisation. Recent locations of the knickzone (1998-2006) were detected from longitudinal thalweg surveys as areas of ongoing upstream migrating bed lowering. Figure 14a-b shows both the rate of knickpoint migration and position of the knickzone. This figure demonstrates a progressive reduction in knickzone retreat rate, from 200-250 m.yr⁻¹ in the mid twentieth century to 100-150 m.yr⁻¹ by the 1990s. An exception to this trend occurred between 1965 and 1969 with approximately 2.4 km of the Wilson River destabilised within this period at an annual rate of 600 m.yr⁻¹. Knickzone retreat was initiated by a meander cutoff at Avenal prior to 1943 (Cohen and Telfer 2006) and then progressively migrated upstream approximately 10 km. By 1989 the knickzone had migrated to the lower end of the study reach and by 1997 it had receded into the middle section of the study area. By 2006 it had reached its present location. No detectable evidence of further upstream migration is apparent in aerial imagery post construction of grade control structures within the study reach in 2007 (Figure 14).
Figure 14 Upstream knickzone retreat along the Wilson River. (A) Normalised annual knickzone retreat rates with (B) locations determined from aerial imagery. Knickzone locations have been qualitatively determined as immediately upstream of laterally eroding reaches, therefore represents the minimum upstream location. 2006 and 1997 locations have been determined from longitudinal profile surveys (Cohen and Telfer, 2006).

Figure 15 highlights bank erosion across three locations within the study reach, the Pear Tree Hole (PTH) composite meander bend and the downstream bedrock pool, with Figure 15a reflecting averaged bank erosion at each site between time series and Figure 15b representing normalised annual bank erosion rates across sites. Annual rates provide a mechanism of comparison between aerial imagery by normalising the data to periods between photo surveys. However, it is likely that bank erosion is event-dependent and therefore not occurring on an annual basis (see Chapter 6). Progressive increases in bank erosion have occurred throughout time, with the greatest rates occurring recently, from 2009 onwards. The increases have predominantly occurred in Zone 2 at PTH (Figure 15c). Ongoing bank erosion has largely been focused at tighter meander bends lacking vegetative protection, with erosion of up to 78 m produced from a single flood in February 2009 (Figure 11).

From analysis of the aerial imagery little geomorphic change had occurred within the study reach between 1943 and 1979 (Figure 16), remaining largely stable and well vegetated, with riparian vegetation becoming denser within this period. By 1989, with the arrival of the knickzone, bank erosion had begun upstream of the bedrock pool at PTH followed by major destabilisation and expansion by 1997 (Figure 9), most likely during the 1995 and 1996 floods. Despite the floodplain’s dominant composition of highly resistant fine sediments, an unconsolidated sub-layer of a coarse grained deposit is now being selectively eroded by the river.
Figure 15 Average bank migration/erosion rates at PTH lateral migration zones represented as (A) absolute bank migration with standard error; (B) normalised annual bank migration rates at lateral migration zones and (C) historical right-bank channel margins in Zone 1 and Zone 2. Flow is from left (zone 1) to right (zone 2).
The PTH composite bend appears to be acting as two distinct zones of lateral expansion following the 1989 expansion (Figure 15c). These zones have been separated by a vegetated inset unit on the convex bank where comparatively less bank migration has occurred. In Zone 1 (Figure 15b), limited bank erosion occurred between 1989 and 2009 despite extensive channel expansion immediately downstream. After initial erosion in 1989, subsequent bank erosion was largely restricted to the upper extent of the zone 1 (Figure 15c) in what appears to be a locally lateral zone of adjustment. This has been succeeded by a progressive downstream translation of bank erosion, with the greatest rate of erosion occurring in the most recent time period. Zone 1 experienced a two-fold increase in bank full channel width between 2009 and 2012, with over 20m of bank erosion following the 2009 flood events and an additional 30m of erosion between December 2010 and February 2012 (Figure 15a).

Up to 200 m erosion of the right bank has occurred downstream of the vegetated inset unit, with approximately 94500 m$^3$ (using an average depth of 3.54 m from survey data) of floodplain sediments liberated into the channel. Following major channel expansion by 1997 (Figure 16), the former low flow channel has been preserved as a flood chute with vegetative stabilisation of a mid-channel bar. Zone 2 has remained laterally active along unprotected alluvial margins, with considerable ongoing expansion and the progressive development of large gravel bars throughout the study reach. The extensive expansion occurring between 1989 and 1997 involved the removal of a stabilised, vegetated point bench upstream of the bedrock pool (Figure 16 - see yellow circle). Persistent erosion at this location has resulted in a local reduction of low-flow meander and channel length. The implications of this realignment are discussed in the following section (Chapter 5.3)
Figure 16 Historical channel changes on the Wilson River study reach, PTH. Note the removal of a vegetated bench in 1997 (yellow circle) and subsequent low flow channel realignment from 2005-2011 immediately above the downstream bedrock pool. The completed rehabilitation engineering works can be seen in the 2011 image. Flow is from top of image to bottom; all images are georeferenced. The red line in 2011 image reflecting the 1943 channel centreline.
5.3 Effectiveness of remediation works and ELJs

5.3.1 Long section bed-level changes

On visual comparison of the survey data between June 2006 and April 2012 it is evident that considerable variability amongst survey periods has occurred despite the statistical magnitude of variance remaining constant (Figure 22). The survey data displays a broad trend of riffle aggradation for most of the reach between recent years. Of the 3 km reach, areas of scour and aggradation can be recognised within an upstream, stabilised sub-reach and downstream, destabilised sub-reach (Figure 17). Downstream of rock girdle 2 (RG2) the bed has predominantly aggraded, with significant aggradation of the riffles immediately upstream of the PTH stabilisation structures (Figure 17a). Accelerated lateral migration and channel adjustment has resulted in spatial variation of pool and riffle positions, though no absolute or systematic changes have occurred in the pool-riffle morphometry (Figure 21).

Degradation of riffle crests and bank erosion above the most upstream stabilisation structure (RG1) suggests potential bed-level lowering (Figure 17 at 25 m). The bed at this point has been previously recognised as the upstream extent of the knickzone (Cohen and Telfer 2006; Telfer 2008) and as such has not been included in an ongoing monitoring programme by PMHC. The 2012 dataset indicates riffle crests have migrated upstream by up to 25 m along with 250 mm of potential bed degradation between 2006 and 2012 (Figure 17). The lack of monitoring above the knickzone, however, prevents determination of whether an overall trend of bed degradation is occurring.

Downstream of the RGs and ELs, lateral instability and associated channel expansion has been accompanied by bed aggradation, but with variable pool scour downstream of ELS3 (Figure 17). In the destabilised sub-reach riffle crests have considerably aggraded by up to 1.2 m since 2006 with 30m downstream translation of riffle position (Figure 17b at 1300-1800 m) and continued channel expansion (Figure 15c – Zone 1). Riffles have become longer and more uniform as pools have aggraded, though pool-riffle amplitude has been maintained with equivalent rise in both riffle and pool bed-level elevations. Significant bar development has occurred adjacent to eroding banks with a surface elevation approximately 2.5 higher than low-flow water level.
Figure 17 Comparative bed survey overview for the Wilson River knickzone at Rolland’s Plains from 2006 to 2012
A detailed comparative analysis of bed-level changes in the primary knickzone recognised in earlier geomorphological studies (Cohen and Telfer 2006) highlighted the changes associated with previous remedial works. Despite four channel-spanning rock structures installed in September 2001, a comparison of thalweg surveys undertaken in 2004 and 2006 indicated ongoing bed degradation of 0.25 - 0.5 m between the structures (Figure 18). Three ELSs were subsequently constructed to provide additional grade control in this over steepened sub-reach (slope of ~0.005) along with bank revetment and flood chute stabilisation. Detailed surveys undertaken since the construction of the ELS structures indicate that ongoing degradation has stopped. The sub-reach is considerably dynamic, however, with dramatic alterations to bed features due to natural LWD accumulations providing localised pool scour and riffle development. Despite this dynamic nature, riffle crests have reverted to elevations equivalent to 2004 values throughout the reach (Figure 18) despite eight bed-mobilising floods, including the flood-of-record in February 2009 with a 48 year return interval (see Chapter 3).

Significant planform changes and lateral instability has resulted downstream of this at PTH (Figure 15C), with up to 78 m of lateral migration and bed degradation of 0.4-0.8 m (Figure 17b at 1800-2200m) following a series of bed-mobilising floods in 2009. Bank revetment structures had previously been constructed in this area, with 70 m of rock toe revetment, five pinned rootballs and riparian revegetation in 2002 (Appendix A). These structures appeared to be successfully promoting pool scour and riffle aggradation. However, subsequent outflanking and failure occurred during the 2009 floods, necessitating the construction of eight ELJs, log pile fields and rock reinforcement. Since then riffles at PTH appear to have shifted to a phase of aggradation, with 0.4 m of riffle aggradation occurring between 2011 and April 2012 and scour
between 1.6 - 1.8 m of bed scour directly associated with ELJs since construction (Figure 23). Pool-riffle amplitude has increased in this sub-reach due to aggradation of riffle crests and formation of scour pools (Figure 17).

These aggradational trends are not recognisable at the tail of the PTH riffle zone, where systematic incision has occurred and gradient increased (Figure 19). The segment of the channel now represents the steepest section of the focus reach with a local channel grade of 0.0068. Channel realignment following the bed-mobilising floods in 2009 has resulted in channel straightening with a 30 percent reduction in thalweg length (Figure 19b). This sub-reach was recognised as a possible secondary knickzone (Cohen and Telfer 2006) with a slope 200% greater than the overall reach channel grade (0.002). Following progressive avulsion over a stable mid-channel bar, this section of the channel is now 400% steeper than the lower Wilson River (Figure 19). Pronounced bed level lowering, with up to 0.7 m of riffle crest degradation and accompanied downstream pool aggradation suggests that this section of the study reach is continuing to actively degrade.

![Figure 19](image.png)

Figure 19 Comparative bed survey of the channel realignment at the downstream end of PTH. April 2008 (grey) displays local grade prior to the meander cut off, with a slope of 0.0042 ($R^2 = 0.2363$). Post-cut off grade in 2012 (black) is 0.0068 ($R^2 = 0.4845$). Dashed lines are the mean trend of associate coloured profile

5.3.2 Bed-level dynamics in an incising gravel bed river

In order to investigate dynamic changes within the degrading channel of the study reach, riffle morphometry and bed-level residuals have been assessed between 2006 and 2012. Five time series of topographic surveys were analysed, each with equivalent data resolution. Differences in elevation through time were assessed at a reach and sub-reach scale using a two-way ANOVA analysis. These analyses demonstrate that no statistically significant changes in bed-level
variance at both the reach and subreach scale can be detected between individual survey periods ($F_{1607} = 0.0001, P = 0.9916; F_{4,607} = 1.5732, P = 0.1798$) (Figure 20).

Figure 20 Averaged sub-reach elevation pooled across years, with standard deviation. Values expressed as a pooled result due to lack of amenable differences. See Appendix D for detailed statistical results.

Over the survey periods there has been no change in pool-riffle amplitude or wavelength (Figure 21a-b). Riffle wavelength has decreased most markedly between March 2011 and April 2012, though remains within error of prior survey results (Fig 18a). This decrease recorded in the 2012 survey is predominately associated with natural LWD accumulations in the upstream sub-reaches. However, no statistical differences in variance of bed topography either before or after ELJ construction has occurred (Figure 22).

Figure 21 Comparative pool-riffle morphodynamics within the study reach.
Figure 22 highlights temporal changes in the spatial variation of sediment storage in the study reach. This plot of topographic residuals reflects deviation from the average elevation, highlighting areas of net sediment accumulation and scour. The reach is characterised by a pattern of alternating sediment scour and accumulation, however distinct changes have occurred in the reach since ELJ construction. In the region where grade control structures have been installed, the pattern of variability has increased and now exhibits a reach with alternating storage and scour (Figure 22c) whereas up until 2008 it was dominated by net accumulation associated with knickzone (Cohen and Telfer 2006). The residual analysis highlights that significant amounts of sediment are now stored upstream of PTH, in contrast to previous survey periods. Surveys undertaken in 2006 and 2008 reflect that this site was previously the greatest source of bed sediment within the reach (Figure 22a-b).

Figure 22 Downstream distributions of mean residual for elevation in (a) Jun 2006; (b) Sep 2008 and; (c) Apr 2012.
5.3.2 Remedial structures and pool scour

Detailed surveys were undertaken in August 2009 prior to the construction of ELJ structures and re-surveyed in 2012. Detailed surveys were undertaken for two scour pools associated with ELJ structures to compare with empirical scour predictions using the Farraday and Charlton (1983) scour estimation method. Velocity was derived using the Manning equation with estimates of channel roughness for gravel-bed rivers derived from Chow (1959). A water surface slope of 0.002 was derived from survey data on the 2012 flood debris, with another slope estimate of 0.0038 from bed-level gradient. Scour predictions resulted in a range of estimates, with those most conforming to observed scour associated with the water surface slope (Table 10). This broadly correlates to a mean velocity of 1.9 m.s⁻¹, a considerably lower value than the 4.65 m.s⁻¹ velocity utilised for the construction design guidelines (see Appendix E). Table 10 shows that predicted scour for ELJ4 ranges from 1.66 m to 4.0 m with an observed scour depth of 1.83 m and ELJ5 has a predicted scour depth between 1.16 m to 3.68 m. A larger range of scour estimates were predicted for ELJ5 due to its orientation to flow. As the structure is situated parallel to flow, hydraulic variable are less empirically predictable and thus a minimum scour and maximum scour produced to define the range of possible scour (Rutherfurd et al. 2000).

Table 10 Predicted scour for Deflector Jams 4 and 5 using the Farraday and Charlton (1983) method for estimating scour in gravel bed channels. Calculations were derived using variables of Manning’s n and channel gradient to determine flow velocity and compared with practitioner's design velocity (design V) and observed scours. Subscripts represent parameter values.

<table>
<thead>
<tr>
<th>Velocity Parameters</th>
<th>Predicted scour</th>
<th>ELJ4</th>
<th>ELJ5 - min</th>
<th>ELJ5 - max</th>
</tr>
</thead>
<tbody>
<tr>
<td>design V₄₆₅</td>
<td></td>
<td>4.00</td>
<td>2.76</td>
<td>3.68</td>
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<td>n₀₀₃, S₀₀₂</td>
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<td>1.75</td>
<td>2.33</td>
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<tr>
<td>n₀₀₂, S₀₀₃₈</td>
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<td>2.26</td>
<td>3.02</td>
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<tr>
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<td>1.98</td>
<td>1.39</td>
<td>1.85</td>
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<td>n₀₀₄, S₀₀₃₈</td>
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<td>1.80</td>
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</tr>
<tr>
<td>n₀₀₅, S₀₀₂</td>
<td></td>
<td>1.66</td>
<td>1.16</td>
<td>1.55</td>
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<tr>
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<td></td>
<td>1.83</td>
<td>1.61</td>
<td>1.61</td>
</tr>
</tbody>
</table>

Point data from the 2009 and the 2012 were used to construct a digital elevation model of the area around ELJ4 and ELJ5. These time intervals represent pre and post construction intervals and allow and assessment of morphological change associated with the construction of the ELJs. The development of the interpolated surfaces allows for the development of a change-detection map to provide detailed channel-wide changes in elevation (Figure 24). Though bed-level
lowering in the primary channel is apparent throughout the sub-reach, all dominant changes in depth are associated with scour upstream and adjacent to LWD. Reductions in low-flow channel elevation have been variable, with localised scours between 0.5- to 1.5 m and a maximum scour associated with DJF4 of approximately 2 m. The change-detection indicates considerable bar development has been initiated bank-side of these ELJ structures and on the convex left bank of the bend (Figure 24). ELJs above this structure have accumulated up to 2 m of sediment since 2009 and in some instances are now completely inundated by stable gravel bars. The structures, along with natural LWD recruitment, appear to be maintaining influence on channel form complexity, with associated scour immediately upstream and adjacent to ELJs with aggradation behind the structures and further upstream. The significant elevation differences associated with ELJ5 (Figure 24) are erroneous due to interpolation errors associated with the lack of in-channel points at this location. Detailed surveying of the proximal high bank and a distance-weighted interpolation has overpredicted the elevation of the channel by up to 3 m. Actual scour is between 0.5 m to 1.5 m, as noted in the observed scour of Table 10.

Figure 23 Scour depth associated with Deflector Jam 4 at PTH. The structure had been partially undermined, with maximum scour occurring mid-way along the face of the structure at a right-angle to flow.
Figure 24 Two-metre change detection DEM of PTH pre-ELJ construction (August 2009) and Post Construction (April 2012). Solid lines reflect low-flow channel and dashed line is the 2009 high-bank location. Elevation change in this area is not representative due to low point sampling and interpolation resolution in the 2009 surface.
6. DISCUSSION

The physical structure of a river channel is influenced by sediment calibre, discharge, channel roughness and structural attributes of the reach (Knighton 1998). Structural changes to the Wilson River channel associated with engineered log jams (ELJs) can be assessed based on the response to geomorphically effective floods. Geomorphic effectiveness has been assessed as the hourly duration above a critical threshold for bed entrainment (394 m³.s⁻¹, see Chapter 4). Providing a more relevant hydrological metric than instantaneous peak discharge, this measure indicates the flood’s capacity to perform work on the channel bed and banks.

Through this consideration, it can be demonstrated that the post-ELJ construction period (post 2007) has had the highest rate of geomorphically effective floods throughout the gauging record, with 3.8 hours of geomorphic work performed per month (Figure 25). Eight geomorphically effective floods have occurred in this period, each experiencing at least 10 hours of bed entrainment threshold-exceedance (Figure 11). Floods in February and May 2009 and June 2011 have been large magnitude-long duration floods, mobilising the bed for 31, 45 and 40 hours, respectively. The remaining bed mobilising flows have exceeded thresholds for 13 to 25 hours. This five year period from August 2007 to February 2012 has equated to an average of one flood above the annual recurrence interval every two and a half months and a total of over 200 hours of peak over threshold (POT) discharge (Figure 25). POT flood frequency is over 25 hours greater than the preceding 17 years, when threshold exceedance occurred at a rate of less than an hour per month (Figure 25) and POT discharges confined to few large magnitude-long duration floods. These floods are comparable to those experienced in more recent years, and by 1989 significant changes to the physical structure of the reach became evident.

Figure 25 Geomorphic effectiveness of wet and dry periods. The division of periods have been determined from analysis of cumulative deviations. Grey columns represent total hours over threshold on the left axis; and black points with the geomorphic effectiveness ratio to the right.
6.1 Incised channel behaviour: a history of disturbance

Past assessments of the role of climate have suggested a dominant influence of alternating flood and drought regimes on channel geometry in south-eastern Australia (Erskine 1999; Erskine and Warner 1999), though human impacts have had an unequivocal role in these changes (Brooks and Brierley 1997; Kirkup et al. 1998). The changes have been a direct response to altered hydraulic and boundary conditions at the time of large floods (Kirkup et al. 1998; Hubble and Rutherfurd 2010). Within decades, rapid catchment clearance, wetland drainage and the removal of riparian vegetation in many catchments transformed discontinuous, swampy watercourses and low-capacity channels to continuous, incised, over-widened channels with sand-slugged, ephemeral watercourses (e.g. lower Bega River - Brooks and Brierley, 1997). Similarly, extensive clearing of north coast catchments in the late twentieth century coincided with a series of large floods, catalysing channel widening through increased runoff and decreased bank strength (Nanson and Doyle 1999).

Similarly, the profound changes to the physical structure of the Wilson River throughout the twentieth century are directly related to anthropogenic-practices and are not a direct reflection of the flood history. Large magnitude floods occurred throughout the early settlement history of the Wilson River (The Maitland Mercury 16/6/1864; 9/7/1864) with no comparative evidence of geomorphic change or destabilisation. Only since the mid twentieth century, with the recent intensification of land use practices, has the magnitude of channel degradation been initiated. Channel incision on the Wilson River was initiated by a meander cutoff in the lower most reaches at Avenal. Whilst, artificial river straightening has been common in south-eastern Australia (Reinfelds et al. 1995; Lester and Boulton 2008), this cutoff on the lower Wilson was most likely a function of extensive clearing in the 1940s, which increased runoff and hydraulic forces. Erosional resistance has been reduced through riparian vegetation and LWD removal and streambank grazing (Table 1). Upstream propagation of the incisional front, the knickzone, has been facilitated by catchment clearance and further exacerbated by commercial aggregate extraction from 1966 to 1995. The initiation of aggregate extraction coincides with the highest rates of knickzone propagation from 1965 to 1969 as the channel destabilised at 600 myr⁻¹, more than double the rate of any other migrational phase (Figure 14). An analysis of the cumulative deviation for both rainfall (Figure 8) and runoff (Figure 10) indicate that this was not a period of above average hydrologic conditions, reinforcing the notion that the rate of knickpoint migration was elevated due to aggregate extraction.
Rates of upstream knickzone propagation on the Wilson River have progressively decreased since its initiation in the early 1940s (excepting the peak associated with aggregate extraction). There are two potential reasons for this. Firstly, a progressive reduction in knickpoint migration may well reflect documented long profile adjustments, as shown in flume experiments by Parker (1977). This work on drainage evolution has demonstrated that rates of knickpoint migration decrease over time as a function of discharge, producing an exponential decline in rates (Figure 26). This has also been demonstrated in the field in North America and in central Italy (Simon and Rinaldi 2006); where the decline is independent of sediment composition, fluvial setting and disturbance type. However, the variance in knickzone retreat rates exhibited on the Wilson River indicates it is not strictly conforming to a model of exponential decline.

An alternative interpretation is that the rates of knickzone migration on the Wilson River are driven by flood-dominated periods producing a stepped or punctuated change in rates (conceptually shown in Figure 25). This argument has previously been presented for theoretical changes to channel morphology in south-eastern Australia (Erskine and Warner 1988; 1999). The period from 1948 to 1978 was generally above average hydrologic activity within the region (Figure 7-8) with a break in 1978 to a drier period of below average rainfall. A corresponding break of 120 m.yr\(^{-1}\) in the rate of upstream knickpoint propagation (Figure 26) represents a punctuated change in the rate of retreat (Figure 26). Given the temporal trends in climate and hydrologic regimes, presumably the rate of degradation is also a function related to these trends with higher rates during wet periods than in dry periods.
Under the model of exponential decline, the decline in retreat rate results from a reduction of the knickzone gradient over time (Robbins and Simon 1983; Simon and Rinaldi 2006), though after rapid initial incision the retreat rate stabilizes (Figure 26a). This is apparent in the Wilson River retreat rates (Figure 26b), and the recent period of highly geomorphic flood activity should have resulted in the additional upstream destabilisation of 0.9 - 1.6 km of the Wilson River channel, depending on the influence of hydrologic activity. However, this has not been the case and recent observations suggest knickzone propagation has successfully been arrested despite the abundance of bed-mobilising floods. Contributing factors to the arrest include densely vegetated stable banks, a high natural LWD load and the grade control structures including both the 2001 constructed rock girdles and 2006-constructed elevated log sills. Considering the complexity of the interaction of these factors, it is highly unlikely that the specific contributions of these factors can be decoupled in order to determine the effectiveness of each mechanism. However, only the installation of the elevated log sills signifies the difference in a mechanistic distinction between the 2004-2006 periods, when 0.5 m of bed degradation occurred, and the 2006-2012 period in which riffles aggraded 0.5 m to 2004 levels. Recent observations suggest the elevated log sills have succeeded in preventing further bed incision.

Downstream, channel incision and expansion has exposed unconsolidated coarse gravel in the channel margin that is being exploited during flood events. Prior to bed-level lowering, this unit would not have been available for selective lateral erosion. Channel expansion at the PTH composite bend has occurred as the knickzone has remained fixed upstream (Figure 15). Flows have concentrated excess energy along susceptible boundaries as the reach progresses from a constricted channel to a relatively unconfined channel with reduced roughness (Schumm et al. 1984). The rate at which lateral adjustment has occurred has increased dramatically in recent years. During five floods from February to November 2009 (Figure 11) 92 m of channel expansion at Pear Tree Hole occurred and 48 m at the upstream extent of the composite bend. This had an associated increase in sediment transport capacity as the liberated sediment is transported downstream during effective floods (Simon and Darby 1999). The increase in bank erosion and the onset of aggradation indicates that this reach is in an evolutionary phase of lateral adjustment to early channel recovery. The phases are typical of incised channels in south-eastern Australia (Erskine 1999; Brierley and Fryirs 2005) as expansion occurs in response to instability caused by the recent passage of a knickzone moving through the reach.

The extensive failure of the banks is a result of reduced bank-soil shear strength from the clearing of riparian vegetation further exacerbated by the lack of cohesive resistance in the
gravel sub-layer. It is inferred that the temporal-coincidence of these factors and high flood activity has resulted in mass failure from rapid drawdown during the falling limb of floods (Morgenstern 1963; Simon et al. 1999).

6.2 The effectiveness of engineered structures

The range of hydrological variability since ELJ construction has provided conditions to thoroughly assess the effectiveness of such remedial structures. Between the 2004 and 2006 channel surveys, considerable incision occurred in spite of a lack of pronounced flood activity. Despite the construction of four channel-spanning rock girdles, 0.5 m of bed-level lowering occurred and bed stability was recognised as a primary management issue (Cohen and Telfer 2006). Following the construction of ELJs in this reach, eight POT floods have occurred, including largest flood on record in 2009 (1845.5 m$^3$s$^{-1}$) with an approximate 50 year recurrence interval. The high energy flow conditions of the post-construction period have provided a capacity for significant degradation of channel morphology. The opposite appears to be the case, with as much as 0.5 m of riffle crest aggradation in the knickzone (Figure 18) and a maintained meso-scale complexity. No significant homogenisation or loss in the pool-riffle morphodynamics has been detected, a common issue in incised river channels (Montgomery and Buffington 1997; Brooks and Brierley 2004).

As a proxy for sediment storage, residual analyses indicate that immediately downstream of ELS3, between Stage 1 and Stage 2 works, has been a zone of sediment removal throughout the survey period (Figure 22). It is likely that sediment sourced from this zone was previously transported through the reach as no significant downstream accumulation zones are apparent in the 2006 and 2008 residual analyses (Figure 22a-b). A major zone of accumulation at Pear Tree Hole has developed since the construction of ELJs (Figure 22c). It is suggested this accumulation is due to the transverse alignment of the ELJs, producing local backwater effects and a reduced hydraulic grade. These effects have been observed to become more pronounced when channel blockage ratios exceed 10% (Gippel et al. 1996b). Sediment is now being stored on the riffles and adjacent bars, further accentuated by the additional sediment supplied by increased bank erosion. The backwater effect has had a compounding effect, inducing further upstream aggradation and riffle stability (Figure 17b, 1400 - 1800 m). Upstream propagation of probable backwater effects is related to increased boundary roughness and reduced hydraulic forces from up to 1.2 m of riffle crest building.
Downstream at Pear Tree Hole (Figure 27b), eroding banks have been stabilised since ELJ construction undertaken in early 2011. The colonisation of grasses and riparian rehabilitation plantings has been maintained despite flood level debris indicating these banks were inundated by 3.5 m of floodwaters (Figure 11, f8-f9). ELJs have provided bank revetment by deflecting flow, creating eddying and flow separation whilst promoting bar development behind the structures. The aggradation and lack of ongoing lateral adjustment at Pear Tree Hole indicates higher sediment storage potential and a forced phase shift to an early stage recovery associated with altered hydraulic impacts from ELJs. This suggests ELJs can effectively promote channel stability within relatively short timeframes, and is consistent with ELJ demonstrations on the Williams River, where bed complexity in a planar-bed reach rapidly increased after ELJ construction (Brooks et al. 2004).

Upstream propagation of the knickzone appears to have been sufficiently restrained, though the reach remains in a dynamic, steepened state with a riffle-pool morphology. Since construction, the ELJ structures have largely remained stable and performed to engineering standards. The Stage 1 remedial structures in the upstream part of the study reach (rock girdles and elevated log sills; Figure 27a) all display varying degrees of weakening as a result of the recent period of elevated flood activity. In some cases structures appear to be under-engineered and are being partly outflanked (Figure 28c-d). Whilst the bed level data does not provide evidence of bed level incision the widespread bank erosion, increased flood chute activation and bar formation, and weakening of the structures would suggest that this sub-reach is on the verge of
destabilising, requiring further management. At Pear Tree Hole (Figure 27b), ELJ1 failed after outflanking from upstream erosion and ELJ4 has been partially undermined, though not significantly enough to induce failure or prevent effective flow deflection. The effect of undermining has compounded pressures on the downstream pin groyne with several pins removed during floods (Figure 28a). Most structures appear to be performing as intended, with downstream bar formation and several structures being buried by gravel. Bed stability has largely been achieved, eroding banks have been stabilised and morphological complexity has been maintained with an ancillary response of pool formation.

Figure 28 (A) the removal of timber pins from pin groynes at Pear Tree Hole; (B) LWD additions from local bank collapse and bar erosion around rock girdle (top left); (C) outflanking and partial failure of root wad bank protection structure; and (D) outflanking of engineered log sill. Photos B-D by Tony Preen

This is not to suggest the reach is now in a good condition with no additional management issues. Lateral adjustment and channel re-alignment has occurred at localities under geomorphic pressure prior to flood events and have not treated by remedial structures. Increased erosion at the upstream extent of the composite bend has corresponded with ELJ
construction at the downstream bend (Figure 15B), reflecting the river’s capacity to dissipate energy during peak flow events that are now largely confined to the channel.

In 2006, the tail of the Pear Tree Hole riffle zone (Figure 19) was recognised as a possible secondary knickzone with a gradient of 0.004 (Cohen and Telfer 2006). Despite issues of an oversteepened bed, remediation at this location has primarily focused on bank protection rather than grade control. In 2009, floods resulted in low-flow channel realignment with a 30% reduction in thalweg length and a 70% increase in channel gradient. Local channel gradient is now 0.0068, causing further destabilisation of the channel. Reactivation of destabilising processes would compound pressures on current instabilities and undermine existing remediation structures, causing failure and additional financial expense. As upstream propagation of the knickzone has been a historical trend on the Wilson River, this seems a likely process if left unmanaged.

6.3 How can incised rivers be managed with wood?

The method LWD reintroduction emulating natural LWD structures remains contentious, though the geomorphic importance of wood has been well demonstrated (Abbe et al. 2003; Brooks et al. 2006b). Ideally, the reintroduction of LWD should be designed on local observations of undisturbed reference sites. However, in south-eastern Australia rapid, extensive disturbances have dramatically, and in many instances permanently (eg. Brierley et al. 1999), transformed the biophysical properties of river systems. Typically these incised channels have become a feature of degraded landscapes with a range of persistent environmental issues (Lester and Boulton 2008). Prior to European settlement, natural streams were generally narrow and constricted, with considerably different boundary conditions and hydraulic forces (Brooks and Brierley 2004). Broadly speaking, these channels are now shallower and vastly wider with highly degraded banks and riparian vegetation. Rivers now have the capacity to maintain much higher discharges and are comparatively disconnected from their floodplains. Though large rivers existed prior to European settlement, these are geomorphically distinctive from the present river forms. In the instance of incised, over-widened channels, mimicking natural accumulations may not be sufficient to achieve specific rehabilitation goals. The natural analogues necessary to provide a framework for large woody debris in current degraded agricultural systems are largely non-existent. The channel capacity of streams today has not been experienced in south-eastern Australia in about 8000 years when fluvial discharges were much higher than present levels (Cohen and Nanson 2007).
Documented observations on natural woody debris accumulations to establish natural counterparts for rehabilitation in Australia have been limited (Webb and Erskine 2003; Brooks and Brierley 2004) and lack the rigorous observational classification of North American accumulations (Abbe and Montgomery 1996; Abbe and Montgomery 2003). Rehabilitation has relied on relatively limited undisturbed catchments within the region; generally small, narrow rivers or tributaries such as the Thurra River (Brooks 1999; Brooks and Brierley 2004) and Jones Creek (Cohen 2003). Wind throw, bush fires and cantilever failure have all been recognised as mechanisms for LWD introduction (Webb and Erskine 2003; Erskine et al. 2012), yet the patterns and mechanics of accumulation have not been sufficiently quantified. The hydraulics and LWD distribution in narrow channels are sufficiently different from many over-widened channels as to countermand their reference.

Erskine et al. (2012) documented LWD in the Ngarradj Creek catchment, Northern Territory, and Namoi-Gwydir river in north-western NSW, Australia. It is argued that engineered structures modelled on North American analogues (Brooks and Brierley 2004; Brooks et al. 2006b) are unsuitable for Australian rehabilitation efforts. The riparian ecology and subsequent LWD of North American rivers are unlikely to represent natural analogues for Australian systems (Erskine et al. 2012). Though a legitimate argument, the broad differences in the ecology-hydrology-geomorphology of the respective wet-tropical and arid landscape is equally disparate to the temperate-forest coastal streams of south-eastern Australia.

The fundamental purpose of reintroducing LWD is the multi-faceted benefits they provide to rivers (social, engineering, ecological and geomorphic). LWD can provide geomorphic resistance to degrading processes whilst simultaneously providing ecological habitat not supplied by conventional engineering methods. Considering the lack of suitable reference sites and the scale of LWD removal in Australian streams, determining the structure of natural accumulations that meet the remediation requirements will be difficult and in many instances unachievable. Emulating natural analogues may prove an unrealistic expectation for the remediation of a degraded river in a degraded landscape. The timescale necessary to address both social and ecological solutions makes this solution untenable. Legitimate hazards of flood conveyance and infrastructure damage negate the “just add wood (and let the river do the rest)” mechanism recommended by Erskine et al. (2012). Rather than be snagged by the lack of natural Australian models, it remains a logical tactic to utilise internationally effective models, so long as natural considerations and scientific constraints are applied to the design process (Brooks et al. 2006b).
6.4 Limitations

The nature of this study has led to a number of limitations due to its restricted timing and capacity. The shortfalls of this study are also some of the benefits, as it relies on a method relevant to the capacities of most stream management authorities. The monitoring method outlined by Brooks et al. (2004) provides a more scientifically robust procedure capable of capturing reach wide variability and changes. The difficulty with this method is the lack of feasibility and financial capacity to undertake such a rigorous application for most management agencies. However, an implicit assumption in the method used for this study lies in the qualitative judgements of the surveyor and comparative repeated measures. Appreciable differences and deficiencies in the data sets will not likely detect intra-reach channel complexity and result in potentially erroneous conclusions.

A further limitation of this study is the limited ability to incorporate hydraulic modelling in the geomorphic interpretation of ELJ effectiveness. Flood discharge was interpreted from a gauge downstream, providing an indication of discharge in the reach. This method has provided the timing, duration and relative magnitude of each flood event but not absolute values relevant for the study reach. Determining discharge at the study reach and modelling flow characteristics would assist in understanding the hydraulic characteristics of such large remedial structures.

6.5 Recommendations

6.5.1 PMHC Wilson’s River Management

Though this study has provided a basis for the effective stabilisation of an incising reach using ELJ technology, several issues require the attention of management authorities. Further monitoring is required to adequately determine reach stability and identify additional instability. Establishing a monitoring protocol for future surveys will provide an effective basis for repeated measuring and effective comparison. This is particularly relevant given the identification of potential riffle-crest lowering at the upstream end of the study reach and additional pressures within the reach. This protocol should include a survey of:

- The channel thalweg (lowest continuous line) throughout the reach, with particular focus on riffle crests and pool depths;
• Upstream to Marlo Merrican Creek, to determine bed stability and confirm no further propagation of stream incision;
• Flood chute activity;
• Selected cross sections along rock girdles and riffles;
• Selected cross sections along channel to monitor channel expansion;
• Permanent benchmarks established using high resolution spatial coordinates

Current pressures will need to be addressed in order to prevent ongoing destabilisation of the Wilson River. A key priority should be given to repairing upstream structures, therefore preventing failure and further bed instability. Bank erosion at the upstream extent of the PTH composite bend will require remediation to prevent further channel expansion. The recent increase in bank erosion at this site suggests possible intervention at a scale comparable to the downstream works will be required to induce bank stability.

Monitoring and rehabilitation of the secondary knickzone immediately upstream of the bedrock pool should be undertaken to prevent upstream propagation. Considering the infancy of the shift in low-flow channel position, remediation could utilise methods of low-flow channel realignment to restore the original pre-avulsion channel position and gradient, as outlined by Rutherfurd (2000). Natural channel features could be utilised to assist this realignment by reinforcing pre-existing natural hard points. ELJ technology has been successful in achieving such responses on the Hoh River in Washington, North America (Thacker 2005). A comparable project has not been undertaken within Australia though, nonetheless, channel realignment has been successfully accomplished on the Latrobe River at a relatively low cost (Reinfelds et al. 1995; Rutherfurd et al. 2000). The feasibility of such a strategy would need to be considered and designed by expert judgement, and subject to further rigorous monitoring as with the current ELJ programme.

6.5.2 Australian LWD management

As the reintroduction of LWD gains momentum within stream management, a range of projects are likely to present opportunities for further research and development. This should be encouraged to further promote the flow of knowledge in LWD management and successful rehabilitation mechanisms.
Arguments focused on how to reintroduce and manage LWD are relevant issues that require attention. Given the densities and physiological distinctions of Australian timber, it would seem logical to develop a classification of Australian LWD and LWD rehabilitation scenarios relevant for both incised and non-incised river channel. Whilst the few documented reference studies in near pristine environments are useful, many fluvial settings in south-eastern Australia are now distinct from their pre-European counterparts. A classification scheme centred on detailed observations of natural Australian LWD analogues would help guide reintroduction designs and projects. The development of this classification should consider the relevant morphological distinctions currently being experienced in disturbed streams and attempt to utilise suitable analogous systems capable of achieving rehabilitation goals.
7. CONCLUSION

This study suggests that the construction of ELJs can effectively arrest active destabilisation. The hydraulic response to this installation requires further understanding, but the Wilson River rehabilitation strategy provides evidence that bed stability can be achieved through the reintroduction of LWD. Multiple elements are contributing to bed stability in the reach including a high wood loading and variety of remediation structures. However, bed stability (and not bank) has only been achieved since ELJ construction.

This is not to suggest that destabilisation of the Wilson River has entirely ceased. Major threats to geomorphic stability persist and may exacerbate other pressures along the river channel. The ‘fixed’ knickzone in the upstream section of the study reach has likely exacerbated these issues, creating localised stable sections and downstream vulnerable sections. Unvegetated, oversteepened banks are providing an appetising alternative for a ‘hungry’ river with excess energy. It is clear that vegetative constrictions have provided fundamental resistance at a local scale to channel destabilisation and bank erosion, evident of the important long-term role of riparian revegetation. However, the removal of newly established vegetation in subsequent floods suggests alternative solutions will be necessary. ELJs provide an effective interim mechanism within short time frames, until effective riparian buffer zones can be established.

Conventional “quick-fix” approaches of asset protection will not be sufficient to arrest the extensive destabilising processes occurring throughout the majority of rivers in south-eastern Australia. Long-term approaches incorporating a geomorphological understanding of the cause of the problem are required rather than simply addressing the response. Likewise, goals focused on the return to former natural processes will likely be unachievable and should focus on stabilisation to invoke natural recovery. Ongoing monitoring is an essential management tool in recognising persistent, new and relieved pressures to assist in this strategy. Considering the time and funds available to most river management projects, this study provides an easily replicable method for ongoing monitoring within the scope of river management authorities.
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