2014

The shifting sands of Stockyard Creek: the geomorphic response to large wood reintroduction in a sand-bed stream

Rhiannon Hughes

University of Wollongong

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The shifting sands of Stockyard Creek: the geomorphic response to large wood reintroduction in a sand-bed stream

Abstract
In April 2002, 24 Engineered Log Jams (ELJs) were built within a 2 km treatment reach of what was a degraded ephemeral sand-bed stream at Stockyard Creek, Wollombi, NSW. Coupled with ~20 years of ongoing native revegetation this project aimed to increase the geomorphic diversity and ecological characteristics of the ephemeral stream. Commencing in 2002, the experiment was set up as a standard BACI design, with a control reach situated in the upstream limit of the study site. This thesis aims to assess the geomorphic response to the re-introduction of wood by comparing treatment and control reaches. Since construction, the ELJs have experienced a 5 year period of low or no flow conditions, as well as two major bed mobilising flood events which occurred in June 2007 and February 2013. Four detailed topographic surveys of the study reach were completed during the 12 year study period and have been used to construct Digital Elevation Models (DEMs) of the in-channel bed topography.

Differencing between successive DEMs and the development of longitudinal profiles for the study reach indicate the ELJs have been successful in promoting the colonisation of riparian vegetation, as well as increasing the geomorphic diversity of the bed topography. Significantly, the magnitude of change was much greater in the treatment reaches, with one of the treatment reaches (treatment A) having a depth range 1.5 times greater than that of the control, with a maximum scour depth of ~2.5 m. The most pronounced response to ELJ introduction was the development of persistent pools, with 46-50% of new pool volume estimated to have occurred in direct association with the ELJs. Patterns of scour and bar development were observed to vary in association with ELJ design, with the ELJs within the treatment A reach facilitating significant bar development (13.5%) with a net gain of (48.90 m³/1000m² of bed) compared to the preconstruction survey. Despite the influence of the ELJs, the control reach also experienced a significant level of change due to the presence of outcropping bedrock, native re-vegetation and the natural recruitment of woody debris. Both control and treatment reaches are excellent examples of riparian rehabilitation using native species. This thesis provides an assessment of the geomorphic response to the use of ELJs in an Australian sand-bed stream.

Degree Type
Thesis

Degree Name
International Bachelor of Science

Department
School of Earth & Environmental Science

Advisor(s)
Tim Cohen

This thesis is available at Research Online: http://ro.uow.edu.au/thsci/75
Keywords
engineered log jam, sand-bed stream, river rehabilitation, fluvial geomorphology
THE SHIFTING SANDS OF STOCKYARD CREEK:
the geomorphic response to large wood reintroduction in a sand-bed stream

Rhiannon Hughes

A research report in partial fulfilment of the requirements for the award of the degree of

International Bachelor of Science

April, 2014
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.

Rhiannon Hughes

2nd April 2014
ACKNOWLEDGEMENTS

I wish to acknowledge and thank the following people and organisations for their support and assistance at various stages throughout the project. First and foremost to my supervisors, Dr Tim Cohen and Dr Andrew Brooks for their advice, encouragement and support throughout my thesis; I appreciate their patience, knowledge and critical reviews. To Sally and Brian Woodward for their hospitality, access to their property and providing support and information. Thanks for welcoming me into you home on many of occasions The Faculty of Earth and Environmental Sciences for providing the support and equipment I have needed to produce and complete my thesis and the funding to encourage the development of my thesis. Heidi and Chris, thanks for your assistance and guidance in relation to all things ‘GIS’. To Peter Coffey and Daniel Seddon-Powell, your enthusiasm and courage on many a cold winter morning was phenomenal and thanks for teaching me the ropes of surveying, and to Cecilie Yates for her assistance with editing and document formatting.
ABSTRACT

In April 2002, 24 Engineered Log Jams (ELJs) were built within a 2 km treatment reach of what was a degraded ephemeral sand-bed stream at Stockyard Creek, Wollombi, NSW. Coupled with ~ 20 years of ongoing native revegetation this project aimed to increase the geomorphic diversity and ecological characteristics of the ephemeral stream. Commencing in 2002, the experiment was set up as a standard BACI design, with a control reach situated in the upstream limit of the study site. This thesis aims to assess the geomorphic response to the re-introduction of wood by comparing treatment and control reaches. Since construction, the ELJs have experienced a 5 year period of low or no flow conditions, as well as two major bed mobilising flood events which occurred in June 2007 and February 2013. Four detailed topographic surveys of the study reach were completed during the 12 year study period and have been used to construct Digital Elevation Models (DEMs) of the in-channel bed topography.

Differencing between successive DEMs and the development of longitudinal profiles for the study reach indicate the ELJs have been successful in promoting the colonisation of riparian vegetation, as well as increasing the geomorphic diversity of the bed topography. Significantly, the magnitude of change was much greater in the treatment reaches, with one of the treatment reaches (treatment A) having a depth range 1.5 times greater than that of the control, with a maximum scour depth of ~ 2.5 m. The most pronounced response to ELJ introduction was the development of persistent pools, with 46-50% of new pool volume estimated to have occurred in direct association with the ELJs. Patterns of scour and bar development were observed to vary in association with ELJ design, with the ELJs within the treatment A reach facilitating significant bar development (13.5%) with a net gain of (~48.90 m³/1000m² of bed) compared to the preconstruction survey. Despite the influence of the ELJs, the control reach also experienced a significant level of change due to the presence of outcropping bedrock, native re-vegetation and the natural recruitment of woody debris. Both control and treatment reaches are excellent examples of riparian rehabilitation using native species. This thesis provides an assessment of the geomorphic response to the use of ELJs in an Australian sand-bed stream.
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LIST OF ABBREVIATIONS

LWD   Large Woody Debris
ELJ   Engineered Log Jam
DFJ   Deflector Jam
LS    Log Sill
VSW   V-Sill Weir
VW    V-weir
NSW   New South Wales
ARI   Annual Recurrence Interval
GCD   Geomorphic Change Detection
DEM   Digital Elevation Model
DoD   DEM of Difference
1. INTRODUCTION

In Australia’s “degraded” landscape, changing environmental perspectives are significantly influencing river management strategy eliciting an increased use of bioengineered solutions to solve river management issues. Early European agricultural practices, such as land clearing and grazing, have significantly altered the landscape of south-eastern Australia, resulting in negative implications for the riverine environment (Erskine & Webb 2003). Riverine settings, which were once described by the early settlers as densely vegetated with low-capacity narrow channels (Erskine and Webb 2003), have been transformed into homogenous, unstable systems with decreased biodiversity. Early ‘interventionist’ management strategies, such as channel widening and desnagging (the process of removing wood from the river channel), aimed to train rivers so as to quickly disperse flood water and to protect important assets (Erskine 1990). However these methods often resulted in further bed instability and erosion (Erskine 1990; Erskine 1994; Brierley & Murn 1997; Brooks & Brierley 1997; Brierley et al. 1999; Fryirs et al. 2009).

Recently, holistic perceptions of environmental management (Ballantyne et al. 2010) have led to the development of bioengineered management strategies, which enable researchers to ‘design sustainable river systems that provide ecosystem services’ (National Research Council of the National Academies, 2010), rather than just agricultural aims. This change in attitude has recognised the link between the physical and ecological aspects of river management, with geomorphic variability being recognised as an important influence on biodiversity and river health (Bartley & Rutherford 2005; Thorp et al. 2006; Gostner et al. 2013).

Riparian re-vegetation works coupled with the re-introduction of wood into streams, is a significant management strategy currently being utilised for river rehabilitation globally (Shields Jr. & Gippel 1995; Abbe & Montgomery 1996; Hilderbrand et al. 1998; D’Aoust & Millar 2000; Douglas Shields et al. 2003; Brooks et al. 2004; Shields et al. 2004; Brooks et al. 2006; Spähnoff et al. 2006; Lester et al. 2007; Lester & Boulton 2008). Throughout the past few decades wood reintroduction has been achieved through the construction of Engineered Log Jam’s (ELJ’s) in affected regions of the channel. ELJ’s designs are based on naturally occurring Large Woody Debris (LWD) accumulations, and are most often constructed using locally sourced logs (Abbe & Montgomery 1996). Their design is attuned to the local dynamics of the rehabilitation reach in order to fulfil specific restoration goals, such as bank protection,
habitat enhancement or increased bed stability. The central principle underpinning the use of ELJ’s is that rehabilitation methods are most likely to be sustainable if they emulate natural landscape processes (Abbe & Montgomery 1996).

While the construction of ELJ’s is fairly widespread in North America and south-eastern Australia, only a handful of studies have been undertaken to fully evaluate the approach (Brooks et al. 2004; Shields et al. 2004; Brooks et al. 2006). The vast majority of ELJ implementation projects have been undertaken in gravel bed rivers (e.g. Abbe et al. 1997, Brooks et al. 2004, 2006, Abbe & Brooks, 2011) they have been found to stabilise channel features, increase bed form diversity, and therefore increase fish abundance (Brooks et al. 2004; Brooks et al. 2006). Few studies have been implemented in a sand-bed context with the current examples showing mixed success (Shields et al. 2004; Borg et al. 2005; Borg et al. 2007).

In order to assess the geomorphic, ecological and economic effectiveness of bioengineered rehabilitation strategies such as ELJs, it is important to monitor the effect of such structures over multiple time-scales in both gravel and sand-bed settings. Previous studies have included detailed analysis at the sub-reach scale, of both the geomorphic and ecological effect of ELJ’s (Merz et al. 2006; Borg et al. 2007), as well as broader analyses at the reach scale (Brooks et al. 2004; Brooks et al. 2006).

With the increased development and accessibility of geospatial technology, researchers can more quickly and more accurately assess the effect and implications of rehabilitation techniques, such as large wood reintroduction. The use of Digital Elevation Models (DEMs) created from detailed topographic surveys ensures morphological change can be monitored across the entire active channel, and also enables the development of gross reach-scale sediment budgets (Brooks et al. 2006; Fuller & Hutchinson 2007; Wheaton et al. 2013). Presently researchers are striving to understand the inaccuracies associated with such methods so that the implications of river management strategies can be suitably identified (Brasington et al. 2000; Lane et al. 2003; Rumsby et al. 2008; Fuller & Basher 2013).

Research into the effectiveness of bioengineered management strategies are essential in order to understand how integrated management strategies can be used to “restore” or “redesign” degraded landscapes (National Research Council of the National Academies 2010). Therefore, determining the effectiveness of such structures and their ability to increase channel diversity in a variety of contexts, is an important step in understanding whether such intervention options
are viable in the long term. Such investigations also provide insights into how future design aspects for ELJ’s can be altered and designed within a local scale environment (Brooks et al. 2006).

1.1 AIMS & OBJECTIVES

This project will aim to evaluate the effect of river rehabilitation techniques in a sand-bed stream, with specific reference to changes in channel morphology as well as the establishment of riparian vegetation. The study reach is located at Stockyard Creek, a small tributary of the Wollombi Brook in NSW, which has undergone a biophysical transformation since the late 1970’s. What was an incised river system with actively eroding river banks, has been transformed into a stable system with permanent pools and continuous riparian vegetation. These changes coincide with the implementation of a passive weed management and re-vegetation strategy which the landholder commenced in the late 1970’s and still continues today. In addition, the site has been included in a broader in-stream rehabilitation project which commenced in mid-2001 and involved the installation of 24 ELJs as a large scale Before-After-Control-Impact (BACI) design field experiment, with two separate treatment reaches and an upstream control reach. However, the study was not completed due to the onset of drought shortly after it was initiated.

The overall goals of the rehabilitation strategy were to:

- Increase geomorphic diversity within the treatment reach;
- Further stabilise the bed of an already incised stream;
- Enhance and create zones for potential habitat;
- Assess the suitability of future rehabilitation strategies utilising ELJs in a sand-bed context.

In order to address the intended project goals, this study will examine the morphological effect of a bio-engineered approach to river rehabilitation. To facilitate this, the study will aim to:

1. Identify regions of geomorphic change within the study reach;
2. Compare the geomorphic diversity of the treatment and control reaches;
3. Identify and examine patterns of geomorphic change relating to specific ELJ design;
4. Assess whether the applied rehabilitation strategy has successfully increased geomorphic diversity;
5. Examine the change in the extent of riparian vegetation through time;
6. Evaluate the effectiveness of utilising ELJs in an Australian sand-bed context.
It is hypothesised that the channel morphology in the treatment reaches will show increased geomorphic diversity and sediment storage when compared to the untreated reach. This notion is centered on the hypothesis that the re-introduction of wood into rivers increases geomorphic diversity and sediment storage.

In order to assess the possible biogeomorphological benefits of the rehabilitation strategy, a reach with increased geomorphic diversity will be defined as having:

1. A greater range of depth;
2. A pool/riffle structure which is maintained through time;
3. An increase in pool/bar surface area;
4. Increased variability of the longitudinal profile;

The project will also examine recent (over the last decade) topographic changes in the context of an evolving riparian ecosystem that has been progressively stabilised throughout the past 30 years. It is expected that additional revegetation with native species will have further stabilised both the control and treatment reaches acting as a local source of natural wood recruitment.

This study builds on an experiment that was initiated in 2002 as a Before, After, Control, Impact (BACI design) study, but which was not completed due to the onset of drought shortly after it was initiated. No significant flows were experienced for the first five years after the experiment was set up in 2002. Hence, it is only now, some 12 years on, that sufficient flows have been experienced to enable a full evaluation. The original design included a control reach (upstream) and two treatment reaches downstream of the control - treatment A - which included a comprehensive wood-reintroduction strategy; and treatment B, which included a series of three rock and log weirs designed to act as bed control structures. The experimental design was expanded as part of this study to include an external control in an adjacent valley.
1.2 THESIS OUTLINE & SCOPE

This thesis presents a review of the current literature relating to a bioengineered river management strategy with specific reference to the role of Large Woody Debris (LWD). It also examines the mechanisms acting within an Australian sand-bed stream, and the implications of past management strategies within the setting of south eastern Australia. An overview of the study area and rehabilitation strategy is outlined in Chapter 3, where a hydrological history for the site is also developed. In Chapter 4, the process of data collection and analysis is defined with reference to key methodologies in the field of geomorphic change detection. Chapter 5 presents the results of the analysis in relation to the geomorphic change, as well as an assessment of the changing geomorphic diversity of the reach. The following chapter (Chapter 6) provides a discussion of the acquired results in relation to past research in the area of stream management and outlines the limitations of the project methodology. A concluding statement is provided in Chapter 7, which aims to summarise the progress which has been made in achieving the aims of the project, and presents recommendations for future rehabilitation methods utilising ELJs.
2. LITERATURE REVIEW

This chapter reviews the current literature relating to the use of a bio-engineered approach to river management in south-eastern Australia. It pays specific reference to the current condition of the Australian riverine landscape, as well as the increasing recognition of the role of vegetation and LWD in stream management.

2.1 POST-EUROPEAN CHANNEL CHANGE IN SOUTH-EASTERN AUSTRALIA

Catchment wide disturbance, as a result of post-European settlement, has led to significant alterations to the morphology and ecology of south-eastern Australian streams, with > 80% of Australia’s river length predicted to have been effected by disturbance (Land and Water Australia 2002). A large portion of riverine ecosystems are considered to be in a state of degradation, with an excess flow energy, shear stress or stream power, in relation to sediment supply (Darby & Simon 1999). Such change has not only resulted in a marked decline in river health (Gostner et al. 2013), but has also greatly affected the safety and livelihood of many individuals living within the riverine landscape (Erskine 1990). It is therefore essential to establish and understand the cause and response of rivers to change so that sustainable methods of future remediation can be developed.

Variability is a natural characteristic of alluvial rivers (Schumm 2005), however, the rapid extent and magnitude of change observed since post-European settlement has been unique within Australia’s history (Brooks & Brierley 1997). Historically, climatic variability has been suggested as the cause of catastrophic channel change, with periods of morphological change observed to occur in association with periods of frequent flood activity (Erskine 1994). However, such theories have been criticised as they negate the role of anthropogenic disturbance in influencing the severity of floods. Brierley et al. (1999), instead suggest the geomorphic effectiveness of a flood has been enhanced by anthropogenic alterations to the landscape.

The context of recent channel change is best understood through an examination of pre-European channel characteristics. Descriptions of the landscape prior to European settlement have been compiled for many key coastal rivers (Brierley et al. 1999; Erskine & Melville 2008; Hoyle et al. 2008) from fragmentary historical documents and sedimentary records (Erskine & Melville 2008). Generally, pre-European river channels have been described as having a low transport capacity and a small width to depth ratio with stable vegetated banks (Eyles 1977;
Records suggest rivers were well connected to their floodplains and experienced a high frequency of overbank flows (Page 1972). Remnant river systems are thought to provide a sufficient analogue for the pre-European landscape and suggest river channels had a highly complex bed profile associated with a high wood loading (Brooks et al. 2003). Many rivers within south-eastern Australia have been shown to have undergone a process of ‘river metamorphosis’, whereby the morphology of the river and floodplain has been transformed as a function of disturbance (Schum 1969).

Within the first few decades of early European settlement extensive land clearing for the establishment of agriculture enhanced surface runoff resulting in increased peak flows and channel instability (Lester & Boulton 2008). However, the magnitude and effect of channel change is documented to have been spatially variable and dependent upon the level of disturbance (Brierley & Murn 1997). Generally, the common pattern of change includes widespread channel incision, followed by channel expansion and significant alterations to sediment transport (see Table 1 for examples of observed change). The Bega River in NSW, is documented to have widened by up to 340% in response to early land use practices (Brooks & Brierley 1997). Other agricultural practices, such as the introduction of grazing species, has been shown to have further exacerbated processes of incision by decreasing bank stability, resulting in a shift from processes of fluvial erosion to mass failure (Lester & Boulton 2008). The increased geomorphic effectiveness of flow events in the early 19th century significantly altered the balance of sediment transport, as regions of long-term sediment supply were eroded within a few decades (Brooks et al. 2003). Catastrophic channel change during this period led to widespread destruction and the loss of prime agricultural land, therefore in response, the Government initiated intensive river management programs through south-eastern Australia (Erskine & Whitehead 1996).
Table 1 Documented channel change for rivers in south-eastern Australia modified from Rutherfurd (2000)

<table>
<thead>
<tr>
<th>River</th>
<th>Source</th>
<th>Documented Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bega River</td>
<td>Brooks &amp; Brierley (1997)</td>
<td>1850-1920: widening by 340% with increase in sediment load. Transformed from mixed to bed load regime</td>
</tr>
<tr>
<td>Wollombi Brook (NSW)</td>
<td>Page (1972) &amp; Erskine (1986)</td>
<td>100% increase channel width, slug of sand aggraded bed up to 4m, downstream movement sediment slug</td>
</tr>
<tr>
<td>Illawarra Streams (NSW)</td>
<td>Nanson &amp; Hean (1985)</td>
<td>Max cross-section increase 230% to 340% in steep upstream section, channel avulsion and floodplain scour</td>
</tr>
<tr>
<td>Cann River (VIC)</td>
<td>Erskine &amp; Whitehead (1996)</td>
<td>1935-95: widened by 325%, depth increase 40%, chute cutoff and downstream aggradation by slug of sand</td>
</tr>
<tr>
<td>Cobargo Catchment (NSW)</td>
<td>Brierley et al. (1999)</td>
<td>50% sediment removed and 50% of banks eroding in upper catchment</td>
</tr>
<tr>
<td>Tarcutta Creek (NSW)</td>
<td>Page &amp; Carden (1998)</td>
<td>Altered chain of ponds to continuous incised channel, alternating depositional and erosional reaches, increase width 100-200%</td>
</tr>
<tr>
<td>Cann/Thurra River</td>
<td>Brooks et al. (2003)</td>
<td>Comparison ‘natural’ Thurra River and disturbed Cann river. Thurra maintained aggradational regime with highly variable long-profile while Cann experienced significant degradation and mass wasting</td>
</tr>
</tbody>
</table>

Government initiatives, such as the Hunter Valley Flood Mitigation Act (1956), saw the broad-scale desnagging and clearing of riparian vegetation from the early 1880’s to the mid-1990’s (Erskine & Webb 2003). Denagging involves the removal of in-channel LWD with the aim of increasing flood conveyance and decreasing erosion (Erskine 1990). Historical documents indicate that, between 1954 and 1991, a minimum of 8000 trees were removed from within the channel and riparian zone along an 853km section of the Hunter Catchment (Webb & Erskine 2003). In-channel wood was believed to increase flood stage due to increased surface roughness, and the buildup of debris during catastrophic floods caused significant damage to assets (Fryirs et al. 2009). However, due to a limited understanding of the role of wood in stream processes, desnagging further enhanced the instability of streams (Brooks & Brierley 2002). The degradation of the Cann River has been directly linked to desnagging practices, whereby the river channel experienced a 3.7 fold increase in channel width and a 2.6 fold increase in channel gradient (Brooks et al. 2003). The most profound effect of desnagging is the homogenization of the bed profile with an associated decrease in habitat availability (Erskine 1986; Brierley & Murn 1997; Brierley et al. 1999; Brooks et al. 2003; Erskine & Webb 2003). Studies on the Murray River suggest the removal of wood is the greatest factor influencing a decline in fish populations (Lester & Boulton 2008). ‘River training’ initiatives were also widely implemented throughout south-eastern Australia and sought to control the erosion and migration of river channels (Erskine 1994).
In response to a series of catastrophic floods experienced in the mid-1900’s, river management initiatives focused on repair and protection rather than environmentally sustainable practice (Erskine & Webb 2003). Developed in the early 1950’s, ‘River training’ involves the treatment of a river reach using artificial materials, so that both channel alignment and width are controlled (Erskine 1990). Such practices aimed to increase channel capacity for flood conveyance through dredging and artificial modifications to the channel planform. (Erskine et al. 2012). Within NSW, the Hunter region saw the greatest density of river training projects which resulted in significant implications for the riverine environment (Erskine & Peacock 2002). In some cases, processes of nutrient and water exchange have been altered as flood waters are now often confined within a large macrochannel (Gostner et al. 2013). River training initiative’s increased flow velocity, bank erosion and channel gradient, with a decrease in structural diversity due to a low flow resistance (Lester & Boulton 2008). Wide-scale post-European channel change is considered to be the result of poor land use practices and a limited understanding of fluvial and ecological processes (Ballantyne et al. 2010).
2.3 CHANGING PERCEPTIONS IN RIVER MANAGEMENT

In contrast to past management strategy, the increasing recognition of the complex interaction between fluvial and ecological processes (Figure 1) has encouraged recent shifts in river management policy towards a system of Integrated River Management (Gostner et al. 2013). River management has become a multidisciplinary field incorporating facets of ecology, geomorphology as well as engineering, with projects designed to fulfil both engineering and ecological aims.

Figure 1 Factors influencing the ecological integrity of streams (Karr & Chu 2000).

Thorp et al. (2006), suggests the riverine landscape is comprised of a complex mosaic of habitat patches which are controlled by variations in hydrology, morphology and sediment calibre. The complexity of the bed morphology is considered to act as a ‘structural template’ for habitat availability and therefore acts as a surrogate for species diversity (Brierley et al. 1999). The reinstatement of hydraulic variability through the addition of bed roughness elements, such as vegetation and LWD, is therefore a key focus of river rehabilitation. This shift has led to the development of studies which recognise the important role of large woody debris in enhancing channel hydraulics, geomorphology and biodiversity (Gippel 1995; Beechie & Sibley 1997; Gurnell et al. 2002; Abbe & Montgomery 2003; Wallerstein & Thorne 2004; Montgomery & Abbe 2006), as well as the value of revegetation strategies utilising indigenous riparian species (Hupp 1992; Webb et al. 1999; Gran & Paola 2001; Brooks et al. 2003).
THE ROLE OF WOOD IN STREAM MANAGEMENT

Geomorphology and Hydraulics

The importance of LWD for river management has gained considerable recognition throughout the past three decades with numerous studies identifying the direct influence of large wood on channel hydraulics, fluvial geomorphology and ecological diversity (Gippel 1995; Shields Jr. & Gippel 1995; Beechie & Sibley 1997; Brooks & Brierley 2002; Montgomery & Piégay 2003; Webb & Erskine 2003; Wallerstein & Thorne 2004; Borg et al. 2005; Dumke et al. 2010; Erskine et al. 2012). Large wood is comprised of trees, branches and trunks of any length with a diameter of greater than 0.1m (Erskine et al. 2012). The presence of LWD significantly influences channel hydraulics as it enhances flow variability through flow obstruction and constriction of the channel cross-section (Gippel 1995). At the reach scale large wood adds a roughness element to the channel planform which decreases stream velocity and the resulting bed shear stress (Brooks & Brierley 2002). Therefore, LWD is considered to exhibit a local control on channel morphology (Abbe & Montgomery 1996), and has been found to exert a greater influence within small-order streams as wood pieces often equal or exceed channel width (Dumke et al. 2010). However, the magnitude of the overall geomorphic effect depends upon the orientation, spatial distribution and residence time of LWD pieces (Gurnell et al. 2002).

Studies of streams with a high wood loading, indicate the major influence of LWD on channel morphology is through the creation of pools (Abbe & Montgomery 1996). Flume studies suggest woody accumulations alter flow velocity, resulting in regions of scour which are on average deeper and have a greater variation in depth (Abbe & Montgomery 1996) then free-flowing pools (pools which are not influenced by LWD). Not only does LWD induce scour but the associated woody accumulations also create stable, forced pools which are maintained within the bed profile though time (Buffington et al. 2002) (Figure 2).
Due to the large transport capacity and erosive nature of degraded channels, geomorphic features are often readily reworked and short lived (Fryirs et al. 2007). Flow deflection, influenced by the protrusion of LWD, leads to sediment deposition in low flow zones and the entrapment of sediment behind channel spanning jams (Brooks & Brierley 2002). This mechanism is significant in reducing wide scale incision, as in-channel wood dissipates energy at discrete locations along the bed-profile rather than uniformly across the channel (Montgomery & Abbe 2006). Geomorphic recovery is dependent upon sediment availability and channel transport capacity, therefore, in a highly erosive river reach, the re-storage of sediment by LWD can add an aspect of stability to the channel morphology and help to restock depleted sediment stores (Fryirs & Brierley 2001). The enhancement of bed surface roughness

Figure 2 Flow structures and resulting scour observed by Buffington et al. (2002): (a) depth-spanning vertical pier-type obstruction; (b) depth-spanning vertical abutment-type obstruction; (c) pitched obstruction; (d) horizontal obstruction; (e) step pool.
by LWD can also positively increase sediment transport in regulated river systems, by shifting fine bed-load sediment and increasing habitat availability (Merz et al. 2006). Extensive research into the influence of LWD on in-channel hydraulics and fluvial geomorphology has led to an increased recognition of the ecological role of LWD (Abbe & Montgomery 1996; Howell et al. 2012).

Ecological Diversity
Increased hydraulic diversity induced by large wood is considered to be important for ecosystem integrity (Gostner et al. 2013), as geomorphically diverse reaches have been positively correlated with increased biodiversity (Thorp et al. 2006; Ballantyne et al. 2010). Woody debris affects the abundance and distribution of fish species through the creation of pool habitat (Beechie & Sibley 1997), which is important in providing refuge during high flow and an escape from predators (Crook & Robertson 1999). Specifically, wood has been found to play an integral role in the life cycle of some fish species, such as the Australian Murray River Cod, whose habitat is predominately comprised of log piles (Simpson & Mapleston 2002). Wood also directly provides sites for the colonisation of aquatic biota such as microscopic bacteria, fungi and algae (Brooks 2006).

The long-term presence of wood within the water column influences the water chemistry and nutrient balance of stream ecosystems (Wallace et al. 1995). Through decay, wood acts as a source of organic carbon and influences the nutrient cycle by trapping organic matter and providing a site for biofilm development (Ryder et al. 2006). The increased hydraulic variability associated with in-channel wood also raises dissolved oxygen levels, through aeration and the movement of water between the surface and subsurface (Wallace et al. 1995).

The Role of Riparian Vegetation in Stream Management
The presence of riparian vegetation has also been shown to play an important role in stabilising degraded river channels through increased flow resistance and fluvial entrainment (Chalmers et al. 2012). Dense root systems, within the bank and bar substrate, work to increase tensile strength, decrease bed-shear stress and therefore decrease erosion rates (Gran & Paola 2001). In a mixed load systems, such as a sand-bed stream, dense vegetation and mature vegetation stands induce deposition by redistributing flow resistance (Rominger et al. 2010). Studies suggest in contrast to degraded river systems, channels with a well-established riparian margin have both a deeper and narrower channel with a heterogeneous bed profile (Brooks & Brierley 2002; Brooks et al. 2003; Chalmers et al. 2012; Erskine et al. 2012). In the long-term, the
establishment of woody species within the riparian margin acts as a local source of large wood, and therefore plays a vital role in increasing long-term habitat heterogeneity (Curran 2010).

2.4 THE RE-INTRODUCTION OF WOOD INTO STREAMS

Methods of Wood Reintroduction

Many rivers in south-eastern Australia have experienced channel incision with an associated decrease in biodiversity (Brierley et al. 1999). The reintroduction of wood in many such systems has been seen as a positive sustainable step for improving channel stability and achieving geomorphic complexity (Abbe & Montgomery 1996; Gerhard & Reich 2000; Gurnell et al. 2002; Erskine & Webb 2003; Montgomery & Piégay 2003; Brooks et al. 2004; Brooks et al. 2006). Presently, wood loadings are known to be a fraction of those existing prior to human intervention (Brooks et al. 2003), and with the full establishment of riparian recovery expected to take decades (>100 years in some cases), the reintroduction of wood is important as a short-term control on channel morphology (Brooks et al. 2006).

Lester & Boulton (2008), completed a meta-analysis of up to 15 global artificial wood reintroduction initiatives with the aim of identifying significant knowledge gaps in the literature. What became apparent, was that the majority of projects were completed within North America in forested landscapes, with the most common goals being bank stability as well as improved habitat complexity. Methods of wood reintroduction have been highly varied, but most commonly involve the placement of large wood pieces within the low flow channel with heavy machinery (Gerhard & Reich 2000; Brooks et al. 2004).

To date, artificial wood reintroduction has had an experimental focus, with the majority of projects examining the implications of log orientation, size and length, on channel morphology, log mobility and macro-invertebrate communities (Hilderbrand et al. 1998; Gerhard & Reich 2000; Lester et al. 2006; Spänhoff et al. 2006; Lester et al. 2007). Initiatives have involved the systematic replacement of logs, sometimes secured by steel and pine posts (Lester et al. 2007) as well as the random replacement of wood designed to simulate natural log drop (Hilderbrand et al. 1998). The most consistent response to wood reintroduction has been improved habitat diversity, however, the success of wood re-introduction initiatives has been masked by the instability of structures (Lester & Boulton 2008). The instability of re-introduced wood presents implications for management, consequently the use of a bioengineered approach to wood reintroduction through the construction of ELJs is becoming an increasingly common practice (Brooks 2006).
The Engineered Log Jam Concept
ELJ technology is based on the concept that sustainable channel recovery is more likely to be successful if it is conducted in a way which mimics natural processes (Abbe & Montgomery 1996). The concept of improving the stability of rivers with ELJ’s was first developed by Abbe & Montgomery (1996) as a means to reintroduce wood in a relatively safe and controlled manner. Structures were specially developed using both engineering and river management practices to provide ecosystem goals, as well as maintaining structural integrity from an engineering perspective (Figure 3).

The use of ELJs is now fairly widely accepted as a rehabilitation method in parts of North America (Abbe & Montgomery 1996; Abbe & Montgomery 2003; Shields et al. 2004) and south-eastern Australia (Brooks et al. 2004; Brooks et al. 2006; Borg et al. 2007), however, to date, only a handful of studies have rigorously evaluated the approach (Brooks et al. 2004; Shields et al. 2004; Brooks et al. 2006; Borg et al. 2007). These studies have contributed to the development of specific design requirements for ELJ’s and a greater understanding of their influence in a destabilised landscape. Key aspects of ELJ design include the use of ballast rock to counteract the buoyancy of wood, which will tend to decay with time (Daley & Brooks 2013), and the importance of a riparian revegetation strategy to ensure the long-term stability of the structures and associated geomorphic features (Abbe and Montgomery, 2003).

Figure 3 Comparison of an ELJ structure with other methods of wood reintroduction (a) logs placed within the low flow channel by hand and held in place with wire and pine posts, South Danalup River, WA (Till & Davy 2000); (b) Deflector Jam and log sill constructed at Stockyard Creek, 2002.

One of the most notable examples of wood reintroduction within south-eastern Australia is the ELJ demonstration project conducted by Brooks et al. (2004) on the Williams River at Munni, NSW. This project saw the construction of 20 ELJ’s in a treatment reach of the Williams River, and documented the long-term geomorphic and ecological response of the structures using a
BACI experimental design. Flow deflection and grade control structures based on ELJs developed by Abbe (1997), were altered for Australian conditions and included deflector jams, Bank Apex Jams, Bank Revetment Structures and Log Sills (see Table 2 for specific design aspects of ELJs).

Table 2 ELJ description and function for the Williams River project, (Brooks et al. 2006).

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<tr>
<th>Log structure type</th>
<th>Primary characteristics</th>
<th>Functional attributes</th>
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<td><strong>Deflector Jams (DFJs)</strong></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 inducement — adjacent to upstream stream-ward edge of structure; complex habitat within structure itself</td>
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<td><strong>Bar Apex Jams (BAJs)</strong></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; inducement of bar/island deposition; complex habitat</td>
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<tr>
<td><strong>Bank Revetment Structures (BRVTs)</strong></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>
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<tr>
<td><strong>Log Sill Structures (LSs)</strong></td>
<td>Small stacked log accumulations (generally pyramidal in section) generally buried into bed perpendicular to flow, ideally with DFJ or BAJ abutments on either side</td>
<td>Bed control structures; inducement of step-pool type morphology; recreation of hyporheic exchange functioning</td>
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Through the collection of detailed topographic surveys of the in-channel morphology and the development of change detection analysis (Figure 4), after a 5 year period, the treatment reach was found to have a greater geomorphic complexity then the control reach and experienced a net increase in sediment storage (Brooks et al. 2006). The response of fish populations to the introduction of the structures was also monitored through time, with a positive response for the first year of the study (Brooks et al. 2004). The project on the Williams River was a turning point for river management within Australia, as it proved wood could be re-introduced in a safe and controlled manner while successfully achieving management goals (Brooks 2006).
Figure 4 Regions of bed elevation change within the test reach for the ELJ demonstration project on the Williams River. Reds and yellow shades represent deposition and blues and greens represent scour (Brooks et al. 2006).
At the world-scale, the majority of projects utilising ELJ’s have been applied in gravel-bed settings (Abbe & Montgomery 1996; Abbe & Montgomery 2003; Brooks et al. 2004), however, the use of ELJs within a sand-bed environment pose a differing set of challenges. Conditions within sand-bed streams differ due to a smaller grain size, higher erosion rates and lower bed-slope, therefore, Shields et al. (2004) suggests different design requirements are necessary for wood re-introduction. One of the major engineering issues existing within a sand-bed stream is that there is no coarse grained sediment available for ballast (most often used in other projects), consequently structures often have a higher probability of failure (D'Aoust & Millar 2000). Flume studies and field observation suggests structures which are periodically submerged in an ephemeral environment are more susceptible to decay and increased instability (Shields Jr. & Gippel 1995; Daley & Brooks 2013). Therefore, in order to overcome ensuing buoyant and drag forces, it is sometimes necessary to use earth anchors or artificial cabling, which is less preferable, as materials are less likely to decay along with the structure and cables have been known to come loose under the vibration of the flow (Shields et al. 2004).

Shields Jr. & Gippel (1995), documented the use of bank protection ELJs in an eroding sand-bed environment with a mixed response. Over a 4 year period the structures induced a the development of a more heterogeneous bed-profile and fish communities responded positively (Douglas Shields et al. 2003). However, at the conclusion of the study 35% of the structures failed, further highlighting the difficulties in designing ELJs for a sand-bed environment.

Another challenge identified by Borg et al. (2007) in sand dominated streams is the development of long lasting pools, as resulting scour and deposition have been found to fluctuate with time (Shields et al. 2004). Borg et al. (2005), examined this concept through a study in the Goulburn River Catchment, North-eastern Victoria, with the aim of examining how flume studies and scour models predict scour. As in the Williams River study, a BACI experimental design was used which examined 18 study reaches; 6 with one structure, 6 with 4 structures and 6 with no structures. However, in contrast to the complex structures used in such studies as the Williams River project (Brooks et al. 2003; Brooks et al. 2004), the introduced wood consisted of a simple rectangular geometry elevated above bed-level and oriented perpendicular to flow (Figure 5).
The study aimed to establish the feasibility of using basic ELJs to induce scour during environmental flows on the Snowy River, a highly regulated system and degraded river reach. Structures worked to increase physical diversity through pool scour, however, pool development did not occur as scour models predicted (Borg et al. 2005). This study identified that scour response was not specific to structure type but instead related to variability in flow regime, in particular the size and duration of flow events (Borg et al. 2007). The study within the Goulburn River Catchment highlighted an important consideration for ELJ use; stating that the engineered concept of designing structures based on failure is limited for habitat applications. Instead ELJ design should focus on providing bed-level stability rather than maximum pool scour, as pool persistence is more significant for the survival of aquatic biota (Borg et al. 2005).

2.5 METHODS OF STREAM ASSESSMENT: MONITORING CHANGE

River degradation has been highlighted as one of the key issues of our time, however, the overall value of a rehabilitation strategy is dependent upon the ability to record, monitor and assess both short and long-term change (Woolsey et al. 2007). Throughout the past decade, methods of river assessment have developed substantially due to an increased understanding of ecosystem processes and the advent of new technology (Lane et al. 2003). It is essential for current restoration projects to have explicit and realistic goals (Bernhardt et al. 2005) which incorporate ecological, hydrological and geomorphic aspects, as it is often not possible to restore rivers to pre-disturbance conditions (Gostner et al. 2013).

In order to assess the resulting effect of a rehabilitation strategy, it is common practice to compare the study reach to a predetermined reference condition (Gostner et al. 2013) over differing temporal scales. This often includes the selection of a control reach (Borg et al. 2005;
Brooks et al. 2006; Borg et al. 2007) or a comparison with a remnant river system. Reaches for comparison are usually chosen based on a similar catchment size, flow regime, sediment type, channel geometry and level of disturbance to the rehabilitation reach and are often assessed using both quantitative and qualitative methods (Brierley & Fryirs 2005).

The response of ecological variables, such as fish species and macro-invertebrate diversity, response to ELJ construction is often recorded through methods such as electrofishing (Brooks et al. 2004; Howell et al. 2012). Statistical analyses of data collected at differing stages of the project allows for the quantification of fish assemblages through time, and the establishment of a correlation between the introduction of ELJs and increased species diversity (Wallace et al. 1995; Douglas Shields et al. 2003; Borg et al. 2005; Dumke et al. 2010; Howell et al. 2012). Other variables, such as water quality and condition of the substratum, are often recorded in conjunction with species analysis to assess the overall ecological effect of the ELJ structures (Douglas Shields et al. 2003).

The detection of geomorphic change and altered habitat diversity, is a strong focus of wood reintroduction initiatives, as geomorphic diversity has been positively correlated with species diversity (Gostner et al. 2013). Topographic assessment is usually carried out after geomorphically effective flows which have altered the in-channel topography (Brasington et al. 2000). Through this type of analysis, changes in sediment budget and the overall stability of a reach can be ascertained and related to rehabilitation goals (Merz et al. 2006). Basic methods of assessment have included longitudinal and cross-sectional topographic surveys, as well as localised surveys of scour depth in association with ELJs (Madej 1999; Kaufmann & Faustini 2012). These methods are both cost effective and time efficient for small management organisations, however, they can sometimes result in cross-sectional bias due to the dispersed nature of data sets (Mossop & Bradford 2006).

With the improvement of geospatial technology, river managers are able to more accurately quantify the geomorphic change which has occurred within a study reach at differing timescales (Fuller & Basher 2013). The development of Digital Elevation Models (DEM) from repeated high resolution ground surveys is becoming an increasing common method of assessing morphological change within a study reach (Madej 1999; Brasington et al. 2000; Wheaton et al. 2010; Brasington et al. 2012; Kaufmann & Faustini 2012; Wheaton et al. 2013). Unlike, a conventional cross-section, the collection of elevation point data with an RTK GPS or total station, enables the detection of geospatial rather than linear change (Brasington et al. 2000).
2000), as well as the development of reach scale sediment dynamics. This is imperative for analysing the geomorphic response to ELJ intervention, as changes occur over a large surface area, such as the development of pools through scour (Merz et al. 2006). However, the assessment of morphological change through the development of topographic surfaces can be problematic due to the propagation of error and the uncertainty associated with DEM development (Lane et al. 2003; Wheaton et al. 2010; Brasington et al. 2012). The error associated with geomorphic change detection analysis is further discussed in relation to the project methods in Chapter 4.

Through an examination of the relevant literature, it is apparent anthropogenic alterations to the landscape have significantly affected the condition of Australia’s riverine ecosystems, resulting in wide scale instability and decreased biodiversity (Brooks & Brierley 1997; Brierley et al. 1999; Brooks & Brierley 2002; Lester & Boulton 2008; Gostner et al. 2013). The reintroduction of wood into degraded streams is seen as a positive method of inducing short-term habitat heterogeneity, however, the correct method of reintroduction remains contentious (Erskine et al. 2012). The construction of ELJs has been widely accepted as a key wood reintroduction method, however, few studies have been rigorously tested (Brooks et al. 2004), with the majority of studies conducted in gravel-bed river systems. Therefore, one of the major knowledge gaps examined through this study is the potential success of ELJs in a sand-bed environment with a variable hydrological regime. This study endeavors to address this research area by attempting to quantify the geomorphic influence of ELJs structures within a recovering sand-bed stream.
3. REGIONAL SETTING

Stockyard Creek is a tributary of the Wollombi Brook and is located in the Hunter Valley, NSW (32°54’33.28”S, 151° 4’11.42”E) (Figure 6). The study reach drains a catchment area of ~ 35 km² and has a total length of 2.2 km. The small capacity ephemeral sand bed stream exhibits a partly-confined river style with a discontinuous flood plain (Brierley & Fryirs 2005) and channel slope of 0.003m/m.

Figure 6 Map of the study region located at Stockyard Creek, Wollombi, NSW. The closest BOM daily read rainfall gauges are displayed in relation to the study site. Basemap, Bingmaps, 2013.
3.1 GEOLOGICAL SETTING

Stockyard Creek is situated within the Wollombi catchment and is bounded by the Hunter Range to the south-west. The study area is characterised by a steep sloping mountainous topography, with a narrow river valley and an elevation range of between 94-390 m AHD.

The lithology of the study area is dominated by the Narrabeen Group, consisting of Triassic sandstone with interbedded siltstone and claystone, as well as conglomerate sandstone of the Widden Brook Conglomerate (Figure 7). The upper limits of the Stockyard Creek catchment are overlain by a thick strata of Hawkesbury Sandstone, consisting of coarse-grained quartz sandstone with some minor shale lenses (Saunders et al. 1988). Quaternary Alluvium occupies the floodplain of Stockyard Creek which is comprised of a mix of unconsolidated sands, silts, clays and gravels (McInnes 1997). Stockyard Creek is a sand-bed channel consisting of predominantly coarse sands (<2mm); numerous in channel boulders exist within the low flow channel which work to actively force the in-channel morphology.

Figure 7 Surface geology of the Stockyard Creek study region. The study site at Earthways is indicated by a dashed box while the external control is indicated by a black box. The lithology of the study area is dominated by the Narrabeen Group and Hawkesbury Sandstone formation (NSW Department of Primary Industries 2003).
3.2 BRIEF HISTORY OF SETTLEMENT AND LAND USE

Although no direct record of land use exists for Stockyard Creek, anecdotal evidence suggests the study region experienced a land use history attuned to that of the Wollombi catchment (Woodward B. pers. comm. 2013). Therefore, the following description of land use within the Wollombi catchment is considered applicable to the study site.

Prior to European settlement, the Wollombi region has had a long history of Aboriginal use, with the rivers of the Wollombi catchment belonging to the territory of the Darkinjung people (Department of Environment & Climate Change 2008). Evidence of Indigenous occupation exists at the study site through dispersed rock art, however, there is an absence of records describing Aboriginal land use within the region.

First established as a penal colony in 1831, the Wollombi valley has had a long history of post-European disturbance due its close proximity to Sydney (Rees 1994). The fertile river valleys of the catchment were considered to be prime land for agriculture, and the region was rapidly cleared and established as an agricultural center in the 1860’s (Rees 1994).

Early agricultural industry focused on the growth of wheat and supplementary crops, such as maize, potatoes and tobacco, and the region became the largest wheat growing industry in the colony (Mahony 1994). However, the spread of rust throughout the catchment, between the 1860’s and early 1970’s, inhibited this thriving industry and forced farmers to focus on grazing and dairying (Rees 1994).

In association with early settlement, the narrow valleys were cleared as a source of timber for housing, fencing and firewood (Mahony 1994). In the 1950’s, mechanised logging saw the destruction of much of the native accessible bush land, however, such practices decreased with the establishment of the Yengo National Park in 1988, which forms the western boundary of the study site (Department of Environment & Climate Change 2008).

In the wake of the destructive 1949 flood and the mechanisation of farming, the small farms of the Wollombi Valley became unviable (Griffiths 1994). The degraded nature of the Hunter Catchment prompted a shift in management strategy towards a more environmental focus (Erskine & Webb 2003). Under the Hunter Management Trust (1956), land management initiatives sought to decrease erosion through the regeneration of land and promoted the concept of landcare (Mahony 1994).
Significantly, with time, the main livelihood of the region has shifted from intensive agriculture to tourism, due to the growing recognition of the regions cultural value (Lyons 2010). Under the influence of the ‘urban drift’ in the 1960’s ‘outsiders’ moved to Wollombi seeking an escape from the urban sprawl (Mahony 1994). This began the division of agricultural landholdings and the development of a population with heightened environmental awareness (Mahony 1994). Currently, land use in the region is predominately comprised of dispersed rural dwellings with the development of small scale boutique industries and hobby farms (Lyons 2010). Specifically, the study site at Stockyard Creek is a privately owned environmentally sustainable dwelling with the main focus of land use includes low impact farming and bush regeneration.

Figure 8 Historical photograph of early land use at the study site in 1906. The property was owned by the Sylvester family who grazed cattle in the narrow river valley (Lake Macquarie City Library, 2013).
3.3 CLIMATE AND HYDROLOGY

The study site is located within the Sydney Bioregion (Thackway & Cresswell 1995), which is characterized by a temperate climate with warm to hot summers. The Wollombi Catchment has a mean annual temperature of between 11.3-24.5°C (Department of Environment & Climate Change 2008). There is an extensive network of rain gauges operated by BoM throughout the Hunter Valley. Rainfall data has been sourced from the nearest BOM stations to the study site, and the following section presents a summary of this data including key rainfall totals.

3.3.1 Rainfall Record

In the Wollombi catchment several BOM daily read rainfall gauges are in operation with the closest gauges to the study site being, Wollombi (Narone Creek) and Wollombi (St Johns Church) as shown in Figure 6. However, a 32 year daily rainfall record exists for the study site (referred to as Earthways), and this gauge has been recorded by the property owner. Discontinued BOM rainfall data exists for a station on Stockyard Creek downstream of Earthways known as Wollombi (Stockyard), and is a 10 year rainfall record from 1959-1970. At Earthways, total daily rainfall is recorded between 8-9am on the day of the record, reflecting the previous 24 hour rainfall.

Table 3 Average monthly rainfall and mean annual rainfall for the closest daily read rainfall gauges to Earthways. Rainfall data sourced from BOM and collected by the property owner at Stockyard Creek.

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</tr>
<tr>
<td>OCT</td>
<td>50.8</td>
<td>69.9</td>
<td>44.5</td>
<td>57</td>
</tr>
<tr>
<td>NOV</td>
<td>80.6</td>
<td>62.8</td>
<td>75.6</td>
<td>76.4</td>
</tr>
<tr>
<td>DEC</td>
<td>74.5</td>
<td>117.3</td>
<td>57.5</td>
<td>75.7</td>
</tr>
<tr>
<td>Mean Annual</td>
<td>758.1</td>
<td>813</td>
<td>663.2</td>
<td>818.6</td>
</tr>
</tbody>
</table>
Rainfall within the Wollombi catchment is summer dominated, with a median annual rainfall ranging between 663 – 818mm (Table 3). The wettest months on average for the Earthways gauge occur in February and November, and the total annual rainfall for 2013 was well above the long-term median.

3.3.2 Rainfall Distribution

The daily read data for the Earthways rainfall gauge has been compiled in Figure 10, which portrays the total monthly rainfall distribution as well a cumulative residual mass curve for the 32 year record. The cumulative residual mass curve was calculated as the cumulative variation of the monthly total from the mean rainfall total for that month. A positive trend in the residual mass curve represents a wetter than average period, while a negative trend indicates a dry period. The positive trend indicated in Figure 10, between 1988-1991, denotes a wet period from which resulted in the greatest monthly rainfall (412mm) for the 32 year record at Stockyard Creek.

An examination of the monthly rainfall distribution for the rehabilitation period, between from 2001 to the present (Figure 9), provides a better understanding of the flow conditions existing after to ELJ construction. No to low-flow conditions prevailed during the 5 years after ELJ construction, this is indicated by the downward negative trend in Figure 9, between 2001 and 2007. During this dry period, little to no geomorphic change occurred within the reach due to the absences of geomorphically effective flows. It wasn’t until June 2007 that a flow of sufficient magnitude occurred to initiate change.

Figure 9 Total monthly rainfall distribution and residual mass curve for rehabilitation period 2001-2013, Earthways rain gauge. Each survey period is indicated by an arrow. The total monthly rainfall associated with the June 2007 and February 2013 flow events are also indicated.
Figure 10 Monthly rainfall total and cumulative residual mass curve for the Earthways rainfall gauge between 1981-2013. The cumulative residual mass curve was calculated as the cumulative variation of the monthly rainfall total from the mean average total for that month. A positive trend in the residual mass curve represents a wetter than average period, while a negative trend indicates a dry period. The region represented in grey indicates the rainfall distribution for the study period (2001-2002).
3.3.3 Hydrology

The 32 year rainfall record at Earthways is used as a proxy for stream discharge, as Stockyard Creek is an ungauged stream. The assumption that stream flow response is correlated with rainfall and runoff, is not unreasonable, due to the small catchment size of the study reach (Daley & Brooks 2013). Significantly, the Earthways rainfall distribution is closely correlated with the closest BOM rainfall gauges (Wollombi (Narone) gauge, correlation coefficient of 0.95); therefore, stream flow discharge at gauges within the Wollombi catchment can therefore be assumed to be representative of flood variability within Stockyard Creek.

Flood History of the Wollombi Valley

The Wollombi Catchment has a high flood variability and therefore has a tendency to experience ‘flashy’ catastrophic floods, with numerous high magnitude floods recorded since European settlement in the early 1800’s (Erskine 1994). The largest recorded flood event occurred between the 17th to the 18th of June 1949, and resulted in wide-scale destruction throughout the Wollombi catchment (Erskine & Melville 2008). Between 1949 and 1979, a series of high magnitude flood events further exacerbated the extensive degradation caused by the 1949 flood, with significant events occurring in the years 1893, 1927, 1930, 1955 and 1978 (Table 4) (Lyons 2010).

Table 4 Post-European flood history for the Wollombi Brook calculated using the NSW Office of Water stream flow gauges at Paynes Crossing, Bulga and Warkworth. Red values indicated adjusted peak discharge calculations developed due to inconsistencies in the Wollombi Brook flow record (Lyons 2010).

<table>
<thead>
<tr>
<th>Rank in Annual Series</th>
<th>Paynes Crossing</th>
<th>Bulga</th>
<th>Warkworth</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Year</td>
<td>Peak Flow (m³/s)</td>
<td>Year</td>
</tr>
<tr>
<td>1</td>
<td>1949</td>
<td>2638</td>
<td>1949</td>
</tr>
<tr>
<td>2</td>
<td>1927</td>
<td>1679</td>
<td>1927</td>
</tr>
<tr>
<td>3</td>
<td>1930</td>
<td>1508</td>
<td>1930</td>
</tr>
<tr>
<td>4</td>
<td>2007</td>
<td>1375</td>
<td>2007</td>
</tr>
<tr>
<td>5</td>
<td>1977</td>
<td>1264</td>
<td>1977</td>
</tr>
<tr>
<td>6</td>
<td>1952</td>
<td>1238</td>
<td>1952</td>
</tr>
<tr>
<td>7</td>
<td>1955</td>
<td>1068</td>
<td>1955</td>
</tr>
<tr>
<td>8</td>
<td>1946</td>
<td>960</td>
<td>1964</td>
</tr>
<tr>
<td>9</td>
<td>1989</td>
<td>894</td>
<td>1963</td>
</tr>
<tr>
<td>10</td>
<td>1945</td>
<td>664</td>
<td>1953</td>
</tr>
</tbody>
</table>

A flood within the Stockyard Creek requires the continuous ‘wetting’ of the catchment, leading to higher runoff during the main storm front. The steep topography and flat narrow valley of the Stockyard Creek catchment, translates to the rapid development of destructive flashy floods. Two major flood events occurred during the study period in June 2007 and February 2013, with the 1927, 1949 and 2007 floods estimated to be the highest floods on record for the
Wollombi catchment (Lyons 2010). These high magnitude events resulted in considerable in-channel topographic change but were contained within the large macro-channel.

**June 2007 Flood**

A flood event occurred on Stockyard Creek between the 7th to the 10th of June 2007. The total rainfall recorded at Earthways during the 4 day period was 295 mm, and the maximum daily rainfall was 197 mm occurring on the 9th of June. Based on the rainfall record, intensity-frequency-duration analysis (Table 5) shows that the June 2007 storm event had a return interval of between 20 to 50 years, depending on the duration.

Table 5 Total daily rainfall recorded at Wollombi rainfall gauges during the storm event occurring 7-10th June 2007. The total monthly rainfall and Intensity-Frequency-Duration analysis is also indicated for 24hr and 96hr duration. See Appendix A for BOM, IFD charts used for this analysis.

<table>
<thead>
<tr>
<th>Station Name</th>
<th>Total Daily Rainfall (mm)</th>
<th>Monthly</th>
<th>Intensity-Frequency-Duration</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>7th</td>
<td>8th</td>
<td>9th</td>
</tr>
<tr>
<td>Earthways</td>
<td>45</td>
<td>40</td>
<td>197</td>
</tr>
<tr>
<td>Wollombi (Narone Ck)</td>
<td>12.2</td>
<td>44.2</td>
<td>187</td>
</tr>
<tr>
<td>Wollombi (St Johns)</td>
<td>11</td>
<td>42.8</td>
<td>174</td>
</tr>
<tr>
<td>Congewai (Greenock)</td>
<td>17</td>
<td>60</td>
<td>200</td>
</tr>
<tr>
<td>Yallambie (Mt Auban)</td>
<td>10</td>
<td>41</td>
<td>185</td>
</tr>
<tr>
<td>Watagan Central</td>
<td>12.2</td>
<td>44.2</td>
<td>187</td>
</tr>
</tbody>
</table>

The June 2007 flood was the first major flow event to have occurred after ELJ construction and was estimated to be a 1:20 ARI event within the Stockyard Creek catchment (Daley & Brooks 2013). Assessments are based on stage-discharge estimates from Hec-Ras analysis completed within the reach at the time of structural design (Brooks 2014). The stage height of the flood was noted to have been comparable to the 1978 flow event, which resulted in major channel expansion and degradation at the study site (Woodward B. pers. comm. 2013). This estimated ARI is comparable to return periods compiled by Lyons (2010), with the June 2007 flow event having an estimated return interval of between 25-40 years (Table 6).

Table 6 Estimated return period for the June 2007 flow event for the NSW Office of Water stream flow gauges within the Wollombi catchment (Lyons 2010)

<table>
<thead>
<tr>
<th>NSW Office of Water Stream Gauge</th>
<th>ARI (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wollombi Brook D/S Brickman’s Bridge</td>
<td>40</td>
</tr>
<tr>
<td>Wollombi Brook at Bulga</td>
<td>25</td>
</tr>
<tr>
<td>Wollombi Brook at Warkworth</td>
<td>30</td>
</tr>
</tbody>
</table>
The June 2007 flood was the largest event to have occurred within the valley since the catastrophic flood of June 1949 which is predicted to have had an ARI on Wollombi Brook of 87 years (Erskine 1994).

2013 Flood Event

Another smaller magnitude flow event occurred at Stockyard Creek from the 21st to the 25th of February, 2013. The 5 day rainfall total for the storm period ranged between 93.6mm at Wollombi (Narone) to 122 mm at Yallambie in the Upper catchment. Earthways received a total daily maximum of 67 mm, with the February 2013 storm event predicted to have a return interval of less than 1 year (Table 7).

Table 7 Total daily rainfall recorded at Wollombi gauges during the storm event occurring 21st -25th, February, 2013. The total monthly rainfall and Intensity-Frequency-Duration analysis is also indicated for 24hr and 120 hr duration. See Appendix A for BOM, IFD charts used for this analysis.

<table>
<thead>
<tr>
<th>Station Name</th>
<th>Total Daily Rainfall (mm)</th>
<th>Intensity-Frequency-Duration</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>21st</td>
<td>22nd</td>
</tr>
<tr>
<td>Earthways (Stockyard Ck)</td>
<td>4</td>
<td>11.5</td>
</tr>
<tr>
<td>Wollombi (Narone Ck)</td>
<td>6.8</td>
<td>4.8</td>
</tr>
<tr>
<td>Yallambie (Mt Auban)</td>
<td>8.6</td>
<td>18.4</td>
</tr>
<tr>
<td>Watagan Central</td>
<td>6.8</td>
<td>4.8</td>
</tr>
</tbody>
</table>

Anecdotal evidence (Woodward B. pers. comm. 2013) and discharge calculations for surveyed flood debris (Table 8) at the study site suggest the 2007 flow event at Stockyard Creek was marginally larger than the February 2013 event, which is supported by the difference in estimated return interval for the two storm periods.

Table 8 Discharge flow estimates calculated using Manning’s equation and surveyed flood debris levels for the 2013 and 2007 flow event at Stockyard Creek. Recurrence intervals estimated using unpublished HEC-RAS data for the Stockyard Creek catchment (Brooks 2014).

<table>
<thead>
<tr>
<th>Mannings ‘n’</th>
<th>Discharge Estimate 2013 Q (m³/s)</th>
<th>ARI</th>
<th>Discharge Estimate 2007 Q (m³/s)</th>
<th>ARI</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.03</td>
<td>19.2</td>
<td>2.5</td>
<td>73.8</td>
<td>15</td>
</tr>
<tr>
<td>0.04</td>
<td>14.4</td>
<td>2</td>
<td>55.3</td>
<td>6</td>
</tr>
<tr>
<td>0.05</td>
<td>11.5</td>
<td>2</td>
<td>44.3</td>
<td>5.5</td>
</tr>
</tbody>
</table>
3.4 CHANNEL MORPHOLOGY AND HISTORY OF REHABILITATION WORK

The study reach at Stockyard Creek is characterised by a narrow, 20 to 50 m wide sand-bed channel with a discontinuous sandy floodplain. The planform of the current channel is controlled largely by the valley morphology, with ‘forced’ pools occurring where the channel impinges against outcropping bedrock (Figure 13). The channel in the study reach is often characterised by a compound channel cross-section, with vegetated inset alluvial benches (Figure 11) and a width/depth ratio of 15 – 17. In-channel units include bedrock forced pools, and vegetated bank-attached bars with riparian vegetation dominated by River oak (Casuarina cunninghamiana) and woody species such as Eucalyptus saligna.

![Cross-section 11 representing the current compound channel morphology of Stockyard Creek. The cross-section location is indicated in Figure 13.](image)

Although no historical record of channel change exists for Stockyard Creek, extensive studies of the resulting degradation caused by a series of high magnitude floods between 1949 and 1979 has been established for the Wollombi catchment (Erskine 1994; Erskine & Peacock 2002; Erskine 2008; Erskine & Melville 2008).

Prior to European settlement, river channels within the Wollombi valley have been documented as having a compound cross-section, with a narrow, low capacity, sinuous channel (Erskine 2008). Isolated scour pools with a depth of between 1-3 m were observed by the early settlers in association with outcropping bedrock (Erskine 1994).

In tandem with the peak period of settlement, early alterations to the landscape were observed in association with a series of flood events between 1838 and 1867, whereby channel incision was documented in the upper reaches of the catchment (Erskine & Melville 2008). However,
catchmentwide catastrophic channel change was not initiated until the 1949 flood and was further exacerbated by a series of flood events between 1949 and 1979 (Erskine 2008).

Studies suggest the morphological response throughout the catchment was spatially variable and dependent upon the level of valley confinement and the reach position within the catchment (Erskine 2008). However, partly-confined reaches, such as Stockyard Creek, experienced extensive incision and expansion due to the forced erosion of in-channel benches and long-term floodplain deposits (Erskine 1994). As a result, large volumes of sand which would have usually been stored within the upstream tributaries (Erskine 2008), in-filled the characteristic pool morphology of the Wollombi Brook. This has resulted in a homogenous and unstable bed profile with aggradation of up to 4 m occurring downstream of Warkworth (Erskine 1994).

Historical photographs suggest Stockyard Creek has experienced a similar trajectory of change to that of the degradation observed throughout the Wollombi catchment. Figure 12a, depicts the over-widened homogenous channel existing at the study site in 1979, while Figure 12b indicates the downstream morphology of Stockyard Creek not long after the 1949 flood. Note the limited vegetation cover and the highly erosive vertical banks, a characteristic of unstable channels in a post-European landscape (Brooks & Brierley 1997; Page & Carden 1998; Brierley et al. 1999). Since the destabilisation of Stockyard Creek, the floodplain is no longer inundated and floods are confined within the large macrochannel.

Figure 12 Historical photographs of Stockyard Creek; (a) upstream of the control reach at the study site, 1979; (b) Stockyard Creek downstream of the treatment B reach after the 1949 flood. Note the sparse vegetation and the over widened homogenous channel with highly eroded banks.
3.4.1 The Revegetation Strategy

The following history of re-vegetation was compiled through personal communication with property owner at Earthways, Brian Woodward. Prior to ELJ construction, the study site has experienced an extensive riparian revegetation strategy which dates back to the early 1980’s. The revegetation work was initially carried out with the aim of improving the stability and species diversity of the sparsely vegetated reach. Historical photographs and anecdotal evidence (Woodward B. pers. comm. 2013) suggests the riparian margin consisted of highly erosive banks with some isolated trees (Figure 12). The dominant species existing prior to rehabilitation were sparsely distributed Acacia mearnsii seedlings and exotic species, such as Domestic Peach and Blackberry (Rubus fruticosus). Lomandra longifolia existed as the only remnant vegetation inhabiting the unstable bank features.

Initially the property owners sought a method of natural regeneration, however, such efforts proved unsuccessful due to the prevalence of exotic species within the reach. Therefore, an alternative revegetation strategy was undertaken with support from the Hunter River Catchment Authority, which saw the planting of Willows (Salix spp.), within the control and treatment A reach, to reduce erosion and protect the bank (see Figure 13, for Willow planting locations). This was a common practice implemented throughout the Hunter River Catchment (Erskine & Webb 2003), and the trees are still present at the study site due to the role they play in stabilising the bank and bed substrate.

For the major phase of the revegetation strategy 2,640 longstem tubestock, consisting of native species, were planted within the macrochannel on bench and bank features between the low-flow channel and the floodplain (see Appendix B Revegetation Species List). Lomandra longifolia were planted on bare point bar features close to the low-flow channel, however, few of the plantings survived. The tubestock were sourced locally, by the then DLWC, and consisted of woody species which were documented to have originally inhabited the region prior to human settlement (Vernon 1994). The planting process was carried out in a haphazard fashion by the property owners, and a continuing weed removal strategy was implemented to promote the establishment of native species.

A qualitative analysis of the vegetation change which has occurred at the study site is presented in, Chapter 5, section 5.4.
Figure 13 Map of the study reach at Stockyard Creek indicating the layout of the BACI experimental design with ELJ locations. The channel planform is controlled by the valley morphology, with outcropping bedrock in the low-flow channel. The location of willow plantings are indicated in green.
3.4.2 The Reintroduction of wood into Stockyard Creek – the ELJ Strategy

Background

Beginning in 2001, a 2.2 km reach of Stockyard Creek was divided based on a Before-After-Control-Impact (BACI) experimental design, into an upstream control (no ELJs), treatment A and treatment B reach as seen in Figure 13. No record of past river management practices exists for Stockyard Creek, however, anecdotal evidence suggests the practice of desnagging was implemented at the site up until the beginning of the ELJ project (Woodward B. pers. comm. 2013).

In response to channel incision and habitat loss, the broad-scale project was developed in conjunction with a wood reintroduction initiative designed for the treatment B reach by the the Department of Land Water and Conservation (DLWC). The study site at Earthways was identified as a suitable site for a wood reintroduction experiment, as the observed morphological and land use history was considered to be representative of the Wollombi catchment. The extent of the property also allowed for the development of an appropriate experimental design with a consistent management strategy throughout (Brooks A pers. comm. 2013). In contrast to past ELJ initiatives conducted within the Hunter region, the sand-bed morphology and revegetation strategy at Stockyard Creek provided a unique setting for testing the application of a variety of ELJ designs in a progressively stabilised reach.

ELJ Design

The wood reintroduction strategy was developed with the aim of increasing bed stability and habitat complexity. In April 2002, a variety of ELJs were constructed throughout the two treatment reaches using hard wood logs sourced from industrial sites within the Hunter region.

Treatment A

Within a 950m reach, 22 engineered ELJs were constructed based on structural designs developed for the Williams River wood reintroduction project (Brooks et al. 2004; Brooks et al. 2006). However, the structures built at Stockyard differ from those implemented in other regions of the catchment, as they were scaled to suit the small ephemeral channel and included the use of an experimental v-weir design (Figure 14). Log sill and deflector jam structures were built in association with pre-existing depositional features, such as point bars, as a means of bank protection through flow deflection (Figure 15 see LS7 and LS11). The v-weir log sills were built within a relatively straight and homogenous section of the reach to promote bed scour and bar formation (Figure 16, see VW13a and VW17).
For stability, the log-sill structures were entrenched below bed-level (1-1.5 m) and incorporated Geofabric woven through the stacks of sub-surface logs to prevent undercutting (Figure 9). Natural boulders existing along the bank line were used to stabilise the structures with the head of logs wedged into the opposite rock bank, while some structures used artificial anchoring such as cabling. The ELJs were built using logs with a diameter of between 30-70cm and often included root wads for stability.

Table 9 Description of ELJ design and function for structures built within the treatment A reach. Structural designs were based on ELJs constructed in the Williams River (Brooks et al. 2004; Brooks et al. 2006) project, however, the strategy included the use of an experimental v-weir design not implemented elsewhere in the catchment.

<table>
<thead>
<tr>
<th>Structure Type</th>
<th>Number</th>
<th>ELJ Design and function within the treatment A reach</th>
</tr>
</thead>
<tbody>
<tr>
<td>Log Sill (LS)</td>
<td>4</td>
<td>Log stack with perpendicular transverse logs trenched 1-1.5 m below bed surface. Backfilled so that structure sits 30 cm above current bed-level; bed control, upstream sediment trap &amp; inducement of step pool (Figure 15, see LS3)</td>
</tr>
<tr>
<td>V-weir log sill</td>
<td>10</td>
<td>2 v-weir log sill designs, transverse logs trenched 1m below bed surface medium logs keyed into bank with sub-aerial deflector wing lower and upper transverse logs with longitudinal log sitting flush with bed-level; upper transverse log buried into bank toe; habitat enhancement through scour initiation (Figure 15, see VW 6, 13a)</td>
</tr>
<tr>
<td>Deflector Jam (DFJ)</td>
<td>7</td>
<td>Logs trenched in place, backfilled with sand and acacia branches; often include cross-spanning scour log raised 0.1 m above bed surface; flow deflection, bank protection &amp; bar development</td>
</tr>
<tr>
<td>Bank Revetment Jam (BRVT)</td>
<td>1</td>
<td>Combined with log sill design; several stacked logs positioned parallel to flow at bank toe; fluvial erosion control through bank protection &amp; habitat creation.</td>
</tr>
</tbody>
</table>

Figure 14 Two styles of v-weir log sill structures constructed on Stockyard Creek with idealised deposition (grey) and scour (blue) developing around the structures. Broken line represents approximate thalweg location (Daley & Brooks 2013).
Figure 15 ELJ structural layout for upstream end of the treatment A reach. Pool depths are based on the pre-construction topography. Plan modified from AutoCAD drawings (Brooks 2000).
Figure 16 ELJ structural layout for downstream end of the treatment A reach. Pool depths are based on the pre-construction topography. Plan modified from AutoCAD drawings (Brooks 2000).
Treatment B

The ELJ strategy developed for the treatment B reach differed to that of the treatment A and consisted of a lower frequency of structures utilising a V-sill Weir design developed by Allan Raine (DLWC) (Figure 17). In contrast to the complex structures developed by Brooks et al. (2006), the v-sill weir consisted of vertical split posts buried to a depth of greater than 1 m, with some structures including the placement of large boulders and longitudinal logs downstream of the log complex (Table 10). The split log V design was developed as a grade control mechanism in response to the occurrence of incision and habitat loss and was implemented in relatively straight and homogenous sections of the reach (Figure 18).

Table 10 Description of ELJ design and function for structures built within the treatment B reach. The strategy differed from that of the treatment A reach with a low frequency of structures and different ELJ design.

<table>
<thead>
<tr>
<th>Structure Type</th>
<th>Number</th>
<th>ELJ Design and function within the treatment B reach</th>
</tr>
</thead>
<tbody>
<tr>
<td>V-Sill Weir (VS)</td>
<td>3</td>
<td>Transverse logs angled 20-30 degrees from channel cross-section; vertical split posts buried to depth of &gt;1 m upstream of log stack and lined with Geotech; Bed control, upstream sediment trap &amp; inducement of downstream scour.</td>
</tr>
</tbody>
</table>

Figure 17 Representation of the V-sill weir design constructed in the treatment B reach at Stockyard Creek with idealised deposition (grey) and scour (blue) developing around the structures. Image not to scale.
Treatment B - Structure Layout

Figure 18 ELJ structural layout for treatment B reach. Pool depths are based on the pre-construction topography. Plan modified from AutoCAD drawings (Brooks 2000)
3.4.2 External Control Reach

Due to the interconnected nature of the treatment and control reaches at Stockyard Creek, as part of this project, an external detailed topographic survey was carried out in a neighbouring stream. The external control reach is located at Bagnells Creek (between 32°53'22.41"S, 151° 5'26.94"E and 32°53'17.80"S, 151° 5'20.97"E) approximately 1.2 km upstream from the confluence of Bagnells and Stockyard Creek (Figure 6). The purpose of this survey was to indicate the potential in-channel morphology of a reach without the influence of a re-vegetation or structural rehabilitation strategy. In contrast to the study site at Stockyard Creek, the reach at Bagnells is surrounded by primarily active agricultural land with ploughed fields on the adjacent floodplain. Like Stockyard, it is partly confined by the valley margin with a discontinuous floodplain. The reach has a simple in-channel morphology with few distinguishable geomorphic features except at the downstream end of the reach where three pools up to 1m in depth were present adjacent to a bedrock bend (Figure 19). Boulders were fixed within the channel and are predicted to have actively forced the pool morphology. The reach at Bagnells Creek drains the same lithology as the study site and has a slightly smaller upstream catchment area of 26 km². Vegetation within the external control is examined in section 5.4 while the thalweg variability of the reach is examined in section 5.3.2.

Figure 19 Map indicating the location of the surveyed reach at Bagnells Creek including observed pool locations and the resulting interpolated DEM surface. Basemap sourced Bingmaps 2013.
4. METHODS

4.1 IN-CHANNEL MORPHOLOGICAL RESPONSE TO ELJ INTERVENTION

4.1.2 Detailed Topographic Survey

To quantitatively analyse the geomorphic change which has occurred at the study site, four detailed topographic surveys were completed during an 11 year period after bed mobilising flows (Table 11). As discussed in Chapter 2, the use of a detailed topographic survey enables a more direct analysis of the change occurring within a reach, as detailed point elevation data enables the identification of spatially distributed change and removes the risk of cross-sectional bias (Brasington et al. 2000).

To ensure the temporal topographic surfaces were comparable and consistent, a benchmark network of known station points was established in 2001. This network has been consistently used to collect point elevation data throughout the study period. The field surveys were undertaken using a Trimble M3 and Leica TCRM1201 Total Station (Figure 20) and were processed by a registered surveyor (see Appendix C for detailed surveyor report). The use of a RTK GPS would have allowed for the faster collection of elevation data points, however, limited satellite signal exists within the narrow valley at Stockyard Creek. The collection of elevation point data was focused within the active channel, and points were collected randomly with a greater point density on topographical variable regions. Specific site features such as ELJs, LWD, thalweg and debris trash lines were surveyed into the dataset. The 2013 survey took three people five days (26-30/8/13) to complete and was completed in GDA94 MGA Zone 56 with elevation data collected in AHD.

Table 11 Survey attributes for each point data set used for the development of DEMs. The time period of the survey in relation to ELJ construction is indicated by ELJ Stage with “pre” representing pre-construction and “post” representing post construction period.

<table>
<thead>
<tr>
<th>Date of Survey</th>
<th>ELJ Stage</th>
<th>Number points within channel</th>
<th>Point Density (pt/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>April, 2002 (Baseline)</td>
<td>pre</td>
<td>1940</td>
<td>0.104</td>
</tr>
<tr>
<td>May, 2002</td>
<td>post</td>
<td>2404</td>
<td>0.129</td>
</tr>
<tr>
<td>19th July 2007</td>
<td>post</td>
<td>1343</td>
<td>0.092</td>
</tr>
<tr>
<td>2nd August 2013</td>
<td>post</td>
<td>4562</td>
<td>0.245</td>
</tr>
</tbody>
</table>
Figure 20 Trimble M3 Total Station used to collect elevation data points within the study reach; a) Total Station set up within treatment b reach; b) Staff and theodolite used to collect elevation data points, a higher density of points were collected for regions with a sharp change in gradient.

Figure 21 The process of surface development from field survey to ArcGIS 10.0: a) Detailed Topographic survey for study reach August 2013 indicating elevation point distribution; b) section of TIN surface in treatment A reach created from elevation point data; c) resulting DEM for the treatment A reach clipped to bottom bank line. See Appendix E for GIS Data layers.
4.1.3 Development of Topographic Surface

The surveyed point elevation data was later processed using Delauney Triangulation in ESRI, ArcGIS 10.0, to create a Triangular Irregular Network (TIN) surface for each survey date. TIN interpolation is a common method of creating terrain surfaces from detailed topographic surveys as it incorporates the exact elevation data as vertices in the surface and is well suited to irregularly spaced data (Wheaton et al. 2010; Wheaton et al. 2013).

Three dimensional break lines were digitised from elevation data points for the bottom and top of bank boundaries and used to edit the TIN surface. This process is important to prevent interpolation occurring across significant breaks in slope (Brasington et al. 2000). In order to restrict the TIN interpolation a hard clip polygon was drawn around the survey data points (Wheaton et al. 2010). The TIN surfaces were later processed into a concurrent raster DEMs with a cell size of 1 m and natural neighbour interpolation. Brasington & Richards (1998), suggest the use of a finer resolution can potentially introduce spurious artefacts into DEM generation.

DEM surfaces were extracted by raster mask using the bottom of bank line and later masked by study reach extent. This method ensured cells at the outer limit of the study reach were not affected by the influence of edge effects, and the in channel change could be detected. The development of concurrent raster surfaces ensures each DEM has exactly the same spatial extent and that the datasets are correctly aligned for geomorphic change detection analysis (Wheaton et al. 2010). An external detailed topographic survey was carried out in Bagnells creek, a neighbouring stream to Stockyard Creek. TIN and DEM surfaces for Bagnells Creek were created using the same method, however, due to the absence of previous benchmarks the survey was conducted in relation to the total station.
4.1.4 Quantification of Morphological Change

Geomorphic Change Detection

To quantify the morphological change which has occurred since ELJ construction, Geomorphic Change Detection 5.0 (GCD 5.0) tool for ArcGIS 10.0 (Wheaton et al. 2013) was used to perform a DEM of Difference (DoD) analysis.

DoD analysis involves the subtraction of the oldest DEM from the youngest DEM in order to quantify the elevation change which has occurred between the two survey periods (see Figure 22 for a representation of DoD analysis).

\[
\text{NEW} - \text{OLD} = \text{DoD}
\]

‘DEM 2\textsuperscript{nd} August 2013 – DEM April 2002’

= change in elevation between April 2002 and 2\textsuperscript{nd} of August 2013

Negative Change = Erosion

Positive Change = Deposition

Figure 22 Visual representation of DoD process with example from the study site at Stockyard Creek (Wheaton et al. 2013)

Negative elevation change values for the DoD represent regions of erosion, whereas positive elevation change values represent regions of deposition. The analysis was completed for each survey date compared to the baseline survey (April 2002) as well as between consecutive survey years. This process was performed to indicate the overall geomorphic efficiency of the 2007 and 2013 flow events.

Throughout the past decade DoD analysis has become a common practice utilised by fluvial geomorphologists to assess temporal changes occurring within a study reach (Brasington et al. 2000; Lane et al. 2003; Fuller & Hutchinson 2007; Rumsby et al. 2008; Fuller & Basher 2013; Wheaton et al. 2013). This type of analysis allows for the identification of spatial patterns of change as well as the quantification of volume changes in relation to ELJ distribution. Such an analysis can be performed manually using Raster Calculator, however, the GCD 5.0 tool allows for a faster processing time as well as the ability to further examine the nature of morphological change occurring at the site (see section 5.3, Dominant Scour Mechanisms).
**GCD Accuracy**

The accuracy of change detection analysis is highly reliant upon DEM quality (the ability of the DEM to represent the survey data) (Fuller & Basher 2013). Research into the error associated with change detection analysis, has identified four specific areas of error propagation; survey point quality, sampling strategy, surface composition, topographic complexity and interpolation methods (Wise 1998).

For this study the following steps have been taken to ensure the DEM surface best represents the in-channel topography at Stockyard Creek:

- repeat observations of control points throughout the survey period and the use of continuous benchmarks throughout the 11 year study period (Brasington et al. 2000);
- post processing of elevation point data to remove survey error;
- the use of well tested and utilised methods of DEM creation which have been shown to create the most accurate surface out of irregular topographic point datasets (Brasington et al. 2000; Brooks et al. 2006; Rumsby et al. 2008; Fuller & Basher 2013; Wheaton et al. 2013);
- the creation of concurrent DEMs to ensure the correct alignment of raster layers (Wheaton et al. 2010);
- the use of a minimum level of detection (minLOD) to distinguish significant change from ‘noise’ (Lane et al. 2003) in the DoD;

Brasington et al. (2003), showed individual errors within the DEM can be propagated into the DoD surface resulting in regions of ‘noise’ (elevation changes due to DEM error). Therefore a minimum level of detection (minLOD) of ± 0.1 m was applied to each DoD to threshold out elevation change values between -0.1 and 0.1 m.

\[
\delta u_{DoD} = \sqrt{\delta z_{new}^2 + \delta z_{old}^2}
\]

Equation 1 (Brasington et al. 2003)

This value was calculated using Equation 1, whereby, \(\delta u_{DoD}\) is the propagated error in the DoD, and \(\delta z_{new}\) and \(\delta z_{old}\) are the individual errors in the new DEM and the old DEM, respectively (Wheaton et al. 2010). Calculations using the misclose survey error of ±2.5cm for the 2013 survey and the maximum error suggested for points collected with a total station (±10cm) (Wheaton et al. 2010) resulted in a minLOD of ±0.103 m. To test the effectiveness of this threshold at Stockyard Creek, two DEMs were created using sections of the same point
data set. This threshold was shown to be efficient at removing ‘spurious noise’ created in these regions.

Wheaton et al. (2010), suggest a complete error budget would require specific data collection and testing protocols that stretch beyond typical knowledge and survey practice. Therefore, due to the time constraints of this project and the limitations imposed by the previous topographic surveys, the DEMs used for this study are considered to be the best possible representation of the in-channel morphology at Stockyard Creek.

**Temporal Sediment Dynamics**

Morphometric sediment analysis utilises DoD outputs to volumetrically quantify erosion and deposition for a required study reach. The identification of volumetric change provides a relative record of channel stability and a means to assess habitat change (Merz et al. 2006). Net sediment change and sediment turnover were calculated based on per pixel volume change. As indicated in Figure 23, sediment turnover is calculated as the sum of the absolute values of total erosion and deposition for the chosen survey date. It indicates the effectiveness of a flow event to mobilise sediment and is a surrogate for sediment transport (Brooks et al. 2006). Net sediment change is calculated by the subtraction of the total volume of erosion from the total volume of deposition (Wheaton et al. 2013), and indicates net displacement due to fluvial forces compared to the Baseline survey. Volumes were calculated based on the elevation and surface area of each pixel, and should be considered as a gross minimum value of volume change (Wheaton et al. 2013).

\[
\textbf{Sediment Turnover} = \text{absolute volume of Erosion} + \text{absolute volume of Deposition}
\]

\[
\text{DoD between consecutive surveys}
\]

\[
\textbf{Net Sediment Change} = \text{total volume of Erosion} - \text{total volume of Deposition}
\]

\[
\text{DoD Compared to Baseline survey}
\]

Figure 23 Equations for Sediment Turnover and Net Sediment Change used for volumetric change calculations for the study site at Stockyard Creek.
4.1.5 Assessment of Geomorphic Diversity

**Longitudinal Profile**

Temporal longitudinal profiles were developed for each study reach using the April 2002 thalweg elevation data points. Elevation values were extracted using the April 2002 thalweg data set for each DEM surface. The elevation data was later plotted into a temporal longitudinal profile separated by reach. Set point locations were used to create the profiles as detailed topographic data was not collected for the purpose of thalweg analysis, and was therefore too irregular for distance calculations with a differing point density.

**Indices of Variability**

One of the major aims of ELJ reintroduction is to increase geomorphic diversity through enhanced flow variability. Three morphological indices were chosen to quantify the complexity of the three study reaches through time. The morphological indices were chosen based on their previous use in stream rehabilitation and management such as the Williams River demonstration project (Brooks et al. 2006), as well as their proven correlation with specific ecological and hydraulic variables (Bartley & Rutherford 2005).

*Standard Deviation of Depth* – developed and tested by Bartley & Rutherford (2005) to assess the difference in the complexity of a degraded reach to that of a more ‘natural’ reach. The SD of Depth is calculated as the standard deviation of residuals from the thalweg profile developed via linear regression. A larger SD has been shown to represent a reach with a greater variation in vertical depth, a factor which is considered to be important for the creation of fish habitat (Gostner et al. 2013).

*3D Morphological Complexity* – calculated as the standard deviation of the elevation change values for the DoD compared to the baseline survey. Used by Brooks et al. (2006) to assess the influence of ELJs on depth change. A reach with a greater range in elevation change values will have a larger SD of 3D Morphological Complexity.
Potential Habitat Creation
To assess the ability of the ELJs in promoting the development of new habitat, the DoD analysis compared to the baseline survey, was classified into new pool habitat and new bar habitat. To remove the subjectivity of a supervised classification, the DoD surfaces were classified by a threshold of ‘> 0.4 m’ for new bar habitat and ‘> - 0.4m’ for new pool habitat, using Raster Calculator. The new pool and bar surface areas were later calculated as a percentage of the total surface area for inter-reach comparison. A threshold of 0.4 m was used based on the methods of Brooks et al. (2006).
Dominant Scour Mechanism
To assess the contribution of differing obstructions to pool development, the ‘Budget Segregation’ function of ‘GCD 5.0 tool’ was used. This process involved the use of a classified polygon mask to divide the elevation change data based on the most prominent scour mechanism. Scour mechanisms were identified based on field observation and established using the pool classifications developed by Webb & Erskine (2005). In the field, the upstream and downstream end of each pool feature was logged as waypoints with a Garmin GPS, and later used to classify the August 2013 – April 2002 new pool habitat layer. For this study, the August 2013 – April 2002 new pool habitat layer was used for the classification process as the associated scour mechanisms for the past DEMs could not be identified. The dominant scour mechanisms are shown in Figure 24.

<table>
<thead>
<tr>
<th>ID</th>
<th>Class</th>
<th>Description</th>
<th>Example of Pool</th>
</tr>
</thead>
<tbody>
<tr>
<td>elj</td>
<td>Log-affected</td>
<td>formed downstream of ELJ with no influence of other scour forming mechanisms</td>
<td>(a)</td>
</tr>
<tr>
<td>nwr</td>
<td>Natural Wood Recruitment</td>
<td>formed downstream of naturally accumulated debris</td>
<td>(b)</td>
</tr>
<tr>
<td>cop</td>
<td>Compound</td>
<td>formed by a combination of processes. At Stockyard this involved a combination of ELJ &amp; Bedrock (Webb and Erskine 2005)</td>
<td>(c)</td>
</tr>
<tr>
<td>bep</td>
<td>Non-log Affected</td>
<td>scour around bedrock outcrop or where stream impinges against bedrock (Webb and Erskine 2005)</td>
<td>(d)</td>
</tr>
<tr>
<td>po</td>
<td>Free-form alluvial pools</td>
<td>not caused by scour or impoundment but formed by natural interaction of flow and sediment transport (Webb and Erskine 2005). At Stockyard this included the possible interaction of willow roots with bed-substrate</td>
<td>(e)</td>
</tr>
</tbody>
</table>

Figure 24 Dominant scour mechanism classes used to segregate regions of ‘new’ scour based on field observation.
4.2. QUALITATIVE ANALYSIS OF VEGETATION CHANGE

Historical aerial photographs of the study reach were sourced from the National Library of Australia, however, due to the rural location of Stockyard Creek only one image was obtained. The aerial photograph was georeferenced to Bing basemaps in ArcGIS 10.0. To assess the nature of the establishment of riparian vegetation the 1952 aerial photograph was visually compared to the present Bingmaps basemap (2013).

Historical ground photographs were sourced from Mark Elsley (Department of Lands Soil Services, Scone) and recreated to indicate the temporal vegetation change which has occurred at the site. Through field observation and a photographic record, the extent of riparian vegetation cover at Bagnells Creek was assessed and compared to that of Stockyard Creek. The accumulation of natural LWD within the active channel was also recorded with a Garmin GPS and photographically logged.
5. RESULTS

5.1. IN-CHANNEL MORPHOLOGICAL CHANGE AT STOCKYARD CREEK

Four DEMs were created via TIN interpolation from each detailed topographic survey collected at Stockyard Creek (see Table 11, Chapter 4). The point density for each survey dataset ranged between 0.092 - 0.245 (pt/m²), with three surveys completed after the initial construction of the ELJs. Geomorphic Change Detection 5.0 (GCD 5.0) (Wheaton et al. 2013) tool was used to perform a DoD analysis separated by study reach, with regions of scour having a negative elevation change value and regions of deposition having a positive elevation change value.

5.1.2. Reach Scale Trends

Changes in reach sediment storage were calculated using each DoD to volumetrically quantify volumes of erosion and deposition. As outlined in Chapter 4, sediment turnover indicates the effectiveness of a flow event to mobilise sediment and is calculated using the DoD between consecutive surveys, while net sediment change represents the net displacement due to fluvial forces compared to the baseline survey (Figure 23).

Control Reach

The control reach has changed significantly compared to the baseline survey (April 2002) with 66% of the total reach surface area experiencing a change in elevation (Table 12). Spatially, the most notable regions of scour are associated with bedrock meander constrictions and natural obstructions to flow, such as LWD accumulations (Figure 25a). The majority of erosion within the control reach occurred between 2007 and 2013, with the total volume of erosion for the 6 year period estimated to be 644 m³ (Table 13). Overall, the control reach exhibited an erosional trend compared to the baseline condition, with a net loss between April 2002 and August 2013 of -39 m³ (Table 12).

<table>
<thead>
<tr>
<th>DoD</th>
<th>Erosion (m³)</th>
<th>Deposition (m³)</th>
<th>Net (m³)</th>
<th>% Area of Δ</th>
</tr>
</thead>
<tbody>
<tr>
<td>May 2002 – April 2002</td>
<td>1</td>
<td>0</td>
<td>-1</td>
<td>0</td>
</tr>
<tr>
<td>July 2007 – April 2002</td>
<td>300</td>
<td>424</td>
<td>124</td>
<td>44</td>
</tr>
<tr>
<td>August 2013 – April 2002</td>
<td>580</td>
<td>542</td>
<td>-39</td>
<td>66</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>DoD</th>
<th>Erosion (m³)</th>
<th>Deposition (m³)</th>
<th>Total Turnover (m³)</th>
<th>% Area of Δ</th>
</tr>
</thead>
<tbody>
<tr>
<td>May 2002 – April 2002</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>44</td>
</tr>
<tr>
<td>July 2007 – May 2002</td>
<td>303</td>
<td>425</td>
<td>725</td>
<td>44</td>
</tr>
<tr>
<td>August 2013 – July 2007</td>
<td>644</td>
<td>419</td>
<td>1063</td>
<td>65</td>
</tr>
</tbody>
</table>
Figure 25 DoD August 2013 – April 2002 for the Control reach. Note bottom bank line is included in the DoD for context. Regions of erosion are indicated in red while regions of deposition are indicated in blue. See Appendix E for a representation of the consecutive DoD surfaces.
Throughout the study period, the maximum depth of scour for the control reach compared to the April 2002 survey was estimated as 1.84 m, while the maximum depth of deposition is estimated to be 1.29 m (Figure 26a & 26b). These maximum elevation changes occurred during the 2007 flood. Although Figure 25, suggests the spatial distribution of deposition was great (blue regions), Figure 26d indicates the majority of deposition occurred within a shallow depth range.

Figure 26 Elevation change distribution expressed as surface area and volume per class for the control reach for DoD July 2007 – April 2002 (a) & (b) and DoD August 2013 – April 2002 (c) & (d). Regions in red represent change associated with erosion while regions in blue indicate areas of deposition. The greyed region represents values removed by the minLOD threshold of ±0.1m. See Appendix D for more elevation change distribution histograms.
**Treatment A Reach**

As indicated in Table 14, the treatment A reach is estimated to have experienced a trend of net erosion as a result of the 2007 flood with a net loss of -450 m³ compared to the baseline survey. Presently (2013) the reach is estimated to be in a state of net gain (416 m³) with 80% of the reach total surface area experiencing a change in elevation. It should be noted the net sediment change for May 2002 – April 2002 is assumed to be representative of the ELJ construction phase as no efficient flows occurred during this time period.

Table 14 Net Sediment Change for treatment A reach calculated by DoD compared to Baseline survey. DoD May 2002 – April 2002 represents change due to ELJ construction.

<table>
<thead>
<tr>
<th>DoD</th>
<th>Erosion (m³)</th>
<th>Deposition (m³)</th>
<th>Net (m³)</th>
<th>% Area of Δ</th>
</tr>
</thead>
<tbody>
<tr>
<td>May 2002 – April 2002</td>
<td>141</td>
<td>197</td>
<td>56</td>
<td>21</td>
</tr>
<tr>
<td>July 2007 – April 2002</td>
<td>824</td>
<td>373</td>
<td>-450</td>
<td>37</td>
</tr>
<tr>
<td>August 2013 – April 2002</td>
<td>994</td>
<td>1410</td>
<td>416</td>
<td>80</td>
</tr>
</tbody>
</table>

As seen in Figure 27, the spatial distribution of scour is located directly downstream of the ELJs, with significant deposition occurring upstream of the structures. Table 15 indicates the majority of induced scour occurred between May 2002 and July 2007, with a total erosion volume of 847 m³. However, this elevation change was restricted to only 34% of the total reach surface area and was highly localised downstream of ELJs (Table 15). Significant deposition occurred between July 2007 and August 2013 as a result of the 2013 flow event, with the greatest total sediment turnover occurring during this time period (Table 15).

Table 15 Sediment Turnover for Treatment A reach calculated by DoD between consecutive survey dates. DoD May 2002 – April 2002 represents change due to ELJ construction.

<table>
<thead>
<tr>
<th>DoD</th>
<th>Erosion (m³)</th>
<th>Deposition (m³)</th>
<th>Total Turnover (m³)</th>
<th>% Area of Δ</th>
</tr>
</thead>
<tbody>
<tr>
<td>May 2002 – April 2002</td>
<td>141</td>
<td>197</td>
<td>338</td>
<td>21</td>
</tr>
<tr>
<td>July 2007 – May 2002</td>
<td>847</td>
<td>295</td>
<td>1142</td>
<td>34</td>
</tr>
<tr>
<td>August 2013 – July 2007</td>
<td>641</td>
<td>1358</td>
<td>1999</td>
<td>76</td>
</tr>
</tbody>
</table>
Figure 27 DoD for the Treatment A reach between August 2013 – April 2002. Regions of erosion are indicated in red while regions of deposition are indicated in blue. ELJ locations are shown to highlight the relationship between topographic change and structure location. See Appendix E for a representation of the consecutive DoD surfaces.
The treatment A reach had a greater distribution of scour than the control, with an estimated maximum scour depth of 3.25 m (Figure 28b) for the 2007 compared to the baseline survey. Although this scour was found to have been slightly infilled by the 2013 survey (decrease to 2.7 m), the magnitude of depth obtained by the ELJs was still maintained through time (Figure 28d).

Figure 28 Elevation change distribution histogram expressed as surface area and volume per class for the treatment A reach for DoD July 2007 – April 2002 (a) & (b) and DoD August 2013 – April 2002 (c) & (d). Regions in red represent change associated with erosion while regions in blue indicate areas of deposition. The greyed region represents the thresholded values removed by the minLOD of ±0.1m. Histograms developed using GCD 5.0. See Appendix D for more elevation change distribution histograms.
**Treatment B Reach**

Unfortunately due to time constraints, the treatment B reach was not re-surveyed in July 2007, therefore, only the net change between the pre-construction and 2013 survey can be determined. Table 16, shows the treatment B reach is in a state of net loss, with 69% of the total reach surface area experiencing a change in elevation.

Table 16 Net Sediment Change for treatment B reach calculated by DoD compared to Baseline survey. Note no survey data was collected for Treatment B for July 2007 therefore no sediment volume could be calculated.

<table>
<thead>
<tr>
<th>DoD</th>
<th>Erosion (m³)</th>
<th>Deposition (m³)</th>
<th>Net (m³)</th>
<th>% Area of ∆</th>
</tr>
</thead>
<tbody>
<tr>
<td>May 2002 – April 2002</td>
<td>42</td>
<td>42</td>
<td>1</td>
<td>10</td>
</tr>
<tr>
<td>July 2007 – April 2002</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>August 2013 – April 2002</td>
<td>659</td>
<td>438</td>
<td>-211</td>
<td>69</td>
</tr>
</tbody>
</table>

As seen in Figure 30, scour occurred in direct association with the ELJs and in close proximity to outcropping bedrock at the valley margin. However, in contrast to the observed bedrock scour, the V-Sill weir structures formed oval channel-spanning pools which were consistently deep throughout (Figure 30a).

Figure 29 indicates the treatment B reach had a maximum scour depth of 3.02m and a maximum depositional depth of 0.79m (Appendix F provides descriptive statistics for the DoD surfaces). As with the upstream treatment reach the majority of depositional volume change occurred within shallow depth classes, with a greater distribution of change experienced in regions of erosion (Figure 29).

![Figure 29](image)

Figure 29 Elevation change distribution histogram for the Treatment B (left) and Treatment A (right) reach for DoD August 2013 – April 2002. Regions in red represent change associated with erosion while regions in blue indicate areas of deposition. The greyed regions represent the thresholded values removed by the minLOD of ±0.1m.

59
Figure 30 DoD for the Treatment B reach between August 2013 – April 2002. Regions of erosion are indicated in red while regions of deposition are indicated in blue. ELJ locations are shown to highlight the relationship between topographic change and structure location. See Appendix E for a representation of the consecutive DoD surfaces.
5.1.3. Inter-reach Sediment Dynamics

Values of sediment turnover and net sediment change were normalised to 1000m² of the reach bed surface area, for ease of comparison. Figure 31a, shows the 2007 flood resulted in a comparable sediment turnover for both the treatment and control reaches (134m³/1000m²), while the 2013 flood had a greater geomorphic effect in the treatment A (235m³/1000m²) reach compared to the control (196m³/1000m²). The ELJs within the treatment are assumed to be partly responsible for the greater increase in sediment turnover as the values are normalised to bed surface area.

Figure 31 Sediment Turnover (a) and Net Sediment Change (b) for each study reach at Stockyard Creek. Positive net sediment change values indicate a net gain compared to the baseline survey while negative values indicate the latter. For ease of comparison estimates have been normalised to 1000 m² of the bed surface area.

Values of net sediment change indicated in Figure 31b, illustrate the treatment A reach was a zone of net erosion during the 2007 flood, while the significant increase in sediment turnover after the 2013 flow event was caused by a substantial period of deposition (48.90 m³/1000m² of bed). Presently the control reach is in a state of slight net loss (-7.19 m³/1000m² of bed) and close to the original baseline condition. This is in contrast to the treatment reaches which have experienced a significant change in net sediment volume compared to the baseline survey with the treatment B reach having a net loss 6.8 times greater than the control. Without a detailed topographic survey, for the treatment B reach for July 2007, a consistent trend of net change cannot be determined. At the conclusion of the study, Figure 31 suggests a complex pattern of cut and fill has occurred within all three study reaches with no identifiable trend in net aggradation or deposition. However, it is apparent that the ELJs have induced a significant
magnitude of change compared to the control. This complex pattern of change is further discussed in the Chapter 6.

5.2. GEOMORPHIC DIVERSITY

Geomorphic diversity has been shown to be an important factor contributing to the health of riverine landscapes (Thorpe et al. 2006; Ballantyne et al. 2010; Gostner et al. 2013). The following section will present an analysis of three measures of geomorphic diversity and an examination of the changing complexity of the three study reaches through time.

5.3.2. Longitudinal Profile

An examination of the long profiles for each reach at Stockyard Creek suggests the bed-level variability has increased significantly through time. Pool development is visually apparent as a significant drop in bed-level, with pools becoming a consistent structural element of the bed profile (Figure 32). Compared to the treatment reaches, the long profile of the control has no distinct aggradational features, with the majority of scoured regions associated with bedrock. It is visually evident that some in-channel features are ephemeral, with bars formed in the 2007 flood subsequently removed in the 2013 event.

The high frequency of ELJs within the treatment A reach has produced a pronounced riffle-pool morphology with consistent depositional features (Figure 32a). While pool features within the treatment A reach have been further enhanced by ELJs, the v-sill weir structures within the treatment B reach have created significant pool features which were not evident in the profile prior to construction (Figure 32c). The V-Sill weir design has been successful in storing sediment upstream, with a significant aggradational feature visible in the long profile upstream of VSW2 (Figure 32c).

The bed-level profiles for the control and the external control are presented in Figure 33. The upstream portion of the external control is relatively homogenous, with little variation from the average bed gradient. The bed-profile of the control reach is more variable than that of the external control with a greater pool-riffle amplitude (Figure 33).

At the reach scale, Figure 32 indicates all three study reaches have experienced a significant change in bed-level through time, however, the magnitude of vertical complexity is better explained with the use of variability indices.
Figure 32 Long Profile for each topographic survey collected at Stockyard Creek. Pool features are represented in grey while ELJ’s are labelled for context. Thalweg points from the April 2002 topographic survey were used to extract elevation data from the four DEM surfaces.
Figure 33 Longitudinal profile for the control reach (a) at Stockyard Creek and the external control at Bagnells Creek (b).
5.3.2. Variability Indices

Three morphological indices were chosen to assess the change in variability of the treatment and control reaches throughout the study period. Morphological indices were chosen based on their proven ability to define fluvial complexity, as well as their proven correlation with specific ecological and hydraulic variables.

Table 17 Variability indices used to quantify morphological complexity

<table>
<thead>
<tr>
<th>Indices</th>
<th>Use and Understanding</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Standard Deviation of Depth</strong></td>
<td>Calculated as the standard deviation of thalweg residuals from line of best fit. Used as a surrogate of depth variation or vertical variability of the thalweg profile (Bartley &amp; Rutherford 2005)</td>
</tr>
<tr>
<td>(Thalweg variability index)</td>
<td></td>
</tr>
<tr>
<td><strong>3D Morphological Complexity Index</strong></td>
<td>Standard deviation of the elevation change values for each study reach compared to the baseline survey (Brooks et al. 2006)</td>
</tr>
</tbody>
</table>

Figure 34 Variability indices calculated for Stockyard Creek with associated standard error; a) Standard Deviation of Depths, calculated by the standard deviation of thalweg residuals from line of best fit; b) 3D Morphological Complexity Index calculated as the standard deviation of the depth change values compared to the Baseline Survey.
Figure 34 indicates that the overall geomorphic complexity of the three study reaches has increased significantly with time, however, the relative level of complexity varies by chosen indices. The standard deviation of thalweg depths (Figure 34a), suggests the treatment A reach has the greatest bed-level variability out of the three study reaches with a standard deviation of depth 0.9 times greater than the control.

At the conclusion of the study, in contrast to Figure 34a and using the 3D morphological index, Figure 34b suggests that the Treatment B reach is the most geomorphically complex. This indicates that the Treatment B reach has the greatest distribution of elevation change values compared to the baseline survey which is consistent with Figure 29. However, it should be noted that both graphs highlight the disparity in the variability of the three study reaches, and suggest the treatment reaches were more geomorphically complex then the control at the onset of the study.

5.3.5. Potential Habitat Creation

Figure 35 indicates the change in pool/bar area for each DoD compared to the baseline survey as a percentage of the total reach surface area. Increases in surface area indicate regions of potential habitat development and an increase in geomorphic diversity. Surfaces were classed based on a threshold value, with elevation changes ≥ 0.4 m indicating new bar areas and elevation changes ≤ - 0.4 m indicating new pool regions. From observing Figure 35a, it is evident that there has been an increasing trend in pool area over time for each study reach, with the Treatment B reach experiencing the greatest increase in pool development (12%).

Figure 35 Graph of new pool and new bar surface area as a percentage of total reach surface area. New bar area is classified as change ≥ 0.4 m while new pool area is classified as elevation change ≤ 0.4 m. Analysis was performed using DoD compared to the baseline.
Patterns of new bar development varied between the three study reaches, with the treatment A reach also experiencing an increasing trend in bar surface area (Figure 35b). Figure 35b, indicates the Control reach experienced a slight decrease in bar area as a result of the 2013 flood event, resulting in a bar area close to half that of new pool area. New bar development within the Treatment B reach was marginal and comparable to that of the Control.

5.3. DOMINANT SCOUR MECHANISM

Broad scale volume changes for each test reach were identified in section 5.1.2; however, this section aims to further identify the contribution of specific in-channel features to induced channel change. As mentioned in Chapter 4, analysis of net scour and deposition involves the application of a classified polygon mask to differentiate areas of change between surveys, and as such to infer the process interactions driving the observed change. For this study, the August 2013 – April 2002 new pool habitat layer was used to classify regions of scour, as the associated scour mechanisms for past terrain surfaces could not be clearly defined. The scour mechanisms defined by Webb & Erskine (2005) for natural pools within the Wollombi catchment were used in this study (see Figure 24 for specific classes).

Figure 36 Percentage surface area and volume for the derived dominant scour mechanisms within the treatment and control reaches. Bedrock (bep), Natural Wood Recruitment (nwr), free-forming alluvial pool (po), compound (cop), Engineered Log Jam (elj).
The pie charts in Figures 35a–35f represent the percentage change in area and volume associated with specific scour mechanisms. Within the control reach (Figure 35a and 35b), it is evident bedrock induced scour is the most prevalent scour mechanism for the development of pools, accounting for 51% of the total scour volume. Significantly, the accumulation of natural woody debris has also had a great influence upon scour development accounting for 33% of new scour volume within the reach. This outcome suggests enforced pools exert a significant control within the Control reach.

Figure 35d indicates the combination of ELJ and bedrock constriction has had the most influence on scour development within the treatment A reach. The ELJ frequency within the treatment B reach is significantly less than that of the treatment A, with only 3 out of 15 pools (Table 18) within the reach dominated by ELJ induced scour. However, Figure 35f indicates the low frequency of structures had a greater influence on pool volume change, with 50% of scour directly associated with the ELJs. The relationship evident in Figure 36e and 35f suggests the v-sill structures in the treatment B reach had a tendency to form high volume, small surface area pools.

Table 18 Number of pools (n) as well as % volume of pools formed by each pool forming mechanism. Results calculated for the study reach at Stockyard Creek as well as for the external control at Bagnells Creek.

<table>
<thead>
<tr>
<th>Reach</th>
<th>Total Area (m²)</th>
<th>ELJ Frequency</th>
<th>po (n)</th>
<th>%</th>
<th>nwr (n)</th>
<th>%</th>
<th>bep (n)</th>
<th>%</th>
<th>cop (n)</th>
<th>%</th>
<th>elj (n)</th>
<th>%</th>
<th>Total Pool Frequency (Δ&gt;0.4m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>5425</td>
<td>0</td>
<td>3</td>
<td>16</td>
<td>2</td>
<td>33</td>
<td>4</td>
<td>51</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>9</td>
</tr>
<tr>
<td>TA</td>
<td>8508</td>
<td>23</td>
<td>1</td>
<td>4</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>4</td>
<td>50</td>
<td>10</td>
<td>46</td>
<td>0</td>
<td>15</td>
</tr>
<tr>
<td>TB</td>
<td>4661</td>
<td>3</td>
<td>2</td>
<td>16</td>
<td>0</td>
<td>0</td>
<td>7</td>
<td>34</td>
<td>0</td>
<td>0</td>
<td>3</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>Bagnells Ck</td>
<td>-</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>75</td>
<td>1</td>
<td>25</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>3</td>
</tr>
</tbody>
</table>

po = free-forming alluvial pool
nwr = natural wood recruitment
cop = compound pool
elj = engineered log jam forced pool
bep = bedrock enforced pool
5.4. QUALITATIVE ASSESSMENT OF RIPARIAN VEGETATION CHANGE

As outlined in Chapter 3, the study site has undergone an extensive riparian revegetation strategy since the late 1970’s; this should not serve as a potentially confounding factor as it has been undertaken across the whole experimental reach (i.e. control and two treatments). This section serves to provide a brief qualitative overview of the change in the extent and character of the riparian margin at Stockyard Creek. The vegetation present within the external control is also examined and compared to the revegetated reach at Earthways.

To assess extent of the temporal change in riparian vegetation extent through time, historical aerial photographs of the study reach were compared (Figure 37). Unfortunately, limited aerial photographs of the study region exist with the only available image flown in 1952 (National Library of Australia). Combined with examples of photographs taken on the ground within the Treatment B reach, it is obvious riparian vegetation cover and distribution has increased through time, with the bare sand-bar deposits visible in the 1952 image obscured by vegetation cover in 2013.

Figure 37 Comparative photographs taken within the Treatment B reach at Stockyard Creek; a) the degraded condition of the Treatment B reach in 1978; b) current (2013) riparian vegetation existing in the same location as a result of the revegetation strategy.
Figure 38 Historical aerial photographs of the study reach at Stockyard Creek indicating the increase in riparian vegetation cover through time; a)19/11/1952; b)Present (Bingmaps 20/1/2013)
The study site now has a densely vegetated and self-sustaining riparian margin which is characteristic of the Eastern Riverine Forests of Keith (2004). The bench and floodplain consisted of Open Forest dominated by woody species, such as Forest Red Gum (Eucalyptus tereticornis) and Sydney Blue Gum (Eucalyptus saligna), with a dense understorey dominated by Bracken fern (Pteridium esculentum).

In the downstream end of the treatment B reach a tall narrow stand of Casuarina cunninghamiana (River Oak) was found on the banks of the low flow channel. The region resembles the MU34 Coastal River Oak Forest community (Department of Environment & Climate Change 2008) which is found to occur on the sandy banks of the Wollombi Brook and its tributaries. Warm Temperate Rainforest species, such as Coachwood (Cerapetalum apetalum), Lillypilly (Acmena smithii) and Grey Myrtle (Backhousia myrtifolia), were observed on the steep foot slope where the channel met the steep valley margin.

Due to the ephemeral nature of Stockyard Creek, the low flow channel was densely vegetated by macrophytes. Point bar units were colonised by perennial species, such as Lomandra longifolia with occasional Black Wattle (Acacia mearnsii), Tea tree (Leptospermum polygalifolium) and Prickly Paperbark trees observed within the low-flow channel.

Figure 39 In-channel vegetation observed at Stockyard Creek, 2013; (a) vegetated point bar within the control reach; (b) densely vegetated low flow channel, treatment A reach.
5.4.1 Establishment of vegetation since ELJ Construction

During the construction process, native species (see Table 19) were planted on and around the ELJ structures to provide extra stability and to act as a source of wood recruitment after structural decay. Low to no flow conditions prevailed for the first 5 years after ELJ construction, which allowed for the successful colonisation and establishment of the planted longstem tubestock. Little is known of the interaction between ELJs and riparian vegetation, however, in most cases the vegetation has successfully colonised the ELJs, and is assumed to be assisting with the further stabilization and enhancement of the resulting geomorphic features (Figure 40).

Table 19 Native species planted on and around the ELJ structures during the time of construction. A full species list for the long-term revegetation strategy is included in Appendix B.

<table>
<thead>
<tr>
<th>Species</th>
<th>Common Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eucalyptus tereticornis</td>
<td>Forest Red Gum</td>
</tr>
<tr>
<td>Eucalyptus saligna</td>
<td>Sydney Blue Gum</td>
</tr>
<tr>
<td>Eucalyptus paniculata</td>
<td>Grey Ironbark</td>
</tr>
<tr>
<td>Eucalyptus amplifolia</td>
<td>Cabbage Gum</td>
</tr>
<tr>
<td>Eucalyptus deanii</td>
<td>Deans Gum</td>
</tr>
<tr>
<td>Acmenia smithii</td>
<td>Lilypilly</td>
</tr>
<tr>
<td>Callistemon salignus</td>
<td>Pink-tip Bottlebrush</td>
</tr>
<tr>
<td>Callistemon viminalis</td>
<td>Weeping Bottlebrush</td>
</tr>
<tr>
<td>Melaleuca braceteata</td>
<td>White-cloud Paperbark</td>
</tr>
<tr>
<td>Leptospermum polygalifolium</td>
<td>Creek Teatree</td>
</tr>
<tr>
<td>Leptospermum bracteatum</td>
<td>River Teatree</td>
</tr>
</tbody>
</table>
Figure 40 Photographic comparison of the change in riparian vegetation cover associated with the constructed ELJs. Photographs on the left depict the condition of the riparian margin at the time of construction (2002), while the photographs on the right indicate the same location in 2013.
5.4.2. Natural wood recruitment
During the survey period, numerous accumulations of woody debris were documented within the control and treatment reaches, with the ELJs working to further trap wood pieces. Figure 41, depicts examples of natural wood recruitment observed within the control (Figure 41a) and treatment A reach (Figure 41). Trees growing within the low flow channel have built up significant volumes of debris (Figure 41a and 41b), which is assumed to have further influenced the morphology of the reach.

Figure 41 Examples of natural wood recruitment within the control and treatment A reach: a) protruding log held in place by a tea tree with a consistent buildup of small woody debris and resulting scour occurring downstream due to flow constriction (control reach); b) accumulation of woody debris trapped upstream of a willow trunk; c-d) accumulation of woody debris in conjunction with LS7.
Channel spanning blockages, created due to tree fall were recorded during the 2007 flow event. The constriction of the channel cross-section resulted in significant bank erosion within the control and the failure of DFJ10 within the treatment A reach (DFJ10). After the 2013 flow event, a natural log jam formed within the control which has become a permanent structural feature of the in-channel morphology.

Figure 42 Development of a channel spanning blockage as a result of the 2007 flow event; a) control; b) The debris caused the failure of DFJ10 in the treatment A reach.
5.4.3. Riparian Vegetation at the External Control Reach

In contrast to the dense vegetation cover observed within the study reach at Stockyard Creek, the riparian vegetation of the external control was sparse and less diverse. The most significant difference between the two sites was the absence of native woody species, such as Eucalyptus tereticornis. The bank and bench formations at Bagnells Creek were dominated by sparsely distributed Black wattle (Acacia mearnsii) trees with an understorey Bracken Fern (Pteridium esculentum). A stand of Cypress pines (Callitris glaucophylla) colonised the high bank connecting to the floodplain. With little canopy cover, the low flow channel was choked with perennial grasses, such as Giant Paramatta Grass (Sporobolus fertilis) and tall dense stands (1-2 m) of Broad Leaf Cumbungi (Typha orientalis). Wood accumulations were virtually non-existent, with the only influence of LWD observed at the bedrock bend at the downstream end of the reach. The region is similar to the MU44 Acacia Regeneration community which is observed to occur along river margins following heavy disturbance (Department of Environment & Climate Change 2008).

Figure 43 Examples of vegetation present within the external control reach at Bagnells Creek. Note the homogenous channel is choked with macrophytes and perennial grasses.
Results Summary

Geomorphic change detection analysis indicates all three study reaches have experienced an increase in geomorphic diversity over time. However, at the conclusion of the study results suggest the treatment A reach is the most geomorphically diverse of the three study reaches. Although no consistent trend in sediment storage could yet be identified due to the infrequency of topographic surveys, it is apparent the changes in the treatment A reach are out of phase with those of the control and treatment B reach. Treatment A was in a state of net loss after the 2007 event and net gain in 2013, whereas the opposite was the case for the control and treatment B for the same period of time. An assessment of the drivers of scour suggest, both bedrock and natural wood recruitment play an important role in the development of new pools within the control, whereas the log structures clearly dominate pool formation within the treatment A reach. The low frequency of structures within the treatment B reach demonstrates that while the structures have been important drivers of pool scour, bedrock control is also a key driver of geomorphic change.

Through a qualitative assessment of the riparian vegetation present at Stockyard Creek, it is evident that all three reaches have experienced a significant increase in vegetation cover with time; developing from a reach with sparsely vegetated banks to a self-sustaining riparian zone dominated by woody species. Significantly, natural wood is beginning to be recruited to the ELJs and the geomorphic features have been stabilized with in-channel vegetation. In contrast, the external control reach at Bagnells Creek is sparsely inhabited by woody vegetation and is instead dominated by regenerating Acacia *mearnsii* seedlings. Within the following chapter (Chapter 6), the results will be discussed in relation to the current literature.
6. DISCUSSION

Geomorphic change detection analysis has revealed the study reaches have experienced a significant level of change throughout the 11 year study period. This chapter will seek to further explain the complex trends identified in the results chapter, with specific reference to the resulting geomorphic diversity and variability of the control reach. The observed change suggests ephemeral sand-bed streams are strongly controlled by hydrological variability and are very sensitive to disturbance. However, it is clear the ELJs within the treatment reaches have had a demonstrable effect on channel morphology, sediment storage, in-stream habitat availability and persistence.

6.1 INFLUENCE OF ELJS IN PROMOTING GEOMORPHIC DIVERSITY

The geomorphic diversity of all three study reaches has increased with time, with all reaches having a greater elevation distribution, increased pool/bar surface area as well as an increase in the variability of the long profile compared to the preconstruction in-channel topography. However, in support of the overall project objectives, findings suggest the treatment A reach is the most geomorphically diverse out of the three study reaches with a:

1. Range of depth 1.5 times greater than the control;
2. Persistent pool/riffle structure;
3. Enhanced zones of potential habitat with increased pool/bar surface area;
4. Increased variability of the longitudinal profile;
5. Change in elevation occurring over 80% of total reach surface area;

The spatial distribution of scour indicates a high proportion of morphological change occurred in direct association with the ELJs, supporting the hypothesis that the treatment reaches would show an increased geomorphic diversity compared to the control reach. This outcome affirms the findings of Brooks et al. (2006), whereby the treatment reach was found to be consistently more complex than the control throughout the 5 year study period. However, the magnitude of change observed at Stockyard Creek has been substantial, with logs originally lying 0.3 cm above bed-level, now sitting atop pools of up to 2.5 m in depth (treatment A). This is in contrast to the gravel-bed test reach on the Williams River, which only reached a maximum scour depth of 1.8 m at the conclusion of the study, (Table 20).
Table 20 Indicating values of max scour and max deposition as well as % new pool-bar surface area for the Stockyard Creek and Williams River demonstration project.

<table>
<thead>
<tr>
<th>Reach</th>
<th>Max Scour</th>
<th>Max Deposition</th>
<th>Range</th>
<th>% Pool</th>
<th>% Bar</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>1.84</td>
<td>1.29</td>
<td>3.1</td>
<td>10</td>
<td>4.5</td>
</tr>
<tr>
<td>Treatment A</td>
<td>2.71</td>
<td>1.08</td>
<td>3.8</td>
<td>10</td>
<td>13.5</td>
</tr>
<tr>
<td>Treatment B</td>
<td>3.02</td>
<td>0.79</td>
<td>3.8</td>
<td>12</td>
<td>5</td>
</tr>
<tr>
<td>Brooks et al. (2006)</td>
<td>1.8</td>
<td>2</td>
<td>Test range double control</td>
<td>3.5</td>
<td>4.5</td>
</tr>
<tr>
<td>Williams Control</td>
<td>1</td>
<td>0.8</td>
<td>0.2</td>
<td>2</td>
<td>1</td>
</tr>
</tbody>
</table>

In contrast to the pattern of change observed in the Williams River ELJ project, at Stockyard Creek, the geomorphic complexity of the control has also increased considerably. A number of explanations are possible for the observed pattern of response, and most likely it is a combination of several factors. Research suggests partly-confined ephemeral sand-bed streams are very sensitive to periods of high flow variability due to lateral confinement and a readily mobilised bed-load (Wallerstein & Thorne 2004). A typical response to hydraulic variability within such a system, includes scour in association with bedrock as well as vertical bed-level incision (Fryirs & Brierley 2010). Within the control reach, bedrock is estimated to have contributed to 51% of new scour volume following the two flow events after construction. Anecdotal evidence suggests bedrock pools are an ephemeral component of Stockyard Creek, (Woodward B. pers. comm. 2013), therefore, the variability of the control, can be partially attributed to the natural dynamics of a partly-confined sand-bed stream (Brierley & Fryirs 2005).

Significantly, the majority of new pool development observed within the treatment reaches can be directly associated with ELJ rehabilitation. Re-introduced wood was found to have enforced 46 (treatment A) to 50% (treatment B) of new pool volume, which is in contrast to the dominance of bedrock in the control. LWD has been shown to exert a greater influence within small sand-bed rivers as key members are more readily buried and large wood pieces often exceed channel width (Gippel 1995). The findings of Webb & Erskine (2005) suggest the response within the treatment reach, is characteristic of a partly confined sand-bed stream, as LWD has been found to create scour pools between planform-controlled pools. The evidence from this experiment indicates the majority of new pool development within the treatment reaches was directly influenced by the rehabilitation strategy rather than the natural variability of the reach. The geomorphic response
observed within the study reach, implies ELJ spacing is of great importance as the location of an ELJ will likely enforce the development of a pool.

The natural accumulation of woody debris within the control has also significantly increased the geomorphic diversity of the control reach, with 33% of new pool volume attributed to this mechanism (Figure 36). Bank failure induced by the development of a channel-spanning blockage, supplied a large volume of sediment to the channel, which was redistributed by the establishment of a persistent (> 6 years) natural log jam (Figure 44). The relatively homogenous profile of the external control in association with a low wood loading, suggests this period of wood induced instability can partially explain the substantial increase in the geomorphic diversity of the control.

![Figure 44 Natural Log Jam formed by a channel spanning blockage has become a persistent structural element of the bed profile in the control reach. Formed as result of channel spanning blockage. The natural log jam exerts a similar role to the log sills ELJ through the promotion of riffle aggradation upstream and localised scour downstream resulting in a permanent (> 6 years) pool feature.](image)

The findings of this study along with those of Brooks et al. (2004); Abbe & Montgomery (1996); Brooks et al. (2006), suggest reach-scale wood reintroduction can successfully increase habitat heterogeneity in a geomorphic sense, however, it is important to note hydromorphological diversity does not ensure enhanced biodiversity (Gostner et al. 2013). Species abundance is dependent upon a combination of abiotic features including water chemistry and temperature, therefore, without a temporal record of the ecological conditions existing prior to ELJ construction the ecological effect of the ELJs at Stockyard cannot be established.
6.2. CHANNEL STABILITY AND SEDIMENT STORAGE

6.2.1 Bed Profile Stability
The temporal long profiles presented in Chapter 5, confirm the observations of Montgomery & Abbe (2006), that LWD jams form consistent ‘hard’ points within the bed-profile, therefore providing bed stability and halting widespread channel incision. An examination of the derived long-profiles for Stockyard Creek indicate scour is localised downstream of ELJs, with significant aggradation of up to 1 m occurring upstream of the structures (Figure 32). Although the treatment A reach has shown an increase in sediment storage, the structures at Stockyard Creek have successfully maintained and often enhanced scour features resulting in a spatially variable morphology which is persistent through time. The development of persistent in-channel morphology has been noted as a significant rehabilitation challenge within a sand-bed context, due to a small average grainsize and the high sensitivity of sand-bed channels to change (Shields Jr. & Gippel 1995). In contrast, both Shields et al. (2004) and Borg et al. (2005) noted the tendency of ELJ induced scour to in fill during the receding limb of flow events, therefore decreasing the availability of suitable habitat for aquatic fauna. The development of a stable bed-profile is a significant outcome, as flume studies suggest scour associated with LWD is often short-lived in sand-bed streams (Wallerstein et al. 2001).

The qualitative assessment of historical photographs (Chapter 5, 5.4) suggests riparian vegetation within all three study reaches has increased significantly with time. Vegetation has been shown to serve an important role in stabilising geomorphic features through increased flow resistance and fluvial entrainment (Gran & Paola 2001). Therefore, the persistence of the geomorphic features created within the study reach may have been further enhanced by the presence of in-channel riparian vegetation. The ephemeral nature of Stockyard Creek is assumed to have facilitated the establishment of vegetation during periods of low flow, therefore, the influence of in-channel vegetation may not be as significant in a sand-bed stream with a continuous flow regime.

6.2.2 Structural Stability
In contrast to the work of Shields et al. (2004), the majority of ELJs at Stockyard Creek have maintained structural integrity under the influence of two high magnitude flood events. Significantly, only one major structural failure (DFJ10) has occurred at the study site with the structures recorded to be in a state of moderate decay with minor log displacement (Daley &
Brooks 2013). Shields et al. (2004) recorded a 35% structural failure rate after a 7 year period, while Brooks et al. (2006), also noted the failure of log-sills in the treatment reach of the Williams River. Although wood has been observed to decay at a faster rate in an ephemeral environment, Daley & Brooks (2013) suggest the structures at Stockyard Creek will further provide structural integrity for a period of up to 50 years. However, the stability of the structures may not translate to an unconfined setting where there are no bedrock boulders or riparian vegetation to enhance structural stability.

6.2.3 Sediment Storage

Although the treatment reaches experienced a greater magnitude of sediment change compared to the control, a high degree of inter-reach variability was observed with no constant reach-scale trend of erosion or deposition. The study reach at Stockyard Creek has been progressively stabilised through time, and the variability in net sediment change may reflect a system which is adjusting to post-European disturbance. Fryirs et al. (2007), suggest the storage of within channel sediment is spatially variable and dependent upon the distribution of longitudinal barriers, such as LWD. It can be speculated that the ELJs within Stockyard Creek are working to redistribute sediment through scour and sediment retention, creating local-scale sediment sinks (Fryirs et al. 2007). The intermittent release of stored sediment within a catchment is an observed natural mechanisms of sediment transport (Schumm 2005). Therefore it can be speculated the ELJs have provided local bed-level stability via creating persistent regions of sediment retention over a decadal time-scale.

Another possible explanation for the observed variability in sediment storage within the treatment reaches is the specific design attributes of the ELJs. The overall complexity and frequency of structures differs between the treatment A and B reach, with the treatment A consisting of ELJs with a multi-functional design (Table 21). Findings suggest the increased complexity and frequency of the structures within the treatment A reach, has translated to a greater geomorphic diversity with significant new pool (10%) and bar (13.5%) development. As a result, the treatment A reach is the only reach to have experienced a net gain in sediment storage (48.90 m$^3$/1000m$^2$) compared to the baseline survey, with a concomitant increase in pool area.
Table 21 Summary of geomorphic response to ELJ intervention at Stockyard Creek within the treatment reaches.

<table>
<thead>
<tr>
<th>ELJ Design</th>
<th>Purpose</th>
<th>Observed Response at Stockyard Creek</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Treatment A</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Log Sill</td>
<td>bed control, upstream sediment trap, inducement of downstream step pool</td>
<td>0.8 – 2.5 m deep scour pool, significant upstream riffle development,</td>
</tr>
<tr>
<td>V-weir log sill</td>
<td>Habitat enhancement through scour initiation, upstream sediment deposition</td>
<td>Dominated by continuous pool habitat, elongated scour pool, minor bar development</td>
</tr>
<tr>
<td>Deflector Jam</td>
<td>Flow deflection, bank protection &amp; bar development</td>
<td>Scour adjacent to structure under transverse log, significant bar development (lateral and point bar), stabilisation of bank and bar features</td>
</tr>
<tr>
<td><strong>Treatment B</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>V-sill weir</td>
<td>Bed control, upstream sediment trap &amp; inducement of downstream scour</td>
<td>Permanent round oval shaped pool spanning entire channel cross-section (1-3m depth), significant upstream riffle development, no bar development</td>
</tr>
</tbody>
</table>

In contrast, the V-sill weir structures within the Treatment B reach successfully induced scour (13%) by producing consistently deep, oval shaped pools (Figure 17). However, the structures had little impact upon new bar development (4.5%), resulting in a net loss (- 47.41m³/1000m² of bed) compared to the baseline survey at the conclusion of the study. Flume studies indicate deposition occurs in regions of increased surface roughness and reduced flow velocity, created through channel constriction and flow deflection (Shields Jr. & Gippel 1995). Therefore, the low frequency of structures and the absence of deflector jams within the treatment B reach, may have limited the formation of new depositional features.

The interconnected nature of the control and treatment reaches may have affected the redistribution and storage of sediment within the low-flow channel. Fryirs & Brierley (2001), suggest the limited availability of sediment from upstream can hinder downstream geomorphic recovery. The establishment of a positive (wood and vegetation) and negative (without wood) external control reach from the commencement of the project, would have provided further insight into the complex patterns of scour and fill occurring in association with the ELJs.
6.2.4 The application of ELJs in a sand-bed stream
Despite the fact wood has been widely recognised as an important component of the stream ecosystem, methods of wood reintroduction utilising ELJs remain contentious (Lester & Boulton 2008). The engineered approach to wood reintroduction has been criticised as it involves the application of internationally derived ELJ designs in an Australian context (Erskine 2012). All three study reaches at Stockyard Creek experienced a substantial increase in variability in direct association with wood, with the only natural accumulations of woody debris resulting in mass failure and extensive erosion of the bank profile. This implies the uncontrolled reintroduction of wood may be problematic, with the possibility of further enhancing channel instability. The success of the structures at Stockyard Creek, along with the studies of Brooks et al. (2006), suggest the use of internationally derived ELJ designs can be applied in an Australian context, if the structures are altered to suit the local scale environment.

6.3 Limitations
The nature of this study has led to a number of limitations due logistical and financial constraints. The ability to detect geomorphic change is limited by the infrequency of surveys conducted at the study site. Without a detailed topographic survey for every flow event, the topographic change between survey periods cannot be defined. Fuller & Basher (2013), suggest the use of an event based survey method to ensure changes in scour and fill are detected, however, such a method is not viable in the long-term due to the high cost and the time needed to collect a detailed topographic surface.

The field methods used in this investigation also place some limitations on the accuracy of the resulting DEM surfaces. The collection of detailed topographic data using a total station, has been shown to be effected by survey error propagated due to field practices, such as pole tilt and incision (Wheaton et al. 2010). The collection of point data at the study site was challenging due to the increased complexity of the channel and the development of deep narrow pools within the reach. This meant that a large proportion of survey data points were derived from submerged topography which has been shown to have a greater uncertainty than dry surfaces (Lane et al. 2003). The uncertainty of DEM surfaces derived from point data is spatially variable with more uniform surfaces having a lower associated error. The substantial increase in the complexity of the study reach may have resulted in a greater uncertainty with time (Wheaton et al. 2010). The accuracy of
the DEMs was also limited by the condition of pre-existing data sets which had no recorded error and a low point density.

6.4 Recommendations

Continued Monitoring

The wood reintroduction project at Stockyard Creek is unique as it is set within a successful riparian re-vegetation strategy. To date, the assessments of ELJ rehabilitation strategies have included a short-term (5-7 years) evaluation of their effect, however little is known about the long term implications of their use. Continued monitoring of the site at Stockyard Creek would provide a unique opportunity to assess the long-term processes associated with ELJ rehabilitation and to develop a lifecycle analysis for the use of ELJs within Australian streams.

Future avenues for investigation include:

- The interaction between ELJs and riparian vegetation;
- The decay of ELJs and the resulting future implications for channel stability;
- The recruitment of LWD from a re-vegetated riparian margin;
- The interaction between ELJs and naturally recruited wood;
- The development of long term guidelines for the management of ELJs;

Due to the ephemeral nature of Stockyard Creek the ELJs have only been exposed to two high magnitude flow events. A long-term analysis of channel change could provide a better understanding of their effect on sediment storage. The inconsistent trend of net change observed throughout the study period may be a factor of the infrequent nature of flows.

Development of a detailed riparian vegetation study

A detailed study of the riparian vegetation present at Stockyard Creek would provide a means of assessing the effect of vegetation on the change geomorphic complexity of the reach. A vegetation/habitat cover map could be integrated with the change detection analysis presented in this study to assess the correlation between processes elevation change and vegetation extent. Such an analysis could provide valuable insights into the interaction between ELJs and riparian vegetation.
7. CONCLUSION

Since the late 1970’s the study site at Stockyard Creek, has been successfully transformed from an incised river system with actively eroding river banks, to a stable system with near permanent pools and continuous riparian vegetation. This study suggests the reintroduction of wood through the construction of ELJs, can successfully increase geomorphic diversity and stability in a partly confined sand-bed stream. Geomorphic change detection analysis, indicated the ELJs worked to redistribute sediment throughout the study reach by creating localised pool and bar features within the bed-profile. Significantly, the ELJs within the treatment A reach facilitated a net gain of 48.90 m$^3$/1000m$^2$ of bed, compared to the preconstruction survey. Despite the fact all three study reaches experienced a significant increase in geomorphic diversity, the magnitude and persistence of change within the treatment reaches was not observed in the control. Such an outcome suggests ELJs can potentially provide a stable pool habitat for the promotion of species diversity, which has been identified as a challenge in degraded sand-bed streams.

The outcomes of this study also suggests ELJ design and frequency can significantly affect the pattern of pool and bar development at the reach scale. The V-sill weir design of the treatment B reach, was found to produce a consistently deep, oval, channel spanning pool with little associated bar development (4.5%). This is in contrast to the complex log sill, v-weir and deflector jam structures of the treatment A reach, which commonly produced a step pool morphology, with a comparable increase in pool (10%) and bar surface area (13.5%).

Temporal long profiles of the three study reaches, suggest the most pronounced geomorphic change to have occurred at the site, is the development of near permanent pools. Pool surface area analysis suggests all three study reaches experienced a comparable increase in pool area, with the control and treatment B reaches experiencing an increase of 10% to 12% respectively. However, even in the presence of bedrock, process segregation analysis revealed the treatment reaches are dominated by ELJ enforced pools, with 46% (treatment A) to 50% (treatment B) of new pool volume associated directly with this scour mechanism. This is in contrast to the control reach which is heavily influenced by outcropping bedrock (51%). Such a result suggests in-channel wood can directly induce change outside the realm of natural variability.
Significantly, the quantified variability of the control reach suggests the natural recruitment of wood and the presence of in-channel vegetation play an integral role in the formation and maintenance of geomorphic features. In addition to the presence of structural bedrock pools, the build-up of LWD is predicted to have enforced 33% of new pool volume within the control reach. The dynamic nature of the control reach, emphasises the need to develop rehabilitation strategies which cater to the natural behaviour of streams.

Wood reintroduction using ELJs is seen as a short-term method of enhancing geomorphic diversity and channel stability, however, few wood reintroduction initiatives have been rigorously monitored through time. The detailed study at Stockyard Creek is unique, as it was carried out over a long monitoring period (11 years) and coupled with a ~ 20 year riparian rehabilitation strategy. This study suggests in-channel wood plays a vital role in the development and stability of geomorphic features within sand-bed streams.
REFERENCES


NSW Department of Primary Industries 2003. *Geology 250K NSW Statewide*.


APPENDIX A - IFD TABLES FOR THE WOLLOMBI CATCHMENT

### Intensity-Frequency-Duration Table

**Location:** 32.9005° S 151.075° E, Wollombi
**Issued:** 2/4/2014

Rainfall intensity in mm/h for various durations and Average Recurrence Interval

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<tr>
<th>Duration</th>
<th>1 YEAR</th>
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<th>5 YEARS</th>
<th>10 YEARS</th>
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(Raw data: 88.55, 60.85, 1.66, 48.46, 11.62, 3.49, std.err=0.09, F2=4.32, F50=15.58) © Australian Government, Bureau of Meteorology

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**DESIGN RAINFALL INTENSITY CHART**

**Location:** 32.9005° S 151.075° E, Wollombi
**Issued:** 2/4/2014

**Average Recurrence Interval**
- 100 Years (upper curve)
- 50 Years
- 20 Years
- 10 Years
- 5 Years
- 2 Years
- 1 Year (lower curve)

(Raw data: 20.95, 5.00, 1.60, 40.46, 11.62, 2.49, std.err=0.09, F2=4.32, F50=15.58) © Australian Government, Bureau of Meteorology

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APPENDIX B - REVEGETATION SPECIES LIST

Longstem native tubestock

Acmenia smithii (Lillypilly)
Baeckea virgata (Heath Myrtle)
Casuarina cunninghamianax cristata (River Oak)
Casuarina cunninghamiana/glauc (Swamp Oak)
Callistemon sieberi (Bottlebrush)
Callistemon salignus (Pink-tip Bottlebrush)
Callistemon viminalis (Weeping Bottlebrush)
Eucalyptus botrioides var Nana (Bangalay)
Eucalyptus amplifolia (Cabbage Gum)
Eucalyptus deanii (Deans Gum)
Eucalyptus fibrosa (Broad-leaf Ironbark)
Eucalyptus maculata (Spotted Gum)
Eucalyptus microcarpa (Grey Gum)
Eucalyptus paniculata (Grey Ironbark)
Eucalyptus saligna (Sydney Blue Gum)
Eucalyptus tereticornis (Forest red Gum)
Leptospermum bracteatum (Northern Teatree)
Leptospermum polygalifolium (Creek Teatree)
Melia azadarch (White Cedar)
Melaleuca bracteata (White-Cloud Paperbark)
Melaleuca linariifolia (Narrow Leaf Paperbark)
Melaleuca styphelioides (Prickly Paperbark)
Melaleuca spp. (Paperbark)
Tristaniopsis laurina (water Gum)
APPENDIX C – SURVEYOR REPORT

The surveyors report compiled after the Earthways survey has been included on the thesis disk as a separate folder named: “Appendix C”—file name: “Surveyor Report”.
Control Reach

August 2013- April 2002

July 2007- April 2002
Treatment A Reach

May 2002 - April 2002

August 2013 - April 2002
Treatment B Reach

August 2013 - April 2002

May 2002 - April 2002
APPENDIX E — GIS DATA

The GIS DATA derived from the Earthways survey has been included on the thesis disk as a separate folder named: "Appendix E"—file name: "GIS DATA".
## APPENDIX F - DESCRIPTION STATISTICS FOR ELEVATION CHANGE VALUES

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Key:

2 – 1: DEM May 2002 – DEM April 2002

3 – 1: DEM July 2007 – DEM April 2002

4 – 1: DEM August 2013 – DEM April 2002

Elevation change values were extracted from the resulting DoD surface and description statistics were calculated in excel.