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The role of vegetation in catastrophic floods: A spatial analysis

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Abstract
River response to large magnitude floods can vary significantly and a range of factors can influence this variation. Catchment and riparian vegetation represents a significant control over sediment supply and bank stability and yet is the control most vulnerable to human disturbance. Extensive vegetation clearing from the channel and floodplain in the period following European settlement has altered the hydrology and sediment regime of many Australian rivers, likely altering the geomorphic effectiveness of floods. Two major floods occurred in the Lockyer Valley, Queensland in January of 1974 and 2011. This study assessed the role of woody riparian vegetation in enhancing or inhibiting geomorphic change during these large floods.

Woody vegetation coverage in 1971, 1974, 2009 and 2011 was measured by classifying orthophotos. Changes in the spatial extent of woody vegetation between the two time periods were identified using a post classification change detection method. A combination of GIS methods and statistical analysis were used to assess the effect of this vegetation change on erosion and deposition occurring during the floods for three study reaches in contrasting valley settings. Analysis of geomorphic change occurring during the 1974 flood demonstrates the change occurring in lower reaches was much more significant in relation to the upper catchment. This study suggests that unvegetated banks in the 1974 flood were more susceptible to rapid geomorphic change. Furthermore, the results demonstrate that along the banks of two of the three reaches; woody vegetation was associated with more significant deposition and less erosion during the January 2011 flood. This was not consistent in the third reach, where significant erosion and deposition occurred in areas that were unvegetated or where vegetation was removed in the 2011 flood. This highlights that vegetation alone was not the only control on channel response to the large 2011 flood.

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The role of vegetation in catastrophic floods:

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Bronte Smith

 

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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.

Bronte Smith

Cover image: Before and after image of the 2011 flood at Fifteen Mile Creek.

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Abstract

River response to large magnitude floods can vary significantly and a range of factors can influence this variation. Catchment and riparian vegetation represents a significant control over sediment supply and bank stability and yet is the control most vulnerable to human disturbance. Extensive vegetation clearing from the channel and floodplain in the period following European settlement has altered the hydrology and sediment regime of many Australian rivers, likely altering the geomorphic effectiveness of floods. Two major floods occurred in the Lockyer Valley, Queensland in January of 1974 and 2011. This study assessed the role of woody riparian vegetation in enhancing or inhibiting geomorphic change during these large floods.

Woody vegetation coverage in 1971, 1974, 2009 and 2011 was measured by classifying orthophotos. Changes in the spatial extent of woody vegetation between the two time periods were identified using a post classification change detection method. A combination of GIS methods and statistical analysis were used to assess the effect of this vegetation change on erosion and deposition occurring during the floods for three study reaches in contrasting valley settings. Analysis of geomorphic change occurring during the 1974 flood demonstrates the change occurring in lower reaches was much more significant in relation to the upper catchment. This study suggests that unvegetated banks in the 1974 flood were more susceptible to rapid geomorphic change. Furthermore, the results demonstrate that along the banks of two of the three reaches; woody vegetation was associated with more significant deposition and less erosion during the January 2011 flood. This was not consistent in the third reach, where significant erosion and deposition occurred in areas that were unvegetated or where vegetation was removed in the 2011 flood. This highlights that vegetation alone was not the only control on channel response to the large 2011 flood.

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List of Abbreviations

ARI	Annual Recurrence Interval
DSITIA	Department of Science, Information Technology, Innovation and the Arts
ENSO	El Nino Southern Oscillation
GIS	Geographic Information Systems
GCP	Ground Control Points
LWD	Large Woody Debris
RMSE	Root Mean Square Error
SEQ	Southeast Queensland

1. Introduction

Flooding is a natural attribute of rivers, but due to the widespread use of alluvial floodplains for agriculture and infrastructure, floods can have a severe impact on the surrounding community (Knighton 1998). A flood event can be defined as a substantial increase in flow resulting in significant bed scour, bank erosion and sediment transport (Brierley and Fryirs 2005).

Extreme or catastrophic floods can cause considerable changes to the river channel and floodplain. Effects of a large magnitude flood event are conventionally thought to be primarily erosional (Croke et al. 2013b). River bank erosion is a central process in fluvial systems and has important implications for a wide range of physical and economic issues. It can involve the loss of valuable agricultural land and cause significant damage to infrastructure such as roads, building and bridges (Docker and Hubble 2008). Such infrequent events can have a significant impact on the surrounding environment and local population (Baker 1988).

Floods have a varied role in the erosion of stream channels. While some major floods result in relatively insignificant change, considerable channel adjustment has occurred in others (Baker 1988). Exceptional floods can erode and transport large volumes of sediment, resulting in major changes to the fluvial landscape. The potentially devastating impact of large magnitude floods was especially apparent during the January 2011 flood in the Lockyer Creek catchment in southeast Queensland (SEQ), Australia. This event was rated as the second highest flood of the past 100 years, second to the January 1974 flood event (Croke et al. 2013a). This resulted in billions of dollars of damage to local infrastructure and the loss of twenty two lives (Grove et al. 2013; Thompson and Croke 2013).

An understanding of past channel response and sensitivity to change is essential in predicting the response to future flood disturbance (Hoyle et al. 2008). However, contemporary channel dynamics may provide little insight into long term channel processes due to the level of disturbance inflicted on many Australian rivers (Brooks et al. 2003). Australian river systems have undergone extensive channel metamorphosis in the 200+ years since European settlement, resulting in vast changes to channel form and hydrologic regimes (Brooks and Brierley 1997; Brooks and Brierley 2000; Brooks and Brierley 2002). Much of the indigenous vegetation was cleared from stream banks and floodplains for intended improvements to the river associated with agricultural production, river navigation, urbanisation or flood mitigation (Webb and Erskine 2003b). During the 1970's, the clearing of riparian and within channel vegetation as well as the removal of large woody debris (LWD) became mandatory in Queensland, with penalties imposed for non-compliance (Hubble et al. 2010).

Riparian vegetation can be defined as the vegetation growing on fluvial surfaces including the floodplain, river bank and in-channel features. Fluvial surfaces in the riparian zone are inundated or saturated by bank full discharge (Hupp and Osterkamp 1996; Hupp 1999). Extensive human interference has altered conditions, resulting in highly degraded riparian zones in many Australian rivers (Brooks and Brierley 1997; Brooks and Brierley 2000; Brooks et al. 2003). These areas have a unique structure and function within the fluvial environment (Darby 1999; Abernethy and Rutherfurd 2000;2001; Brooks and Brierley 2002; Simon and Collison 2002; Webb and Erskine 2003b; Hubble et al. 2010; Pollen-Bankhead and Simon 2010). The influence of vegetation will be explored further in Chapter 2.

Stream bank erosion is a natural process. However due to the removal of riparian vegetation, accelerated erosion rates have become a significant issue. An understanding of the patterns and processes of bank erosion is important in investigating and predicting changes in river form (Grove et al. 2013). These factors are critical for environmental and economic planning and can help to make informed decisions in regards to monitoring river hazards and implementing stream management strategies.

Ongoing monitoring of the riparian environment is crucial for effective river management due to the significant role vegetation plays in floodplain processes and the overall stability of the channel margin. Geographic Information Systems (GIS) and Remote Sensing provide a cost-effective and time-efficient method of monitoring changes in vegetation cover, particularly over large areas. These technologies therefore have great potential in this field and facilitate the ongoing monitoring of riparian vegetation change. The rapid advancement of this technology has led to an increased availability of remotely sensed imagery from a variety of sources (Xie et al. 2008).

Aerial photography is an important information source in studies of vegetation change and provides valuable historical information on riparian vegetation condition and cover (Okeke and Karnieli 2006; Kollár et al. 2011). Such photography has a much longer temporal history than other sources of remotely sensed data (e.g. Landsat data), often dating back to the 1930s. Furthermore, the high spatial resolution and large spatial extent of aerial photography offer major potential for providing detailed assessments of landscape change at local and regional scales (Kadmon and Harari-Kremer 1999; Okeke and Karnieli 2006).

1.1 Aims and Objectives

Several Australian studies have established the influence of vegetation on the morphology of rivers through impacts on resistance to flow, bank strength and stream morphology (Abernethy and Rutherfurd 1998;2000;2001; Hubble et al. 2010). These studies have documented that vegetation can have a profound influence over the characteristics of a fluvial system.

The purpose of this study was to investigate the role of woody riparian vegetation in enhancing or inhibiting processes of erosion and deposition during the large magnitude flood events which occurred in January 1974 and January 2011 in the Lockyer Valley, QLD.

To address this objective, this study will:

- Map vegetation coverage and quantify changes to riparian vegetation extent through time, specifically examining the periods between 1971 to 1974 and 2009 to 2011. This analysis is performed through the application of change detection techniques to orthophotos for the above time periods.

- Assess the areas of greatest channel change in response to the January 1974 flood event, and interpret the role of vegetation in enhancing or inhibiting this change.

- Determine the effect of vegetation extent on enhancing or inhibiting deposition and fluvial entrainment, and to assess the relationship between the occurrence of mass failure and vegetation during the January 2011 flood event in both confined and unconfined reaches.

- Determine the significance of riparian vegetation in controlling river behaviour and channel response of the large magnitude flood event of January 1974 and 2011.

1.2 Thesis Structure

The following chapter will present a review of the current literature. This chapter will discuss the mechanics of bank erosion and the potential impacts of large floods on the landscape, and the influence of riparian vegetation on channel morphology. This chapter will also discuss techniques that can be used to classify vegetation and quantify vegetation change.

Chapter three will provide an overview of the study location, including an evaluation of the climate and past hydrology of the Lockyer Valley catchment and a history of land use. Chapter four describes the methods taken to complete the vegetation classification and change detection analysis. The approach used to examine the effect of vegetation on erosion and deposition during large floods will also be discussed here. These results will be presented in Chapter five. Chapter six will include a discussion of these results in relation to the broader literature, as well as the limitations of this study. Chapter seven will present conclusions of the study and recommendations for future research and management.

2. Literature Review

This literature review is divided into three sections. The first section discusses bank erosion processes in both small and large floods. Whilst the second section discusses the influence of riparian vegetation on channel morphology and bank stability during high magnitude floods. The final section focuses on the methodologies available to assess the role of riparian vegetation in catastrophic floods, using remote sensing and GIS.

2.1 The mechanics of bank erosion and the impacts of catastrophic floods

Rates of bank retreat and processes of erosion acting on a stream bank are determined by attributes of flow, sediment transport and bank properties (Abernethy and Rutherfurd 1998). Bank erosion can be divided into three types: sub aerial preparation, fluvial entrainment and mass failure. There are significant spatial variations in these processes, which vary in response to large floods.

2.1.1 Sub-aerial preparation and pre-conditioning of river banks

Sub aerial processes occur when the surface of the riverbank comes into contact with air. These processes can either directly erode the bank material or act to weaken the bank, reducing the shear strength of bank soil and enhancing the impact of other erosion processes (Grove et al. 2013). These processes can be highly influential, yet difficult to monitor. The extent of sub aerial erosion experienced will be most important in the period preceding a flood event and likely to be relatively insignificant during bank full conditions of large magnitude floods.

Flood events may or may not be effective in shaping the river valley systems through which they flow (Costa and O'Connor 1995). Some research has focused on the extreme climatic and flood variability to explain morphological change in rivers, through large magnitude floods (Warner 1987; Erskine and Warner 1988). These studies have attributed channel changes in some rivers to multi decadal flood dominated and drought dominated regimes. However, they give little regard to the condition of the channel prior to the occurrence of floods and the significance of the removal of vegetation and wood on modern channel dynamics (Brooks and Brierley 2002). Some studies suggest that invoking secular shifts in climatic regime to explain channel metamorphosis in south-eastern Australia is an oversimplification (Brooks and Brierley 2000), and climatic variability may not be the ultimate cause of documented changes throughout the 20th century (Hoyle et al. 2008).

Catchment scale boundary conditions such as sediment supply, channel gradient and hydraulic resistance, induced by vegetation and wood will influence the landscape sensitivity or resistance to change. In some systems, enhanced channel capacity and the removal of vegetation has increased the geomorphic effectiveness of floods (Hoyle et al. 2008). The wide-scale clearing of riparian and within channel vegetation has driven extraordinary channel change and many Australian rivers have experienced adjustment in hydrologic regime or sediment supply (Brooks and Brierley 1997;2002). Catastrophic changes have in occurred in highly disturbed systems, where riparian vegetation has been removed and within channel wood is limited (Brooks and Brierley 2002).

Erskine et al (2012) document catastrophic change in the highly disturbed system of Widden Brook in the Hunter Valley, Australia. Catastrophic flooding in 1952 and 1955 resulted in significant increases to the width of channel streams and an extended recovery period, in a system largely devoid of riparian vegetation and within channel wood. Brooks and Brierley (1997) also note significant changes in sediment supply and the flood hydrograph in the lower Bega River, in south-eastern Australia. Widespread vegetation clearing has transformed the system from narrow and deep, to a shallow and wide channel. They found that human disturbance has likely increased the geomorphic effectiveness of flood events through the removal of vegetation, and destabilisation of the banks due to stock grazing. They also suggest that documented behaviours of eastern Australian rivers such as catastrophic channel widening and floodplain stripping may reflect the increased effectiveness of flood events in the period since European settlement, although the magnitude of flood events are likely to have remained the same.

2.1.2 Spatial variation in erosion processes

The two processes likely to dominate the erosion of riverbanks during high magnitude flood events are fluvial entrainment and mass failure. Fluvial entrainment refers to the grain-by-grain removal and entrainment of sediment (Rinaldi and Darby 2007; Grove et al. 2013). Mass failure is the down slope movement of sediment or rock as gravitationally induced stresses exceed critical instability thresholds of the bank (Lawler 1992; Lawler 1995; Grove et al. 2013). The structure, geometry and material properties of a river bank will influence the vulnerability of the riverbank to mass failure (Knighton 1998; Brierley and Fryirs 2005). Such geomechanical failure occurs where bank height exceeds a critical threshold as channel depth/bank size increases downstream (Lawler 1995). When a section of the bank fails, slabs of sediment fall to the toe of the bank often as a result of over steepening or under cutting of bank material (Lawler et al. 1997). This sediment is broken down and entrained by the flow.

Downstream variation in discharge, channel form and scale alters the influence each process exerts over riverbank erosion to a greater or lesser extent. Several studies have demonstrated the spatial

zonation of bank erosion processes acting on a river channel. Abernethy and Rutherfurd (1998) demonstrated the occurrence of the three types of erosion on sections of the reaches of the Latrobe River, Victoria.

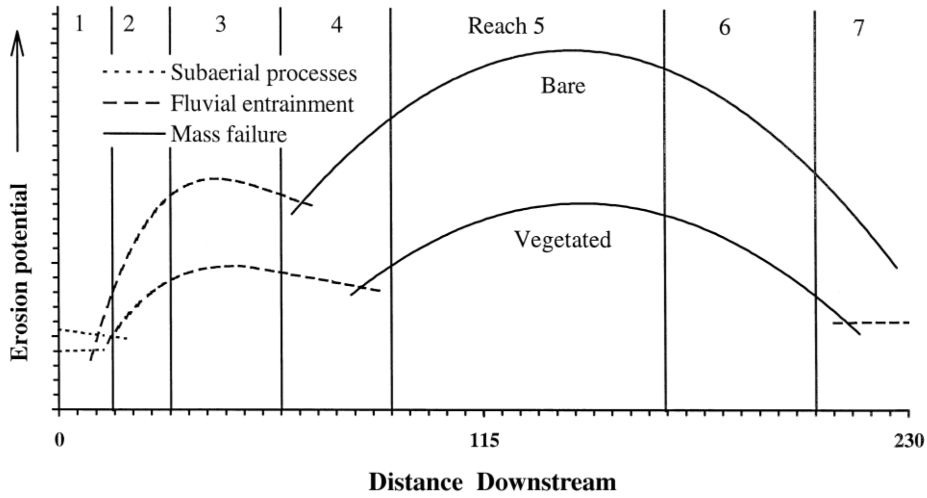

Figure 1 Model for the erosion potential along the Latrobe River showing the spatial zonation of erosion processes and the suggested influence of vegetation (Abernethy and Rutherfurd 1998).

Upper reaches were dominated by sub-aerial erosion processes while fluvial entrainment processes were more prevalent in mid-basin reaches (Figure 1). Resistance to flow is crucial in determining the extent of erosion by fluvial entrainment in these reaches. Mass failure assumes dominance in the downstream reaches of the catchment. Figure 1 shows that the presence or absence of vegetation in these reaches is a determining factor in the extent of erosion occurring by mass failure, due to the root reinforcement of bank vegetation.

Lawler (1992; 1995) suggests a model to explain the spatial zonation in patterns of bank erosion. He notes that, in upper reaches, the energy available for fluvial entrainment is limited due to a low stream power. Bank heights are reduced, making sub aerial erosion the most effective method in these reaches. A combination of erodible bank sediment and stream power peaks in mid-basin reaches result in the dominance of fluvial entrainment processes. Lawler (1992; 1995) also suggests that bank material in lower gradient reaches is cohesive, resistant to shear and that low stream power limits erosion by fluvial entrainment. As bank heights exceed critical instability thresholds, mass failure becomes the most important process of erosion. Mass failure also becomes common in periods of rapid drawdown of flood waters, due to the generation of pore water pressures exceeding the shear strength of bank materials (Simon et al. 1999).

2.1.3 The role of big floods in bank erosion

Floods are important processes of fluvial systems, with durations lasting from minutes to days (Baker 1988). Geomorphic effectiveness is related to the ability of an event, or a combination of events to modify the landscape, and the persistence of the changes incurred (Wolman and Gerson 1978). The effectiveness of a flood ultimately depends on the exceedence of a resistance threshold of bank materials, including vegetation, by the stream power generated by the flood (Baker 1987; Baker 1988; Magilligan 1992). It can be measured in terms of the work performed on the landscape by catastrophic floods, or more frequent floods of smaller magnitude. Wolman and Miller (1960) suggest that the work performed by a river is related to the amount of sediment transported during a given flow.

Catastrophic floods have been defined previously as floods with a peak discharge of at least 10 times greater than the mean annual flood (Baker 1988). Such floods, which generally have an extremely rare occurrence, impose higher than average forces on stream bed and bank materials, potentially causing a large deviation from equilibrium conditions of the channel (Baker 1977). The maximum discharge of a flood is frequently used as a measure to assess the potential for geomorphic change (Baker 1987; Costa and O'Connor 1995). However, channel boundary shear stress and stream power per unit boundary area may be more useful in assessing the role of rare, large magnitude floods in generating substantial geomorphic change. Shear stress is the tangential boundary shear acting on the channel bed and stream power expresses the power per unit length (Magilligan 1992). Stream power is the energy that a river has to accomplish work along its path. This can be expressed as:

$$\Omega = \gamma \, Q \, \mathrm{S}$$

where Ω is the total stream power, γ is the specific weight of water, Q is the water discharge and S is the channel slope (Nanson and Huang 2008).

Floods of similar magnitude and frequency can produce dissimilar geomorphic changes (Baker 1987; Baker 1988; Costa and O'Connor 1995) and various studies have questioned the relative role of floods of varying magnitude in modifying the landscape. Wolman and Miller (1960) suggested that more frequent events of smaller magnitude have a greater role in modifying the landscape than rare, large magnitude floods. In the same year, Hack and Goodlett suggested that in some landscapes, such as the Appalachian region of the eastern US, large magnitude floods are the dominant events responsible for large scale landscape change. Miller (1990) also observed the geomorphic response to large floods in the Appalachians. While the rainfall and discharge were comparable to other events observed through the region, the November 1985 flood produced some of the most severe and widespread floodplain erosion ever documented through the area.

Large floods can generate immense discharges, but in some cases, produce a surprisingly minor geomorphic response. Some studies have attributed the minor geomorphic changes to stream powers unable to exceed resistance thresholds of the landscape (Nanson and Hean 1985). Costa (1974) documented the channel response to the flood generated by tropical storm Agnes in the north-eastern US in June, 1972. Despite the great magnitude of rainfall and flooding, few changes to the channel were observed and recovery occurred quickly. He determined that large floods have a minor role in landscape modification in some systems.

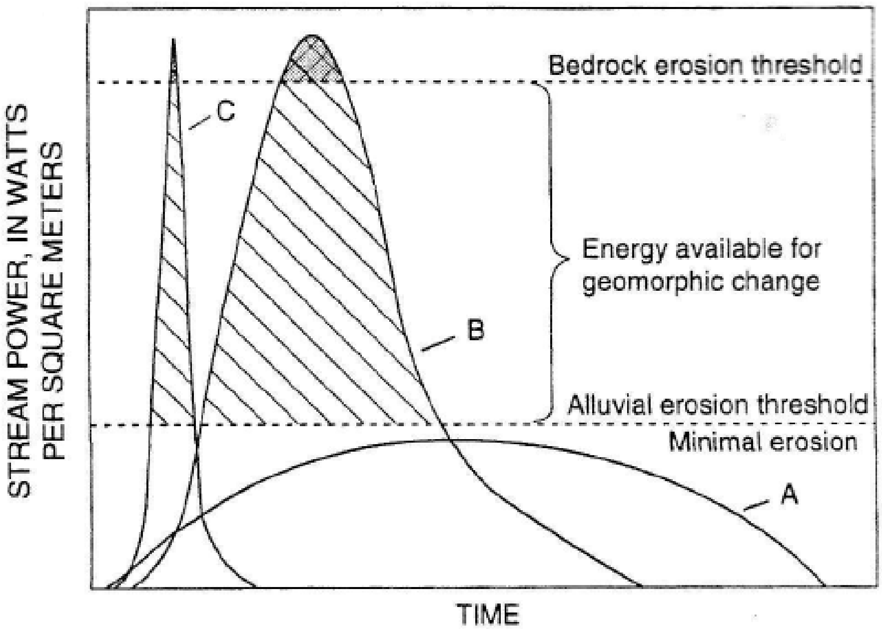

Figure 2 Hypothetical stream power graphs of floods of varying magnitudes to document geomorphic effectiveness (Costa and O'Connor 1995).

Although peak stream power is useful in determining the ability of a flood event to change a landscape (Baker 1987), it is not the sole factor determining the effectiveness of a flood (Costa and O'Connor 1995). Effective floods require an optimal combination of stream power, duration and energy expenditure (Costa and O'Connor 1995). As such, flow duration is critical to determining the effectiveness of a flood event and to understanding how floods of smaller magnitude can have a greater geomorphic impact. Costa and O’Connor (1995) suggest that minor change occurring during a large flood, despite high stream power values, is due to short flood duration. They propose a model documenting the geomorphic effectiveness of floods of different magnitudes (Figure 2). Curve A represents floods such as the Mississippi River flood of 1927, which although had a long duration, generated a small peak power not sufficient to erode the large, low gradient river banks. Curve B describes floods such as those resulting from the dam failure of Lake Missoula (O'Connor and Baker 1992) which had both high values of peak stream power, and a flow duration of several days. These floods are likely to be the most effective and have a great potential to cause tremendous change in

alluvial channels. With enough energy (over the bedrock erosion threshold), these floods can potentially erode bedrock channels.

Floods with high values of peak stream power, but a short duration are represented by curve C, such as the flash floods occurring due to dam failure in Washington and Oregon (Costa and O'Connor 1995) . While these floods may exceed resistance thresholds, they may not be competent in breaking down floodplain vegetation and eroding the floodplain and channel. Vegetation can have a significant influence over equilibrium condition and the subsequent effectiveness of large flood events. In many cases, rivers which have documented catastrophic changes are those systems that have undergone extensive change through the removal of LWD and the clearing of riparian vegetation (Brooks and Brierley 2002). In these systems, the occurrence of equilibrium condition is dependent on the retention of critical controls of riparian vegetation and LWD.

2.2 The impact of riparian vegetation on fluvial geomorphology

Riparian vegetation exerts a critical influence over river systems, playing an important role in resistance to flow, bank strength, sediment storage, bed stability and stream morphology (Darby 1999; Abernethy and Rutherfurd 2000;2001; Brooks and Brierley 2002; Simon and Collison 2002; Webb and Erskine 2003b; Hubble et al. 2010; Pollen-Bankhead and Simon 2010). Many eastern Australian rivers have undergone considerable changes in channel form in the 200 + years since European settlement. These rivers have often been poorly managed in the past with much of the native vegetation cleared from stream banks and floodplains. In Queensland in particular, it became mandatory to clear bank and within channel vegetation in the 1970s (Hubble et al. 2010).

The influence of vegetation over channel form and process has received significant attention over the last 40 years. A large body of literature now exists identifying the changes experienced due to the removal of vegetative controls (Smith 1976; Hickin and Nanson 1984; Thorne 1990; Huang and Nanson 1997; Abernethy and Rutherfurd 1998; Darby 1999; Millar 2000; Brooks and Brierley 2002; Brooks et al. 2003; Webb and Erskine 2003b; Osterkamp and Hupp 2010; Erskine et al. 2012). Vegetation influences width to depth ratios and well vegetated river channels are frequently found to be deeper and narrower than those channels with fewer trees on their banks (Friedman et al. 1996; Huang and Nanson 1997; Brooks et al. 2003). Smith (1976) suggested that vegetated banks were up to 20 000 times more resistant than non-vegetated banks with otherwise comparable characteristics.

Brooks et al (2003) recognised the control of vegetation on channel form and condition. Due to the removal of riparian vegetation and woody debris, the highly disturbed Cann River, in southeast Australia, experienced significant increases in channel depth, slope and capacity. In comparison, the

nearby Thurra River remained in almost pristine condition. Bank conditions of the Cann River were significantly altered, leading to an adjustment in the dominance of erosion patterns, from fluvial erosion to mass failure. In addition, they found that despite the flashy flood regime of the Thurra River, the channel has maintained a stable condition and exhibits resilience to catastrophic events. They attributed this behaviour to the presence of well-established riparian vegetation and within channel wood.

Several studies have identified the influence of vegetation on erosion and bank stability (Thorne 1990; Abernethy and Rutherfurd 2000;2001; Hubble et al. 2010). Riparian vegetation is able to influence the mass stability and enhance the strength of river banks through mechanical and hydrologic mechanisms (Simon and Collison 2002), explored in the next section.

2.2.1 Mechanical mechanisms

Vegetation plays a critical role in flow resistance of the channel bed and bank (Baker 1988). Knighton and Nanson (2002) studied hydraulic conditions of both in-bank and over-bank flow. This study found that a rough floodplain surface, attributed to the presence of vegetation produces significant decreases in the downstream transmission of flood waves. The resistance of the studied floodplain was found to be concentrated at channel bank tops where vegetation density was highest. The bank top vegetation provided a considerable level of flow retardation compared to areas of sparse vegetation.

The lateral stability and channel form of a river is largely dependent on the strength of the materials which comprise the bank, and are significantly influenced by the binding properties of riparian vegetation (Hickin 1984; Brooks et al. 2003). Root reinforcement is a function of root strength, interface friction between the roots and soil and the distribution of roots within the soil. Root reinforcement of soil provides relief of high stress through the transfer of load to regions of lower stress (Abernethy and Rutherfurd 2001).

Riparian and in-channel vegetation and LWD provide the primary source of roughness within the channel (Shields and Gippel 1995). It increases the effective roughness of the boundary and in turn increases the resistance to flow (Hickin 1984; Thorne 1990; Brooks and Brierley 2002). The forces of drag and lift acting on the bank are reduced, as is shear stress. This is equivalent to a reduction in near bank velocity, reducing erosive forces. Abernethy and Rutherfurd (1998) suggest that vegetation can significantly affect mean stream power in upstream reaches, and will reduce the flow's capacity for fluvial entrainment (Figure 3). On the reaches of the Latrobe River where stream power peaks, vegetation achieves a reduction of 30%. The effect of vegetation on mean stream power decreases with distance downstream, however still yields a reduction of 15% in lower reaches.

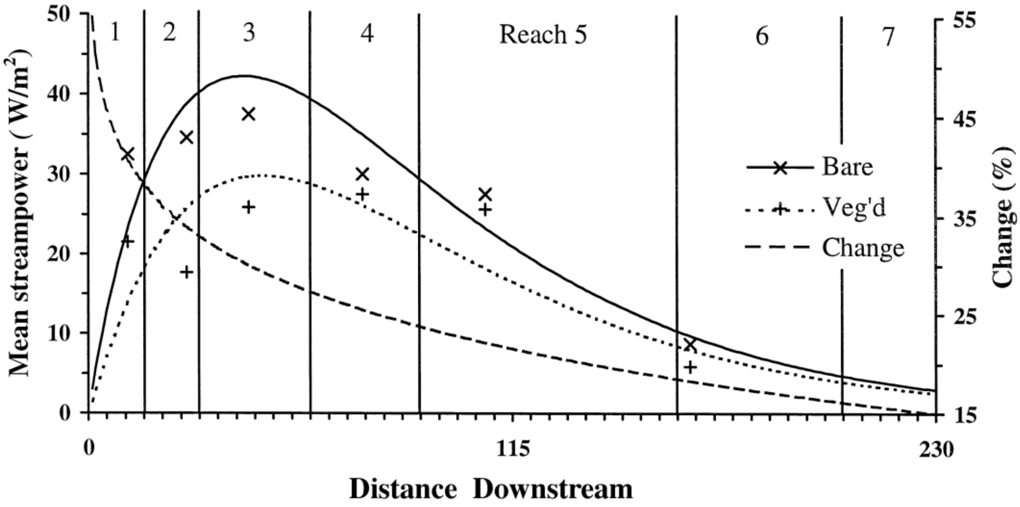

Figure 3 Influence of vegetation on mean stream power as a function of distance downstream for the vegetated and bare banks of the Latrobe River (Abernethy and Rutherfurd 1998).

Huang and Nanson (1997) found that while dense bank vegetation had a significant effect in creating narrower channels, vegetation growing on the bed created boundary roughness, increased the resistance to flow and decreased flow velocity. They note the impact of scale and that variation in vegetation will have a magnified effect in smaller channels compared to the impact on larger channels (Huang and Nanson 1997). The density of vegetation along a channel has also proven important with close spacing of trees required to reduce near-bank velocities (Thorne 1990). This has implications with regards to investigating channel response and the role of vegetation in catastrophic floods. Root permeated soil is strong in both compression and tension, giving enhanced strength compared to non-root permeated soils (Simon and Collison 2002). Strong roots on river banks can offer a greater resistance to lateral erosion than non-vegetated banks of alluvium exposed to the same erosive forces (Hickin 1984). Hickin and Nanson (1984) determined that while other factors remain constant, a river migrating through a cleared floodplain may erode at almost twice the rate of one reworking a naturally forested floodplain.

Driving forces for stream bank instability are controlled by bank height and slope, the unit weight of the soil and mass of the water within it and the surcharge imposed by objects on the bank top, bank surface or within the bank such as trees (Simon and Collison 2002). Studies have demonstrated the ability of riparian vegetation to decrease bank erodibility. Pollen-Bankhead and Simon (2010) determine that even small volumes of roots within the stream bank soil can decrease the erodibiity of the sediment when compared to that of bare soil. During floods, the flow resistance generated can change significantly. A major flood may overcome the resistance threshold that the vegetation provides due to the increase in shear strength and stream power (Erskine et al. 2012).

Slopes covered in dense vegetation experience an increase in resistance to erosion of between one to two orders of magnitude (Smith 1976; Thorne 1990). Riparian vegetation works to directly protect the soil surface, while the roots bind the sediment. Although vegetation does not completely prevent erosion, the critical condition for erosion of a vegetated bank is the threshold of failure of the plant stems by snapping or uprooting rather than the entrainment of the bank material itself (Thorne 1990).

2.2.2 Hydrologic mechanisms

Vegetated banks are drier and better drained than non-vegetated river banks (Thorne 1990), as the canopy prevents approximately 15 to 30 per cent of rainfall water from reaching the soil surface, or plants drawing moisture from the soil. Drier river banks are more stable because the bulk weight of the soil is reduced and internal cohesion is increased (Thorne 1990).

The factor of safety (F_s) is the ratio of resisting forces to driving forces. Values of F_s greater than 1 indicate stability, whilst values less than 1 indicate instability (Simon and Collison 2002). Simon and Collison (2002) demonstrate the importance of hydrological mechanisms in controlling stream bank stability. Analysis of stream bank stability over two time periods established that the roots of trees and shrubs resulted in significant increases in soil strength. During a dry antecedent period, hydrologic effects of rainfall interception and the extraction of soil moisture from the soil were found to increase F_s by 71 per cent. During a wetter than average antecedent period, F_s was found to increase by 29 per cent due to the impact of vegetation. Abernethy and Rutherford (2000) found that riparian corridors of Swamp Paperbark and River Red Gum increase bank stability, with 132% and 175% respective increases in factor of safety. Similarly, Docker and Hubble (2008) aimed to determine the magnitude and distribution of root reinforcement within the soil layer to establish the potential for a river bank to resist mass failure. They found that the presence of the roots increased the shear strength of the soil.

Prolonged rainfall events can alter the stability of a river bank in several ways (Simon et al. 2000). The infiltration of rainfall increases the bulk unit weight of the soil, increasing the driving force on the bank. Infiltration also causes a reduction in cohesion, reducing the resisting force of the bank (Abernethy and Rutherfurd 2000; Simon and Collison 2002). The generation of positive pore water pressures within the bank decreases the frictional strength, creating unstable conditions. Vegetation reduces the magnitude of positive pore pressures that can trigger failure during drawdown of floodwaters, significantly enhancing shear strength and the stability of the river bank (Simon and Collison 2002). This reduces the surface run off after a rainfall event, decreasing the effectiveness in generating surface erosion.

The shape and size of mass failures are related to the geometry of the bank section, geotechnical and hydrological properties of bank material and the density of vegetation present (Abernethy and

Rutherfurd 2000). Bank failures are commonly associated with periods of prolonged rainfall or complete inundation by flood waters, followed by a rapid drawdown of the flow with bank material remaining saturated (Lawler et al. 1997; Abernethy and Rutherfurd 1998;2000; Rinaldi and Darby 2007). During these processes, the strength of the bank material is minimised and weight maximised.

Several Australian studies have addressed the role vegetation plays in preventing bank erosion by mass failure (Abernethy and Rutherfurd 1998;2000;2001; Hubble et al. 2010). These studies have shown a clear link between the absence of riparian vegetation and the occurrence of river bank failures. Results show the presence of riparian vegetation significantly decreased the likelihood of erosion by mass failure, through the reinforcement of soil tree roots and the movement of water through mechanisms of evaporation and transpiration. The inception of rainfall by bank vegetation reduces pore water pressures enhancing mass stability (Pollen-Bankhead and Simon 2010).

Hubble et al (2010) document the role of vegetation in the occurrence of mass failures in eastern Australian rivers. They found that the substantial channel widening experienced was due to a combination of large and frequent floods and widespread clearing of bank and floodplain vegetation. They show that the clearing of vegetation caused a significant reduction of bank shear strength. This study determined that the clearing of vegetation exasperated the potential for mass failure during periods of rapid drawdown of flood waters and that these banks may have remained stable had the remnant riparian vegetation been intact.

Studies have established a clear link between the presence of vegetation and increased bank strength. However, some banks experiencing a large amount of toe scour are likely to fail regardless of the presence or absence of vegetation (Hubble et al. 2010). Therefore, the key question is the role of vegetation in catastrophic floods such as the January 1974 and 2011 floods in the Lockyer Valley, Queensland.

2.3 Remote sensing of vegetation

Remote sensing involves the science of obtaining information about an object without being in physical contact with it (Jensen 2007). Remote sensing can be used to evaluate and monitor the Earth's biophysical characteristics and has proven to be a valuable tool in the mapping and monitoring of riparian environments. The unobtrusive nature of remote sensing is one of the most significant advantages over field based methods (Jensen 2005). Remote sensing methods are cost-effective, less time consuming and can gather information at a greater temporal and spatial scale.

Maps which illustrate the location, density and extent of riparian vegetation are central to catchment management and planning (Yang 2007). Such knowledge can improve the understanding of the

relationships between landscape elements and ecological processes. Traditional vegetation mapping techniques often involve manual interpretation and field observation, which are time-consuming and difficult to repeat on a large scale (Yang 2007). Rapidly expanding technologies in GIS and remote sensing provide effective tools in the historical analysis of riparian areas. A variety of remotely sensed imagery has been used in studies of vegetation mapping and classification at different levels of spatial and spectral resolution (Yang 2007).

Spectral resolution refers to the number and size of wavelength intervals in the electromagnetic spectrum, to which a remote sensing instrument is sensitive (Jensen 2007). Certain regions of the electromagnetic spectrum are favourable in obtaining information on biophysical parameters. For instance, healthy green vegetation typically has a low reflectance in the visible region of the spectrum and a high reflectance in the near infrared region, due to the strong absorption of chlorophylls (Jensen 2005). In contrast, the most spectrally distinctive characteristic of water is high absorption at the near infrared wavelengths. The near infrared band is more suited to distinguishing between water and vegetation than the visible spectral bands alone.

Spatial resolution is defined as the smallest area on the ground surface contained within a pixel (Akasheh et al. 2008). The nominal spatial resolution should be less than one half of the size of the feature to be mapped. Therefore, a high spatial resolution is required to effectively map the narrow, linear distribution and often diverse nature of riparian vegetation. The ideal resolution is scale dependent and relative to the size of the area to be mapped. Yang (2007) suggests that digital aerial photography with a pixel size of less than two metres remains the most suitable medium for the detailed mapping and analysis of riparian areas, despite its often limited spectral resolution.

Temporal resolution refers to how often the sensor collects imagery at a particular location. In order to capture the full extent of vegetation change occurring during the catastrophic flooding of January 1974 and 2011, imagery was required before and immediately after the flood events. Aerial photography has certain advantages in terms of temporal resolution, as it can be collected when required. In addition, aerial photography also provides a much longer temporal history than satellite derived data, making it appropriate for the long term monitoring of riparian vegetation (Ihse 2007).

Despite the limited spectral resolution, multi temporal black and white and true colour aerial photography was used in this study as it met the requirements of spatial and temporal resolution. The following section will explore the common image analysis techniques used to map vegetation change.

2.3.1 Methods of image classification and change detection of riparian vegetation

A wide range of techniques are available for the classification of vegetation and detection of vegetation change, ranging from field based methods, to remotely-sensed methods or a combination thereof (Singh 1989; Lu et al. 2004). Change detection involves identifying differences in the state of an object or phenomenon through observations at different time periods (Singh 1989; Lu et al. 2004) to achieve a better understanding of both human and physical processes (Jensen 2005). Information relating to change of the Earth's surface can provide a better understanding of the relationships and interactions between human and natural trends, to better manage the Earth's resources. This involves the use of multi-temporal datasets to quantitatively analyse the effects of the phenomenon over time.

The most efficient change detection techniques are able to quantify the area, direction and the rate of change and estimate the accuracy of change detection results (Lu et al. 2004). There are three main steps involved in implementing a change detection project. This involves image pre-processing and performing the necessary corrections before undertaking the analysis, the selection of suitable change detection techniques and accuracy assessment. Image analysis techniques such as per pixel and object based approaches are becoming more common, and often more accurate in comparison to manual interpretation (Kollár et al. 2011). The two most commonly used methods of change detection are image differencing and post classification change detection.

2.3.1.1 Post classification change detection

Post classification change detection involves the individual classification of images captured at different times and the area of change is determined through direct comparison of the classification results. As images are independently classified, the use of post classification change detection often minimises the potential problems of normalising for atmospheric differences between dates (Singh 1989). This method is also favoured when images were captured at different times of the year.

Per pixel approach

For more than 30 years, the vast majority of studies completed in vegetation mapping and change detection have focused on the analysis of individual image pixels of remotely sensed imagery (Johansen et al. 2010). The concept of the per-pixel analysis involves the process of estimating biophysical and geophysical properties from the reflectance values of various features on the Earth's surface, mapping an entire scene, pixel by pixel.

Studies of land cover or vegetation change often use parametric algorithms to identify spectrally distinct groups of data (Rogan et al. 2002). Parametric, pixel based classifications are typically

unsupervised, supervised or a hybrid approach incorporating both (Tuxen et al. 2011). A supervised classification involves the use of a combination of prior knowledge, ground referenced data or map analysis in the "training" classification algorithm (Jensen 2005; Tuxen et al. 2011). The spectral characteristics of these training areas are used to classify the remainder of the image and each pixel within and outside the training areas are assigned the class to which it most likely belongs.

An unsupervised classification assigns pixels to classes based on individual spectral signatures without a priori input from the analyst (Tuxen et al. 2011). An unsupervised classification is generally used to identify land cover types when ground reference data is unavailable or features within the image are poorly defined (Jensen 2005). Everitt et al (2004) compared the use of Quickbird false colour satellite imagery and colour infrared aerial photography in the mapping of wetland vegetation. An unsupervised Iterative Self-Organising Data Analysis (ISODATA) method was used to classify both images into four vegetation classes. This study achieved a classification accuracy of greater than 80% and demonstrated the usefulness of parametric classifications to classify vegetation from aerial photography. However, one of the most significant disadvantages in the use of an unsupervised classification is that it relies on the identification of spectrally distinct classes and the ability of the user to associate these classes with meaningful features (Lillesand et al. 2004).

A number of studies have employed a supervised classification in studies of vegetation cover, and a maximum likelihood technique is by far the most common. Assuming a normal distribution of the training points, the classification evaluates variance patterns when classifying an unknown pixel and allocates each pixel based on the mean of the training class (Jensen 2005). Karl et al (2012) use a maximum likelihood classifier to determine the vegetation extent from colour infrared aerial photography in Nevada and New Mexico, USA. Training data was collected to classify each image into two cover types, canopy and non-canopy. The pixel based, maximum likelihood classifier gave an overall accuracy of above 80% for all evaluated sites.

Change detection can be used to assess the extent and direction of change in land cover classes. Post classification change detection has been used repeatedly as a change detection method (Jensen 2005). Post classification change detection involves the individual classification of each image, followed by the pixel by pixel comparison of the classifications to assess whether change has occurred. Apan et al (2000) use a supervised classification, employing a maximum likelihood classifier to assess landscape structural change in the Lockyer Valley Catchment, Queensland. A post classification change detection method was then used to quantify the change that had occurred in the catchment between 1973 and 1997, and give an insight into the state of the catchment. Similarly, Rogan et al (2002) used a maximum likelihood classification and post classification change detection logic to analyse the changes in vegetation cover in southern California between 1990 and 1996 using Landsat imagery.

They found that this method resulted in high accuracies. Jones et al (2004) achieved similar results in the analysis of changes in the distribution of the grey mangrove between 1982 and 1999 using colour infrared aerial photography. The minimum distance and maximum likelihood classification methods were found to give the most realistic representation of mangrove distribution and post classification change detection was used to quantify the change in mangrove cover.

Early aerial photography can often have limited applications due to the absence of spectral data (Mast et al. 1997). However, woody vegetation produces shadows that visually distinguish it from non woody vegetation based on tonal variation within black and white photos (Hudak and Wessman 1998). Carmel and Kadmon (1998) utilised this and applied a maximum likelihood algorithm to classify vegetation. Post classification change detection was completed to derive vegetation change from the historical aerial photography, which classified images based on the differences in the grey levels between individual pixels. The maximum likelihood classification gave an accuracy result of 82% for the 1992 image and 54% for the 1964 image. They attributed this lower accuracy to limited separation between class signatures.

Object oriented approach

There has been an obvious shift in change detection analysis towards the application of object based classification methods rather than per-pixel applications over the last decade (Hay et al. 2005). Object based approaches refer to image-processing techniques that allow the user to divide the scene into many relatively homogenous image objects, resulting in the segmentation of an image into non-overlapping units (Jensen 2005). The spectral and spatial characteristics of these objects are then subjected to image classification.

There are several advantages of object based image analysis in comparison to other methods of classification. Segmentation creates objects representing land cover types that may be spectrally variable at the pixel level. Therefore the ‘salt and pepper’ effect commonly associated with per pixel classification is eliminated. The use of this software allows objects to be classified based on size, shape, pattern and spatial relationships (Platt and Schoennagel 2009). Thus another advantage is that objects can represent more meaningful areas at multiple scales and approximate real world features more realistically than pixels.

Per pixel analysis can present issues in classification of aerial photography, with relatively small pixel sizes combined with fewer spectral bands (Johansen 2008). Object based analysis is able to create a classification which more closely resembles that of manual interpretation and has proven useful in studies of vegetation change and mapping. A great deal of information is contained in the relationship

between adjacent pixels. Encompassing both spectral information and spatial arrangements has been found to improve the classification accuracy (Laliberte et al. 2004; Johansen 2008; Platt and Schoennagel 2009).

Landscapes consist of patches and consequently, it is more appropriate to analyse them as objects rather than pixels. The analysis of landscapes and vegetation change through object based methods produces more ecologically meaningful results (Laliberte et al. 2004; Platt and Schoennagel 2009). Several studies have demonstrated the effectiveness of object based analysis in studies of vegetation change. Platt and Schoennagel (2009) use an object oriented approach to detect the impact of fires within national parks in Colorado and the associated vegetation change. This study compared historic aerial photography from 1938 and 1940 to modern Digital Ortho-imagery Quarter Quadrangles (DOQQs) photos from 1999. They investigated the nature of change in vegetation with respect to slope, aspect, and elevation. An object based analysis was used to segment the images into homogenous objects, creating an initial classification of vegetated and non-vegetated areas within the imagery, and a further classification into visually distinct vegetation types. Based on this classification, the change in vegetation extent between the two time periods was calculated.

An object based analysis has proven to be a valuable tool in the monitoring of vegetation change from aerial imagery within riparian wetlands (Kollár et al. 2011). An object based approach was used to consider different characteristics of tone, colour, shape, size and texture within the images. This method was used in an attempt to increase the accuracy of interpretation, in comparison to spectral based approaches. Final results of the study quantified the change in each habitat class, and provided a useful result for the ongoing monitoring of the wetland area.

Laliberte et al (2004) demonstrated the usefulness of an object based approach over a pixel based classification for the extraction of shrubs from high resolution aerial photography. This study utilised an object based approach on aerial photography captured between 1937 and 1996, to monitor vegetation changes over this time period. The images were segmented based on parameters of scale, spectral information and shape, to produce highly homogenous segments. A classification was performed on these objects to measure the change in shrub cover. An object based approach proved advantageous in the study, as the tonal differences between shrubs within an image may have reduced the accuracy of a per-pixel analysis.

2.3.1.2 Image differencing

Vegetation indices, which quantify the health or greenness of vegetation, are common in studies of vegetation change (Yang 2007; Tuxen et al. 2011). The spectral response of each object on the land differs depending on the reflectance of the object. Vegetation indices can be used to differentiate between green vegetation and other classes of land cover. A wide range of ratio combinations have been used in previous studies of vegetation cover and change, each with its own strengths and weaknesses (Tucker 1979; Purevdorj et al. 1998). Healthy, green vegetation will have a strong reflectance in the near infrared band. For this reason, most vegetation indices will include a ratio between reflectance in the red and near infrared spectral bands (Makkeasorn et al. 2009).

Tucker (1979) assessed the usefulness of red and near infrared ratio combinations, and red and green ratio combinations in providing a measure of vegetation cover. However, he found that vegetation indices which included only the visible bands of the spectrum were limited in their ability to provide a measure of vegetation cover and red/near infrared combinations were found to be superior. Furthermore, Yang (2007) notes that a ratio which includes only the red and green visible bands poorly delineated between dark object such as shadows, water and vegetation.

2.3.2 Modelling relationships between erosion and vegetation

Vegetation plays an important role in controlling soil erosion and a number of studies have used a combination of remote sensing and GIS technologies to classify land cover, and assess this relationship. These studies have used traditional methods of vegetation classification, such as a supervised classification, to assess vegetation cover (Wang et al. 2002). For instance, Jürgens and Fander (1993) applied a maximum likelihood classification and field based methods to determine the relationship between vegetation cover and soil erosion.

A number of studies have aimed to assess the effect of vegetation clearing in relation to agriculture and forestry, on rates of soil erosion on the Loess Plateau of China. Zhou et al (2006) assessed changing vegetation dynamics and erosion, and found that soil erosion was negatively correlated with vegetation. In the same area, Zheng (2006) assessed the effects of vegetation removal and restoration on soil erosion. This study utilised both field based methods and interpretation of aerial photography, to assess vegetation coverage and erosion rates. Tests of variance were completed on estimates of soil erosion, to determine if there were significant differences between forested areas and locations of vegetation clearing. Other studies have used only field based methods to assess the effects of vegetation on erosion. Fattet et al (2011) investigated the relationship between vegetation and erosion

through the collection of soil samples and vegetation data. Statistical analysis was completed to find the variance of soil properties between vegetation types.

Many of these studies use field based methods to measure soil erosion, while utilising remote sensing methods to map vegetation coverage or change. A similar technique can be applied in this study, to assess the effect of vegetation on acquired erosion and deposition measurements that occurred during the flood. The remote sensing and GIS based methods discussed can have significant advantages over field based methods. This approach allows the measurement of vegetation extent over a larger spatial scale than is possible with field based methods alone. The methods of vegetation classification, change detection and sampling of geomorphic change, can be adapted to assess the role of vegetation during the January 1974 and 2011 floods.

3. Regional Setting

The Lockyer Valley catchment is one of the 14 major river catchments of the SEQ region and is a major tributary of the Brisbane River catchment. It has a catchment area of nearly 3000km^2, with the headwaters rising to 888m above sea level, draining to the wide alluvial plains in the lowlands. The Lockyer forms a bowl shape catchment, shown in Figure 4.

This study will examine reaches of confined and unconfined valley settings in the upper and lower catchment.

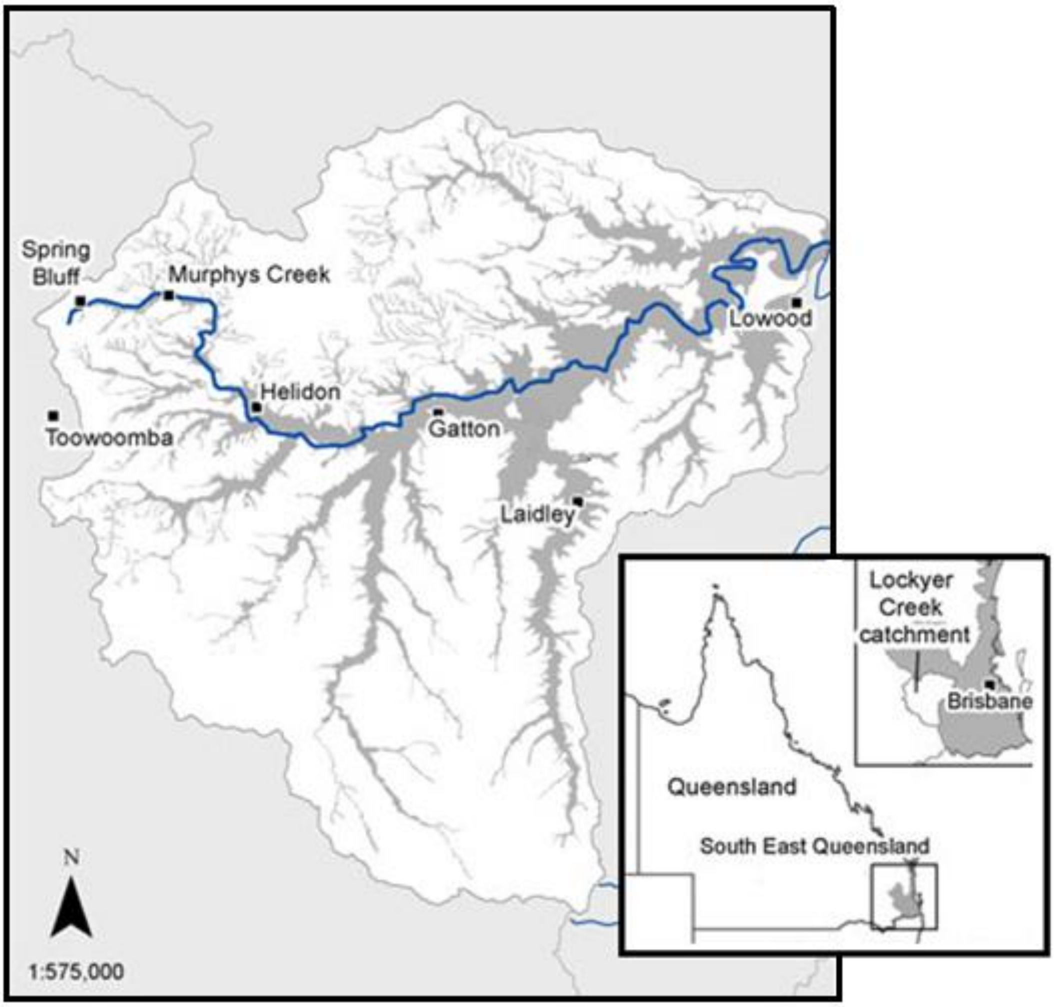

Figure 4 Lockyer Valley Catchment and inset showing location in Queensland, Australia.

3.1 Geological Setting

The Lockyer Valley lies within SEQ, inland from Brisbane and extends to the Great Dividing Range. The steep slopes and valleys of the upper Lockyer form the headwaters of the Lockyer Creek catchment, the largest tributary network of the Brisbane Basin. The upper catchment is steep, well vegetated and the lithology consists of sedimentary rocks of Jurassic and Jurassic-Triassic origin. The region is comprised of rock derived from the Woogaroo Subgroup, comprised of Triassic sedimentary quartzose sandstone with interbedded siltstone, shale conglomerate and coal measures. The Marburg Subgroup is also widespread, comprised of the resistant Gatton Sandstone, a thin- to thick-bedded, coarse- to medium-grained, feldspathic to lithic feldspathic sandstone (Geological Survey of Queensland 2011; Geoscience Australia 2012).

More continuous floodplain development occurs in the lower gradient reaches downstream, shown in Figure 5, and floodplain pockets are confined by Gatton sandstone. Floodplains throughout the catchment are infilled to varying amounts and are formed of alternating, horizontally bedded layers of Quaternary alluvium, comprising fine grained silts, clays and coarser sand units (Geological Survey of Queensland 2011; Grove et al. 2013). Figure 5 shows the geology of the Lockyer Valley catchment, with selected study reaches highlighted.

Figure 5 Geology of the Lockyer Valley Catchment (Geological Survey of Queensland 2011). Red boxes outline selected study reaches: Reach 1, Reach 2 and Reach 3.

3.1.1 Study Reaches

This study will assess the role of riparian vegetation in altering patterns of erosion in three selected study reaches, as shown in Figure 5. Table 1 illustrates characteristics of each study reach.

Table 1 Characteristics of selected study reaches.

Reach	Length	Valley Settings	Average Channel Bed Gradient
Reach 1	3 km	Confined	0.007 m m^{-1}
Reach 2	4.8 km	Unconfined	0.003m m^{-1}
Reach 3	8.5 km	Partly confined	0.0008 m m^{-1}

The headwaters of the Lockyer Creek flow east over the Jurassic Gatton Sandstone formation (Geological Survey of Queensland 2011). The first study reach is 3km, located south of Murphy's Creek (Figure 5). This reach represents a confined valley setting where the channel flows south around the edge of the resistant sandstone unit, with an average stream gradient of 0.007 m m^{-1} (Table 1). The study reach is defined by the joining of two main tributaries, Fifteen Mile Creek and Alice Creek. The upper catchment has remained largely forested and the study reach has intact riparian vegetation.

Study reach 2 is 4.8km in length, encompasses a large meander loop and is positioned immediately downstream of the confined reach (Figure 5). This lower gradient reach (0.003 m m^{-1}) has more continuous floodplain development, which has been largely cleared for agriculture.

Study Reach 3 is 8.5km in length located in the lower catchment next to the town of Gatton and again contains a large meander loop (Figure 5). In the lower reaches of the catchment, bank height and channel size increase and the valley floor is extensive, ranging from 2-13 km (Grove et al. 2013). Average channel bed gradient has again reduced to 0.0008 m m^{-1}. The channel is in a partly confined setting, constrained by resistant sandstone to the north, and alluvial floodplains to the south. These floodplains have been extensively cleared of riparian and native vegetation, for agriculture and urbanisation.

3.2 Climate and Hydrology

3.2.1 Long Term Climatic Conditions

This section will provide a brief summary of the relevant climatic and hydrologic trends likely to impact the role of vegetation, during the 1974 and 2011 catastrophic floods. Climate and rainfall was assessed using three stations in the upper, mid and lower catchment represented by Helidon, Gatton and Lowood.

Rainfall throughout the Lockyer Valley Catchment is characterised by significant inter-annual variability and Table 2 summarizes the monthly average rainfall for the catchment. The Lockyer region has a seasonal climate. The October to March period is the wettest on average and 65 – 70% of the total rainfall occurs in this time while the June to September period is the driest. The El Nino Southern Oscillation Index (ENSO) exerts a significant influence over long term patterns of both rainfall and stream flow in eastern Australia and the SEQ region experiences significant variation in stream flow between ENSO phases (Rustomji et al. 2009). La Nina and El Niño phases, which typically range between 3 and 7 years, generate periods of above average and below average precipitation (Bureau of Meteorology 2008)

Table 2 Rainfall Station statistics for the Lockyer Valley, Queensland.

Station No.	40096	40082	40120
Station Name	Helidon Post Office	University of Queensland Gatton	Lowood Don St
Elevation (MASL)	155	89	51
Period of Record	1870 - Present	1897 - Present	1887-Present
	Average Rainfall		
January	118.6	112.2	116.9
February	109.2	101	103.5
March	83.3	78.4	90.5
April	51.1	49.6	55.9
May	47.4	45.7	49.2
June	46.9	42.5	49.4
July	37.7	37.5	39.1
August	30.3	26.9	29.5
September	36.2	35.3	39.7
October	61.9	65	65.9
November	80.5	79.5	77.3
December	104.6	100.1	101.2
Annual	803.3	773.3	821.7

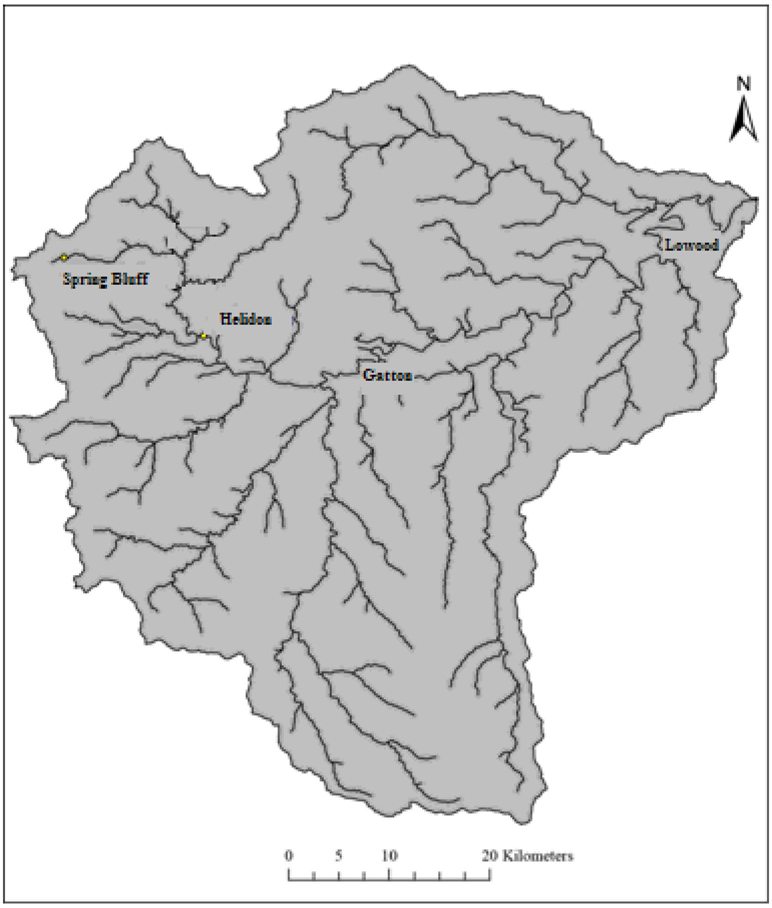

Figure 6 Location of stream and rain gauges used to assess the climate and hydrology of the Lockyer catchment.

The Inter-Decadal Pacific Oscillation (IPO) is the pattern of sea surface temperature variability of the Pacific Ocean, occurring on inter-decadal time scales, and is another source of rainfall, stream flow and flood variability (Micevski et al. 2006; Rustomji et al. 2009). The IPO has been shown to influence the strength of ENSO cycles, with the negative phase of IPO resulting in stronger El Nino and La Nina events. La Nina events are the primary drivers of flood risk, further enhanced under negative IPO phases (Kiem et al. 2003). Past analysis of flood frequency has illustrated that the IPO modifies the flood risk in southern Queensland, with flood quantiles increasing by a factor of 1.7 during IPO negative periods (Micevski et al. 2006).

Rainfall data in the SEQ region has been collected since the 1870s and shows clear trends of periods of below and above average rainfall, consistent with ENSO cycles (Figure 7). Above average rainfall occurred in the period between the 1890s and 1900s. Lower than average rainfall occurred in the period between 1920 and 1950. This was followed by a high rainfall period lasting until the 1990s and the region experienced significant flooding in January 1974. The region has experienced a wetter climatic period since 2008 and significant flooding occurred in 2011 and 2013.

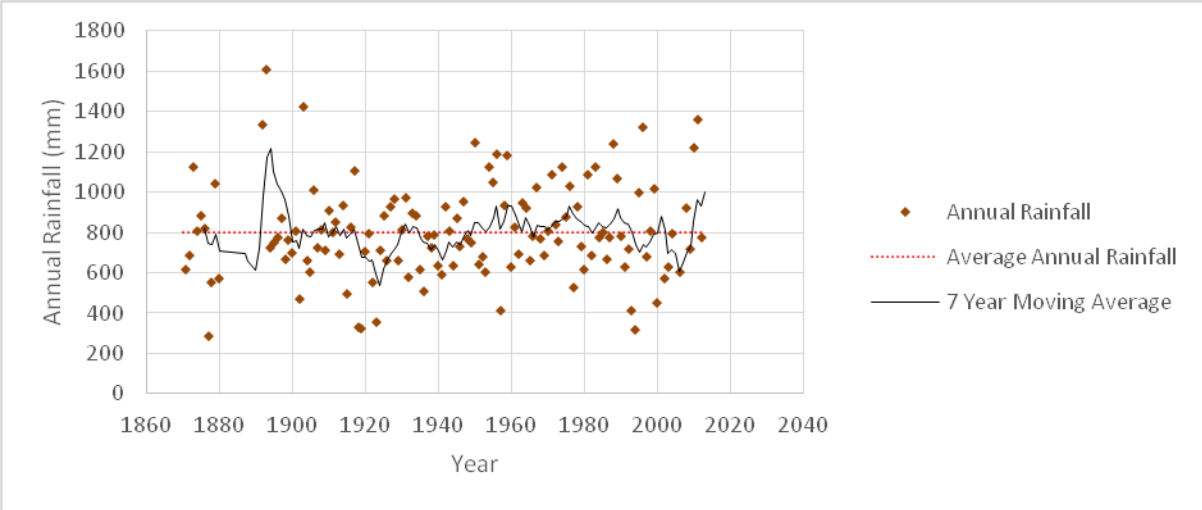

Figure 7 Total Annual Rainfall at Helidon with a 7 year moving average (black line), a typical ENSO cycle. Dashed line shows the long term average annual rainfall for Helidon.

3.2.2 Flood History of the Lockyer Valley

The annual maximum flood series has been used frequently to analyse stream flow data (Rustomji et al. 2009). Flood frequency analyses were completed using FLIKE 4.50 for probability modelling of the annual-maximum flood series. Traditionally, the log Pearson III distribution has been used in flood frequency modelling. However, Rustomji et al (2009) suggests that the Generalised Pareto distribution provides the most suitable estimate of flood modelling in eastern Australia. Discharge was assessed at three stream gauges in the upper, mid and lower catchment: Murphy's Creek at Spring Bluff, Lockyer Creek at Helidon and Lockyer Creek at O'Reilly's Weir, geographically close to Lowood (see Figure 6). Table 3 shows comparative flood frequency results using annual maximum flow for both log-Pearson III and Generalised Pareto distributions.

Table 3 Estimate of peak flood discharge using Generalised Pareto and log-Pearson III flood frequency analysis.

Murphy's Creek at Spring Bluff			Lockyer Creek at Helidon		Lockyer Creek at O'Reilly's Weir	
ARI	LogP3	GenP	LogP3	GenP	LogP3	GenP
1.001	0.027	0.007	0.001	0.043	0	0
1.01	0.098	0.074	0.025	0.436	0	0
1.1	0.541	0.738	1.016	4.569	0	0
1.25	1.284	1.841	5.095	12.312	4.72	11.9
1.5	2.66	3.667	17.534	27.614	31.29	40.75
1.75	4.165	5.482	35.59	45.951	71.9	71.99
2	5.757	7.286	57.928	67.363	120.96	106.47
5	26.672	28.459	450.101	574.061	812.28	741.37
10	60.239	62.712	1139.5	2500.488	1717.88	2476.98
20	118.865	129.424	2287.689	10665.549	2887.35	7767.33
50	257.36	323.272	4661.556	72081.906	4714.74	33854.21
100	432.639	636.89	7191.563	305582.666	6220.89	101819.73
200	698.129	1247.692	10403.034	1295263.14	7768.04	304797.06

Stream gauge data has been collected since 1987 at Helidon and 1979 at Spring Bluff. The mean daily discharge is 0.812m^3/s at Helidon and 0.053 m^3/s at Spring Bluff. The mean annual discharge for both Helidon and Spring Bluff is ~277 m^3/s and ~18 m^3/s respectively. O'Reilly's Weir contains a longer record and stream gauge data has been collected since 1948. The mean daily discharge over the period of record is ~7 m^3/s and a mean annual discharge of ~2245 m^3/s. However, the record contains large periods of no data, with no estimates taken in 1951, 2003, 2004, 2005, 2006 and 2007.

The largest recorded flood in the upper and mid catchment occurred on the 11/01/2011, having a discharge of ~3643 m^3/s at Helidon and ~362 m^3/s at Spring Bluff. The largest recorded flood at O'Reilly's Weir in the lower catchment occurred on the 27/01/1974, having a discharge of ~7360 m^3/s. However, no data was recorded for the January 2011 flood at O'Reilly's Weir, likely due to stream gauge failure. Figure 8 shows the maximum flood for each recorded year at Spring Bluff, Helidon and O'Reilly's Weir with annual recurrence intervals.

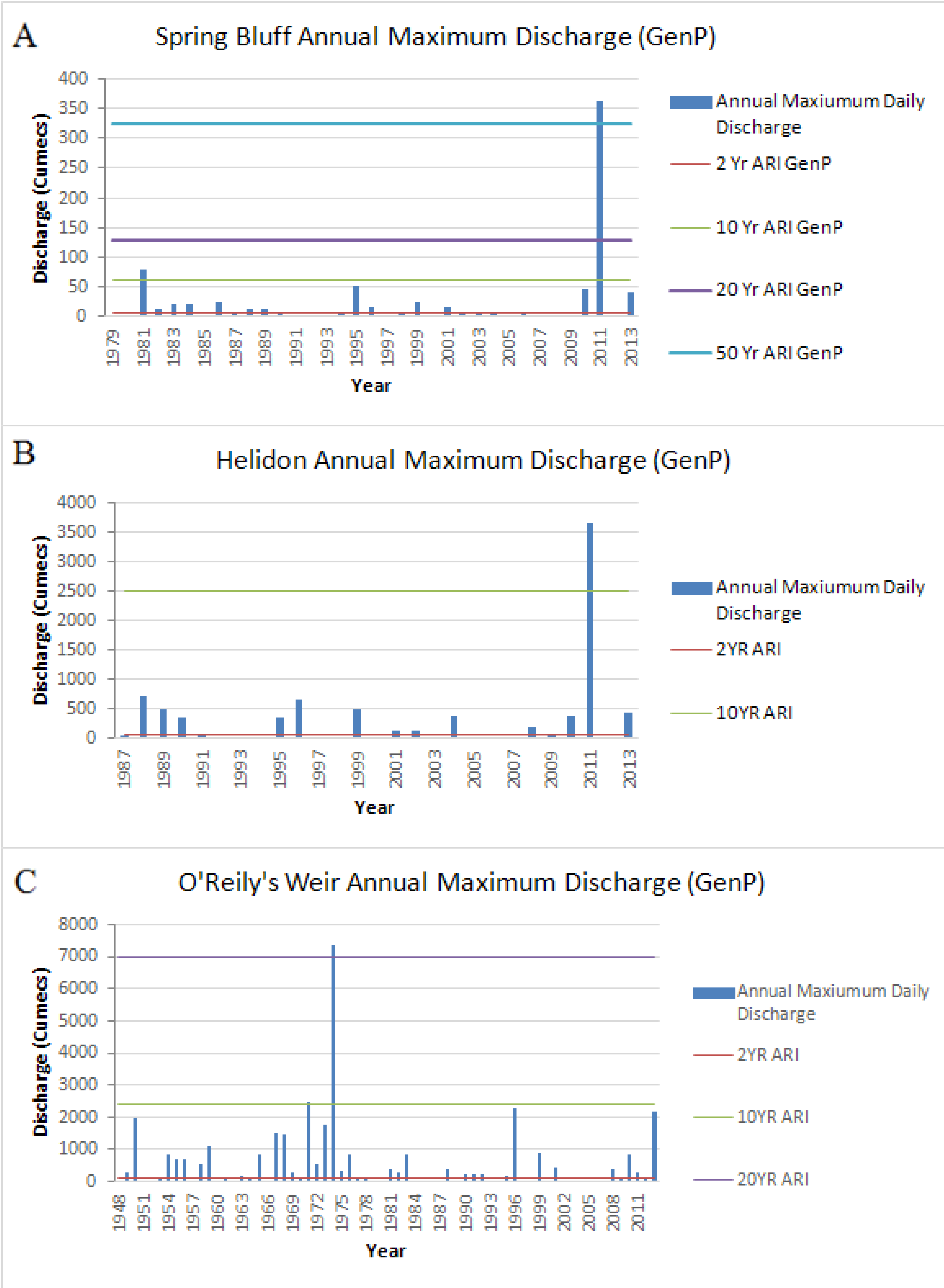

Figure 8 Flood history analyses for the Lockyer Catchment at Spring Bluff (A), Helidon (B) and O'Reilly's Weir (C) displaying maximum daily discharge. Annual recurrence intervals are based on the Generalised Pareto distribution flood frequency analysis (see appendix for log-Pearson III analysis).

A relatively short record of stream gauge data prevents an analysis of the long term flood history of the catchment. However, height data of the Brisbane River has been collected continuously since 1841 and can provide a more long term representation of the Lockyer Catchment.

Table 4 Flood history of the Brisbane River at the Brisbane City Gauge (Babister and Retallick 2011).

Event	Recorded flood level (mAHD)
1841	8.43
1844	7.02
1890	5.33
1893 (5th February, a)	8.35
1893 (19th February, b)	8.09
1898	5.02
1974	5.45
2011	4.27

Significant flooding of the Brisbane catchment was relatively infrequent in the period prior to the 1974 flood. However, extensive floods occurred in 1841, 1844 and on two occasions in 1983, which reached levels in excess of the January 1974 event. Table 4 gives a brief summary of the largest flood events affecting the Brisbane catchment.

Table 5 Return periods for floods on the Brisbane River (Snowy Mountains Engineering Corporation 1975).

Brisbane City Gauge Height (mAHD)	LogP3 ARI
2	11
3	18
4	28
5	40
5.5	50
6	60
6.5	70
7	80
7.5	90
8	110
8.5	130

The January 1974 flood event

Widespread flooding occurred on the Australia day weekend along the Brisbane River in January 1974, resulting from tropical cyclone Wanda. The event caused devastating damage in the cities of Brisbane and Ipswich and the loss of 14 lives (Bureau of Meteorology 2013). Damage resulting from the 1974 event was likely greater than previous events due to the increased development of the floodplain. The flood peak reached 5.45m (Australian Height Datum), according to the Brisbane City gauge height (Table 5). The average return interval (ARI) of the January 1974 event, based on the log-Pearson III analysis of the annual flood series is estimated to be around 50 years for the Brisbane River (Figure 8) and this was the highest flood recorded of the twentieth century (Snowy Mountains Engineering Corporation 1975). The January 1974 flood also had a higher peak in Brisbane than the 2011 flood (Bureau of Meteorology 2013). While a large discharge was recorded for the 1974 flood in the downstream reaches of the Lockyer Valley, the O'Reilly's Weir stream gauge failed to record a discharge for the January 2011 flood. It is also difficult to determine the impact of the 1974 flood event on the upper Lockyer Valley, as stream gauge data does not exist prior to 1979. However, as rainfall was centred nearer to the Brisbane metropolitan area (Snowy Mountains Engineering Corporation 1975), it is likely that the upper Lockyer was more severely impacted by the 2011 event.

The January 2011 flood event

A wet summer resulting from a strong La Niña event preceded the January 2011 flood event. Long term and consistent rainfall occurred over the summer, saturating or almost saturating the soil column. Intense thunderstorm activity occurred across the region on the 9th January and further soaked the catchment, prior to the catastrophic flooding which occurred on the 10th and 11th January 2011 (Jordan 2011b). This saturation prevented the absorption of precipitation, transmitting run off directly to streams.

Gauging stations across the catchment captured the approximate magnitude of the January 2011 event. However, exact flood peak is unknown due to the widespread failure of stream gauges during the flood event, such as that of O'Reilly's Weir. The average return interval (ARI) of the January 2011 flood, based on the Generalised Pareto analysis of the annual flood series is estimated to be around 59 years at Spring Bluff and around 45 years at Helidon (~ 36 km downstream). However, no discharge data was recorded for the 10th or 11th of January 2011 at the O'Reilly's Weir stream gauge, a further 58km downstream, likely due to the failure of the stream gauge.

3.3 A History of Land Use

SEQ is the fastest growing metropolitan in Australia and the most densely populated area of Queensland, with a population of approximately 3.05 million people (Australian Bureau of Statistics 2012; Field et al. 2012). The Lockyer Valley includes the small town centres of Laidley, Mulgowie, Gatton, Helidon, Thornton, Grantham, Withcott, Forest Hill and Plainland and has a population of approximately 35 000 people (Australian Bureau of Statistics 2012).

Settlement of the SEQ region began in the 1840s, with the most productive floodplains of the catchment cleared for agricultural purposes before 1940 (Galbraith 2009). Since that time, approximately two thirds of native vegetation has been cleared. The condition and density of riparian vegetation is variable throughout the catchment with the upper reaches remaining largely forested while the majority of banks in the mid and lower catchment have been cleared of woody vegetation (Grove et al. 2013).

The Lockyer Valley is one of the most fertile and important areas for agricultural production in Australia and the region is often referred to as the “South East Queensland’s salad bowl” due to the dark alluvial soils and good quality water (Galbraith 2009). The region has been used for intensive horticulture, cropping, grazing and development of residential areas (Department of Environment and Resource Management 2010b). The Lockyer Valley region supported dairy farming in the late 1800s, and much of the lower catchment was cleared for cattle grazing (Galbraith 2009). At this time, the extraction of groundwater for irrigation was minimal or non-existent. Clearing of native eucalypt forests exposed the agricultural potential of soils and cultivation of crops began in the 1930s, as did the extraction of groundwater for irrigation (Galbraith 2009; Department of Environment and Resource Management 2010b). The extraction and use of groundwater for irrigation has continued to increase since this time, leading to water shortages during periods of drought. Water is drawn primarily from the alluvium deposits throughout the valley.

Agricultural production has become steadily more intensive and is now heavily reliant on irrigation. The majority of crops are grown on the rich, fertile soils of the alluvial lowlands. Major crops of the region include grains, vegetable and lucerne (Galbraith 2009). Bedrock slopes are commonly used for the stock grazing, which remains an important industry in the region.

Prior to the 1990s, few controls were imposed on Queenslanders in relation to the clearing of vegetation. In the 1970s, the clearing of riparian and within channel vegetation on farmland became mandatory with fines imposed by the Queensland state government for those who refused to comply

(Hubble et al. 2010). This was apparently achieved by dragging bull dozers across the bank face and occurred across river channels in Queensland. Since the introduction of the *Vegetation Management Act (VMA) 1999*, rates of woody vegetation clearing have decreased as the new legislation phased out the "broad scale clearing" of vegetation (Department of Environment and Resource Management 2010b;2010a; Field et al. 2012). Prior to the introduction of this legislation, the large majority of land clearing was completed to create pastures for agriculture, a common activity in the catchment.

There was however, a 25 per cent increase in the rate of woody vegetation clearing from 100 km^2/year in the 2008 – 2009 period to 120 km^2 /year in the 2009 – 2010 period in the southeast Queensland region (Queensland Department of Science Information Technology Innovation and the Arts 2012). This increase was attributed to an increase in forestry clearing. Table 6 displays the rates of woody vegetation clearing in the Lockyer Valley catchment in the 2009 -2010 period. Woody vegetation was predominantly cleared for agricultural purpose in this period.

Table 6 Rate of woody vegetation clearing (km2/yr) for other land uses in the Lockyer Valley catchment (2009 – 2010) (adapted from Queensland Department of Science Information Technology Innovation and the Arts 2012).

Land Use Type	**Rate of woody vegetation clearing (km^2/yr)**
Pasture	3.56
Crops	0
Forest	0
Mining	0.1
Infrastructure	0.1
Settlement	0.1
Total	3.92
Per cent wooded vegetation cover 2009	64.18

Major vegetation types in the SEQ region include eucalypt woodlands, open forests and semi evergreen vine thicket (Sattler and Williams 1999). Extensive areas of eucalypt woodlands and open forest remain on the steep hilly terrain of the upper catchment, with some small areas of semi-evergreen vine thickets occurring in the escarpment areas of the Lockyer Valley. Grassy woodlands typically occur on alluvial plains and largely consist of the Queensland Blue Gum (*Eucalyptus tereticornis*) and Moreton Bay Ash (*Corymbia tessellaris*), with grassy ground cover often dominated by Queensland Bluegrass (*Dichanthium sericeum*) or Kangaroo Grass (*Themeda triandra*) (Galbraith 2009). Although some small patches remain, *Acacia harpophylla,* commonly known as Brigalow, has been extensively cleared through the catchment for agricultural purposes, due to their high fertility soils.

4. Methods

The purpose of this study was to investigate the role of woody vegetation, in enhancing or inhibiting erosion and deposition during large magnitude floods. The following section will explain the methods used to classify woody vegetation, quantify vegetation change between two time periods and determine the effect of woody vegetation on geomorphic change during large floods. While there are many definitions of what constitutes a forest of woody vegetation, for the purpose of this thesis, woody vegetation is defined as stands of native vegetation and regrowth or disturbed areas of native vegetation (Department of Environment and Resource Management 2010b).

4.1 Data Sets

Table 7 Summary of orthophotos used in the study.

Year	Type	Cell Size	Co-ordinate system
1971	Black and White	2m	GDA 1994 MGA Zone 56
1974	Black and White	2m	GDA 1994 MGA Zone 56
2009	RGB Colour	0.5m	GDA 1994 MGA Zone 56
2011	RGB Colour	0.15m	GDA 1994 MGA Zone 56

All post processed imagery was sourced from the Department of Science, Information Technology, Innovation and the Arts (DSITIA). The final post-processed images were ortho-rectified and georeferenced. Image histogram equalising was completed by DSITIA and used to correct any issues caused by differences in the date of photography capture or sun angles along the flight lines. Table 7 outlines the specifications of provided imagery.

Table 8 Summary of other data used in the study

File	Data Type	Resolution	Source
2011 DEM	Raster	4m	Croke et al (2013b)
DEM of Difference	Raster	1m	Croke et al (2013b)
Mapped mass failures	Shape file	Not applicable	Grove et al (2013)
Geomorphic units	Shape file	Not applicable	Croke et al (2013b)

Table 8 outlines all other data used in this study. The DEM of Difference (DoD) was provided from the Croke et al (2013b) study. The DoD was produced by differencing the pre- and post-flood DEMs to calculate the change in elevation and was used to derive estimates of basin scale erosion and deposition. Water bodies and changes in vegetation cover can give false estimates of elevation change. To account for this error, values of erosion and deposition of less than 0.2m were excluded from further analysis and the water covered bed was removed. Mass failures were identified and mapped by

Grove et al (2013) and were removed from erosional data values. Five main geomorphic features were classified in Thompson and Croke (2013), and these were used to assess the relationship between vegetation and geomorphic change.

4.2 Pre-processing

4.2.1 1971 and 1974 orthophotos

In studies of change detection, two images must be registered together to avoid inconsistencies between images, which can result in the invalid detection of changes. Image to image registration was completed on the 1971 and 1974 orthophotos to remove geometric distortion and ensure they were geometrically aligned. Forty ground control points (GCPs) were selected across both images from distinct features, such as houses and roads. The accuracy of image registration is generally mentioned in terms of the root mean square error (RMSE) (Townshend et al. 1992). RMSE values of 0.5 to 1.0 pixels are normally regarded as adequate and results appear acceptable. The GCPs had a root mean square error of 0.5 pixels, corresponding to less than 1m relative to the orthophotos. There were some tonal and brightness differences between the photos taken at different times. These differences were partly reduced through colour balancing when images were mosaicked together. However, some differences still exist in the mosaics.

4.2.2 2009 and 2011 orthophotos

As the 2011 aerial image was received as individual tiles, the required sections for the selected study reaches were mosaicked together to obtain complete coverage for further analysis. The 2009 image was clipped to the same extent as the 2011 sections, for classification and change detection.

When comparing a pair of thematic maps, they must have the same cell size to avoid detecting false changes (Serra et al. 2003). Resampling of orthophotos to a coarser resolution is generally more suitable, as resampling to a finer resolution can detect uncertain changes. To reconcile the differences in spatial resolution between the 2009 and 2011 orthophotos, the 2011 orthophoto was resampled to a common resolution of 0.5m, using the nearest neighbour method. The nearest neighbour method was used as it does not alter the original pixel values (Lillesand et al. 2004), an important aspect when image analysis involves classification.

An image –to-image registration was used to ensure that the 2009 and 2011 images matched each other spatially and remove geometric distortion. The 2011 orthophotos from both the upstream and downstream reaches were used as a base image for registration. Similar to the 1971 and 1974 process,

forty GCPs were selected from features around the orthophotos such as houses. The GCPs had a RMSE of 0.5 pixels, corresponding to less than 0.25m, relative to the orthophoto.

4.3 Image Analysis

4.3.1 Vegetation classification

Section 2.3.2 discusses the methods available for vegetation classification and change detection. Both per pixel and object-oriented methods have been used frequently in previous research to classify vegetation from high resolution aerial photography. Although both methods have achieved high classification accuracies, some studies have indicated that an object-oriented approach is favourable. An object oriented approach involves a multi-segmentation process (Rittl et al. 2013). The image is segmented based on parameters such as scale, shape and colour, which are defined by the user. While this method was trialled, the complex and time consuming nature of this meant that it was out of scope for this project. Nevertheless, a number of studies have demonstrated the usefulness of the traditional per-pixel approach for this category of vegetation classification. Due to the absence of the near infrared band in the aerial photography, the use of a vegetation index was not an available method to pursue.

Four supervised classification methods were tested: minimum distance to means, mahalanobis distance, spectral angle mapper and the maximum likelihood supervised classification methods. These initial results were visually assessed to determine how they represented the orthophotos. The maximum likelihood classification achieved the most visually accurate result and appeared to depict the coverage of land cover classes most realistically. The maximum likelihood classifier is commonly used in studies of vegetation change and several of these reviewed in section 2.3.2 have recognised the advantages of the maximum likelihood classifier over other algorithms for supervised classification.

Image classification: 1971 - 1974

A supervised classification involves collecting training data and evaluating the complete image based on the spectral signature of the training sets for each land cover class. Studies have suggested that woody vegetation produces shadows that are visually distinct from non woody vegetation and other land cover classes, based on tonal variation within black and white photos (Hudak and Wessman 1998). Visual inspection of the orthophotos showed that woody vegetation was much darker than areas of paddock, grass or bare surfaces. Training samples were repeatedly collected until the classification result was visually acceptable for the two classes. ArcGIS 10 was used to complete the

maximum likelihood classification and classify the 1971 and 1974 orthophotos into two classes: vegetated and non-vegetated.

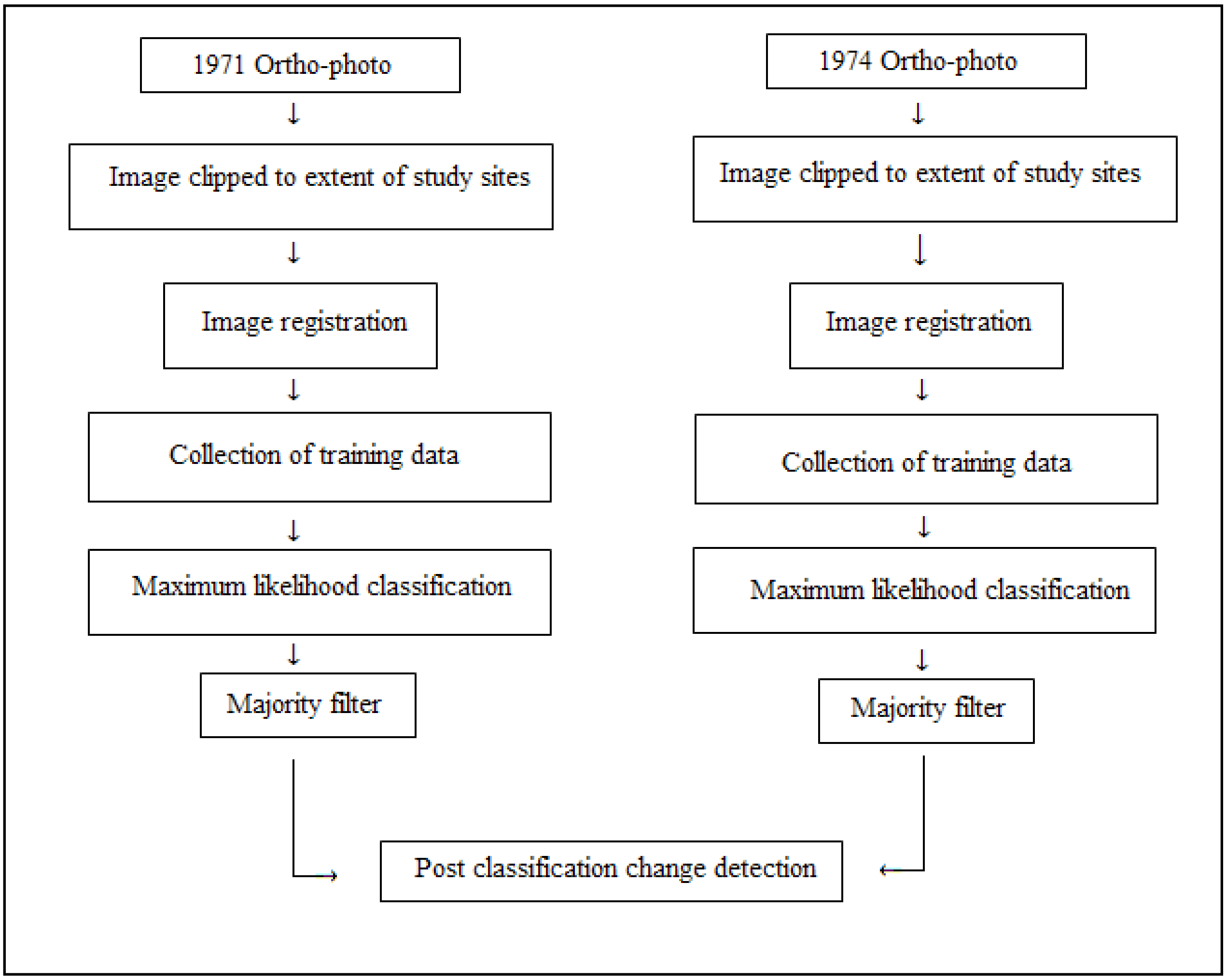

Figure 9 Flowchart of methods undertaken for the analysis of 1971 and 1974 orthophotos.

Classification of high spatial resolution orthophotos can often show a 'salt and pepper' appearance due to the high variability present (Lillesand et al. 2004). When classification is performed on a per-pixel basis, smoothing can decrease the effects of unwanted variation (Fierens and Rosin 1994). A majority filter has been frequently used by previous studies and relies on the spatial neighbourhood of the classified pixels (Martínez et al. 2010; Paneque-Gálvez et al. 2013). Smoothing also increases spatial coherence and may have the effect of improving the accuracy of the classification (Fierens and Rosin 1994). A 3x3 pixel majority filter was applied to the classification results. This size was chosen considering the scale of vegetation. Figure 9 summarises the steps taken to classify the 1971 and 1974 orthophotos.

Image classification: 2009 - 2011

Visual inspection of the 2009 and 2011 orthophotos revealed four classes of land cover. ENVI 4.8 was used to complete the maximum likelihood classification on the 2009 and 2011 orthophotos and classify four land cover classes: bare surfaces (including buildings, road and bare soil), woody vegetation, grass (or pasture) and water. In a supervised classification, the aim of training data is to derive a representative sample of each land cover class (Chen and Stow 2002). To ensure the optimal accuracy of the classification result, the suggested amount of training data consists of between 100 and 1000 times the number of bands in the image (Jensen 2005). Collection of too few training samples may produce statistics unrepresentative of the land cover class. Ideally, training data should be based on in-situ data collection (Chen and Stow 2002). However, it is also common to derive training data directly from the image. Training samples were collected in polygons of relatively homogenous pixels, directly from the orthophotos and were distributed evenly to ensure they were representative of the entire image. As the available imagery had three bands, between 3000-5000 pixels were collected for each land cover class.

The success of a supervised classification depends on the extent of separation between the spectral signatures of each land cover class (Jones et al. 2004). The separation of the classes was assessed using the n-d visualiser tool and the calculation of the Jeffries–Matusita transformed divergence index (Richards 1999). This index calculates a measurement between 0 and 2 as a measurement of the discrimination between classes. A measurement of 2 would imply 100% accuracy, whilst a value of less than 1 generally indicates poor separation between classes.

The application of a 3x3 pixel majority filter was repeated on the 2009 and 2011 classifications to reduce variation and improve accuracy. Quantifying the change of woody vegetation was considered the most important outcome of this study. The three classes of grassland and pasture, bare surfaces and water were reclassified into one class, as the change in other land cover classes was not relevant for this study. This resulted in just two classes within each classified image, representing areas of woody vegetation and non woody vegetation. Figure 10 illustrates the complete workflow used to classify the 2009 and 2011 orthophotos.

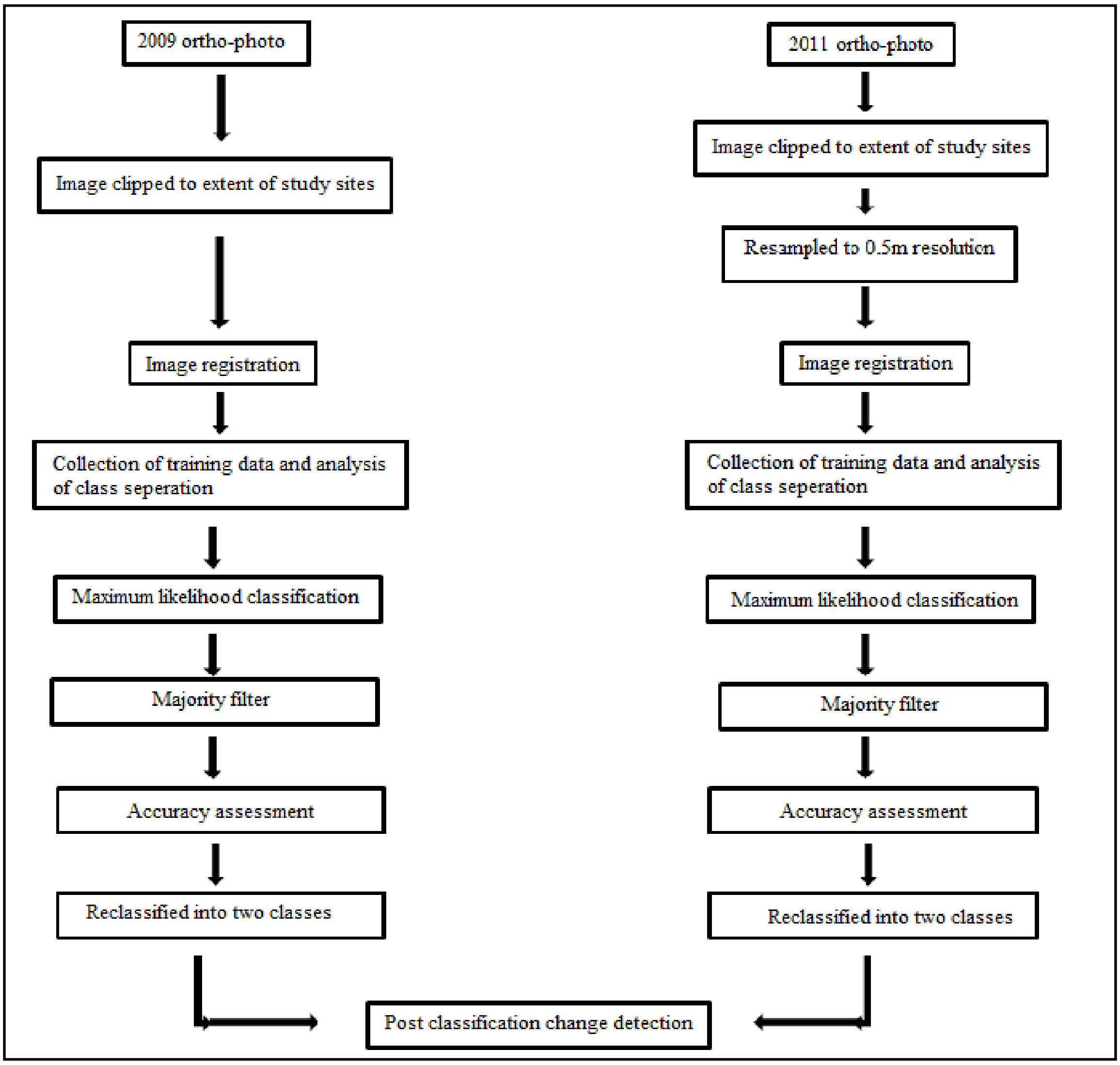

Figure 10 Flowchart of methods undertaken for the analysis of 2009 and 2011 orthophotos.

4.3.2 Accuracy assessment

A random sample of 200 points was generated using ArcGIS 10 for each reach. These points were based on the proportional area of each class, with a constraint that no point could be within five metres of another point. Each point was manually compared to the orthophotos, to determine how the classification reflected the field.

The results from this comparison were calculated in an error matrix, showing overall accuracy as well as producer's and user's accuracy for each classified image. User's accuracy indicates the probability that a pixel classified into a given category, actually represents the category on the ground whilst producer's accuracy indicates how well pixels of a given cover type are classified (Lillesand et al. 2004).

4.3.3 Change detection

The objective of change detection is to compare the spatial representation at a particular point across time, to measure differences in the variable of interest (Lu et al. 2004). A post classification change detection technique was used to quantify the changes in vegetation. This involved the individual classification of orthophotos, followed by the pixel-by-pixel comparison of the classification to assess the change that has occurred. A post classification change detection method can provide a matrix of change directions (Lu et al. 2004).

Post classification change detection was completed for both the 1971 and 1974 and the 2009 and 2011 time periods. Four classes of vegetation were produced in the change detection analysis for each year group:

(1) decrease in vegetation,

(2) no change in non-vegetated areas,

(3) no change in vegetated areas and

(4) vegetation increase through natural growth

These results were then used to assess the relationship between vegetation and geomorphic change during the catastrophic flood events of 1974 and 2011.

4.4 Interaction of vegetation in big flood events

4.4.1 Assessment of erosion and deposition during floods

A variety of sampling strategies that have been previously applied to studies of soil sampling or sampling of vegetation cover, can be applied in this study (Webster 1977; Webster and Oliver 1990). Sampling involves the selection of a subgroup from the total population, used to estimate properties of that population. Systematic sampling methods are popular in earth and environmental studies due to the efficiency in which they gather information, and geostatistical analysis frequently uses a grid sampling design (Pennock et al. 2007). Systematic sampling strategies have also proven to be more precise than random sampling designs (Webster 1977; Webster and Oliver 1990). When using a systematic sampling strategy, the distance between sampling points should be much smaller than the

distance required to represent the variability of the data, and grid designs with a small space between points can provide highly detailed information. Furthermore, the sample spacing should be based on knowledge of the study area.

This study used a systematic sampling strategy to assess the association between vegetation classes and erosion. This method was adapted from Xu et al (2008) who assessed the relationship between vegetation and erosion using a 5m x 5m grid, to capture the variation in erosion across their study site. A 5m x 5m grid was created and both the value of elevation change and vegetation class was assessed for each point in the centre of the grid.

The role of vegetation in geomorphic change during the January 1974 catastrophic flood

To assess the effect of vegetation on geomorphic change during the January 1974 flood event, areas of visible change throughout reach 1, 2 and 3 were identified and mapped. As discussed above, a 5m x 5m grid was created in ArcGIS 10 to the extent of the selected study reaches. All points which fell within the specified areas of change were extracted for analysis. Within each mapped polygon, the most extensive vegetation class was recorded and graphed, to determine if there was a difference in the extent of change occurring between vegetated and non-vegetated areas.

The control of vegetation on fluvial entrainment and deposition during the 2011 flood

Statistical analysis was completed to determine the effect of vegetation on erosion and deposition, during the catastrophic flooding of January 2011. Values of fluvial entrainment and deposition were tested for variance between vegetation classes. Sample points for both fluvial entrainment and deposition were collected separately according to the sampling design described above.

To check that the collected data represented a normal distribution, a Shapiro-Wilk Test for Normality was completed and outliers in the data were detected. This test confirmed that outliers were present in the data, and that the collected values were not normally distributed. Therefore, the data did not meet the requirements for the use of parametric statistical tests. The Kruskal-Wallis test is the non-parametric alternative to the one-way ANOVA test, used to determine variance (Sheskin 2000). For this reason, the Kruskal-Wallis test was used to assess whether there were statistically significant differences in the distributions of fluvial entrainment or deposition, between vegetation classes. When

a significant result was detected, pair wise comparisons, using a Bonferroni correction, were completed to determine where differences between groups lied.

The control of vegetation on the occurrence of mass failure

To assess the relationship or lack thereof, between the occurrence of mass failure and vegetation cover, the most extensive vegetation class within and adjacent to each mass failure was assessed. Buffer widths of 10m, 20m and 40m were applied to determine how vegetation cover varied along the banks, nearby each mass failure. Again, this was completed using a 5m x 5m grid. As no mass failures occurred in the steep upper catchment, reach 1 was excluded from this analysis.

5. Results

In order to ascertain the response of the Lockyer Creek to large magnitude floods, two time intervals were chosen to assess the role of vegetation in stabilising river banks and inducing deposition; 1971-1974 and 2009 – 2011. The results in this chapter are presented based on a fixed buffer width (either side of the river) for each reach as well as percentage change within the macro-channel, shown in Figure 11. For all following results sub-sections ‘unvegetated’ refers to areas of non-woody vegetation.

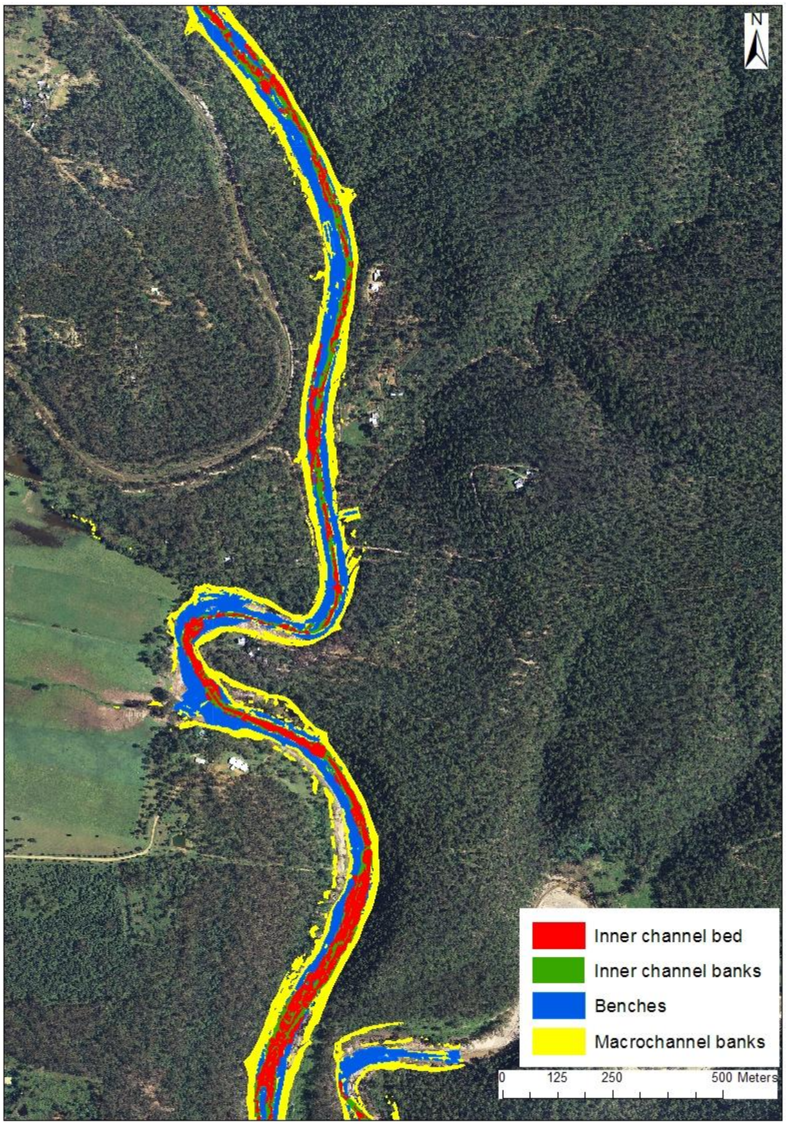

Figure 11 Reach 1 showing the areas defined by the macro-channel, comprised of the inner channel bed and bars, the inner channel banks, benches and macro-channel banks, classified by Thompson and Croke (2013).

5.1 Image analysis: 1971 – 1974

5.1.1 Vegetation classification

A maximum likelihood classification was completed on the 1971 and 1974 black and white orthophotos for all three reaches (refer to Appendix 2). Woody vegetation produces shadows that distinguish it from other land cover classes such as pasture or bare surfaces. Therefore, these classifications focused on the tonal differences between vegetation and other land cover classes.

The maximum likelihood classification discriminated well between areas of vegetation, developed areas and pasture. Accuracy assessment should be completed wherever possible in vegetation classifications. Due to the quality of the 1971 and 1974 orthophotos and the limited spatial and spectral resolution, accuracy assessment of these classifications was impractical. However, visual inspection of the classification presents some uncertainty. Woody vegetation and water had a similar tone in both the 1971 and 1974 orthophotos, and therefore some sections of water were misclassified as woody vegetation. Misclassifications also occurred between some areas of pasture and woody vegetation, due to a similar tone.

5.1.2 Change detection

Figure 12a-b shows that in the upstream reach, riparian vegetation was not continuous in either time series but remained relatively constant between years, with 78% riparian vegetation cover in 1971 and 85% in 1974 (Appendix 2). Of the small amount of vegetation loss that has occurred between 1971 and 1974 in reach 1, most was removed from within the macro-channel during the January 1974 flood (Figure 12c). It should also be noted that only a maximum of 5.8% of the buffer area investigated was actually unvegetated (Table 9) prior to the flood.

Reach 2 is more agriculturally developed than reach 1, shown in Figure 13a-b and vegetation cover is therefore less continuous, representing approximately 35% in both 1971 and 1974.The 1974 flood appears to have had a more significant effect in reach 2 than in reach 1, and vegetation loss within the macro-channel represented 22% (Figure 13c; Table 9). Areas not vegetated prior to the flood were considerable, representing 31% of the macro-channel.

Reach 3 is the most agriculturally developed of the three studied locations and is located the furthest downstream (Figure 14a-b). The areas represented by grass and paddock, used for agriculture and development remained constant between 1971 and 1974, representing approximately 75% of the

buffer in both years (Table 9). The 1974 flood appeared to remove a significant amount of woody vegetation in the downstream reach, with vegetation loss accounting for 21.8% of the channel boundary (Figure 14c; Table 9).

Table 9 Percent of each vegetation class within the 300m buffer and channel boundary zone in reach 1, 2 and 3 in 1971-1974.

Reach	Vegetation Class	Percent of Area: 300m buffer	Percent of Area: Channel Boundary
Reach 1	1. Vegetation Loss	8.4	11.4
	2. No change, no vegetation	5.8	3.9
	3. No change, vegetation	71.6	71
	4. Vegetation increase	14.3	13.7
Reach 2	1. Vegetation Loss	8.7	14.6
	2. No change, no vegetation	41.7	31
	3. No change, vegetation	23.6	44.1
	4. Vegetation increase	26.1	10.2
Reach 3	1. Vegetation Loss	17.5	21.8
	2. No change, no vegetation	56.7	46.2
	3. No change, vegetation	8.1	17.2
	4. Vegetation increase	17.7	14.7

1. Vegetation loss represents the removal of woody vegetation; 2. No change, no vegetation represents areas where there was no woody vegetation in both 1971 and 1974; 3. No change, vegetation represents area where there was woody vegetation between time intervals; 4 Vegetation increase represents areas of expanding woody vegetation between time series.

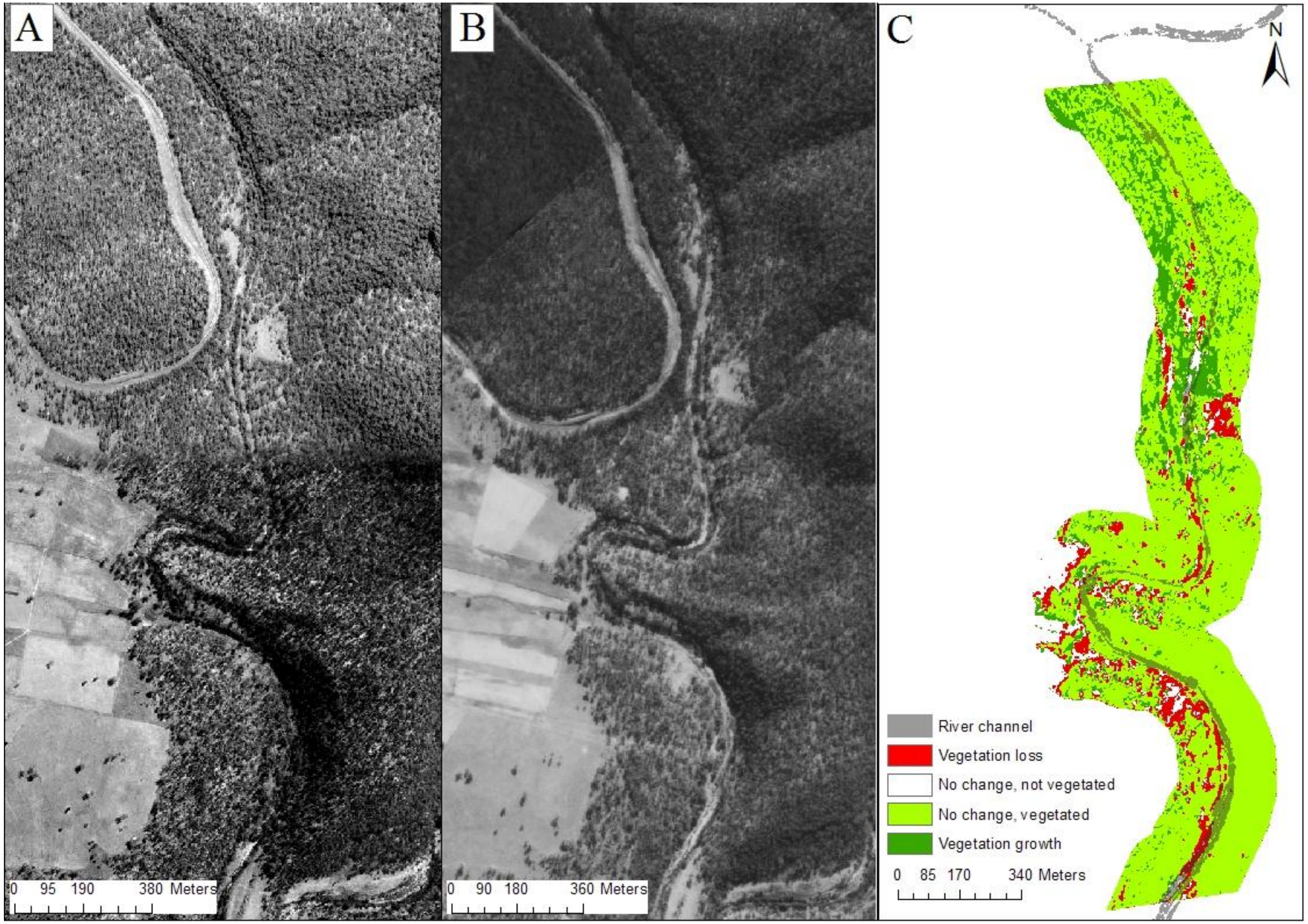

Figure 12 Pre-flood (A) and post-flood (B) orthophotos of reach 1 in 1971 and 1974. Post classification change detection image (C) shows vegetation loss in red, areas not vegetated prior to the flood in white, areas that remained vegetated after the flood in light green, and areas of natural vegetation growth in dark green. River channel is shown in grey. Flow is from top to bottom.

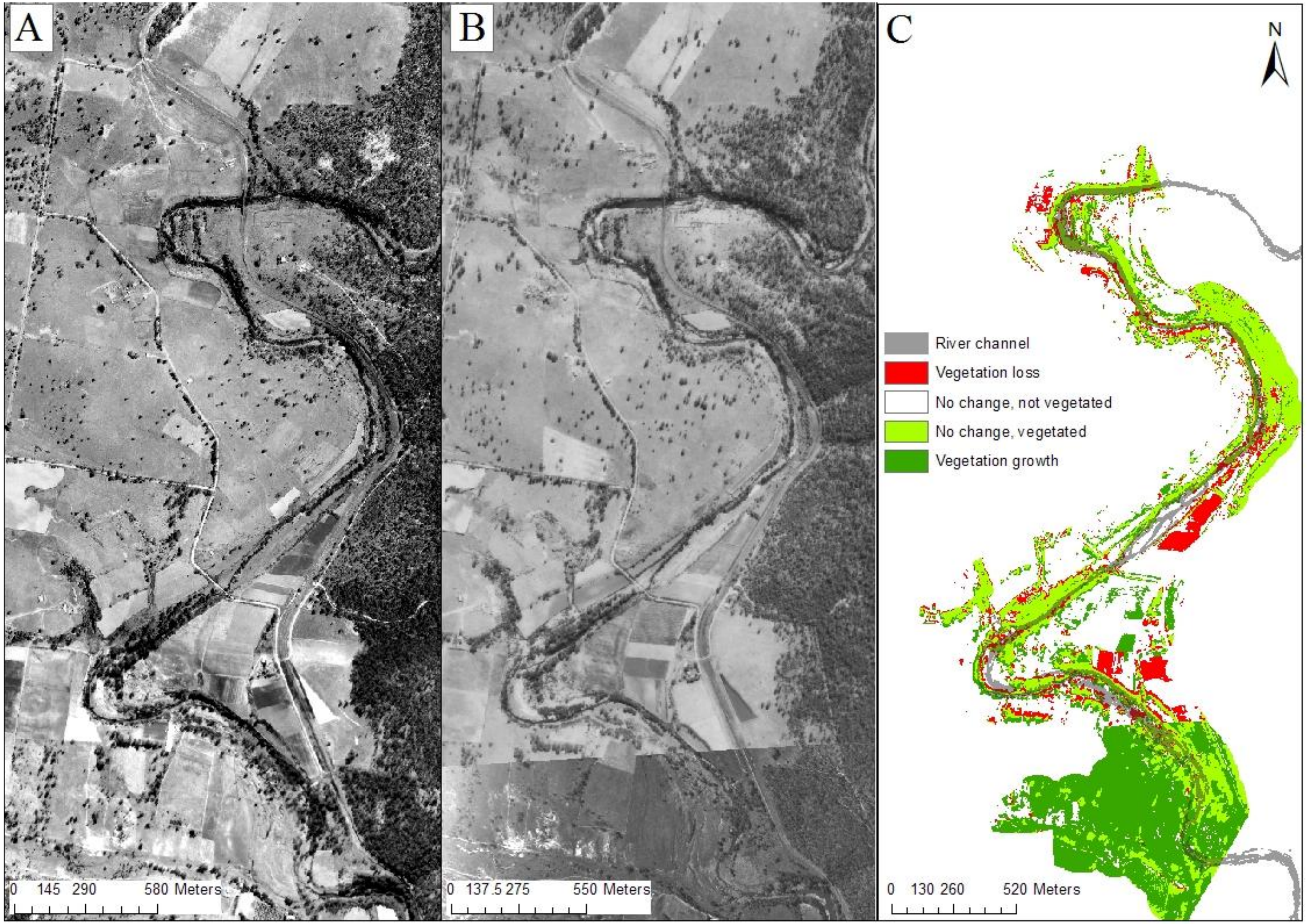

Figure 13 Pre-flood (A) and post-flood (B) orthophotos of reach 2 in 1971 and 1974. Post classification change detection image (C) showing areas of vegetation loss, areas not vegetated prior to the flood, areas that remained vegetated after the flood and natural vegetation growth. River channel is shown in grey. Flow is from top to bottom.

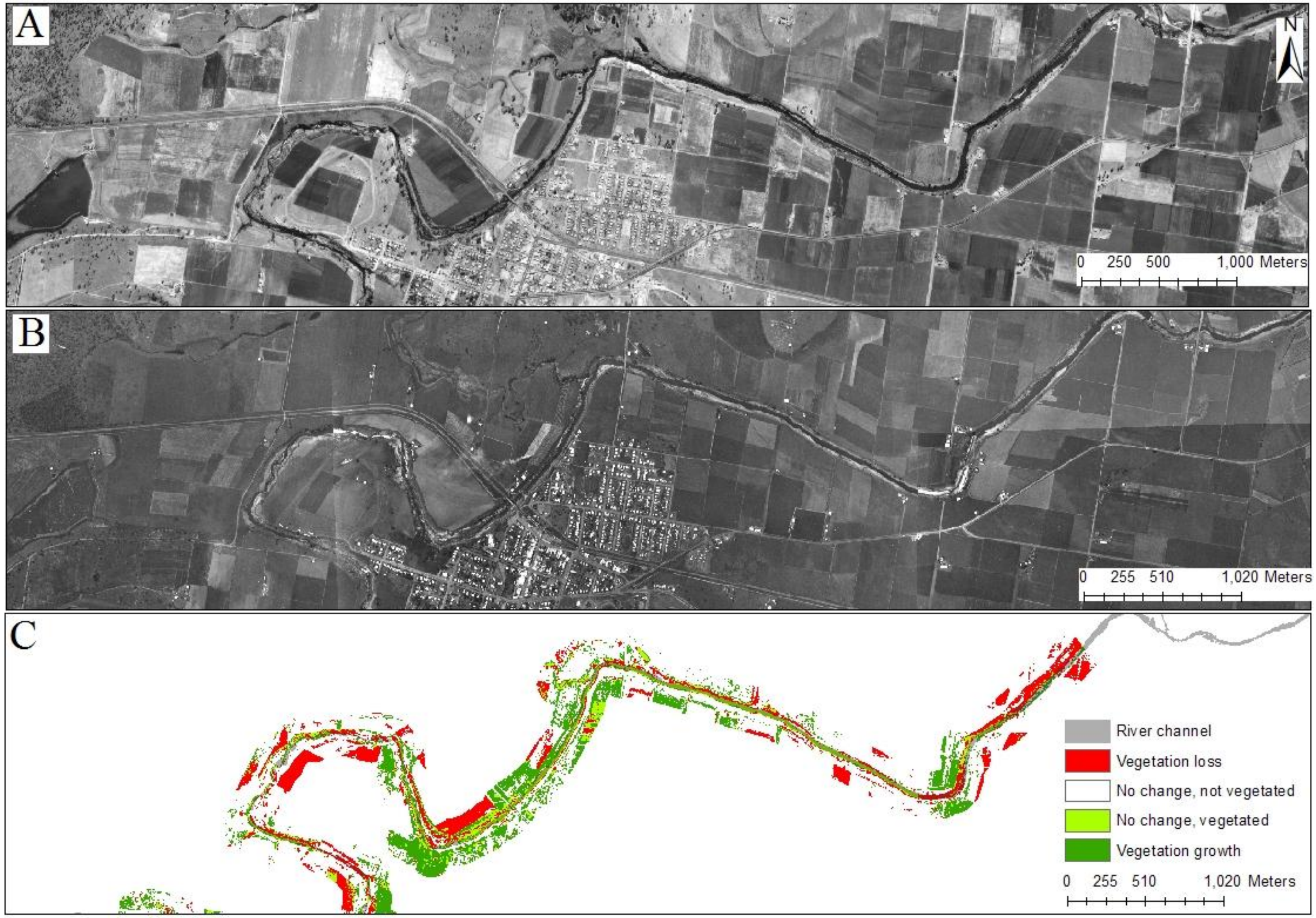

Figure 14 Pre-flood (A) and post-flood (B) orthophotos of reach 3 in 1971 and 1974. Post classification change detection image (C) showing areas of vegetation loss, areas not vegetated prior to the flood, areas that remained vegetated after the flood and natural vegetation growth. River channel is shown in grey. Also note the increased development in comparison to reach 1 and 2. Flow is from left to right.

5.2 Image analysis: 2009 – 2011

5.2.1 Vegetation classification

A maximum likelihood classification was performed to classify both the 2009 and 2011 orthophotos (shown in Appendix 3). Error matrixes were used to complete the accuracy assessment, calculating the user's and producer's accuracy in addition to overall accuracy. The overall accuracy results are presented in Table 10 (see Appendix 3.8 – 13 for error matrixes and user's and producer's accuracy).

Table 10 Accuracy assessment of the 2009 and 2011 classifications.

Overall Accuracy	2009	2011
Reach 1	92%	90.5%
Reach 2	64.5%	81%
Reach 3	70%	85.5%
Average	75.5%	85.7%

The separation between land cover classes was analysed with the use of the n-d visualiser, and the transformed divergence index was calculated for each combination of classes. The transformed divergence index represents the separation between classes; a score of less than 1 indicates poor separation and a score of 2 represents clear separation between classes. In the 2009 orthophoto, some areas of woody vegetation were misclassified as water, due to the dark colour and the absence of the near infrared band. Separation was limited, with an average transformed divergence index of 1.49. In the 2011 orthophoto, due to the high volume of sediment in the river immediately following the flood, water was easily distinguished from woody vegetation with an average transformed divergence index of 1.99. The maximum likelihood classification discriminated well between the classes of bare surfaces and woody vegetation in both the 2009 and 2011 orthophotos, with a transformed divergence index of 1.94 and 1.98 respectively.

Vegetation classifications in 2009 and 2011 achieved an average overall accuracy of 76% and 86% respectively. Although this is a relatively high result, it also suggests some uncertainty in classifying between different land cover classes and differences were also observed through the three reaches. The low user's and producer's accuracy in class 2 and 4 of the error matrixes (Appendix 3) illustrate that in 2009, the greatest source of error came from distinguishing between areas of woody vegetation and water.

Distinction between woody vegetation and pasture was also a source of error in both the 2009 and 2011 classifications, due to the spectral similarities between the two classes. Poor discrimination

between water and bare surfaces reduced the overall accuracy of the 2011 classifications as a result of the high sediment content after the flood. However, these errors had few implications on the overall study, as the next stage reclassified other land cover classes of water, pasture and bare surfaces into one class.

5.2.2 Change detection

The upper catchment remained largely forested between 2009 and 2011, with 80% vegetation cover in 2009 and 75% vegetation cover in 2011. However, Figure 15a-c shows that the January 2011 flood removed ~ 42% of riparian vegetation from the macro-channel (Table 11). Similar to the 1971 – 1974 time series, Figure 15 shows that only a small area of the reach was unvegetated prior to the 2011 flood.

Reach 2 is more agriculturally developed than reach 1, shown in Figure 16a-b, and a considerable area of the macro-channel was unvegetated prior to the 2011 flood. The 2011 flood appears to have had a more significant effect in reach 2, than in reach 1 and vegetation loss due to the flood was significant, representing a 37% within the channel boundary (Figure 16c; Table 11). Figure 16b shows Lockyer siding, (blue circle) which represents an area of significant vegetation loss and geomorphic change as the river emerged from the confined reach resulting in significant erosion and deposition.

Figure 17a-b shows that reach 3 is the most agriculturally utilised, with pasture representing the highest percentage of land use in both 2009. A large amount of pasture was removed by the 2011 flood. In reach 3, riparian vegetation was less extensive than reach 1 and 2 in 2009 and as a result, less vegetation loss occurred during the January 2011 flood (Figure 17c). Woody vegetation loss represented 27.2% of the channel boundary (Table 11).

Table 11 Percent of each vegetation class within the 300m buffer and channel boundary zone in reach 1, 2 and 3 in 2009 – 2011.

Reach	Vegetation Class	Percent of Area: 300m buffer	Percent of Area: Channel Boundary
Reach 1	1. Vegetation Loss	17.1	41.9
	2. No change, no vegetation	8.5	12.4
	3. No change, vegetation	63.3	40.3
	4. Vegetation increase	11	5.4
Reach 2	1. Vegetation Loss	23.2	37.3
	2. No change, no vegetation	42.7	36.5
	3. No change, vegetation	18.5	16.9
	4. Vegetation increase	15.6	9.3
Reach 3	1. Vegetation Loss	11.8	27.2
	2. No change, no vegetation	60.9	48.5
	3. No change, vegetation	11.5	19.6
	4. Vegetation increase	15.9	4.6

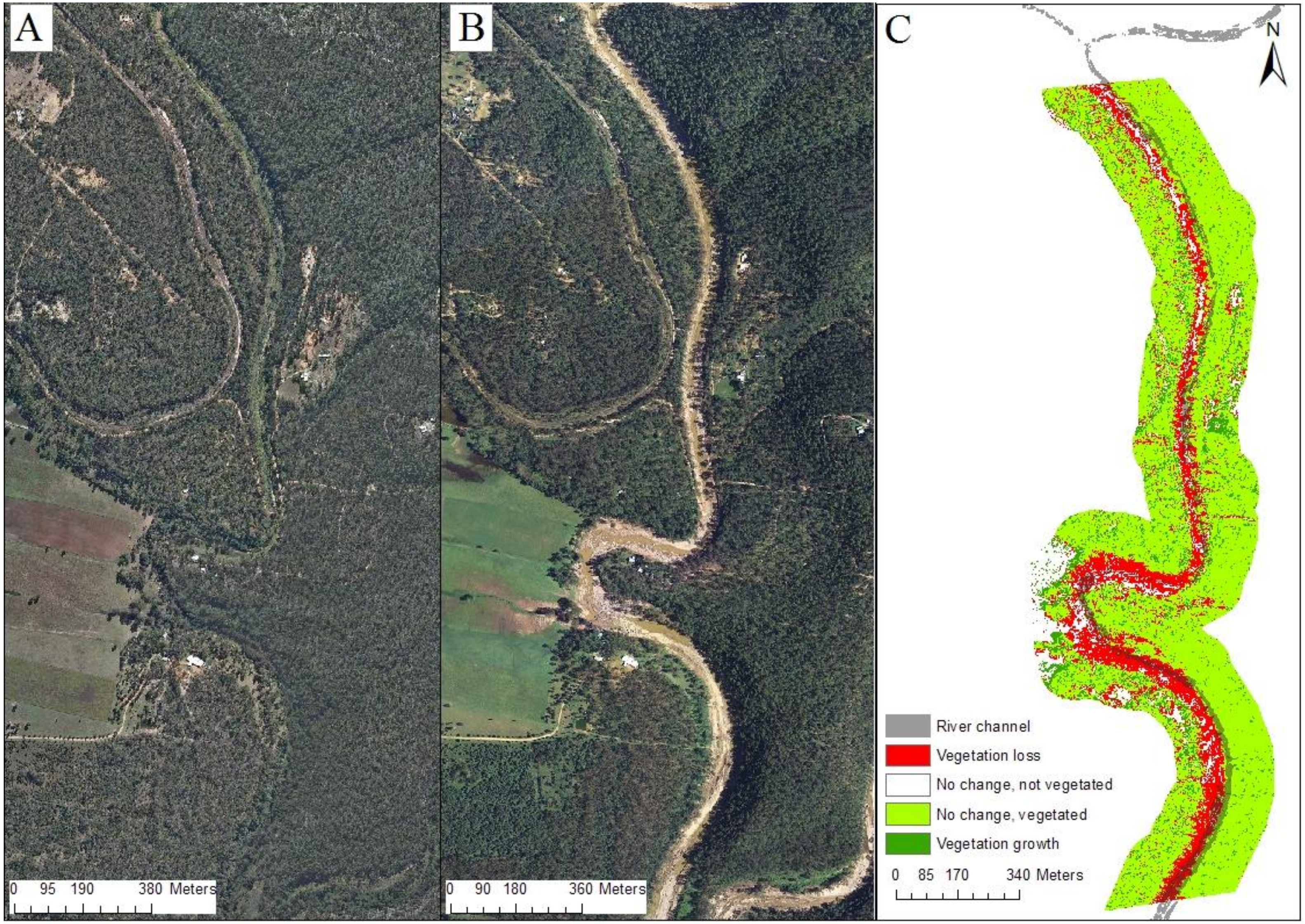

Figure 15 Pre-flood (A) and post-flood (B) orthophotos of reach 1 in 2009 and 2011. Post classification change detection image (C) showing areas of vegetation loss, areas not vegetated prior to the flood, areas that remained vegetated after the flood and natural vegetation growth. River channel is shown in grey.

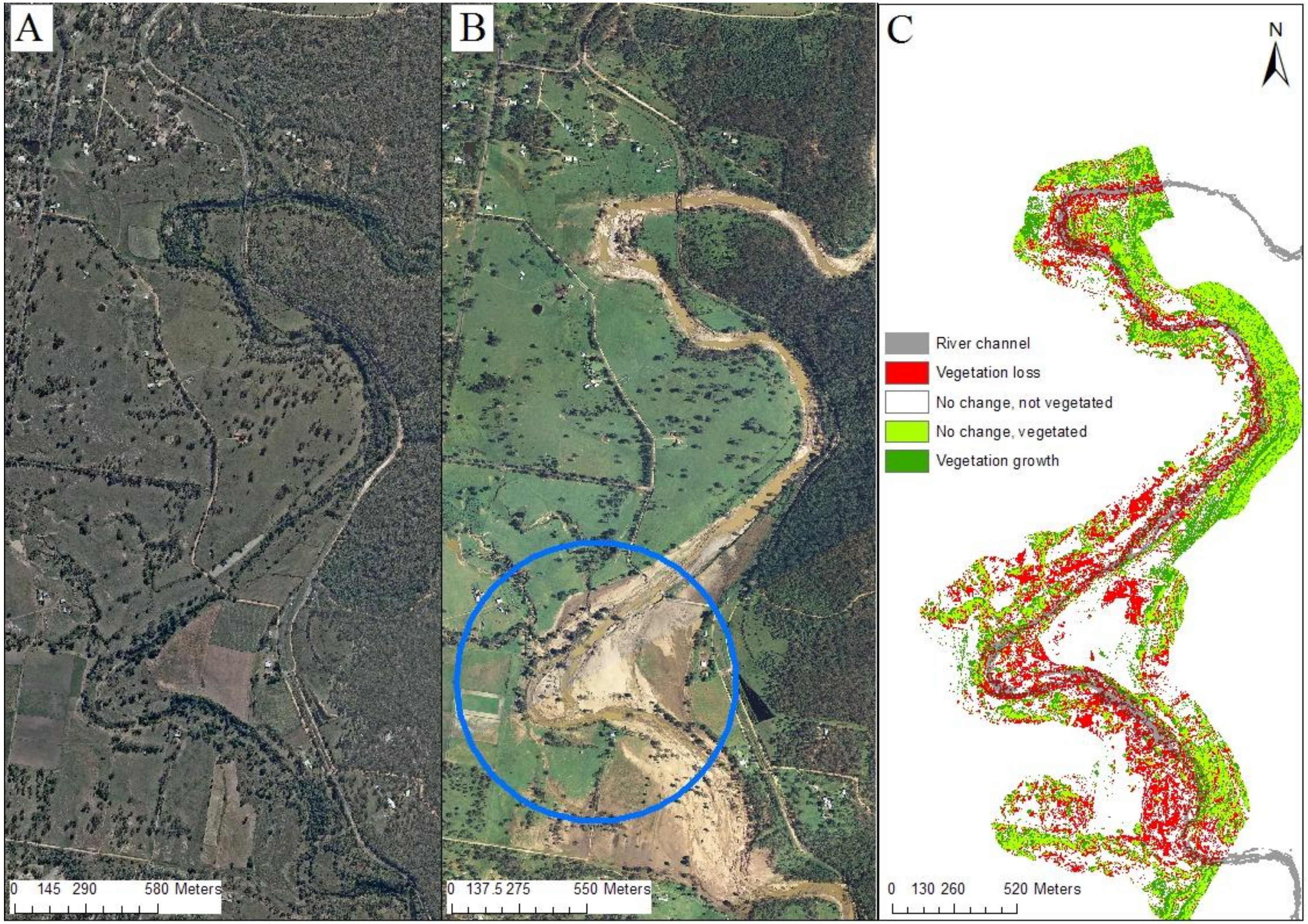

Figure 16 Pre-flood (A) and post-flood (B) orthophotos of reach 2 in 2009 and 2011. Post classification change detection image (C) showing areas of vegetation loss, areas not vegetated prior to the flood, areas that remained vegetated after the flood and natural vegetation growth. River channel is shown in grey. Also note the significant change which occurred at Lockyer Sidings (blue circle).

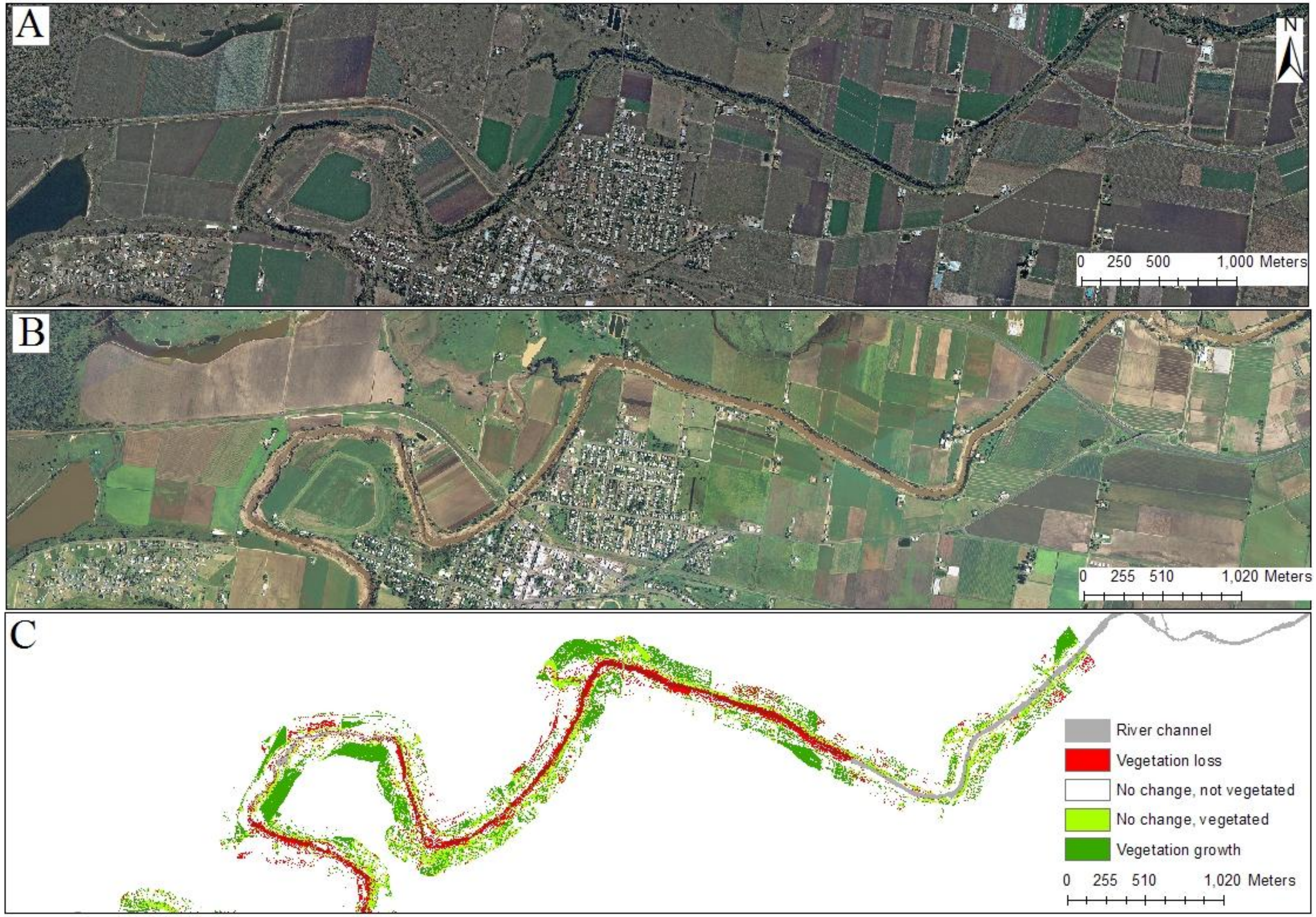

Figure 17 Pre-flood (A) and post-flood (B) orthophotos of reach 3 in 2009 and 2011. Post classification change detection image (C) showing areas of vegetation loss, areas not vegetated prior to the flood, areas that remained vegetated after the flood and natural vegetation growth. River channel is shown in grey.

5.3 Interaction of vegetation in big flood events

5.3.1 The role of vegetation in geomorphic change during the January 1974 catastrophic flood

Areas of visible geomorphic change were digitised and the most extensive vegetation class within each polygon was noted and compared across the three reaches. In reach 1, the 1974 flood had a less significant impact than the more downstream reaches. Change most commonly occurred in areas that were vegetated was removed by the flood (Figure 18). It should also be noted that only a small amount of change occurred in areas unvegetated before the flood, as the upper catchment is largely forested.

Figure 18 shows that geomorphic change occurred most frequently in areas unvegetated prior to the 1974 flood, in Reach 2. No significant change occurred in areas where woody vegetation remained after the flood. More significant geomorphic change occurred in reach 3 compared to the other study reaches. Significant geomorphic change occurred in areas not vegetated prior to the 1974 flood. No visible change occurred in areas that remained vegetated after the flood. Whilst not an absolute measure of vegetation presence or absence, the results clearly show that in the lower two reaches that the greatest geomorphic change occurred in areas where there was the least amount of vegetation prior to the flood.

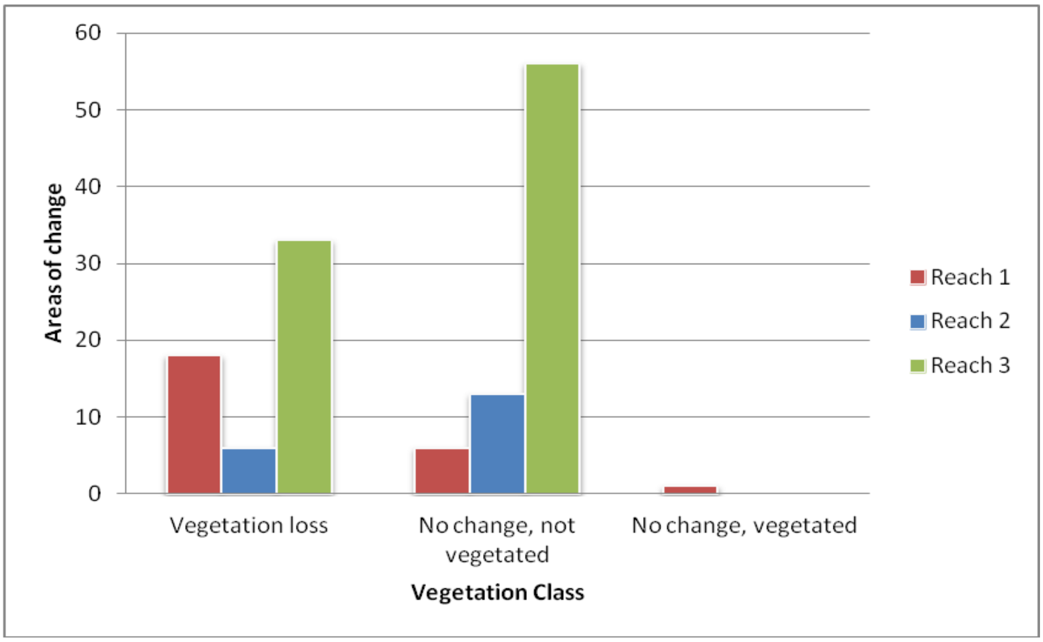

Figure 18 Relationship between vegetation and areas of change in reach 1, 2 and 3: 1971 – 1974.

5.3.2 The control of vegetation on erosion and deposition during the 2011 flood

Values of erosion and deposition were derived by differencing the Digital Elevation Model (DEM) of before and after the 2011 flood event (Croke et al. 2013b). Figures 19-21 show elevation change from the DEM of Difference (DoD) with erosion in red and deposition in blue in the three study reaches. The values of erosion and deposition were assessed to confirm if there was a significant difference between the values' occurring in the four vegetation classes.

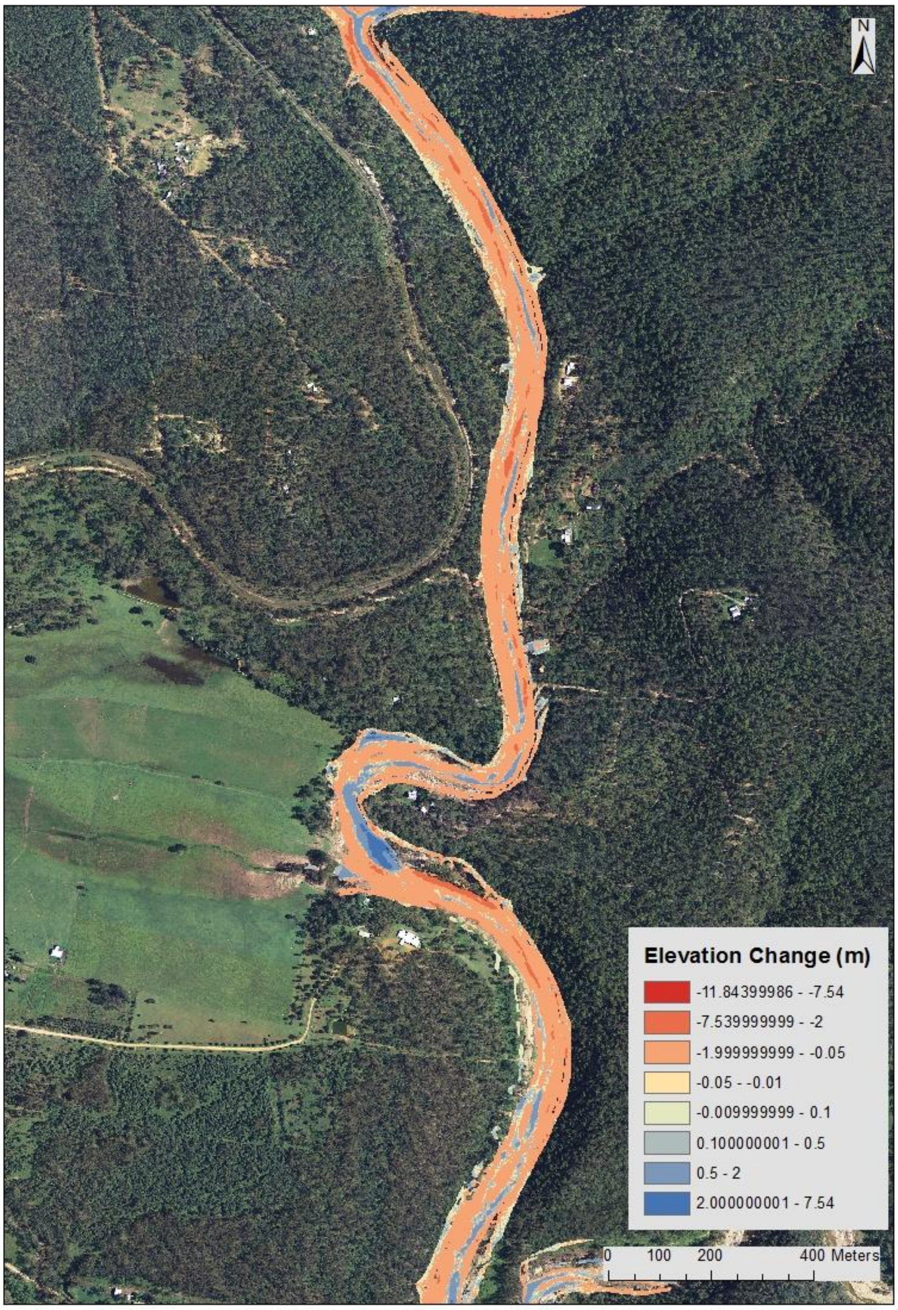

Figure 19 Elevation change after the 2011 catastrophic flood event in reach 1, showing erosion in red and deposition in blue. Flow is from top to bottom.

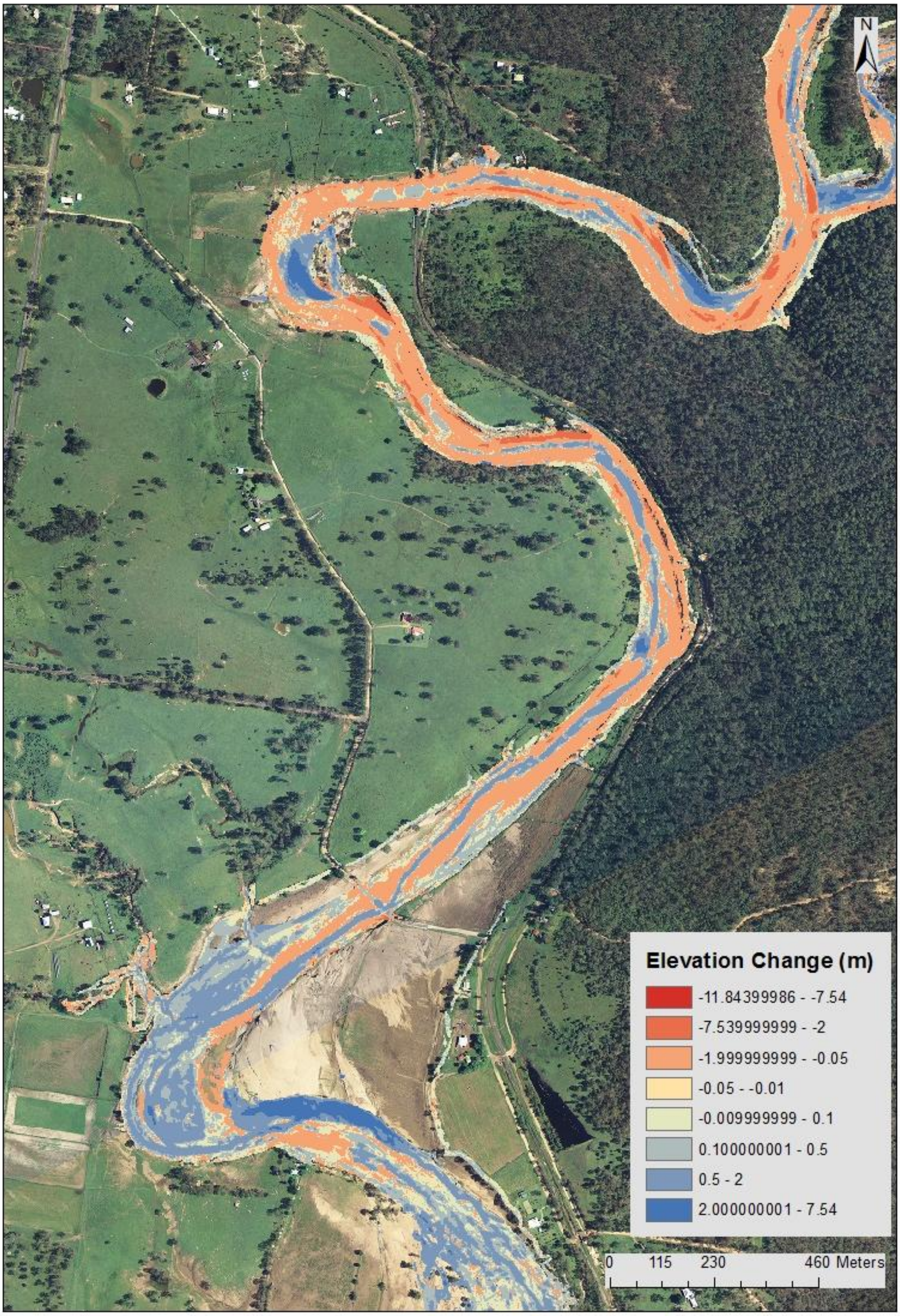

Figure 20 Elevation change after the 2011 catastrophic flood event in reach 2, showing erosion in red and deposition in blue. Flow is from top to bottom.

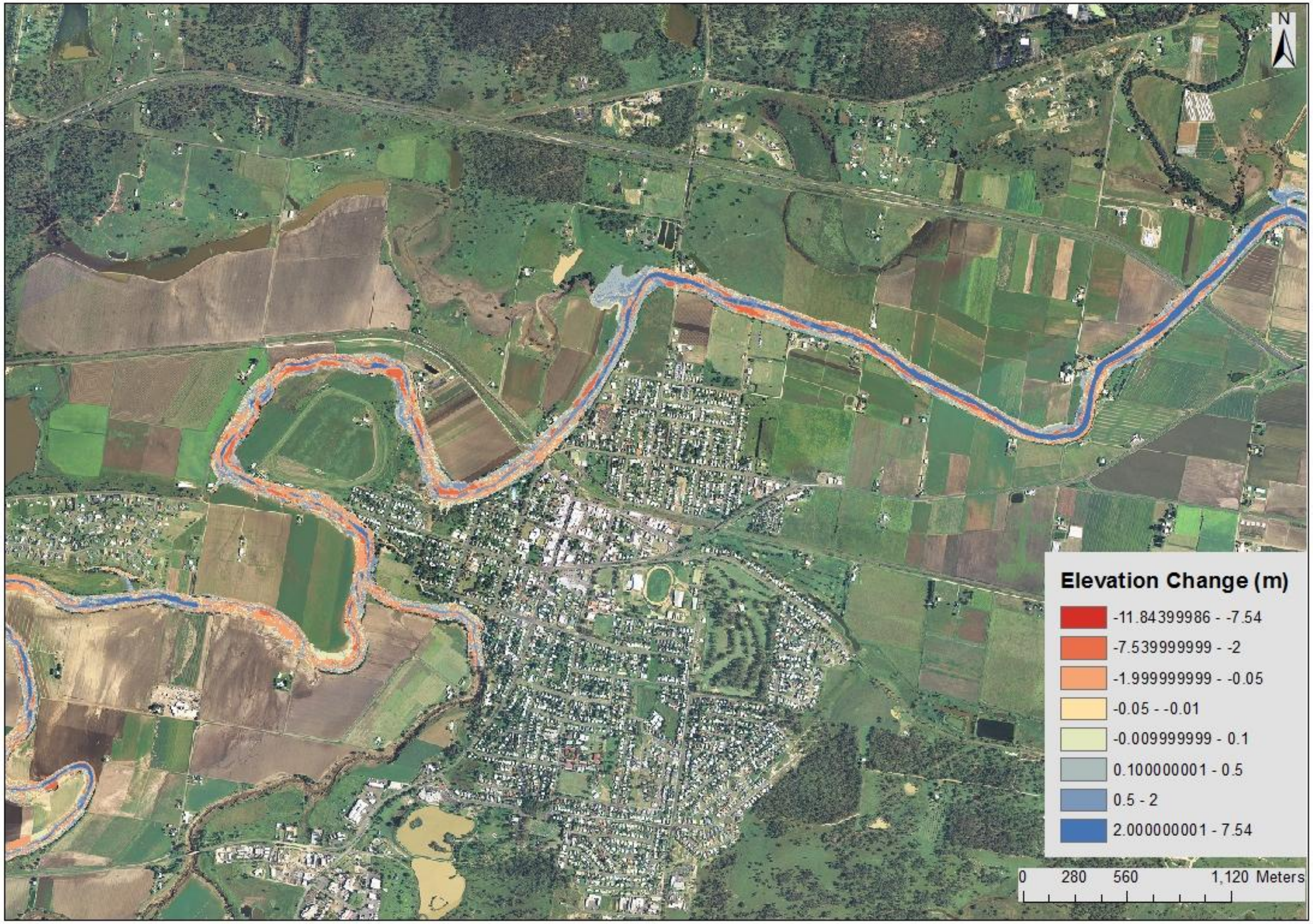

Figure 21 Elevation change after the 2011 catastrophic flood event in reach 3, showing erosion in red and deposition in blue. Flow is from left to right.

5.2.2.1 The control of vegetation on deposition during the 2011 flood

Differences in the values of deposition (metres elevation change) between vegetation classes were assessed using a Kruskal-wallis test. This was completed to determine the relationship between the rates and spatial occurrence of deposition to the presence/absence of vegetation. This approach focused on geomorphic units including inner channel (bed and bars), inner channel banks, benches and macro-channel banks (Figure 11).

Reach 1

Figure 19 shows that little deposition occurred in reach 1, during the January 2011 flood, and that the changes occurring were primarily erosional. More significant deposition was generally associated with areas where vegetation was unchanged or expanding after the 2011 flood in reach 1. Analysis showed statistically significant differences between values of deposition (in metres elevation change) between vegetation classes (inner channel ($p = 0.021$), benches ($p= 0.003$) and macro-channel banks ($p = 0.015$).

On inner channel bed and bars, analysis showed a statistically significant difference between values of deposition in areas of vegetation loss and vegetated areas ($p = 0.012$). During the 2011 flood, more deposition occurred on the inner channel bed and bars in areas where riparian vegetation had expanded over the two time year period (median = 1.66). The lowest amount of deposition occurred in areas where vegetation was removed by the flood (median = 0.64). Appendix 4.4 shows the combinations of vegetation classes that were statistically significantly different.

Along the benches of reach 1, the most significant deposition occurred in vegetated areas (median = 1.34), whilst the least amount of deposition occurred in unvegetated areas (median = 0.56) and where vegetation was removed during the flood (median = 0.52). In contrast, Figure 22 shows that on macro-channel banks, more deposition actually occurred in areas of vegetation loss (median = 0.54).

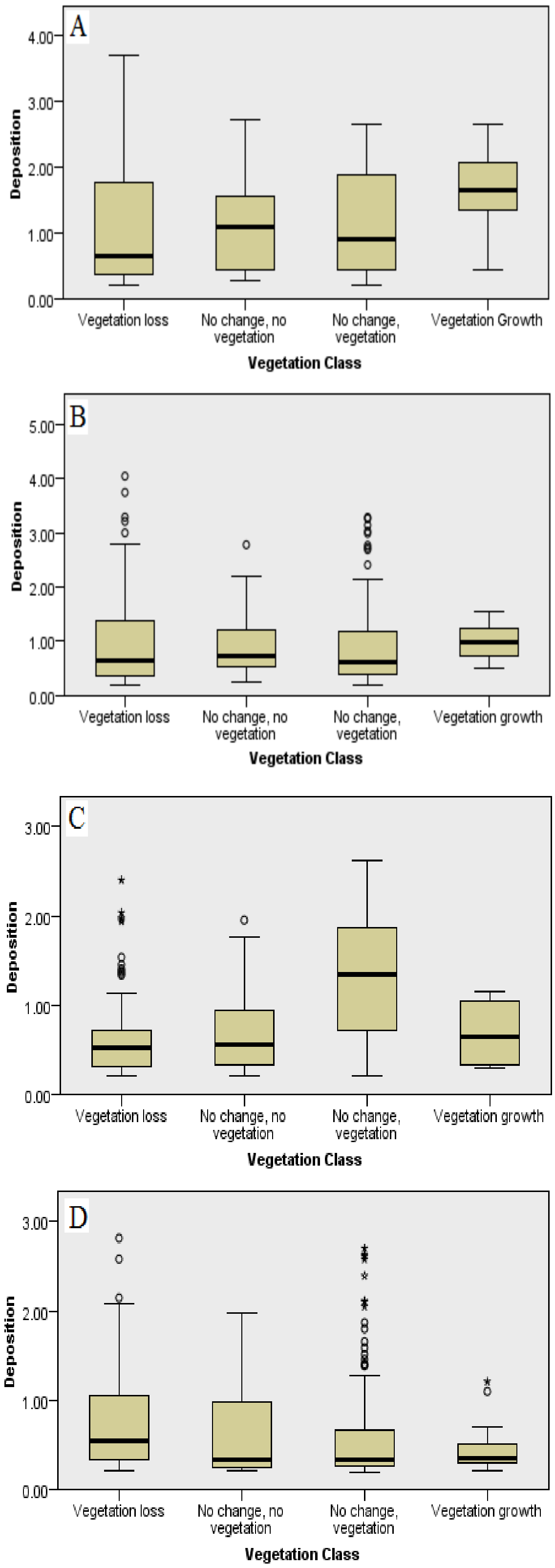

Figure 22 Values of deposition occurring in each vegetation class in inner channel bed and bars (A), inner channel banks (B), benches (C) and macro-channel banks (D) in reach 1.

Reach 2

Figure 20 shows that a significant amount of deposition occurred as the river emerged from the confined settings of reach 1, onto the unconfined floodplain of reach 2 (also highlighted in Figure 16b). Statistically significant differences in metres of deposition between vegetation classes were found along inner channel bed and bars ($p = .015$), benches ($p = <.001$) and macro-channel banks ($p = <.001$).

In reach 2, all geomorphic units demonstrated similar trends, in that deposition during the 2011 flood was most significant in areas of vegetation loss (Figure 23). Along inner channel bed and bars, the most substantial deposition occurred in areas of vegetation loss and the smallest in vegetated areas. Deposition along benches demonstrated a similar trend with the largest amount of deposition occurring in areas of vegetation loss (median = 0.578). However, the least amount of deposition occurred in areas that were unvegetated before the 2011 flood (median = 0.471). Likewise, deposition during the 2011 flood was most significant in areas of vegetation loss along macro-channel banks. The lowest amount of deposition occurred in areas where vegetation was unchanged (median = 0.390) or expanding (median = 0.345) between 2009 and 2011.

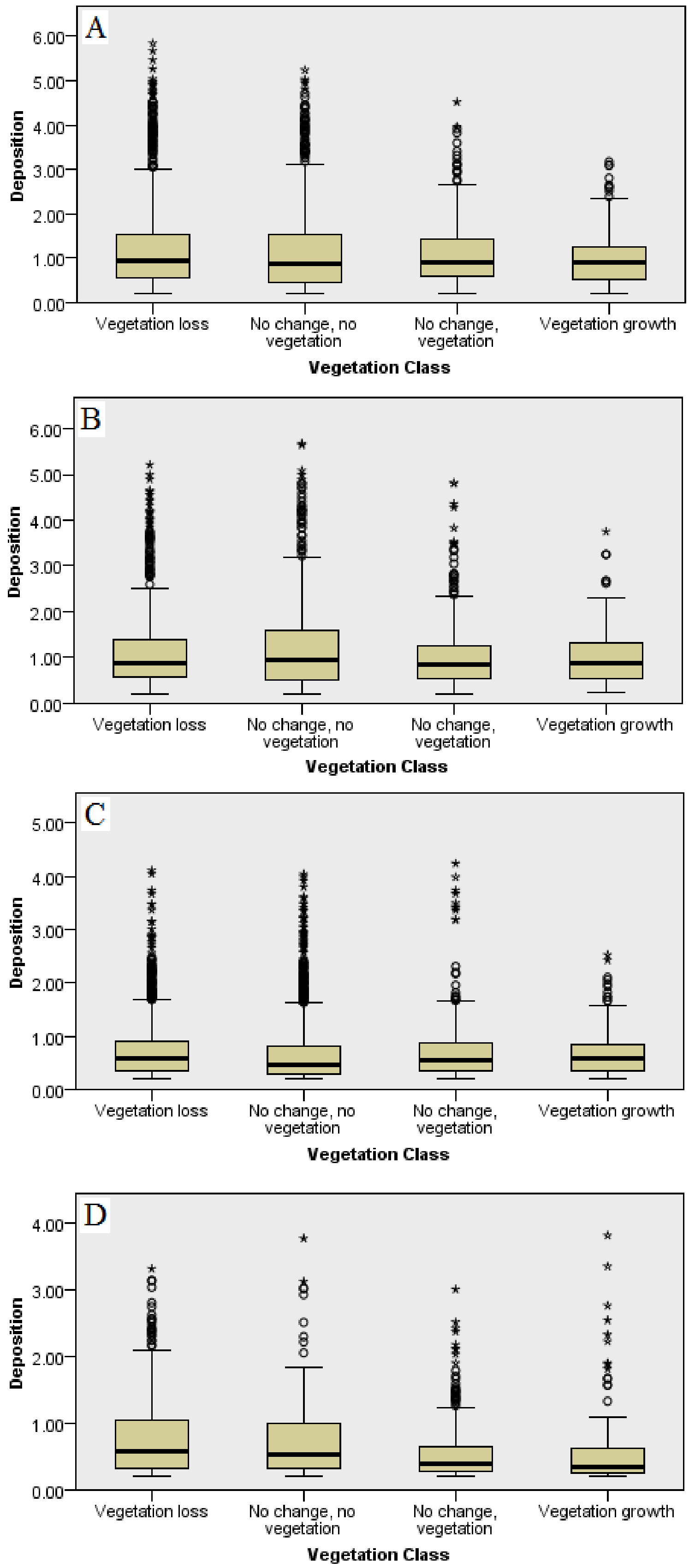

Figure 23 Values of deposition occurring in each vegetation class in inner channel bed and bars (A), inner channel banks (B), benches (C) and macro-channel banks (D) in reach 2.

Reach 3

Figure 13 shows that a significant amount of erosion and deposition occurred along the river channel in reach 3. Significant differences in deposition between vegetation classes were found along inner channel bed and bars (p = <0.001), benches (p = <0.001) and macro-channel banks (p = <0.001). Along the inner channel bed and bars of reach, deposition was most significant in areas where vegetation was unchanged (median = 2.375) or expanding (median = 2.552) between 2009 and 2011. In contrast, the last amount of deposition occurred in areas of vegetation loss (median = 1.945) and areas that were unvegetated prior to the 2011 flood (median = 2.00).

Along benches, the greatest amount of deposition occurred in areas that remained vegetated after the 2011 flood (median = 0.453) while the least amount of deposition occurred in unvegetated areas (median = 0.369). Figure 24 shows that the opposite trend occurred along macro-channel banks as the greatest amount of deposition occurred in areas of vegetation loss (median = 0.415). The least amount of deposition occurred in areas were vegetation was unchanged (median = 0.352) or expanding (median = 0.319) between the two year period.

Along the inner channel bed and bars, inner channel banks and benches, the greatest amount of deposition occurred in areas where vegetation was unchanged or expanding after the flood. In these geomorphic features, the least amount of deposition occurred in areas that were unvegetated prior to the flood, or where vegetation was removed during the flood. However, this trend was reversed on macro-channel banks, with greater deposition occurring in areas of vegetation loss. Some differences occurred across the three studied reaches. Reach 3 and reach 3 exhibit similar trends in patterns of deposition during the 2011 flood as greater deposition generally occurred in areas where vegetation as unchanged or expanding after the January 2011 flood. The opposite trend was shown in reach 2, where the greatest deposition occurred in areas of vegetation loss.

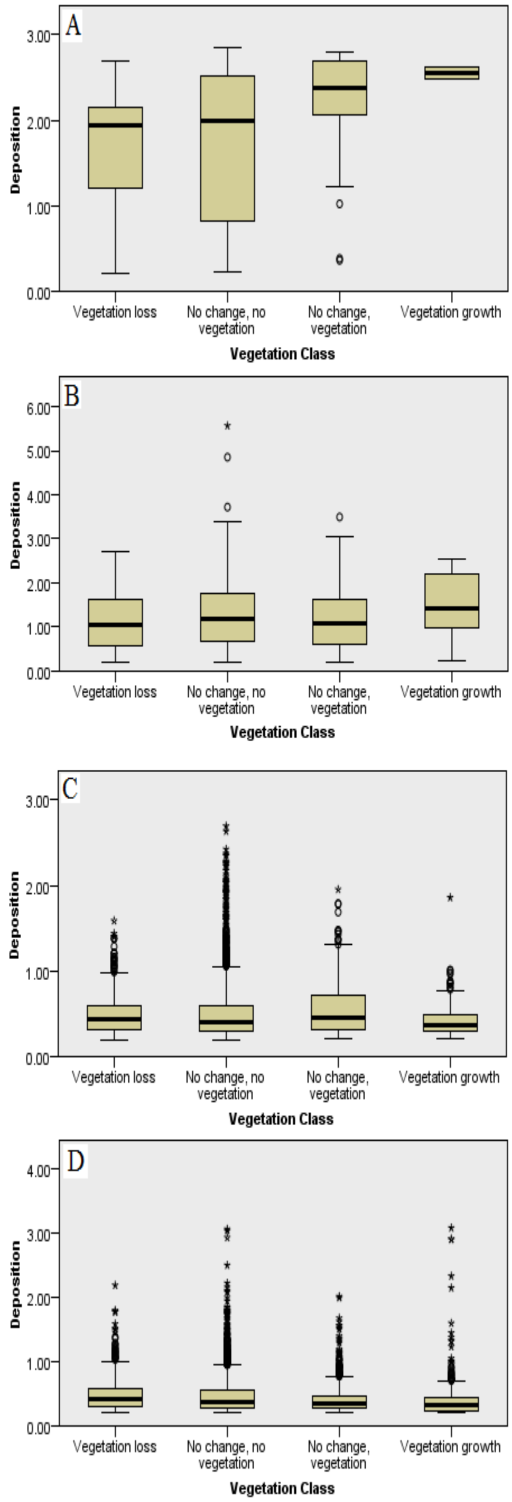

Figure 24 Values of deposition occurring in each vegetation class in inner channel bed and bars (A), inner channel banks (B), benches (C) and macro-channel banks (D) in reach 3.

5.2.2.2 The control of vegetation in fluvial entrainment

An approach similar to that discussed in the above section was used to determine the effect of vegetation on fluvial entrainment during the January 2011 flood. A Kruskal-Wallis test was completed to assess the variance in fluvial entrainment between vegetation classes, focussing on the geomorphic units outlined in Figure 11.

Reach 1

Figure 19 shows that significant erosion occurred during the 2011 flood in reach 1. Differences in values of fluvial entrainment between vegetation classes were statistically different along benches ($p = <0.001$) and macro-channel banks ($p =<0.001$). Along benches, the greatest amount of erosion occurred in areas where vegetation was unchanged (median = 1.55) or expanding (median = 1.235) after the 2011 flood on benches in reach 1.

The opposite trend was seen on macro channel banks (Figure 25), where the most significant erosion occurred in areas of vegetation loss (median = 0.850), and areas that were unvegetated (median = 0.760) before the 2011 flood. The least amount of erosion occurred in areas where vegetation was unchanged (median = 0.710) or expanding (median = 0.590) after the flood. In reach 1, fluvial entrainment appeared to be most significant in areas where vegetation was lost during the flood, or areas that were unvegetated prior to the 2011. This is in contrast to areas that remained vegetated, or where vegetation was expanding where deposition has occurred primarily.

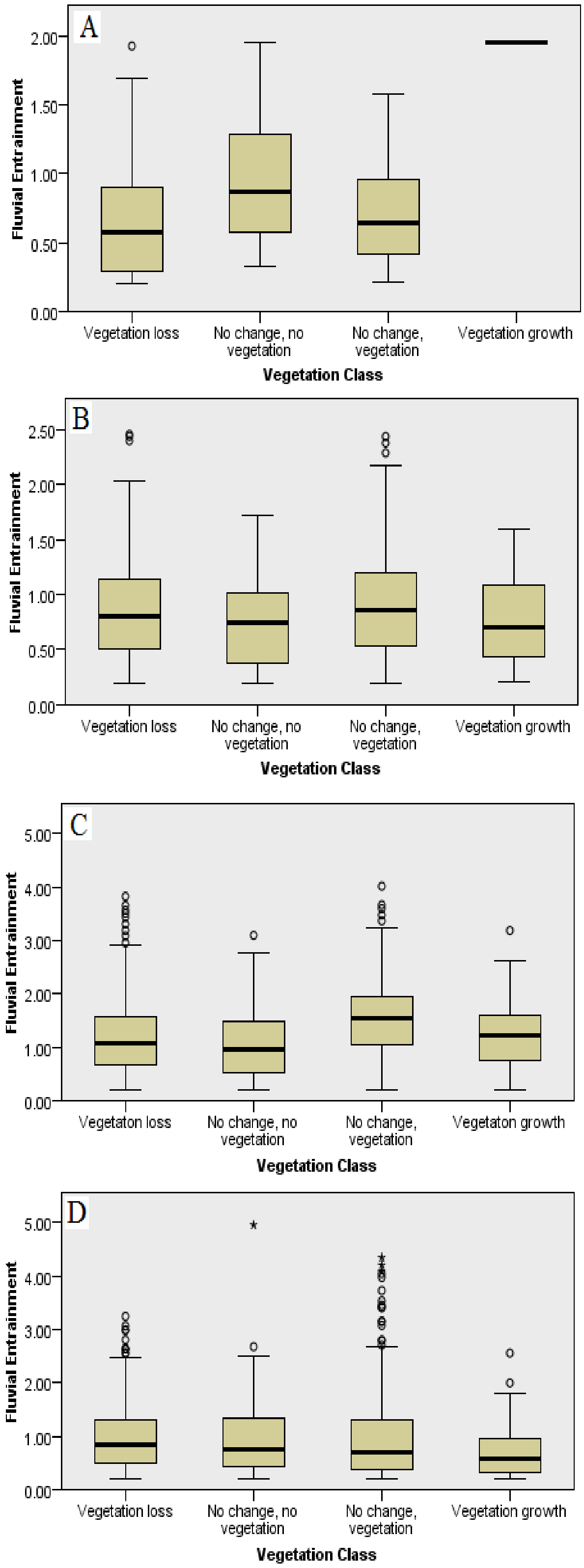

Figure 25 Values of fluvial entrainment occurring in each vegetation class in inner channel bed and bars (A), inner channel banks (B), benches (C) and macro-channel banks (D) in reach 1.

Reach 2

Significant erosion occurred in the upstream section of reach 2, shown in Figure 16. Statistically significant differences in fluvial entrainment between vegetation classes occurred along benches ($p = <0.001$) and macro-channel banks ($p =<0.001$). The most significant erosion occurred in areas where vegetation was unchanged (median = 1.08) or expanding (median =1.11) after the 2011 flood on benches. The least amount of erosion occurred in areas where vegetation was removed by the flood (median = 0.890) or that were unvegetated before the flood ($p= 0.017$).

In contrast, Figure 26 shows that the most substantial erosion occurred in areas of vegetation loss (median = 0.750) and areas that were unvegetated (median = 0.665) prior to the 2011 flood along macro-channel banks. The least amount of erosion occurred in areas where vegetation was unchanged (median = 0.560) or increasing (median = 0.540) between 2009 and 2011.

In reach 2, the greatest amount of erosion during the 2011 flood generally occurred in areas of vegetation loss, or areas that were unvegetated prior to the flood. However, the opposite trend was seen on benches, where the most significant erosion occurred in vegetated areas.

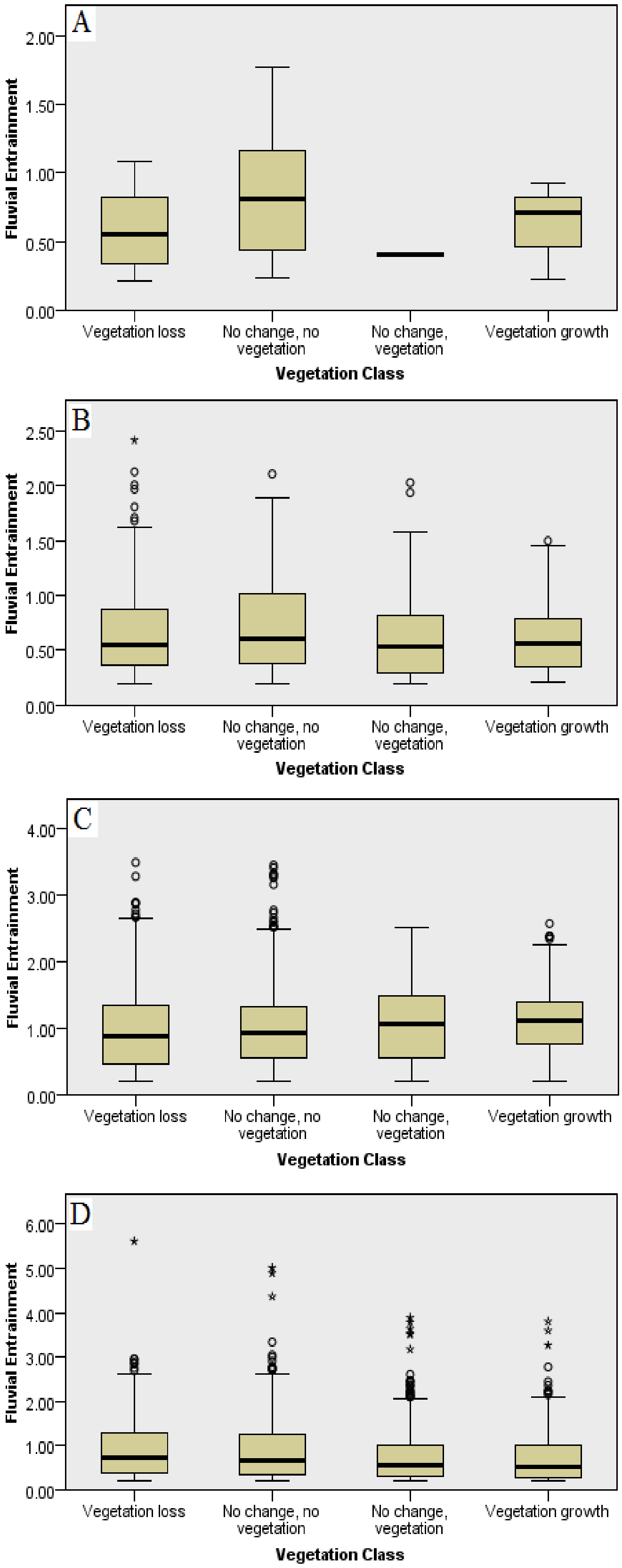

Figure 26 Values of fluvial entrainment occurring in each vegetation class in inner channel bed and bars (A), inner channel banks (B), benches (C) and macro-channel banks (D) in reach 2.

Reach 3

Figure 21 highlights the areas of the most significant erosion occurring in reach 3. Differences in erosion between vegetation classes were not statistically different on the inner channel bed or inner channel banks. However, fluvial entrainment was most significant in areas that were unvegetated prior to the flood, or where vegetation was removed.

Values of fluvial entrainment were statistically significantly different between the vegetation classes for benches ($p = <.001$) and macro-channel banks ($p =<.001$). Figure 27 shows that along benches, the most significant erosion occurred in areas of vegetation loss (median = 1.195). More erosion occurred in areas where vegetation was unchanged (median = 1.145) or expanding (median = 1.19), than in areas that unvegetated in 2009 (median = 0.490). Along macro-channel banks, the greatest amount of erosion occurred in areas of vegetation loss (median = 0.960) and areas that were unvegetated before the 2011 flood (median = 0.650). The least amount of erosion occurred in areas of unchanged (median = 0.630) or expanding (median = 0.520) vegetation between the two year period.

In reach 3, the greatest amount of erosion typically occurred in areas where vegetation was removed by the 2011 flood or areas that were unvegetated prior to the flood. Across the three studied reaches, the least amount of erosion occurred in vegetated areas. Simultaneously, the most significant amount of deposition appears to be occurring in vegetated classes across the three studied reaches, as discussed in the previous section. However, a different trend occurred along benches as the most significant erosion was associated with vegetated areas.

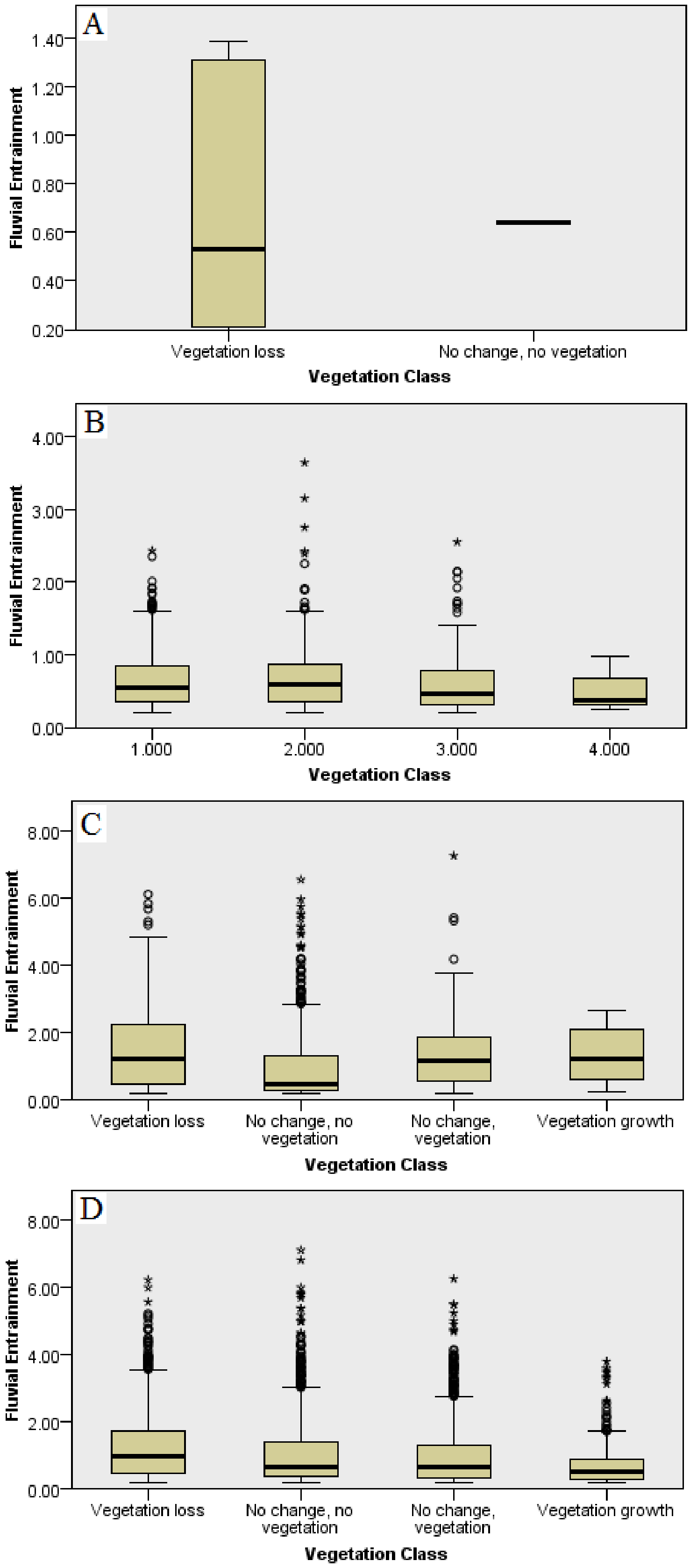

Figure 27 Values of fluvial entrainment occurring in each vegetation class in inner channel bed and bars (A), inner channel banks (B), benches (C) and macro-channel banks (D) in reach 3.

5.2.2.3 The control of vegetation on the occurrence of mass failure

In addition to extensive fluvial entrainment and deposition occurring during the 2011 flood, large areas of the channel underwent mass failures. Such mass failures ranged in size from 65 m^2 to 3023 m^2 in reach 2 (Figure 28) and 21 m^2 to 10953 m^2 in reach 3 (Figure 30). These failures are most pronounced in the lower gradient reaches. In order to assess the potential role of riparian vegetation in instigating or impeding mass failure, the vegetation class within and adjacent to each mass failure, was analysed.

The most extensive vegetation class within each of the mapped mass failures was noted and compared across the three study reaches. A similar method was also used to analyse the most spatially extensive vegetation class in the surrounding area, to determine if there was a relationship between the occurrence of mass failures and vegetation (and adjacent) cover. As no mass failures occurred in the reach 1, mass failures which occurred in reach 2 and 3 were evaluated.

Reach 2

Figure 28 Mass failures occurring in reach 2.

During the January 2011 flood, 10 mass failures were mapped in reach 2. A significant number of these mass failures also occurred in areas of vegetation loss. However, Figure 29 shows that the greatest number of mass failures occurred in areas that were actually unvegetated prior to the flood.

The fewest mass failures occurred in areas that remained vegetated during and after the flood event (Figure 29). This pattern remains relatively consistent when the adjacent vegetation cover was analysed, using a fixed buffer width of 10m, 20m and 40m (Appendix 4). In the 10 metres around each mass failure, areas of vegetation loss are most common. However, this trend changes with the application of a 20m buffer, and areas that were unvegetated prior to the flood occur more frequently. When a 40m buffer is applied, the number of mass failures occurring within the buffer zones in vegetation classes becomes equal. There were fewer mass failures in vegetated areas that remained vegetated during and after the 2011 flood.

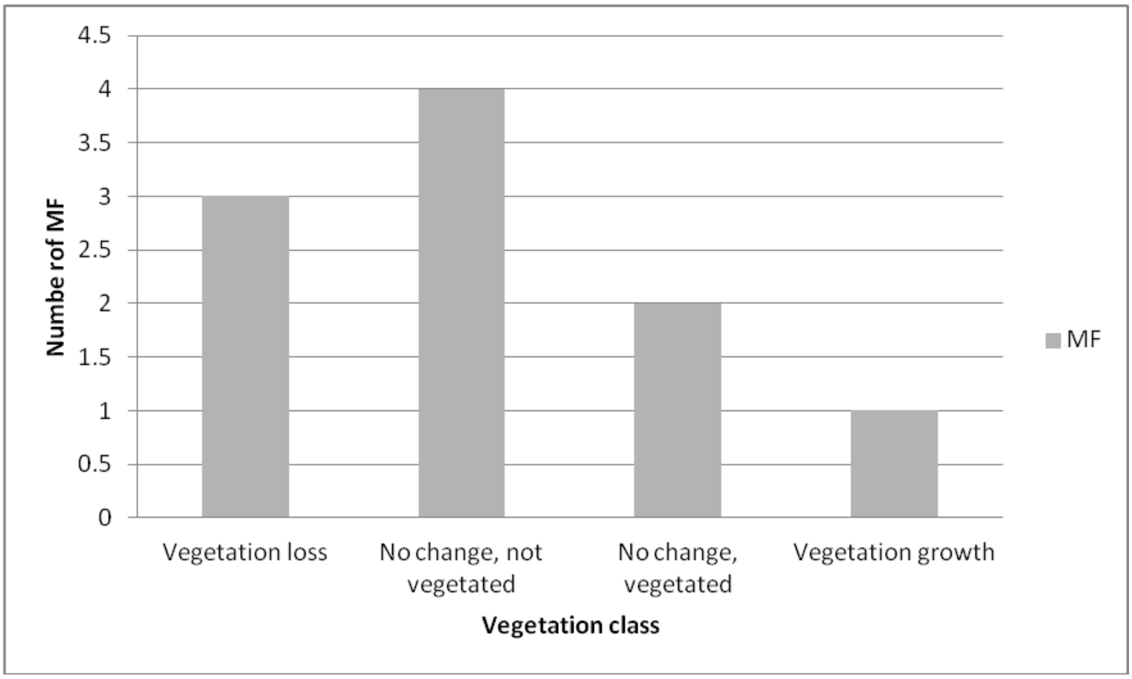

Figure 29 Number of mass failures occurring within each vegetation class in reach 2.

Reach 3

Figure 30 Mass failures occurring in reach 3.

A high number also occurred in areas that were unvegetated prior to the flood and considerably fewer mass failures occurred in areas that remained vegetated after the flood. Reach 3 is characterised by extensive mass failures (shown in Figure 30) with 137 mass failures occurring during the January 2011 flood. More than half of the mapped mass failures in reach 3 occurred in areas of vegetation loss (Figure 31).

The application of buffer zones showed a different trend (Appendix 4). When a 10m, 20m and 40m buffer was applied, the area surrounding mass failures occurred more frequently in the areas that were unvegetated prior to the 2011 flood. In all three applied buffers, few of the mass failures occurred in vegetated areas.

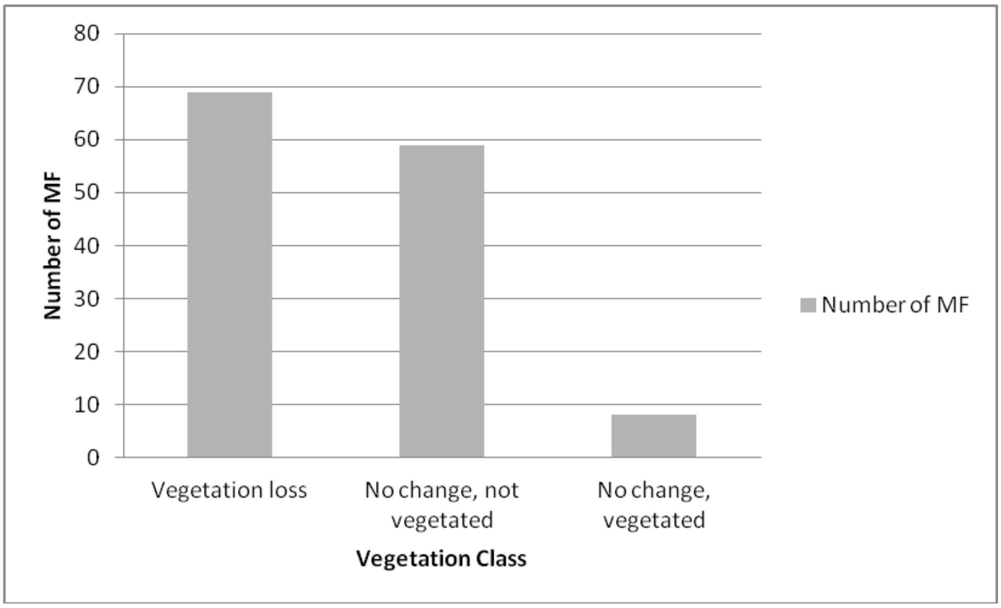

Figure 31 Number of mass failures occurring within each vegetation class in reach 3.

5.3 Key Findings

The purpose of this study was to investigate the role of woody riparian vegetation in enhancing or inhibiting processes of erosion and deposition during two large magnitude floods in January 1974 and 2011, affecting the Lockyer Valley, QLD. Between 1971 and 1974, there were relatively consistent trends in relation to patterns of geomorphic change and the absence or presence of vegetation. In reach 1, geomorphic change resulting from the January 1974 flood event was less significant than the other studied reaches and the most important changes occurred in areas of vegetation loss. This is in contrast to the other studied reaches, where the most significant physical changes occurred in areas that were unvegetated before the catastrophic flooding of 1974.

Similar trends were also apparent from analysis of the 2009 – 2011 time series. In reach 1 and 3, vegetated areas appear to be associated with the most significant areas of deposition. The least amount of deposition, and likewise the greatest areas of fluvial entrainment occurred in areas of vegetation loss, or areas that were unvegetated prior to the 2011 flood. However, a different trend was evident in reach 2. Areas of vegetation loss, and areas that were unvegetated in 2009, represent the areas of most significant overall geomorphic change, with high values of both deposition and fluvial entrainment, highlighting reach-scale variations in response to extreme events. This will be discussed further in the following chapter.

During the catastrophic flooding of January 2011, large sections of the channel experienced mass failures. Significantly fewer mass failures occurred in the upstream reaches than the lower catchment. Mass failures in reach 2 most frequently occurred in areas that were unvegetated prior to the 2011 flood, and this trend remained consistent when the vegetation cover of the adjacent area was also assessed. Extensive mass failures occurred in reach 3, and occurred most frequently in areas of vegetation loss. However, when a buffer was applied to encompass the effects of adjacent bank cover mass failures occurred most commonly in areas that were unvegetated. In both reaches, very few cases occurred where vegetation remained or was expanding between 2009 and 2011.

6. Discussion

Two major analyses were undertaken in this project. The first was the classification of woody vegetation in the Lockyer, and change detection between the two time periods of 1971-1974 and 2009-2011. The second was the interpretation of these classifications in relation to erosion and deposition during the 1974 and 2011 flood events. This chapter discusses the results of this analysis in relation to the aims of the study, and the implications of these results while also addressing the limitations of the study.

6.1 Vegetation classification and change detection

The aims of this section were to, firstly, classify woody vegetation in selected study reaches of the Lockyer Valley, and secondly, to quantify change in vegetation extent through time; specifically examining the periods between 1971 to 1974 and 2009 to 2011. Sections 5.1.1 and 5.2.1 discussed the uncertainty encountered in discriminating between land cover classes.

Uncertainly in the 1971 and 1974 classifications was largely due to issues in discriminating between water and woody vegetation. This can be attributed to a combination of limited spatial and spectral resolution and the similar tone of woody vegetation and water. Although there are significant limitations of black and white aerial photography in terms of spatial and spectral resolution, historical aerial photography is the largest source of information available for research of long term vegetation dynamics. Distinction between water and woody vegetation was also somewhat problematic in the classification of the 2009 orthophoto. This is also reflected in the low estimate of user's accuracy in the water class (class 2) in the 2009 error matrix (Appendix 3.8 – 3.10). This figure indicates a low probability that a pixel classified as water actually represents water in the field. As discussed in section 3.1, although vegetation and water have distinct spectral signatures in the near infrared spectral region, these differences are negligible in the visible region of the spectrum. Consequently, a key limitation of the data used in this study is the limited spectral content of the black and white and colour orthophotos - specifically the absence of a near infrared band proven useful for vegetation mapping.

Other studies have recognised difficulties in discriminating between dark water bodies and vegetation when using true colour aerial photography and have resolved this problem by applying a water mask (Yang 2007). However, due to the extent of vegetation covering the water, the application of a water mask in this study was unsuitable, as it resulted in the removal of a significant amount of riparian

vegetation. As there was a high concentration of sediment in the water following the 2011 flood, the 2011 classification achieved higher accuracies. Discrimination between woody vegetation and pasture was a source of error in both time periods. Heavily cropped or vegetated pasture was classified as woody vegetation due to similar spectral characteristics. The use of higher spectral resolution data is likely to reduce this error. In addition, the use of data with a limited spectral resolution prevented the detailed analysis of woody vegetation type.

Several limitations must be considered in relation to the image classification and change detection completed in this study. These reflect restrictions in data availability, time and capacity. Data availability was one of the most significant restrictions in the image classification procedure. As discussed in section 2.3, the mapping of the narrow linear distribution of riparian vegetation requires a high spatial resolution. Most satellite based imagery commonly used in the mapping of vegetation, such as Landsat, doesn't meet these requirements. In addition, due to the relatively recent development of these technologies, there is also a limited availability of historical satellite data. Although this study encountered limitations in the data related to limited spectral resolution, the orthophotos used were the most appropriate data type considering the spatial and temporal requirements of this study.

The completion of an accuracy assessment is important for understanding the results of the classification and should be taken into consideration in decision making, or using these results for further study (Lu et al. 2004). An error matrix is the most common way to achieve this, and has been recommended by previous studies (Congalton 1991). This involves examining a sample of pixels from the thematic map against field or reference data (Richards 1999). This study used a random sampling method to complete the accuracy assessment. Random sampling is common in selecting points for accuracy assessment. However, the main disadvantage of random sampling is that it tends to under sample small classes, which can affect the overall accuracy (Lillesand et al. 2004). In this study, water bodies covered the smallest areas and as a result were under sampled in the accuracy assessment. To overcome this issue in future and calculate more reliable results, stratified random sampling can be used by selecting a minimum number of samples from each class. Furthermore, an increase in the number of samples may also make accuracy assessment results more reliable (Congalton 1991).

A key limitation in this project was the limited availability of field or reference data to complete the accuracy assessment and this is a common problem when undertaking historical analysis using aerial photography. As discussed in section 4.3.2, the completed classifications were validated by selecting a sample of points and examining them against the orthophotos. This method provides an indication of

the accuracy of the classifications. However, when assessments are conducted from the same data set as was used to train the classifier, accuracy results can be over-estimated (Congalton 1991).

6.2 Catastrophic flooding in the Lockyer Valley

The geomorphic effectiveness of large, rare floods in relation to smaller, more frequent floods has been debated since Wolman and Miller (1960) questioned the importance of floods as geomorphic agents. While large discharges are necessary, they are not always sufficient for significant channel change (Miller 1995).There are a range of factors that determine the geomorphic effectiveness of floods, and the response of the channel. The results in the previous chapter consider the channel response in relation to vegetation cover in catastrophic floods affecting the Lockyer Valley in January 1974 and 2011.

The January 1974 flood was the largest flood affecting the Lockyer Valley in the 20th Century. Although the short term record of stream gauge data prevents analysis of the magnitude of the 1974 flood in the upper Lockyer, evidence suggests impacts were more severe in the lower Lockyer catchment, and the Brisbane catchment (Snowy Mountains Engineering Corporation 1975). Flood frequency analysis shows that the January 1974 flood was significant in the lower catchment, with a recurrence interval of more than 20 years. However, the failure of the stream gauge during the 2011 flood prevents comparison between the two events in the lower catchment. The January 2011 flood was the second largest affecting the Lockyer Valley in the last 100 years, second to the January 1974 event and one of the largest recorded in Australia (Thompson and Croke 2013). High stream powers caused significant geomorphic change during this event and the event had a recurrence interval of more than 45 years in the upper catchment.

6.2.1 The role of vegetation in catastrophic floods

Vegetation exerts a primary control on the fluvial system, impacting hydrology, sediment supply and the sensitivity of a landscape to flood induced channel change (Thorne 1990; Lawler et al. 1997). Some studies suggest the increased likelihood of catastrophic changes in highly modified or cleared catchments (Thorne 1990; Lawler et al. 1997; Fuller 2008) and there has been considerable dispute over the relative role of both natural and anthropogenic induced channel change in Australian rivers.

Geomorphic change during the 1974 flood

Although areas of deposition, fluvial entrainment or mass failure couldn’t be confidently defined due to the quality of the orthophotos, areas of significant geomorphic change were visible. The 1974

catastrophic flooding appeared to have a less significant impact on the bedrock confined reaches of the upper Lockyer valley. In reach 1, the most significant change occurred in areas where vegetation was removed by the flood. This area of the catchment remained well vegetated and had only minor impacts of land use. This would suggest that the impacts of the flood were not exasperated by the clearing of vegetation prior to the flood.

In the lower gradient, unconfined reaches, the results suggest a relationship between the areas of most significant geomorphic change and vegetation cover. In both cases, more geomorphic change occurred in areas that were unvegetated prior to the 1974 flood than in areas of vegetation loss. Little change occurred in areas that were vegetated before and after the 1974 flood or where vegetation cover increased. In both reach 2 and reach 3, riparian cover was less continuous than the upper catchment. Extensive clearing of catchment and floodplain vegetation can destabilise river banks, modifying the geomorphic effectiveness of floods (Brooks and Brierley 1997). These results suggest that land use practices of the lower catchment and the extensive clearing of riparian vegetation have reduced the stability of river banks in the lower reaches, potentially increasing the effectiveness of floods.

Deposition in the January 2011 flood

The January 2011 catastrophic flooding of the Lockyer Valley resulted in both significant deposition and erosion throughout the catchment and there were vast differences in patterns of change occurring between the three studied reaches. A number of factors are responsible for these differences including changes of land use practices and rates of vegetation clearing between the upper and lower catchment and spatial changes in channel gradient and valley configuration. The pre- and post- flood orthophotos (Figure 15) illustrate the magnitude of change which occurred during the 2011 event in reach 1. Floodwaters removed a considerable amount of vegetation from within the channel. Significant change occurred in the upper catchment during the 2011 flood, and most of this change was erosional. Deposition occurred over the small areas of the floodplain of reach 1 and was generally most significant in areas where vegetation was unchanged or expanding after the 2011 flood. The least occurred in areas unvegetated prior to the flood, or where vegetation was removed. However, along macro-channel banks, where stream power peaked (Thompson and Croke 2013), more significant deposition occurred in areas of vegetation loss.

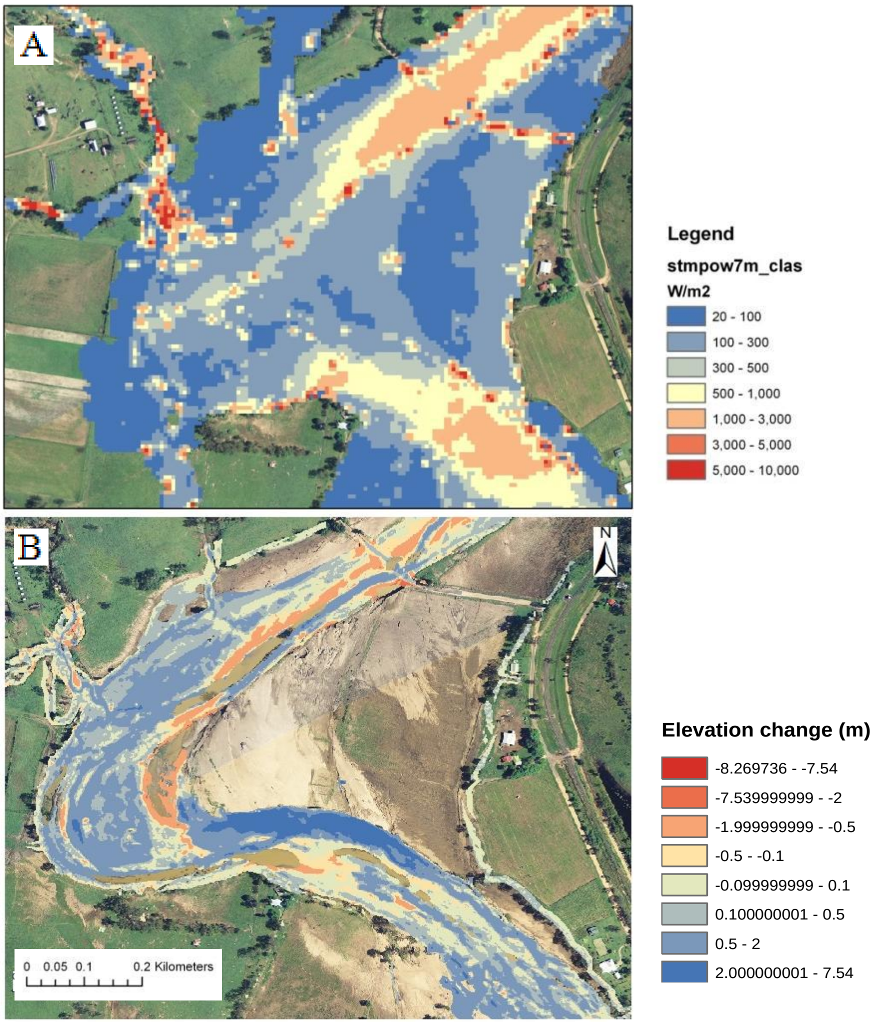

Figure 32 Reach 2 showing a reduction in stream power in blue (A) and increase in deposition in blue (B) at Lockyer Sidings after the 2011 flood. Adapted from Thompson and Croke (2013).

As the flood emerged from the confined reaches, and channel gradient and stream power reduced, deposition became the dominant process in both of the unconfined reaches, and this is highlighted in Figure 32. Floodwaters stripped a large proportion of riparian and within channel vegetation from reach 2, highlighted by the large amount of sediment on the floodplain and benches. Therefore, both fluvial entrainment and deposition were most significant in unvegetated areas while less erosion and deposition occurred in vegetated areas in reach 2. The macro-channel banks of reach 3 displayed this same trend. Along all other geomorphic units deposition was most significant in vegetated areas.

Fluvial entrainment

The upper catchment has experienced minimal anthropogenic disturbance in comparison to the lower two reaches. Floodwaters stripped sand, gravel, cobbles and boulders from benches, channel banks and bed of the upper catchment (Thompson et al. 2012). This is highlighted by pre- and post-flood orthophotos, as well as the extent of vegetation loss following the event. During the 2011 flood, reach 1 underwent substantial channel widening through lateral erosion and these changes were generally restricted to the macro-channel boundary. Although significant differences were found in values of fluvial entrainment between vegetated and unvegetated areas, it's likely that vegetation played a secondary role in controlling the extent of erosion.

Spatial changes in valley configuration can drastically influence the variation in erosion and deposition within a catchment (Thompson and Croke 2013). Large magnitude floods in steep valley settings are more likely to leave a lasting impression than floods of similar magnitude in low gradient floodplains (Miller 1995). In contrast to reach 1, the extent of fluvial entrainment in the unconfined reaches was reduced. Thompson and Croke (2013) demonstrate high stream power as the flood emerged from the confined reaches immediately upstream of reach 2, while the remainder of reach 2 experienced lower stream powers (also shown in Figure 32). As a result, more significant erosion occurred leading into reach 2, where channel bed gradient was higher and declined as slope reduced. Fluvial entrainment in the lower catchment was generally greatest in areas where vegetation was removed by the flood and areas that were unvegetated prior to the flood. Some studies have considered that changes in land use and the clearing of vegetation can increase the geomorphic effectiveness of large floods, resulting in more significant change (Brooks and Brierley 1997). It is likely that vegetation had a greater influence in determining patterns of fluvial entrainment, in relation to the upper catchment.

Mass failure

A number of studies have considered the role of riparian vegetation in preventing or inducing mass failures, and whether well vegetated river banks are more resistant to failure during drawdown of floodwaters (Docker and Hubble 2001;2009; Hubble et al. 2010). They have suggested that failure occurs more commonly on devegetated river banks, and that vegetation may reinforce banks during rapid drawdown that can trigger mass failure during floods. Mass failures that occurred during the January 2011 event were primarily related to wet flow processes, taking place as saturated material was removed from the bank face (Thompson et al. 2013). Previous work on the catastrophic flooding of the Lockyer demonstrated that mass failures occurred across a range of river lengths and catchment areas and were not spatially restricted to the downstream reaches of the catchment.

Large sections of the river channel in unconfined, lower gradient settings underwent significant mass failures during the 2011 flood. In reach 2, mass failures most commonly occurred in areas that were unvegetated prior to the flood and this trend was similar in the areas immediately adjacent to each mass failure. Mass failures were much more extensive in the downstream reaches of the catchment, where channel gradient is significantly reduced. Such failures occurred in both vegetated and unvegetated areas, suggesting no clear relationship between riparian vegetation and mass failure. Interestingly, mass failures in reach 3 were most common in areas where the adjacent area to each mass failure was unvegetated prior to the flood. This would suggest a relationship between the incidence of mass failure and the vegetation cover of the area surrounding the failure itself.

The number of mass failures occurring during the 2011 flood was significantly higher than previous events (Thompson et al. 2013) and these differences cannot solely be explained by increases in flood magnitude. The January 2011 event occurred during a wet summer, saturating the catchment. Docker and Hubble (2001) documented a similar response along the Nepean River and this study described large scale mass failures occurring on the banks largely cleared of native vegetation. The banks of the lower catchment have been extensively cleared for agriculture, and this is highlighted in Figure 33. Although clearing predates the 1974 flood event, this in combination with bank saturation, and subsequent pore pressure differences resulting from rapid drawdown, resulted in the loss of critical bank strength. The saturation of the banks is likely to have exasperated the influence of land clearing on mass failure, resulting in more extensive features throughout the catchment during the 2011 flood.

Figure 33 Pre-flood (A) and post-flood (B) orthophotos in 2009 and 2011, highlighting vegetation clearance for agriculture in reach 3 and a number of mass failures which occurred during the 2011 flood.

6.2.2 Channel response to extreme floods

Large magnitude flooding can have highly variable results on channel morphology. Section 2.1.3 discusses a range of channel responses documented in the large body of literature; debating the relative importance of large, rare floods or smaller, more frequent floods in modifying the landscape. Floods of similar magnitude and frequency can produce dissimilar channel response, at times within the same catchment (Costa 1974; Miller 1990; Costa and O'Connor 1995). A number of factors drive change during large magnitude floods, and can be invoked to explain the varied channel responses, and the role of riparian vegetation.

Channel change in response to the January 1974 and January 2011 floods varied considerably between the three studied catchments in the upper and lower Lockyer, and a number of factors are likely to have influenced the changes occurring and the relative influence of vegetation. Wide-scale clearing of riparian vegetation and stock disturbance of river banks have altered flood hydrology, increasing the capacity for floods to widen the channel (Brooks and Brierley 2000). Brooks and Brierley (1997) note extensive channel widening on the Bega River, NSW which reflect the role of human disturbance on the catchment through extensive vegetation clearing. Modification of the river and riparian boundary conditions and the resulting increase in the geomorphic effectiveness of floods were primarily responsible for the catastrophic changes in channel morphology (Brooks and Brierley 1997; Brooks and Brierley 2000). These studies discuss the vegetation clearing and human alteration of rivers as a cause of catastrophic erosion during large magnitude floods. However, vegetation clearing is not a requirement for catastrophic channel change (Rutherfurd 2000). As flood flows dissipated over the floodplains in lower gradient, unconfined settings of reach 2 and 3, flood power was limited, reducing the potential for catastrophic erosion and depositional processes became more extensive (Thompson and Croke 2013). In contrast, the steep, confined settings of reach 1 experienced high stream power, resulting in significant channel enlargement through lateral erosion and a considerable loss of vegetation in the upper Lockyer catchment.

Spatial changes in valley configuration influenced patterns of erosion and deposition demonstrated in the Lockyer Valley. Variations in valley width and channel orientation can determine the severity of flood impacts (Miller 1995). Significant differences were found in the extent of erosion and deposition occurring between vegetated and non-vegetated areas. However, catastrophic changes occurred regardless of the vegetation cover in the upper catchment, and therefore, the impacts of the flood were not exaggerated by land use practices or vegetation clearing. Other studies have documented similar accounts of the impact of valley configuration on channel response. Miller (1995) suggests that large floods in steep narrow valleys are more likely to have a long-term influence on the

landscape than floods of comparable magnitude in wide, low gradient valleys. Fuller (2008) also noted discontinuous channel change after a large flood in New Zealand, causing catastrophic channel changes in some locations and relatively minor changes in others.

Secular changes in climatic regime have occasionally been invoked to explain catastrophic channel changes (Erskine and Warner 1988). These studies suggest that a series of large floods occurring in flood dominated periods can devastate river channels and floodplains and recovery occurs as floods ease. The impact of humans and associated land use changes are reduced to a secondary role to explain geomorphic response to floods. Some studies question the legitimacy of these climatic regimes (Kirkup et al. 1998) and others suggest the erosion occurring during flood dominated periods would not be so extensive had the catchment not been cleared of vegetation (Brooks and Brierley 2000). Rainfall patterns in the Lockyer certainly reflect periods of higher than average and lower than average rainfall and the catastrophic floods occurring in 1974 and 2011 occurred in especially wet periods. However, results of this study show clear trends between the areas of most significant erosion and areas that were unvegetated prior to the 1974 and 2011 floods.

Channel changes produced by extreme events can persist for a long period of time (Baker 1977). The January 1974 may have played a role in pre-conditioning the banks of the Lockyer Creek, for the catastrophic changes that occurred during the January 2011 flood. However, estimating the influence of the 1974 flood is tricky, and large time gaps between capture of orthophotos prevents the assessment of channel recovery after the 1974 flood.

Despite the questions surrounding the role of land use and the application of climatic regimes to explain morphological change in rivers, the vulnerability of rivers to change during extreme floods is certain (Rutherfurd 2000). Catastrophic changes occurred in the steep upper catchment as stream powers peaked, despite the well vegetated setting. Vegetation may have played a more significant role in the lower, highly altered catchment where stream powers and flood magnitude were reduced.

6.4 Limitations

This study has provided a preliminary assessment of the role of vegetation during the catastrophic floods affecting the Lockyer Valley in January 1974 and January 2011. There are several limitations relating to the procedure undertaken to ascertain the role of vegetation in large floods due to the restricted nature of the project. Due to the limited time and capacity, it was only possible to undertake a detailed analysis of three reaches in contrasting valley settings. This provided a clear understanding of the role of vegetation during the January 1974 and 2011 floods. However, factors such as valley configuration, the channel response to the floods, and the extent of vegetation varied considerably through the catchment. Consequently, the small scale of the study meant that it wasn't possible to fully capture this variation.

There were also limitations present in the data used and created, affecting the accuracy and precision of the study. To account for error associated with false estimates of elevation change due to changing river height or ground cover, visible water bodies and areas of less than 0.2m+/- erosion and deposition were removed from further analysis. However, this may also result in the over- or underestimation in some parts of the DEM (Croke et al. 2013b). Estimates of erosion and deposition assessed in incorrectly classified pixels will affect the overall result of the study.

A further limitation is the restricted availability of long term stream gauge data for the Lockyer Valley. Much of the catchment has a relatively short record of stream gauge data, which prevented the analysis of the magnitude of the January 1974 flood in the upper Lockyer. Flood frequency analysis of the lower Lockyer and Brisbane catchments can only give an indication of the magnitude of the flood event affecting the upper reaches of the Lockyer catchment. Furthermore, widespread failure of stream gauges before the flood peak in 2011 also prevented a comparison between the magnitude of the 1974 and 2011 floods, which would have aided in interpreting the role of vegetation and the impact of changing land use in the period between 1974 and 2011.

6.5 Recommendations

6.5.1 Vegetation classification

This study has provided a basis to ascertain the influence of vegetation during catastrophic floods on the three studied reaches and several suggestions can be made for the future work for the Lockyer catchment. Considering the limitations of this study, similar work could be conducted in future to assess the role of vegetation in catastrophic floods of the Lockyer Valley. Future studies should examine alternative approaches to vegetation mapping. A number of studies have discussed the usefulness of an object oriented approach when classifying vegetation from high resolution aerial photography. Although it was beyond the scope of this project, an object oriented approach may improve accuracies of vegetation classifications, especially concerning difficulties in distinguishing between woody vegetation and pasture. Limited spectral resolution of the ortho-photos was considered a limitation of this project. Therefore similar studies utilising data with an improved spectral resolution may also improve accuracies and resolve issues between the separation of dark water bodies and woody vegetation. Furthermore, different types of woody vegetation will influence bank stability to a varying degree. The use of data with a greater spectral resolution may be more valuable in the discrimination between woody vegetation types.

6.5.2 Lockyer catchment

One of the most significant limitations recognised in the study was the small scale. As discussed above, time restrictions prevented analysis on a larger scale or catchment scale. A catchment wide scale or further studies assessing a greater area of the catchment would be more likely to capture the variation present in factors affecting the role of vegetation, thereby giving a more realistic understanding of the role of vegetation during large floods. Jordan (2011a) has also previously suggested that detailed hydrological modelling of the January 2011 flood could be undertaken to quantify the influence of vegetation on bank stability during the flood event.

Monitoring of land use changes and rates of vegetation change should continue. This information can be used to assess the extent of change occurring within the Lockyer Valley, and similar research can be undertaken in future floods of the region. The lower catchment has undergone significant development and the extent of woody riparian vegetation is much less than the upper reaches of the catchment. The results of this study show that vegetation clearing may exasperate erosion during large magnitude flooding events. Planning and management of riparian areas may help to mitigate the

negative consequences of development in the catchment, and reduce the implications of vegetation clearing on stream bank erosion.

7. Conclusions

This study aimed to evaluate the role of vegetation in catastrophic floods through enhancing or inhibiting geomorphic change. Although further research into the role of vegetation is recommended, this study provided a preliminary assessment into the effect of vegetation on erosion and deposition during the large floods of January 1974 and 2011.

The results of this study demonstrate that change occurring as a result of the January 1974 flood was much more significant in the lower reaches of the catchment relative to the upper reaches of the catchment and several reasons may explain these trends. Flood magnitude affecting the lower reaches of the catchment was likely to be greater in relation to the upper catchment. However, these results also suggest the unvegetated banks of reach 2 and reach 3 were more susceptible to rapid geomorphic change during the flood event.

The results showed similar trends in deposition occurring during the January 2011 flood in reach 1 and reach 3. In these areas vegetation was generally associated with greater deposition and less significant fluvial entrainment. In contrast, in reach 2, unvegetated areas and areas of vegetation removal were associated with higher levels of both erosion and deposition. However, this is not to suggest that vegetation was the most important control of change during the flood events. It is likely that multiple factors contributed to the catastrophic changes that occurred during the large magnitude floods.

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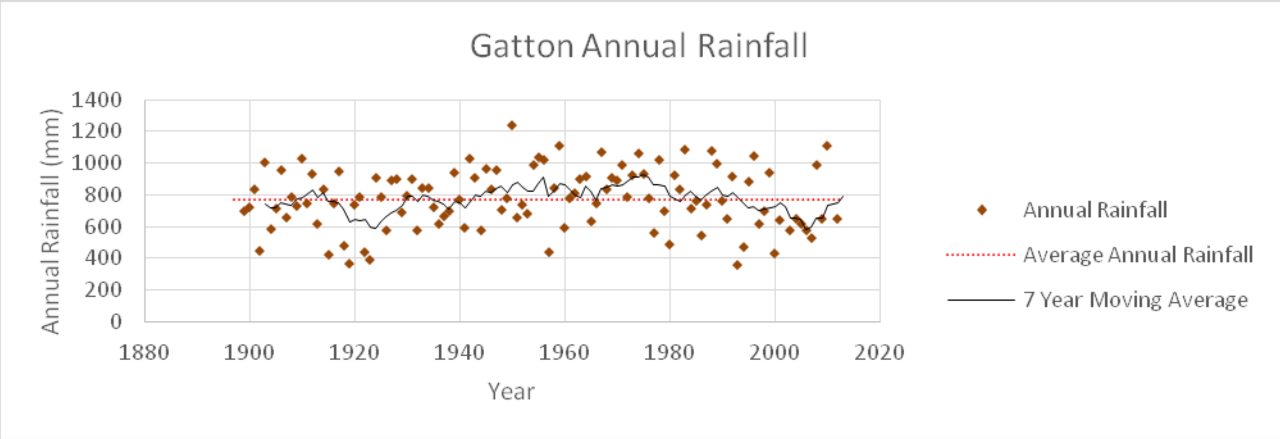
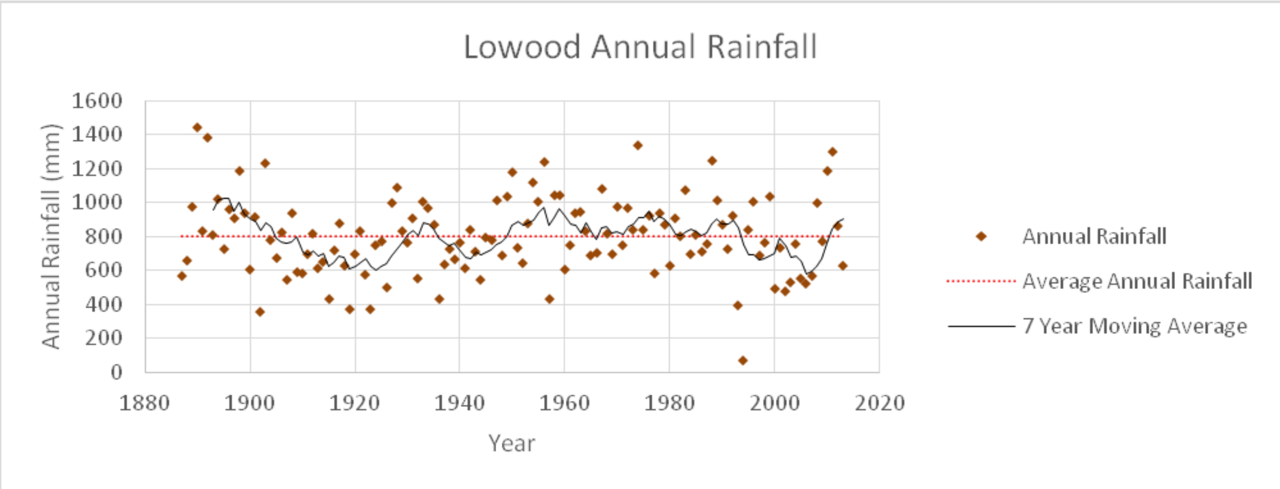
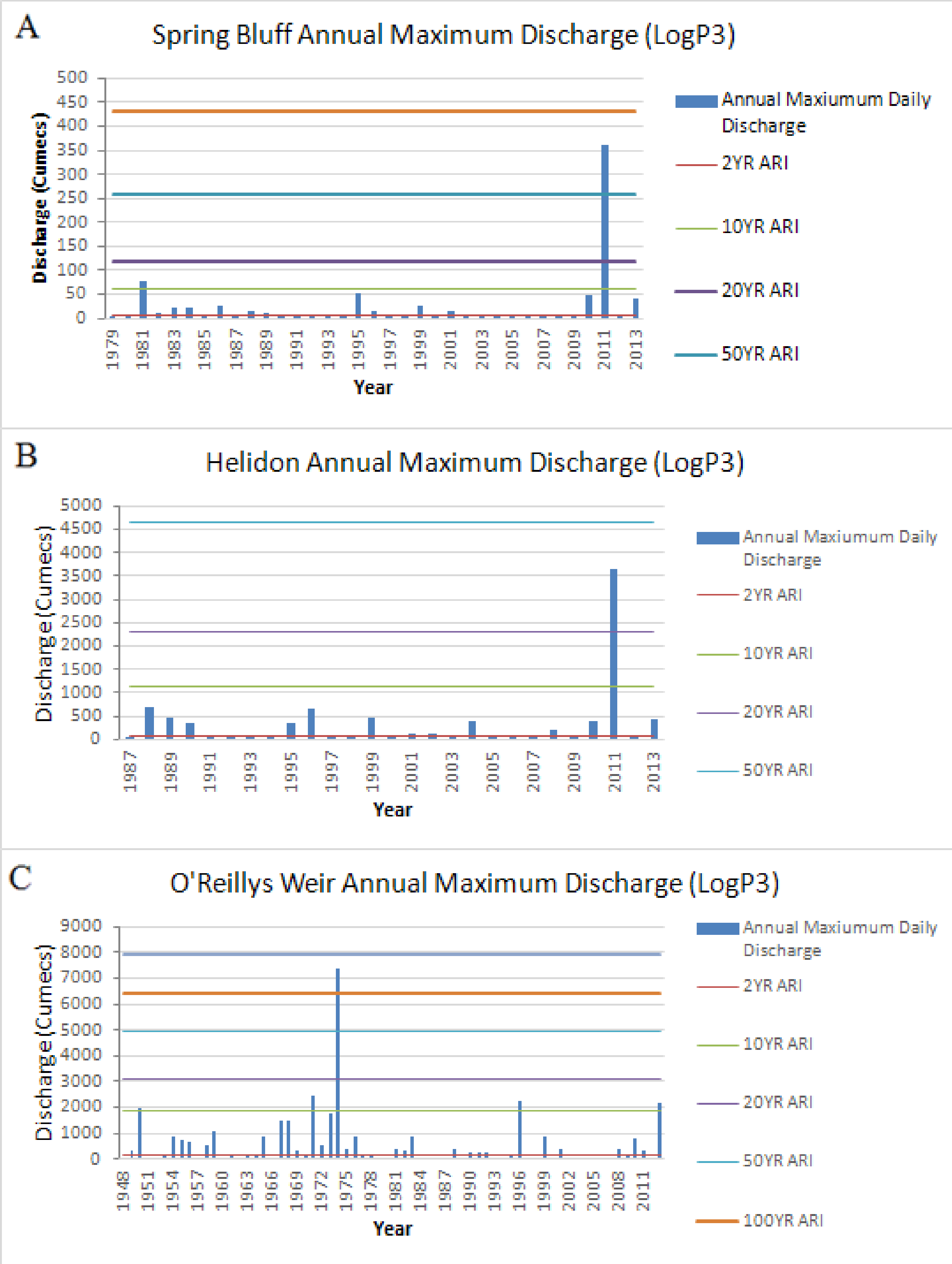
Appendices

Appendix 1



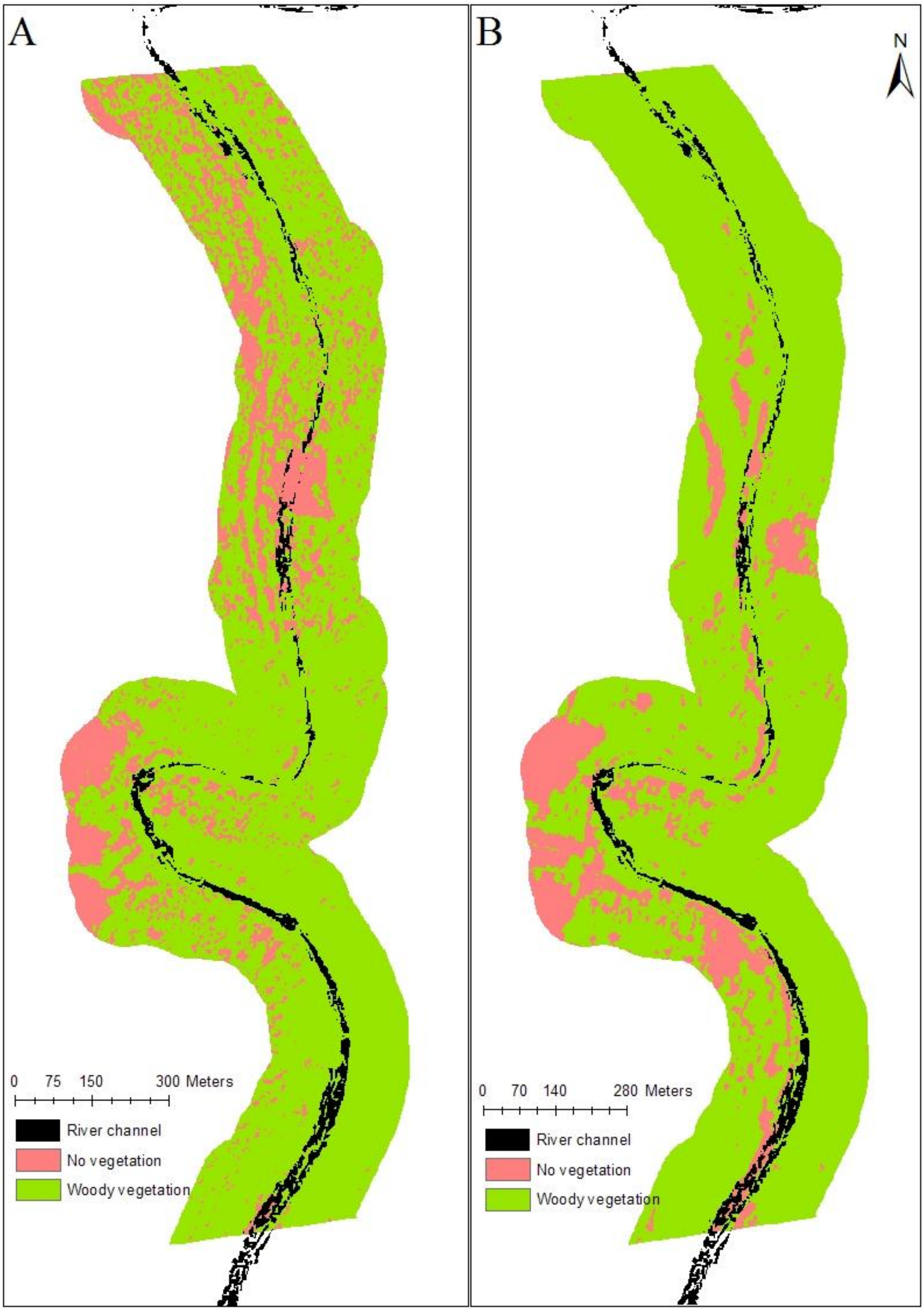


A1.1 Total Annual Rainfall at Gatton and Lowood with a 7 year moving average (black line), a typical ENSO cycle. Dashed line shows the long term average annual rainfall for Helidon.

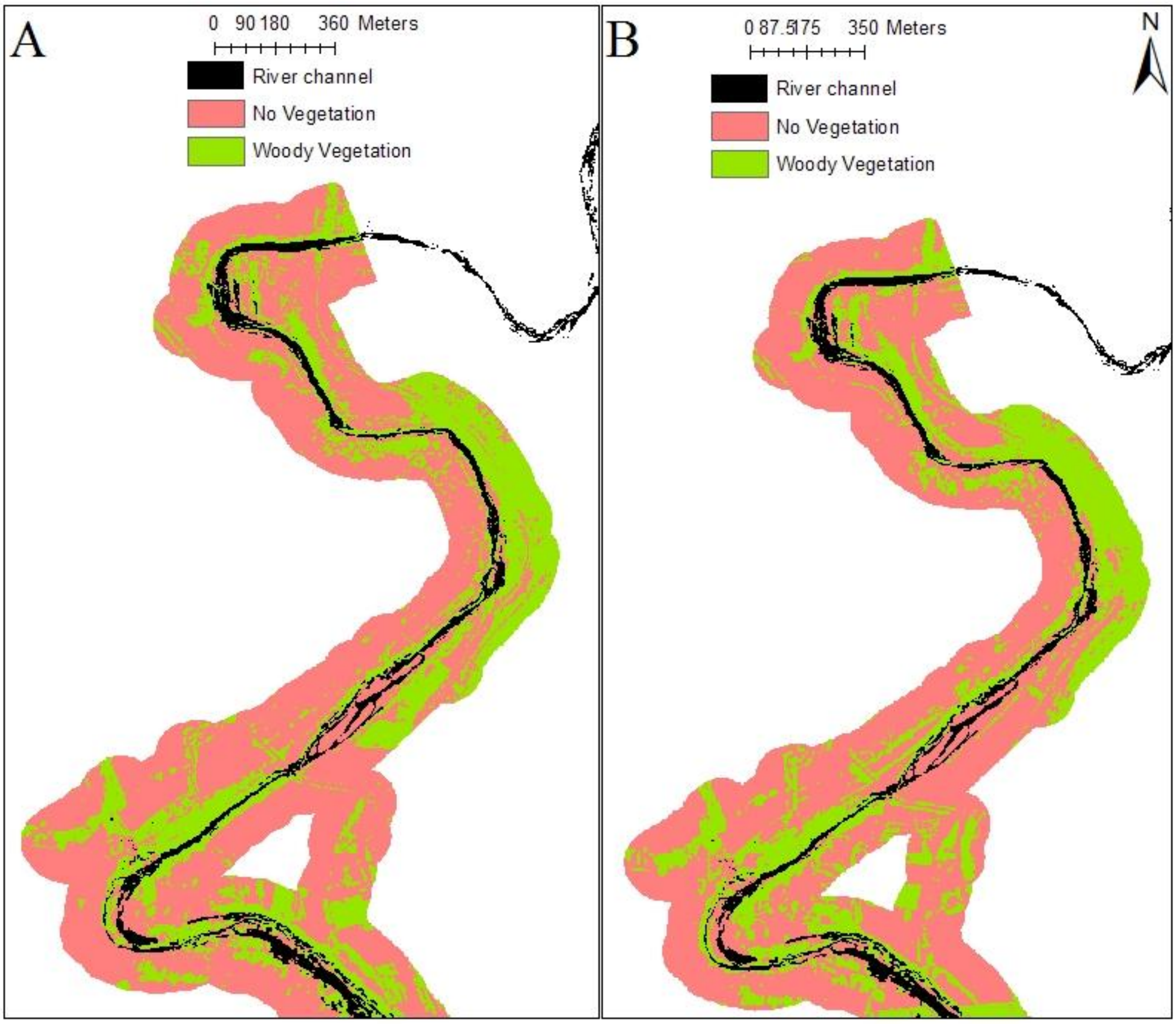


A1.2 Flood history analyses for the Lockyer Catchment at Spring Bluff (A), Helidon (B) and O'Reilly's Weir (C) displaying maximum daily discharge. Annual recurrence intervals are based on the log-Pearson III flood frequency analysis.

Appendix 2



A2. 1 Vegetation classification for reach in 1971 (A) and 1974 (B), showing areas of woody vegetation, no vegetation and the river channel.



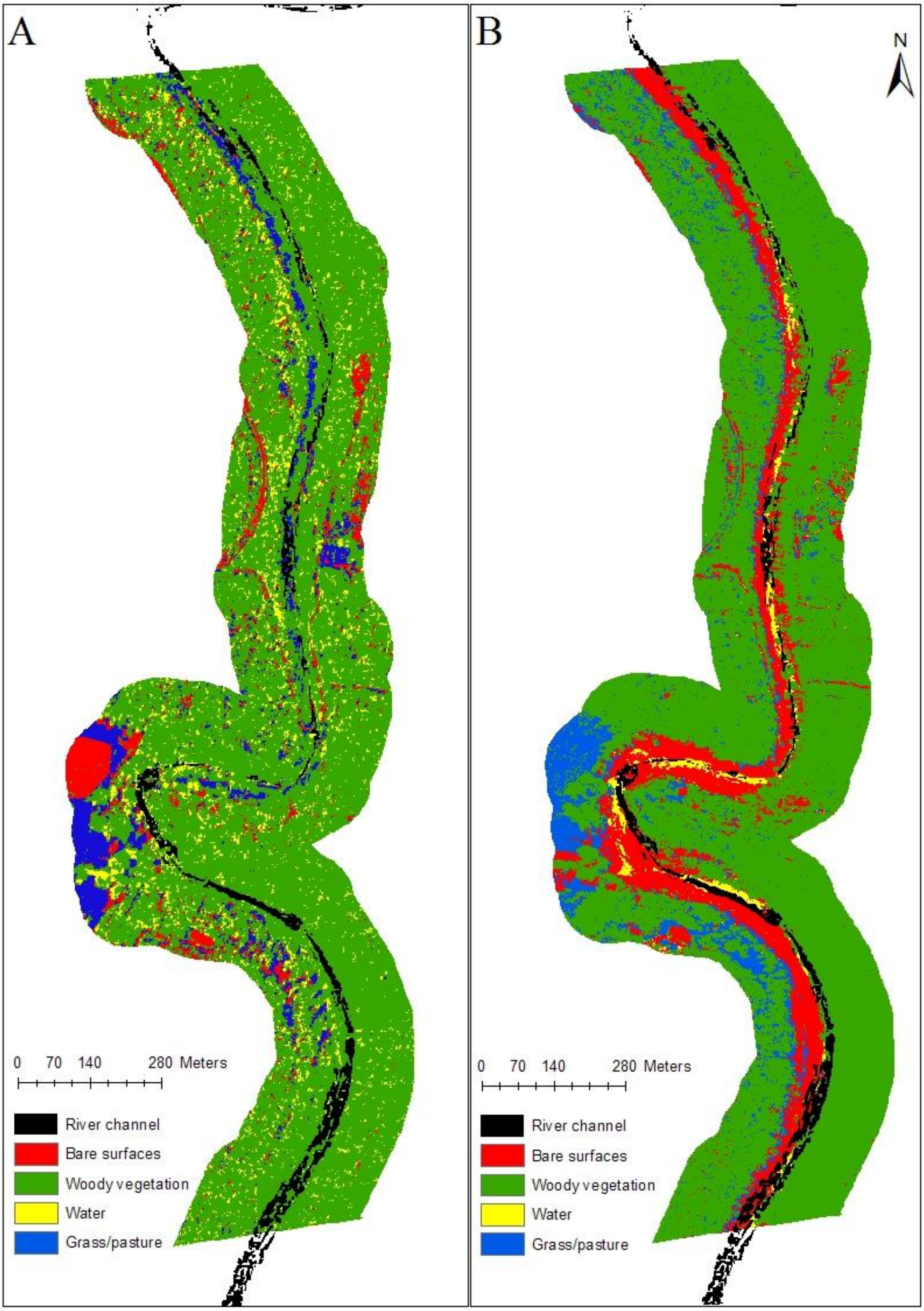
A2.2 Vegetation classification for reach 2 in 1971 (A) and 1974 (B).

A2. 3 Vegetation classifications for reach 3 in 1971 (A) and 1974 (B).

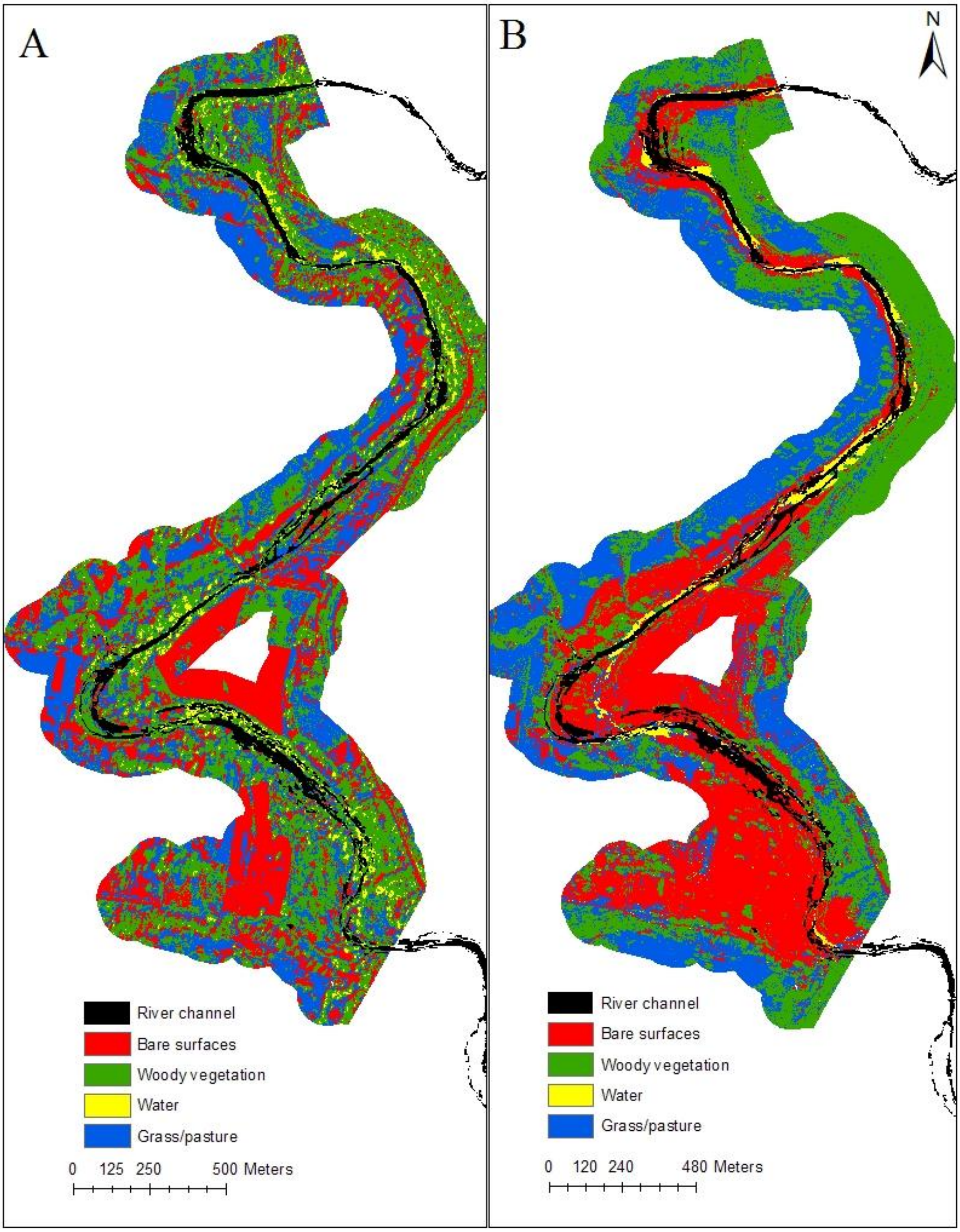
A2. 4 Area of and cover class in the 1971 and 1974 supervised classifications.

Reach 1: 1971	**Class**	**Percent Area**
	Woody Vegetation	77.7
	No vegetation	22.3
Reach 1: 1974	**Class**	**Percent Area**
	Woody Vegetation	85.4
	No vegetation	14.6
Reach 2: 1971	**Class**	**Percent Area**
	Woody Vegetation	35.5
	No vegetation	64.5
Reach 2: 1974	**Class**	**Percent Area**
	Woody Vegetation	34.4
	No vegetation	65.6
Reach 3: 1971	**Class**	**Percent Area**
	Woody Vegetation	25.6
	No vegetation	74.4
Reach 3: 1974	**Class**	**Percent Area**
	Woody Vegetation	25.8
	No vegetation	74.2

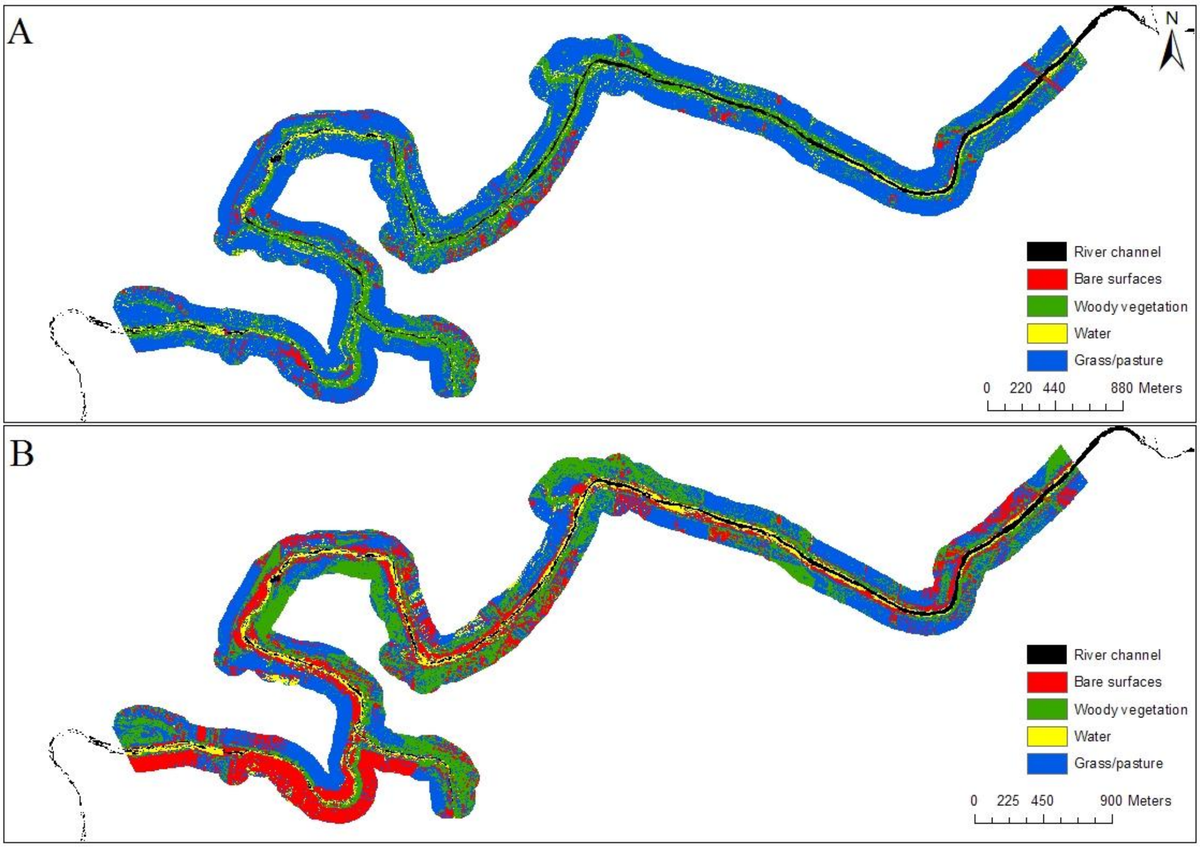
Appendix 3



A3.1 Vegetation classification for reach 1 in 2009 (A) and 2011 (B).



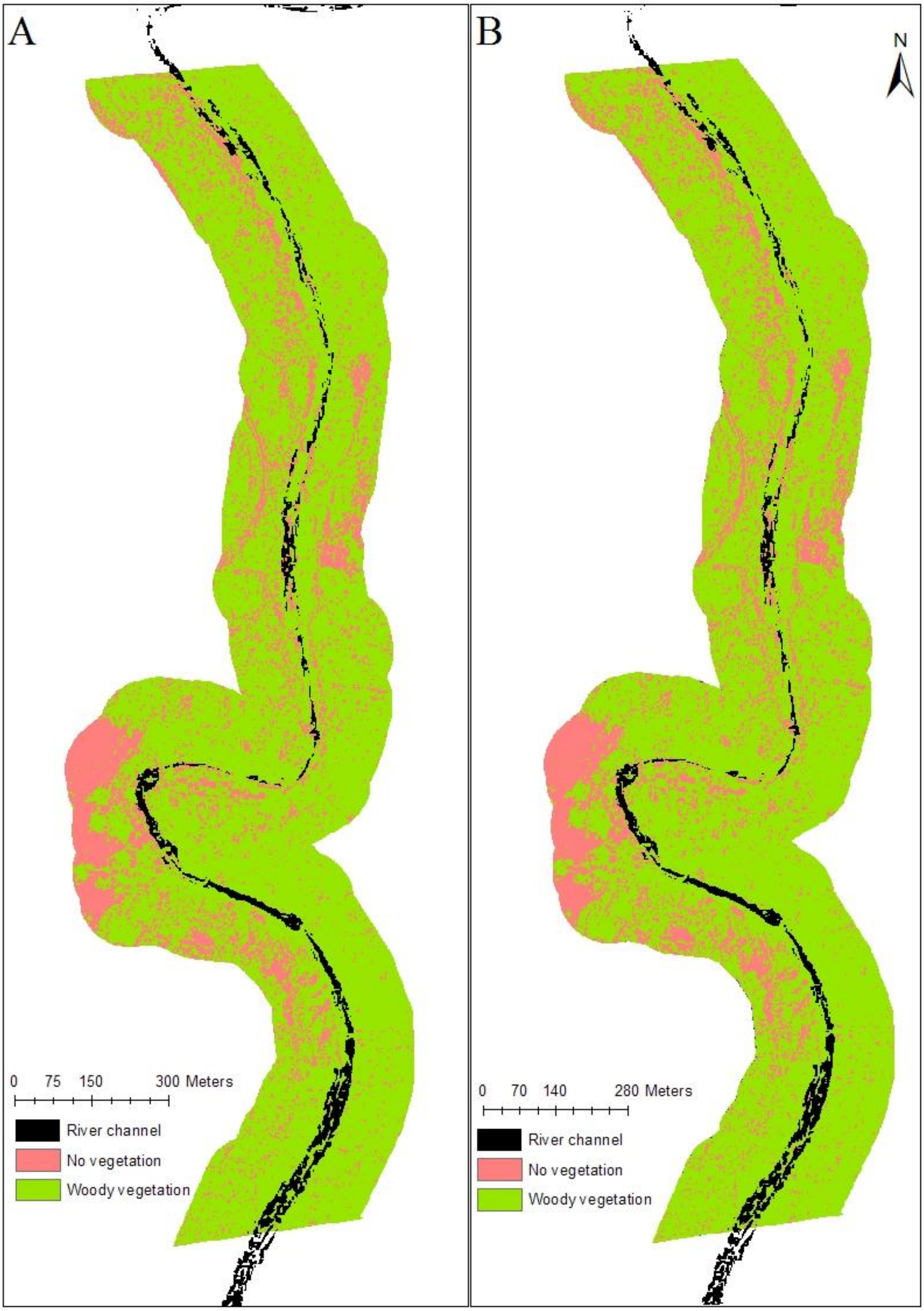
A3. 2 Vegetation classifications for reach 2 in 2009 (A) and 2011 (B).



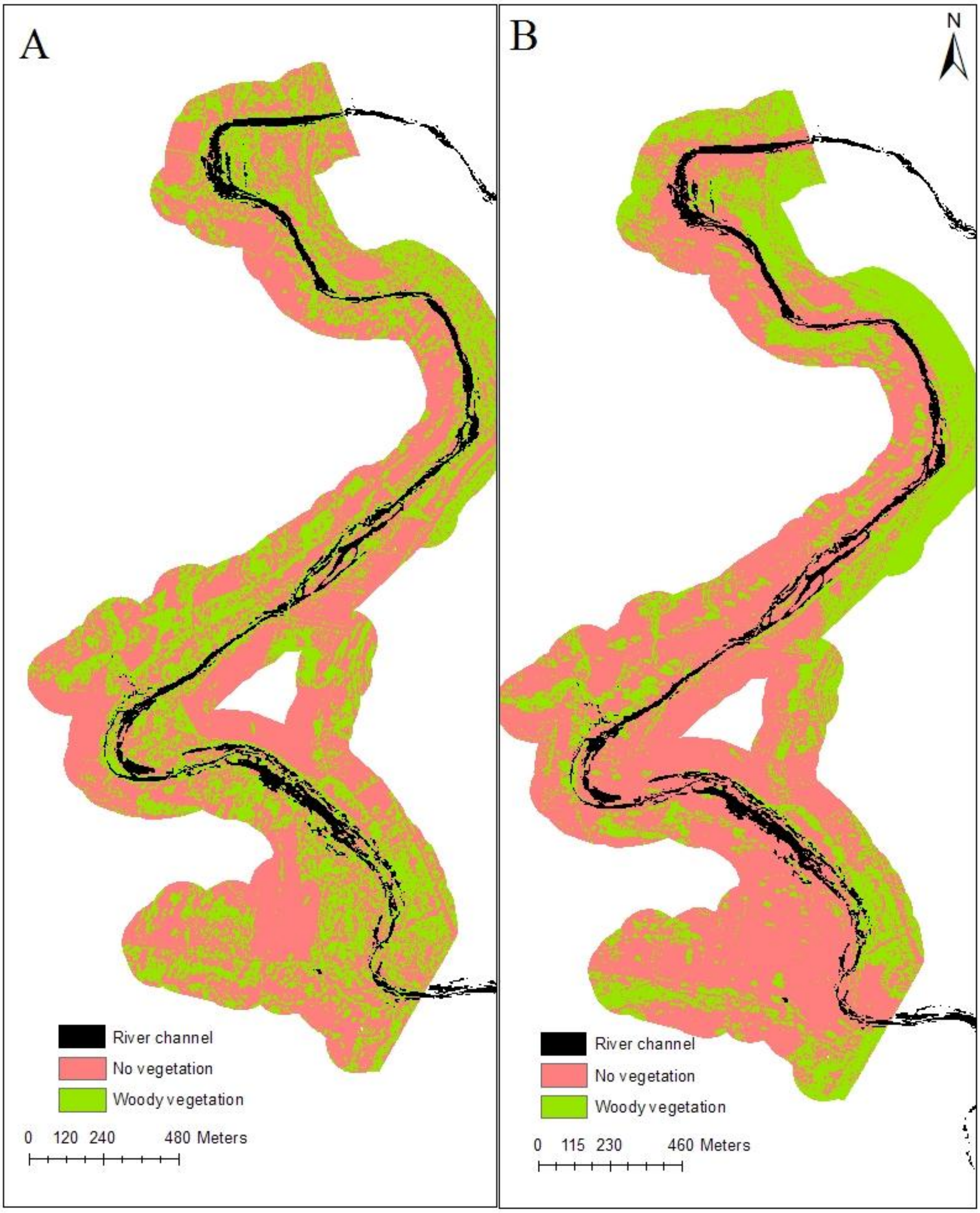
A3. 3 Vegetation classifications for reach 3 in 2009 (A) and 2011 (B).

A3. 4 Area of each land cover class in the 2009 and 2011 supervised classifications

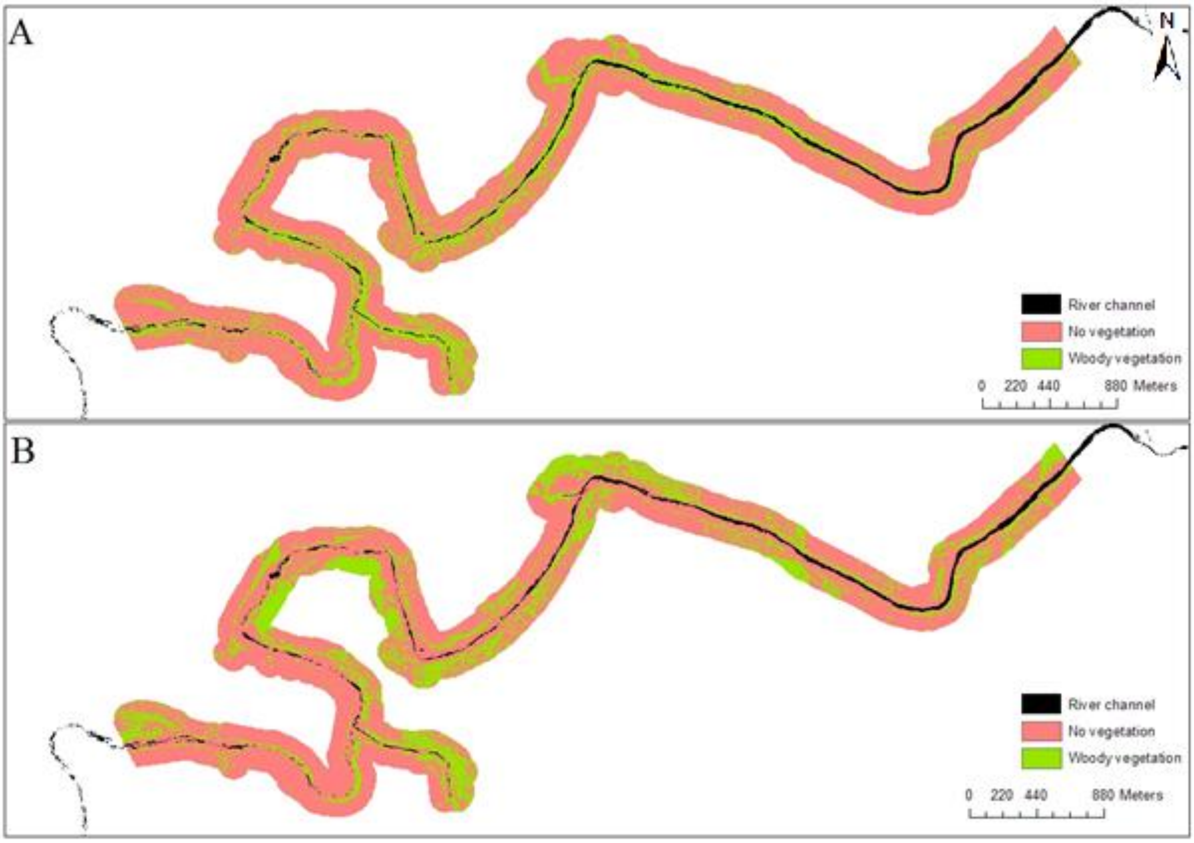
Reach 1: 2009	**Class**	**Per cent Area**
	Bare Surfaces	6.021418419
	Woody Vegetation	80.44891274
	Grass/Paddock	6.315964059
	Water	7.213704786
Reach 1: 2011	**Class**	**Per cent Area**
	Bare Surfaces	15.88080723
	Woody Vegetation	74.37029854
	Grass/Paddock	7.820035314
	Water	1.928858913
Reach 2: 2009	**Class**	**Per cent Area**
	Bare Surfaces	26.39242575
	Woody Vegetation	41.68651525
	Grass/Paddock	27.61404706
	Water	4.30701193
Reach 2:2011	**Class**	**Per cent Area**
	Bare Surfaces	33.96823263
	Woody Vegetation	34.08449986
	Grass/Paddock	28.07801289
	Water	3.869254609
Reach 3: 2009	**Class**	**Per cent Area**
	Bare Surfaces	4.590493052
	Woody Vegetation	24.86368671
	Grass/Paddock	70.54582024
	Water	7.006955226
Reach 3: 2011	**Class**	**Per cent Area**
	Bare Surfaces	23.36179563
	Woody Vegetation	27.31690924
	Grass/Paddock	39.62511982
	Water	9.696175301



A3. 5 Reclassified supervised classification showing non-vegetated and vegetated areas in reach 1 in 2009 (A) and 2011 (B).



A3.6 Reclassified supervised classification showing non-vegetated and vegetated areas in reach 2 in 2009 (A) and 2011 (B).



A3.7 Reclassified supervised classification showing non-vegetated and vegetated areas in reach 3 in 2009 (A) and 2011 (B).

A3.8 Error matrix: Reach 1, 2009

		Classification					
Map		**1**	**2**	**3**	**4**	**Total**	**Users accuracy**
	1	5	3	0	0	8	**62.5**
	2	2	154	5	0	161	**95.65217391**
	3	1	4	13	0	18	**72.22222222**
	4	0	1	0	12	13	**92.30769231**
	Total	8	162	18	12	200	
	Producers accuracy	62.5	95.06173	72.22222	100		
	Overall accuracy	92					

1. Bare surfaces; 2. Woody vegetation; 3. Pasture; 4. Water

A3.9 Error matrix: Reach 2, 2009

		Classification					
Map		**1**	**2**	**3**	**4**	**Total**	**Users accuracy**
	1	31	0	0	0	31	**100**
	2	2	50	4	5	61	**81.96721311**
	3	29	28	47	1	105	**44.76190476**
	4	0	2	0	1	3	**33.33333333**
	Total	62	80	51	7	200	
	Producers accuracy	50	62.5	92.15686	14.28571		
	Overall accuracy	64.5					

A3.10 Error matrix: Reach 3, 2009

		Classification					
Map		**1**	**2**	**3**	**4**	**Total**	**Users accuracy**
	1	6	1	7	0	14	**42.85714286**
	2	0	21	12	6	39	**53.84615385**
	3	1	24	111	5	141	**78.72340426**
	4	0	4	0	2	6	**33.33333333**
	Total	7	50	130	13	200	
	Producers accuracy	85.71429	42	85.38462	15.38462		
	Overall accuracy	70					

Average accuracy (2009) 75.5

A3.11 Error matrix: Reach 1, 2011

		Classification					
Map		**1**	**2**	**3**	**4**	**Total**	**Users accuracy**
	1	29	6	0	1	36	**80.55555556**
	2	3	135	2	0	140	**96.42857143**
	3	0	4	14	0	18	**77.77777778**
	4	0	3	0	3	6	**50**
	Total	32	148	16	4	200	
	Producers accuracy	90.625	91.21622	87.5	75		
	Overall accuracy	90.5					

A3.12: Reach 2, 2011

		Classification					
Map		**1**	**2**	**3**	**4**	**Total**	**Users accuracy**
	1	61	14	1	0	76	**80.26315789**
	2	0	38	0	0	38	**100**
	3	4	14	55	0	73	**75.34246575**
	4	3	2	0	8	13	**61.53846154**
	Total	68	68	56	8	200	
	Producers accuracy	89.70588	55.88235	98.21429	100		
	Overall accuracy	81					

A3.13: Reach 3, 2011

		Classification					
Map		**1**	**2**	**3**	**4**	**Total**	**Users accuracy**
	1	52	7	4	0	63	**82.53968254**
	2	0	19	1	0	20	**95**
	3	0	13	86	0	99	**86.86868687**
	4	0	0	4	14	18	**77.77777778**
	Total	52	39	95	14	200	
	Producers accuracy	100	48.71795	90.52632	100		
	Overall accuracy	85.5					

Average accuracy (2011) 85.66667

Appendix 4

A4.1 Median: Reach 1 – IC Bed and Bars	
Vegetation Class	Deposition
Vegetation loss	.64250
No change, no vegetation	1.08800
No change, vegetation	.91350
Vegetation Growth	1.66500
Total	.84100
Median: Reach 1 – IC Banks	
Vegetation Class	Deposition
Vegetation loss	.64950
No change, no vegetation	.73200
No change, vegetation	.62400
Vegetation growth	.98600
Total	.68000
Median: Reach 1 – Benches	
Vegetation Class	Deposition
Vegetation loss	.51800
No change, no vegetation	.55700
No change, vegetation	1.34400
Vegetation growth	.65450
Total	.55800
Median: Reach 1 – MC Banks	
Vegetation Class	Deposition
Vegetation loss	.54100
No change, no vegetation	.32650
No change, vegetation	.33900
Vegetation growth	.35300
Total	.38100

A4.2 Median: Reach 2 – IC Bed and Bars	
Vegetation Class	Deposition
Vegetation loss	.95950
No change, no vegetation	.86350
No change, vegetation	.90150
Vegetation growth	.89750
Total	.91650
Median: Reach 2 – IC Banks	
Vegetation Class	Deposition
Vegetation loss	.88900
No change, no vegetation	.93700
No change, vegetation	.84200
Vegetation growth	.87000
Total	.87700
Median: Reach 2 – Benches	
Vegetation Class	Deposition
Vegetation loss	.57800
No change, no vegetation	.47100
No change, vegetation	.56600
Vegetation growth	.56900
Total	.53100
Median: Reach 2 – MC Banks	
Vegetation Class	Deposition
Vegetation loss	.58700
No change, no vegetation	.53250
No change, vegetation	.39050
Vegetation growth	.34500
Total	.45800

A4.3 Median: Reach 3 – IC Bed and Bars	
Vegetation Class	Deposition
Vegetation loss	1.94500
No change, no vegetation	2.00000
No change, vegetation	2.37500
Vegetation growth	2.55250
Total	2.02600
Median: Reach 3 – IC Banks	
Vegetation Class	Deposition
Vegetation loss	1.03200
No change, no vegetation	1.17050
No change, vegetation	1.09000
Vegetation growth	1.43400
Total	1.06400
Median: Reach 3 – Benches	
Vegetation Class	Deposition
Vegetation loss	.43100
No change, no vegetation	.36900
No change, vegetation	.45300
Vegetation growth	.39900
Total	.40700
Median: Reach 3 – MC Banks	
Vegetation Class	Deposition
Vegetation loss	.41450
No change, no vegetation	.37800
No change, vegetation	.35200
Vegetation growth	.31900
Total	.36800

A4.4 Significant differences between vegetation combinations for values of deposition in reach 1, 2 and 3.

Deposition	Geomorphic Unit	Class combination	p-value
Reach 1	Inner channel bed	Vegetation loss - vegetation growth	0.012
	Benches	Vegetation loss - no change, no vegetation	0.001
		No change, no vegetation - no change, vegetation	0.021
	Macro-channel banks	Vegetation loss - no change, vegetation	0.011
Reach 2	Inner channel bed	Vegetation loss - no change, no vegetation	0.027
	Benches	Vegetation growth - no change, no vegetation	0.037
		No change, no vegetation - no change, vegetation	0.004
		Vegetation loss - no change, no vegetation	<0.001
	Macro-channel banks	Vegetation growth - no change, no vegetation	<0.001
		Vegetation loss - vegetation growth	<0.001
		No change, no vegetation - no change, vegetation	<0.001
		Vegetation loss - no change, vegetation	<0.001
Reach 3	Inner channel bed	Vegetation loss - no change, vegetation	<0.001
		Vegetation loss - vegetation growth	0.048
		No change, no vegetation - no change, vegetation	0.009
	Benches	Vegetation loss - vegetation growth	0.009
		Vegetation growth - no change, vegetation	0.001
		No change, no vegetation - no change, vegetation	0.028
	Macro-channel banks	Vegetation loss - vegetation growth	<0.001
		Vegetation loss - no change, no vegetation	0.01
		No change, no vegetation - no change, vegetation	<0.001
		Vegetation loss - no change, vegetation	<0.001
		Vegetation growth - no change, no vegetation	<0.001
		Vegetation growth - no change, vegetation	<0.001

A4.5 Median: Reach 1 – IC Bed and Bars	
Vegetation Class	Fluvial Entrainment
Vegetation loss	.57500
No change, no vegetation	.87000
No change, vegetation	.64000
Vegetation growth	1.96000
Total	.66000
Median: Reach 1 – IC Banks	
Vegetation Class	Fluvial Entrainment
Vegetation loss	.80000
No change, no vegetation	.75000
No change, vegetation	.86000
Vegetation growth	.70000
Total	.83000
Median: Reach 1 – Benches	
Vegetation Class	Fluvial Entrainment
Vegetation loss	1.08000
No change, no vegetation	.96000
No change, vegetation	1.55000
Vegetation growth	1.23500
Total	1.17000
Median: Reach 1 – MC Banks	
Vegetation Class	Fluvial Entrainment
Vegetation loss	.85000
No change, no vegetation	.76000
No change, vegetation	.71000
Vegetation growth	.59000
Total	.75000

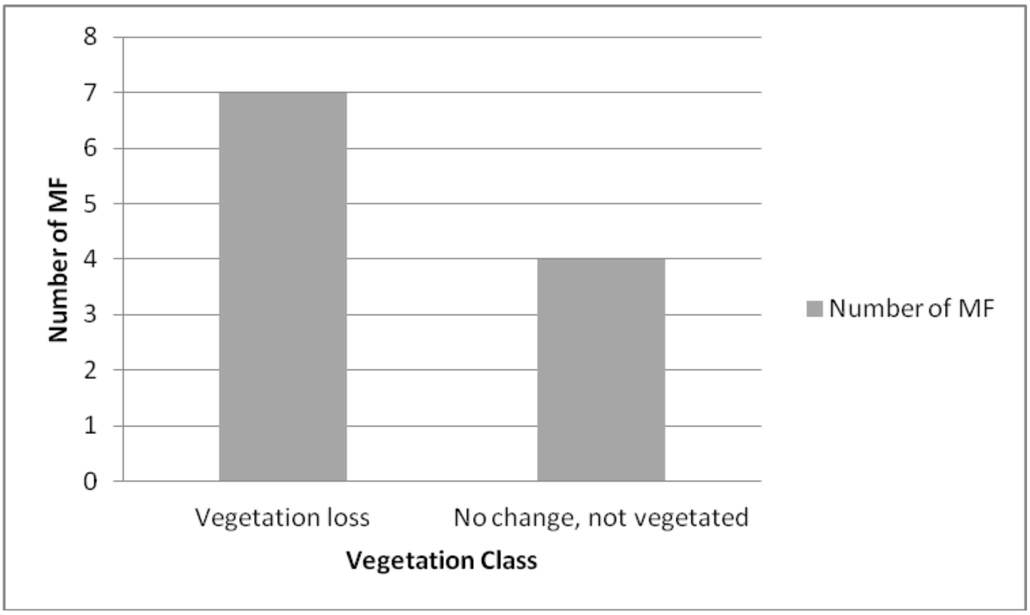
A4.6 Median: Reach 2 – IC Bed and Bars	
Vegetation Class	Fluvial Entrainment
Vegetation loss	.55000
No change, no vegetation	.81500
No change, vegetation	.41000
Vegetation growth	.71000
Total	.65500
Median: Reach 2 – IC Banks	
Vegetation Class	Fluvial Entrainment
Vegetation loss	.55000
No change, no vegetation	.60000
No change, vegetation	.54000
Vegetation growth	.57000
Total	.57000
Median: Reach 2 – Benches	
Vegetation Class	Fluvial Entrainment
Vegetation loss	.89000
No change, no vegetation	.93000
No change, vegetation	1.08000
Vegetation growth	1.11000
Total	.94000
Median: Reach 2 – MC Banks	
Vegetation Class	Fluvial Entrainment
Vegetation loss	.75000
No change, no vegetation	.66500
No change, vegetation	.56000
Vegetation growth	.54000
Total	.62000

A4.7 Median: Reach 3 – IC Bed and Bars	
Vegetation Class	Fluvial Entrainment
Vegetation loss	.53000
No change, no vegetation	.64000
Total	.58500
Median: Reach 3 – IC Banks	
Vegetation Class	Fluvial Entrainment
Vegetation loss	.54000
No change, no vegetation	.58000
No change, vegetation	.46500
Vegetation growth	.38500
Total	.54000
Median: Reach 3 – Benches	
Vegetation Class	Fluvial Entrainment
Vegetation loss	1.19500
No change, no vegetation	.49000
No change, vegetation	1.14500
Vegetation growth	1.19000
Total	.67000
Median: Reach 3 – MC Banks	
Vegetation Class	Fluvial Entrainment
Vegetation loss	.96000
No change, no vegetation	.65000
No change, vegetation	.63000
Vegetation growth	.52000
Total	.71000

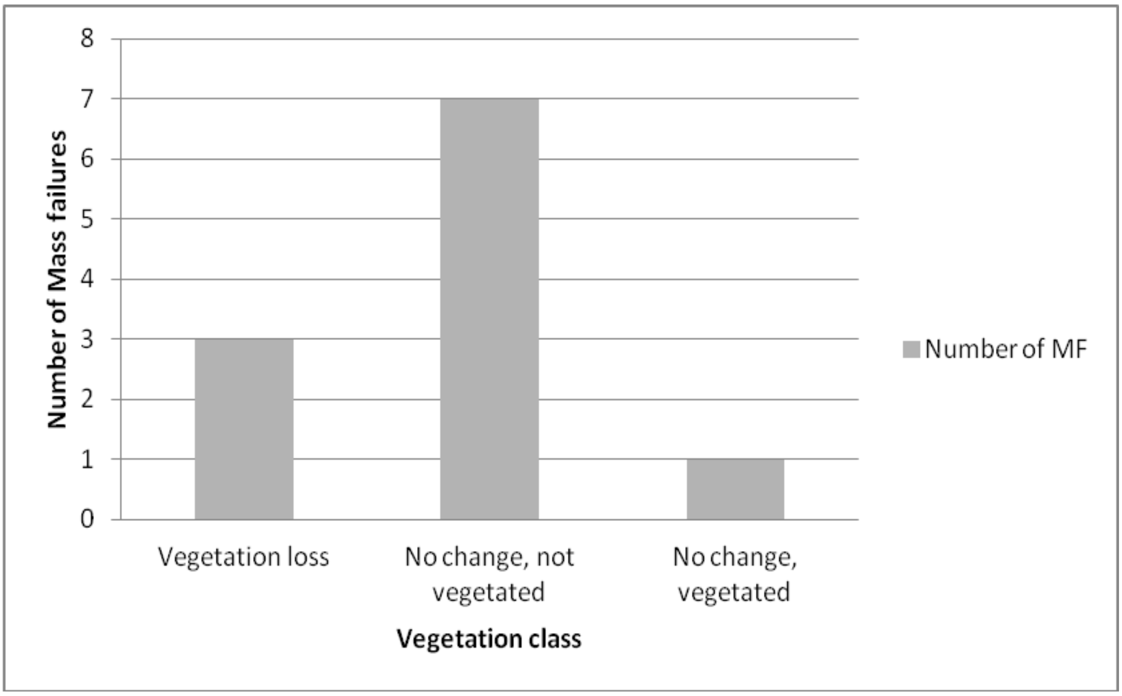
A4.8 Significant differences between vegetation combinations for values of fluvial entrainment in reach 1, 2 and 3.

Fluvial Entrainment	Geomorphic Unit	Class combination	p-value
Reach 1	Benches	Vegetation loss - no change, no vegetation	0.016
		No change, no vegetation - no change, vegetation	<0.001
		Vegetation loss - no change, vegetation	<0.001
		Vegetation growth - no change, vegetation	0.003
	Macro-channel banks	Vegetation growth - no change, vegetation	0.037
		Vegetation growth - no change, no vegetation	0.016
		Vegetation loss - vegetation growth	<0.001
		Vegetation loss - no change, vegetation	0.021
Reach 2	Benches	Vegetation loss - no change, vegetation	0.017
		Vegetation loss - vegetation growth	<0.001
		Vegetation growth - no change, no vegetation	0.005
	Macro-channel banks	Vegetation growth - no change, no vegetation	0.015
		Vegetation loss - vegetation growth	<0.001
		No change, no vegetation - no change, vegetation	0.004
		Vegetation loss - no change, no vegetation	<0.001
Reach 3	Benches	No change, no vegetation - no change, vegetation	<0.001
		Vegetation loss - no change, no vegetation	<0.001
	Macro-channel banks	Vegetation loss - vegetation growth	<0.001
		Vegetation loss - no change, no vegetation	<0.001
		Vegetation loss - no change, vegetation	<0.001
		Vegetation growth - no change, no vegetation	<0.001
		Vegetation growth - no change, vegetation	0.002

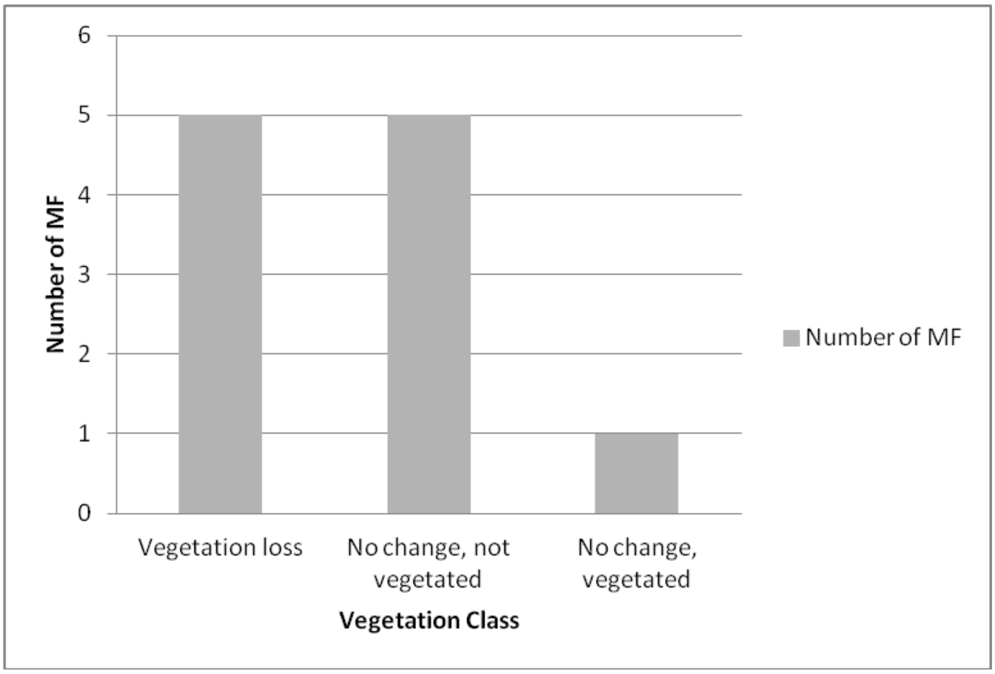
Appendix 5



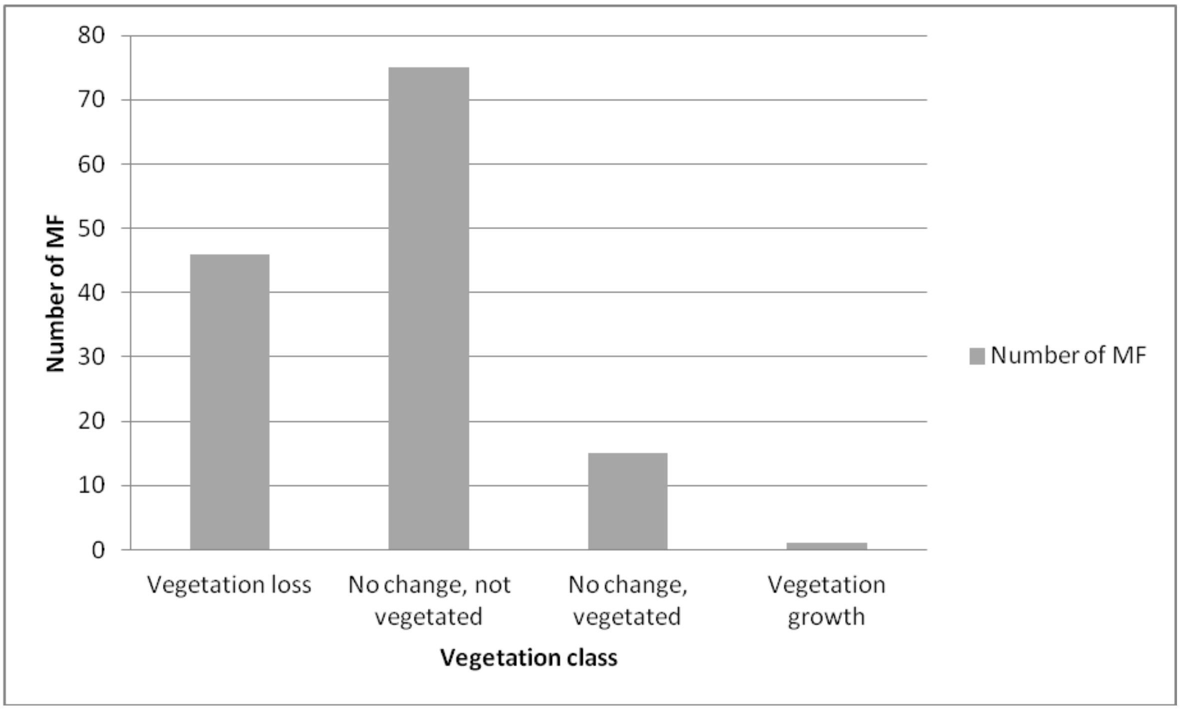
A5.1 Vegetation class in the 10m buffer surrounding each mass failure in reach 2.



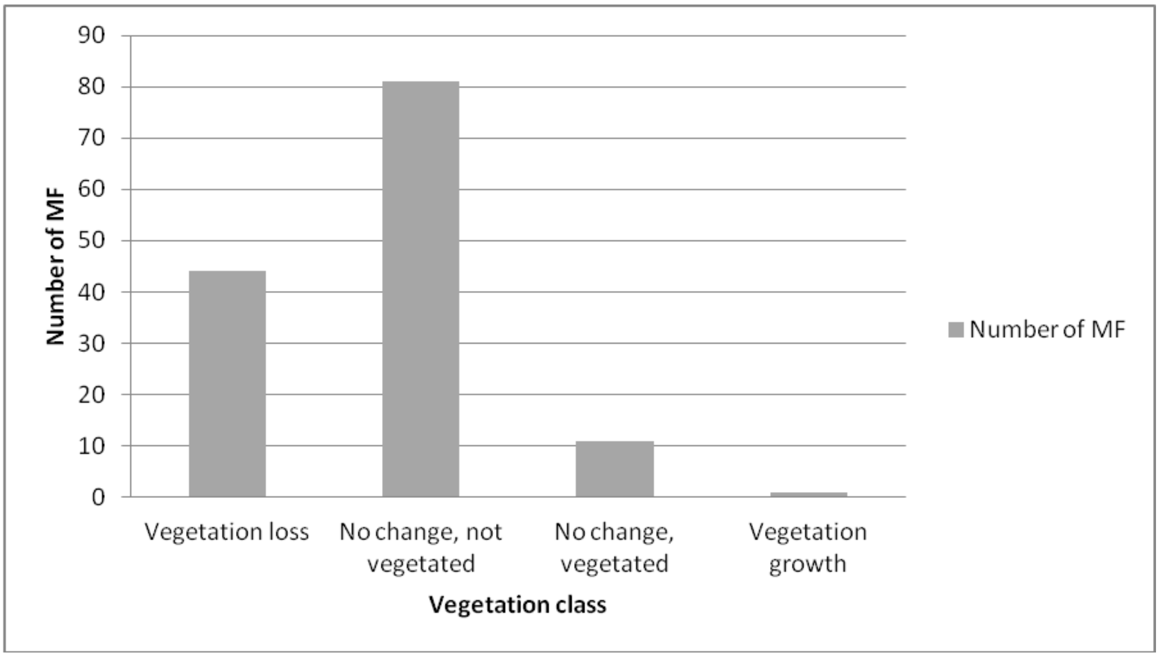
A5.2 Vegetation class in the 20m buffer surrounding each mass failure in reach 2.



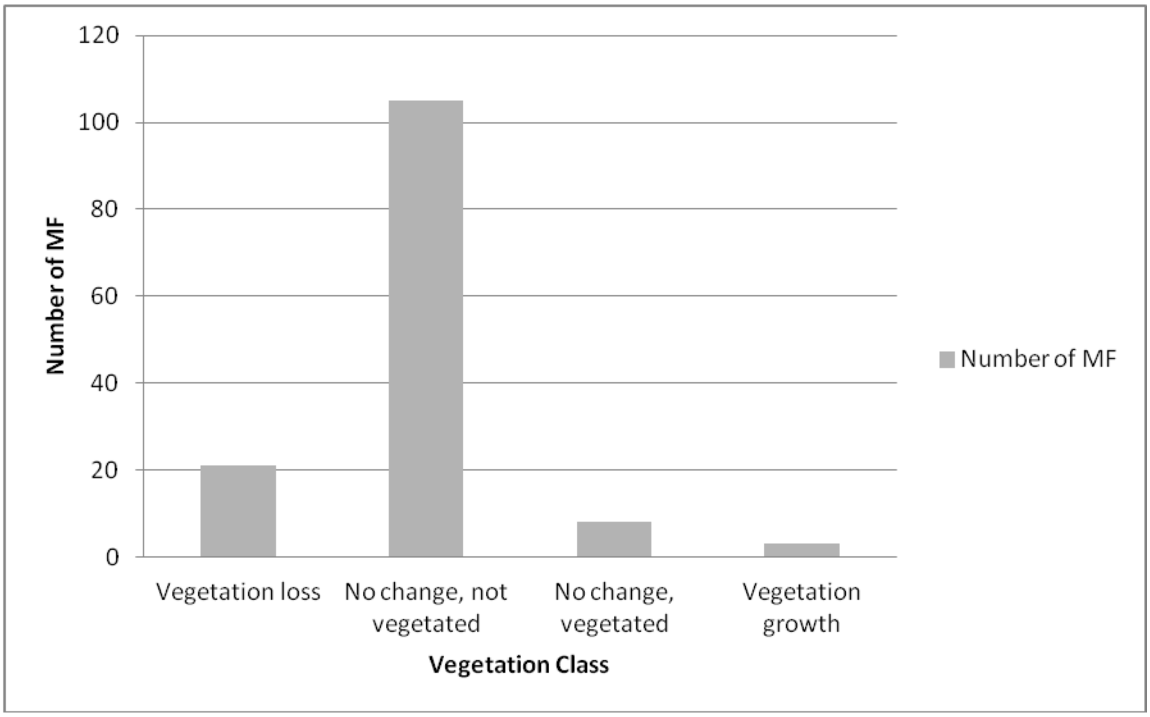
A5.3 Vegetation class in the 40m buffer surrounding each mass failure in reach 2.



A5.6 Vegetation class in the 10m buffer surrounding each mass failure in reach 3.



A5.7 Vegetation class in the 20m buffer surrounding each mass failure in reach 3.



A5.8 Vegetation class in the 40m buffer surrounding each mass failure in reach 3.