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LAND USE AND ITS RELATIONSHIP TO RIPARIAN ZONE ORGANIC CARBON STORAGE ON THE UPPER HUNTER RIVER

Christopher Doran

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Abstract

Anthropogenic influences and land use practices in eastern Australia over the past 200 years have resulted in vastly altered channel and catchment conditions. This has not only reduced geomorphic diversity but also vegetation diversity and ecological functioning. As such, identifying the impact of various land use regimes is highly important when developing future riparian zone management strategies. To investigate the influence land use (specifically grazing) has on the riparian zone and river system, 12 in-channel river deposits were studied on the Hunter River between Muswellbrook and Aberdeen. Three land use types were selected — i) never grazed, ii) crash grazed and iii) perennially grazed — and samples were taken at three study reaches (Aberdeen, Downstream Aberdeen and Dart Brook Mine). One hundred and eleven (111) soil samples were collected from bars and benches in order to determine organic carbon content and fine sediment retention. The soil samples were analysed using loss-on-ignition (LOI) testing to determine the percentage (%) of organic carbon (OC). The Malvern Mastersizer was used to analyse average grain size and to determine the dominant sediment fraction within each soil sample. Hand sieves (-4 phi and -1 phi) were used to determine the main sediment fractions as a measure of bar variability. Spatial and hydrologic analyses were undertaken to determine historical and recent changes in both vegetation and river geomorphology. Results from the sample analysis showed that sites that had never been grazed had an average increased OC concentration of 6.43% and were also comprised of the finest sediment (FS), at 108.7μm. Study locations that had been subjected to controlled grazing (3.02% OC and FS 324.4μm) fell on average between permanently grazed (2.68% OC and FS 376.4μm) and never-grazed locations across most variables analysed. Riparian zone management is a prevalent and important topic and these results provide guidance for developing management strategies. It has been found that stock may be useful in removing exotic vegetation as part of a larger weed management program, however in doing so they may decrease the amount of carbon sequestered and fine sediment retained. Decreased organic carbon can affect the nutrient cycling and the removal of nitrogen and phosphorus from water prior to entering the stream. In addition, decreased fine sediment retention may result in increased turbidity and therefore decreased light availability throughout the water column. These results may also have implications on global carbon storage through the riparian zone and its associated role in mitigating climate change.

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LAND USE AND ITS RELATIONSHIP TO RIPARIAN ZONE ORGANIC CARBON STORAGE ON THE UPPER HUNTER RIVER

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Christopher Doran

12th October, 2016

ABSTRACT

Anthropogenic influences and land use practices in eastern Australia over the past 200 years have resulted in vastly altered channel and catchment conditions. This has not only reduced geomorphic diversity but also vegetation diversity and ecological functioning. As such, identifying the impact of various land use regimes is highly important when developing future riparian zone management strategies. To investigate the influence land use (specifically grazing) has on the riparian zone and river system, 12 in-channel river deposits were studied on the Hunter River between Muswellbrook and Aberdeen. Three land use types were selected — i) never grazed, ii) crash grazed and iii) perennially grazed — and samples were taken at three study reaches (Aberdeen, Downstream Aberdeen and Dart Brook Mine). One hundred and eleven (111) soil samples were collected from bars and benches in order to determine organic carbon content and fine sediment retention. The soil samples were analysed using loss-on-ignition (LOI) testing to determine the percentage (%) of organic carbon (OC). The Malvern Mastersizer was used to analyse average grain size and to determine the dominant sediment fraction within each soil sample. Hand sieves (-4 phi and -1 phi) were used to determine the main sediment fractions as a measure of bar variability. Spatial and hydrologic analyses were undertaken to determine historical and recent changes in both vegetation and river geomorphology. Results from the sample analysis showed that sites that had never been grazed had an average increased OC concentration of 6.43% and were also comprised of the finest sediment (FS), at 108.7μm. Study locations that had been subjected to controlled grazing (3.02% OC and FS 324.4μm) fell on average between permanently grazed (2.68% OC and FS 376.4μm) and never-grazed locations across most variables analysed. Riparian zone management is a prevalent and important topic and these results provide guidance for developing management strategies. It has been found that stock may be useful in removing exotic vegetation as part of a larger weed management program, however in doing so they may decrease the amount of carbon sequestered and fine sediment retained. Decreased organic carbon can affect the nutrient cycling and the removal of nitrogen and phosphorus from water prior to entering the stream. In addition, decreased fine sediment retention may result in increased turbidity and therefore decreased light availability throughout the water column. These results may also have implications on global carbon storage through the riparian zone and its associated role in mitigating climate change.

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1 INTRODUCTION

1.1 BACKGROUND

The introduction of western land use practices to the riverine landscape has resulted in widespread channel metamorphosis on a global scale (Schumm 1969; Brierley et al. 2005). Following the arrival of Europeans to the Australian environment, there have been unprecedented morphological changes (catastrophic channel widening and associated sediment release) and ecological changes (loss of aquatic habitat, introduction of exotic species and the vast reduction in diversity of native species) on many south-east Australian rivers (Bartley & Rutherfurd 2005; Hoyle et al. 2008). These changes have been attributed to two dominant causes: anthropogenic (Brierley & Murn 1997; Brooks & Brierley 1997) and climatic variability (Erskine & Bell 1982; Erskine & Warner 1988; Webb et al. 1999). As further research has been undertaken, the importance of anthropogenic influences on the riparian zone has begun to be understood and appropriate management of the riparian zone has become increasingly important (Brierley & Fryirs 2009).

Numerous case studies have shown that the underlying cause of channel change over the past 200 years is the result of anthropogenic land use practices (Brooks & Brierley 1997; Brierley et al. 1999; Brooks et al. 2003). The widespread removal of catchment vegetation, woody debris and the introduction of stock and exotic species have resulted in the altered contemporary channel conditions (Hoyle et al. 2008). Due to the threat unstable channels have posed to valuable floodplain assets and housing, efforts have been made to manage and control unstable eroding riverbanks with varying objectives dependent on the time of installation (Hoyle et al. 2008; Spink et al. 2009). Early control structures typically involved the use of engineered wooden and concrete structures to reduce flow velocities, divert flow from the banks and increase bank strength (Spink et al. 2009). As river system functioning (both geomorphic and ecological) became better understood in the 1980s, principles of geomorphology began to be applied and this resulted in changes in the aims of river management. Associated was a shift in the mechanisms of river management from a heavily engineered background to a more holistic ecosystem approach, incorporating the use of vegetation such as willows to stabilise banks (Spink et al. 2009).

Many of the early river management strategies that caused bank instability and channel incision, such as artificial channel straightening, the removal of in-stream woody debris and riparian vegetation, have ceased, however some activities detrimental to the riverine environment continue (Spink et al. 2009). The ongoing access of stock to the channel results in the reduction of bank strength and degradation of the riparian zone (Trimble & Mendel 1995). Early efforts of river management also introduced a number of exotic vegetation species to the riparian zone in order to facilitate bank stabilisation, which have since taken hold and propagated, leading to environments as seen in Figure 1. The modern Hunter River is one, which is dominated by contrasting vegetation settings: densely weed-dominated communities (Figure 1) or pasture-dominated riparian zones (Figure 2). This contrast reflects the role of grazing and riparian zone management strategies. This poses questions on how to appropriately manage the riparian zone to meet the goals of modern river management.

The riparian zone and riparian vegetation play an important role in ensuring ecological diversity, increasing bank resistance and maintaining or improving water quality (Gurnell 2014). Given this importance, establishing best management practices for the riparian zone vegetation is of high importance. This thesis will address issues of grazing and weed management, how they affect river condition and the implications for river management.

Figure 1 Never grazed location on the Hunter River. Note the dense weed dominated vegetation.

Figure 2 Perennially grazed bar and bench location on the Hunter River.

1.2 AIMS AND OBJECTIVES

The primary aim of this thesis is to quantify the impact land use has on carbon storage and fine sediment retention on river bars and benches throughout the study reach in the upper Hunter. This thesis also aims to provide some recommendations on best management practice based upon the results from field studies.

This project has a series of minor aims, which were established to ensure that the overall goals of the project were achieved:

- Assess the difference between benches and bars within different land use regimes in terms of sedimentological, geochemical and morphological parameters.
- Investigate historical land use and vegetation change and relate this to the climatic and hydrologic record.
- Relate literature and observed field conditions to current riparian zone management practice and the direction of riparian zone management.

1.3 HYPOTHESES

The nature of this study is such that it will have a series of testable hypotheses comparing the different site conditions. These hypotheses are stated below:

H_o: There will be no statistically significant difference between grazed and ungrazed locations in terms of median grain size, fine sediment proportions and organic carbon storage.

H: There will be a statistically significant difference between grazed and ungrazed locations in terms of median grain size, fine sediment proportions and organic carbon storage.

1.4 STUDY DESIGN

Three study sites were selected following an investigation through satellite imagery and historical aerial photography, in conjunction with consultation with landholders. Sites were chosen in order to address the objectives of the thesis meeting the following criteria;

- Sites were required to have two different types of land use practices in close proximity with clear boundaries.
- Both types of land use were required to have both a significant bar and bench suitable for sediment sampling
- Be located on the Hunter main stem within the study reach between Aberdeen and Muswellbrook

Two sites were selected in the Aberdeen area named (ABB – Aberdeen & DAB – Downstream Aberdeen). These sites were both used to compare grazed and ungrazed locations. The third site (DBM – Dart Brook Mine) selected was on the Dart Brook Mine property to the south of the Aberdeen sites. This locality was important as it was used to compare a crash grazed or restricted access location to a site which was never grazed. This site was selected through consultation with the landholder to establish the controlled grazing regime and obtain the nature of the changes observed at the site. At this location approximately 400 cows were granted access to the floodplain, bars and benches in January 2016, over a weeklong period before being removed. This was approximately five months prior to the sampling program undertaken in this study.

At each of the three sites two bars and two benches were sampled ensuring that a bar and bench were sampled from each different land use type. At each bar or bench nine surface samples (10 cm deep soil samples) were taken. These were taken according to the pattern seen in Figure 3, to account for sedimentologic variability within the bar or bench (Hoyle et al. 2007).

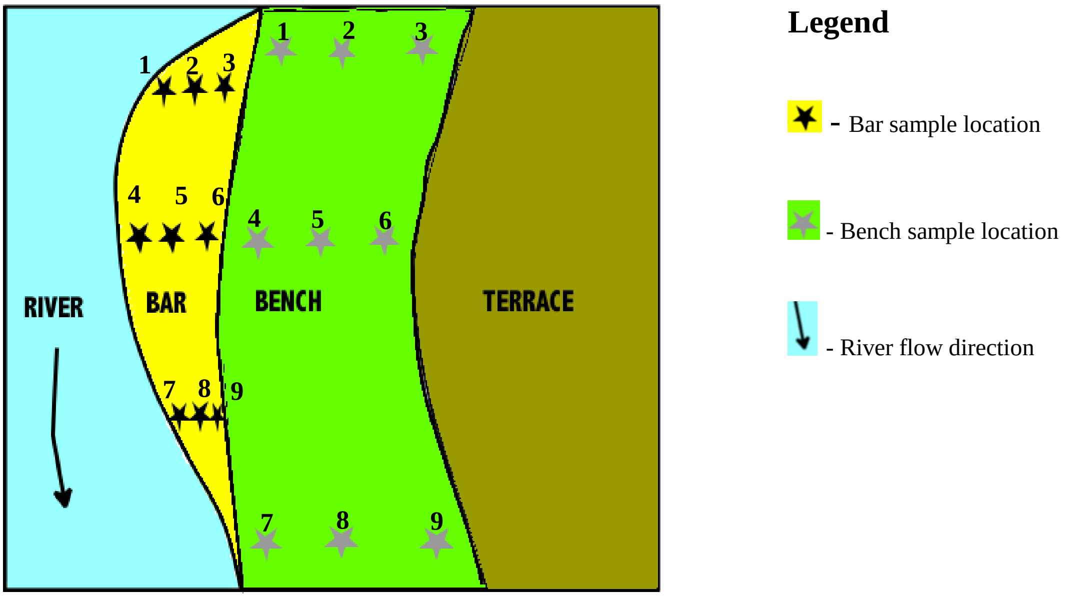


Figure 3 Sampling pattern undertaken at six bars and six benches between Muswellbrook and Aberdeen.

1.5 THESIS OUTLINE AND SCOPE

This thesis presents a review of the current literature surrounding riparian zone management, specifically relating to the role of grazing on the riparian zone and the establishment of riparian zone buffers (Chapter two). It also examines contemporary river management practices within a typical south-east Australian river. Chapter three presents the contextual setting of the study locations and establishes the various influences on the Hunter River such as flood history, climate, land use and vegetation. Chapter four establishes the methodology utilised to compile both field and spatial data but also the process by which various analyses were undertaken. Chapter five presents a summary of results derived from the analysis of spatial and hydrologic data. In this chapter, a history of the site locations is established utilising historical aerial photography and vegetation data. Chapter six presents the findings from sedimentary analysis of bar and bench samples taken from the field. Following the results, Chapter seven provides a discussion relating the results from this experiment to the broader picture and details the management implications this study presents, whilst also addressing the limitations of the study. A summary of the key findings and implications is presented in Chapter eight in conjunction with some concluding remarks and recommendations.

2 LITERATURE REVIEW

2.1 INTRODUCTION

This chapter aims to provide the context to current river management in Australia by providing an account of the changes rivers have experienced since European settlement. In analysing historical and current management strategies, the direction of current river management and its goals can be fully assessed. This will be achieved through a thorough description of historical examples, outlining various factors controlling riparian and riverine ecosystem health.

2.2 POST-EUROPEAN IMPACTS ON SOUTH-EAST AUSTRALIAN RIVERS

South-east Australian rivers have undergone dramatic channel change or channel metamorphosis in the post-European time period (Brierley & Murn 1997). The dramatic changes in the nature of the catchment conditions (vegetation, sediment and hydrology) have resulted in the rapid channel response in the form of widespread incision and expansion of many river systems (Brierley et al. 2005). Associated with this channel response is the release of large amounts of stored sediment, which reduces geomorphic diversity and aquatic ecosystem complexity (Bartley & Rutherfurd 2005).

The origin of this channel metamorphosis has been attributed to two primary causes; anthropogenic influences and climatic variability. Early work by Erskine (1982) attributed the changes in river system structure to the alternation between flood dominated regimes (FDR's) and drought dominated regimes (DDR's; Erskine & Bell 1982; Erskine & Warner 1988). Through FDR periods it is interpreted that increased amounts of rainfall cause clusters of floods (Erskine & Bell 1982). The increased frequency and velocity of large flows provides increased stream energy and an increased ability for the river to perform geomorphic work (e.g. channel incision and expansion; Erskine & Warner 1988). Erskine and Bell (1982) associated periods of major channel adjustment with the timing of FDR periods.

However, more recently the generally accepted hypothesis attributes an increased importance on the anthropogenic influence than that of climatic variability (Brierley & Murn 1997; Brooks & Brierley 1997; Brooks et al. 2003). Brooks' 2003 study of the Thurra and

Cann rivers found that climatic variability was not the predominant driver of channel change, instead attributing an increased importance to European land use practices (e.g. clearance of catchment and riparian vegetation, removal of woody debris from channels and the introduction of stock to the riparian environment; Brooks et al. 2003). While climatic variability is not the predominant driver of channel change in south-east Australian rivers, its influence is not negligible and has resulted in a delayed response time between catchment disturbance and the expression or response of the channel (Hoyle et al. 2008). Hoyle et al. (2008) proposed the idea of a critical threshold existing whereby sufficient change to catchment conditions and a flood of sufficient magnitude must occur to cause geomorphic change. In the case of south-east Australian rivers, changes to catchment conditions have occurred both during FDR and DDR periods, however, major channel response were only expressed in FDR periods (Brierley et al. 2005; Hoyle et al. 2008). European land use practices have resulted in the reduction of channel resistance, which increases the geomorphic effectiveness of floods and the channels susceptibility to change (Brooks & Brierley 1997; Webb & Erskine 2003; Brierley et al. 2005; Hoyle et al. 2008).

The character and nature of Australian rivers prior to European disturbance can be ascertained through field studies on undisturbed river systems. Historical records and descriptions in conjunction with early photographs or sketches can be utilised to provide an understanding as to how the river systems have progressively changed with increased development. Prior to European settlement south-east Australian rivers were characterised by their relative geomorphic stability (Eyles 1977). This geomorphic stability was a function of the dense riparian vegetation, the abundance of in-stream woody debris, and the high hydraulic resistance of riverbanks in combination with the low erosive potential of the rivers (Figure 4; Brierley et al. 2005; Brooks et al. 2006; Hoyle et al. 2008). Riverbanks were dominated by native species, which stabilised the banks, allowing the development of narrow but deep channels (Brierley & Murn 1997; Huang & Nanson 1997; Mika et al. 2010). Developing this understanding of the pre-disturbance condition of the channel is important to establish realistic goals for river rehabilitation (Brooks et al. 2003; Brierley & Fryirs 2009).

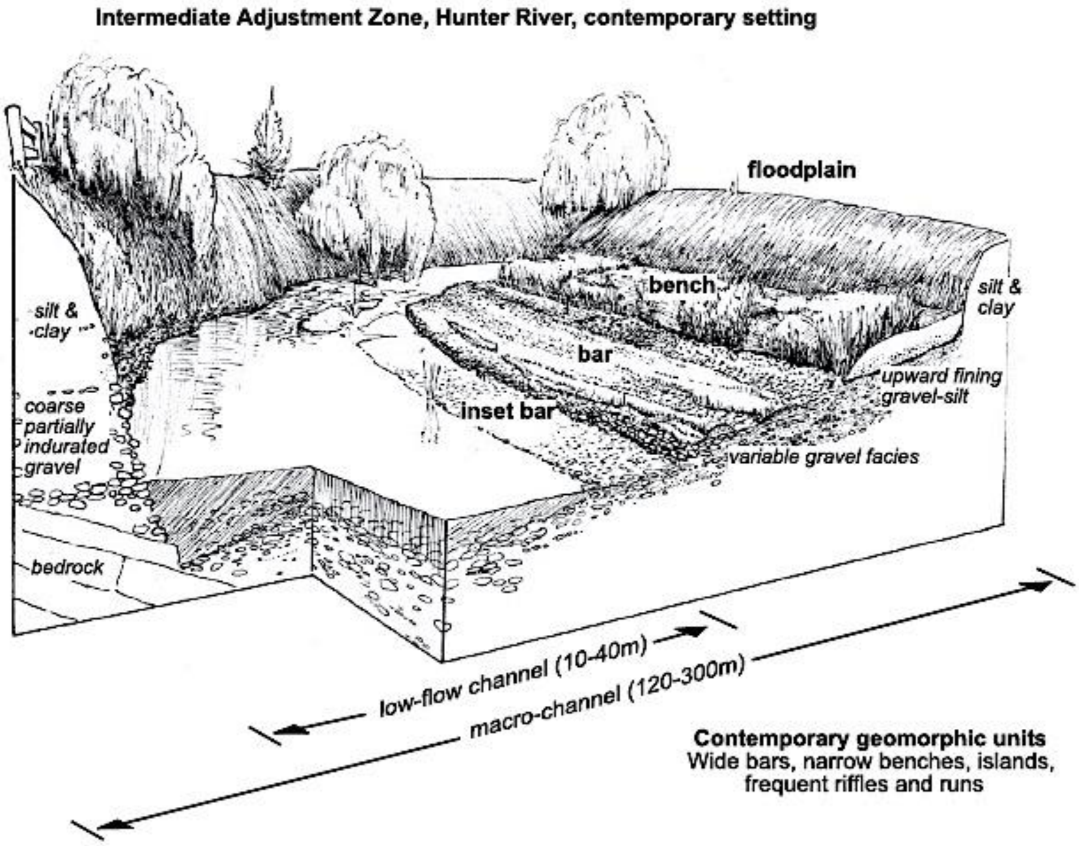


Figure 4 A depiction of the modern day channel Post-European impacts. Note the reduced vegetation cover, woody debris and the expanded macro-channel boundaries. Taken from Hoyle et al. 2008.

In the 200-year period following the introduction of European land use practices, numerous rivers have demonstrated a general trend of channel expansion through the processes of erosion and incision (Hoyle et al. 2007; Hoyle et al. 2008). This has led to a state where the contemporary channel (Figure 4) is vastly different to pre-disturbance conditions (Figure 5). The most notable differences are in channel width and structure and in riparian zone vegetation diversity and density (Hoyle et al. 2008).

A series of studies conducted to quantify the extent of the channel expansion are presented in Table 1. The results of these studies suggest that rapid channel expansion has resulted in a large increase in sediment transport to the downstream reaches (Brierley & Murn 1997; Brooks et al. 2006). The increased sediment transport capacity of many rivers and the release of massive amounts of sediment through channel expansion have resulted in the formation of sediment slugs migrating slowly downstream (Bartley & Rutherfurd 2005; Brooks et al. 2006). This release of sediment is associated with the morphological simplification or homogenisation of many south-east Australian rivers (Brierley & Murn

1997; Bartley & Rutherfurd 2005; Brooks et al. 2006). Associated with this morphological simplification is a reduction in the aquatic habitat and ecologic diversity (Brooks et al. 2006).

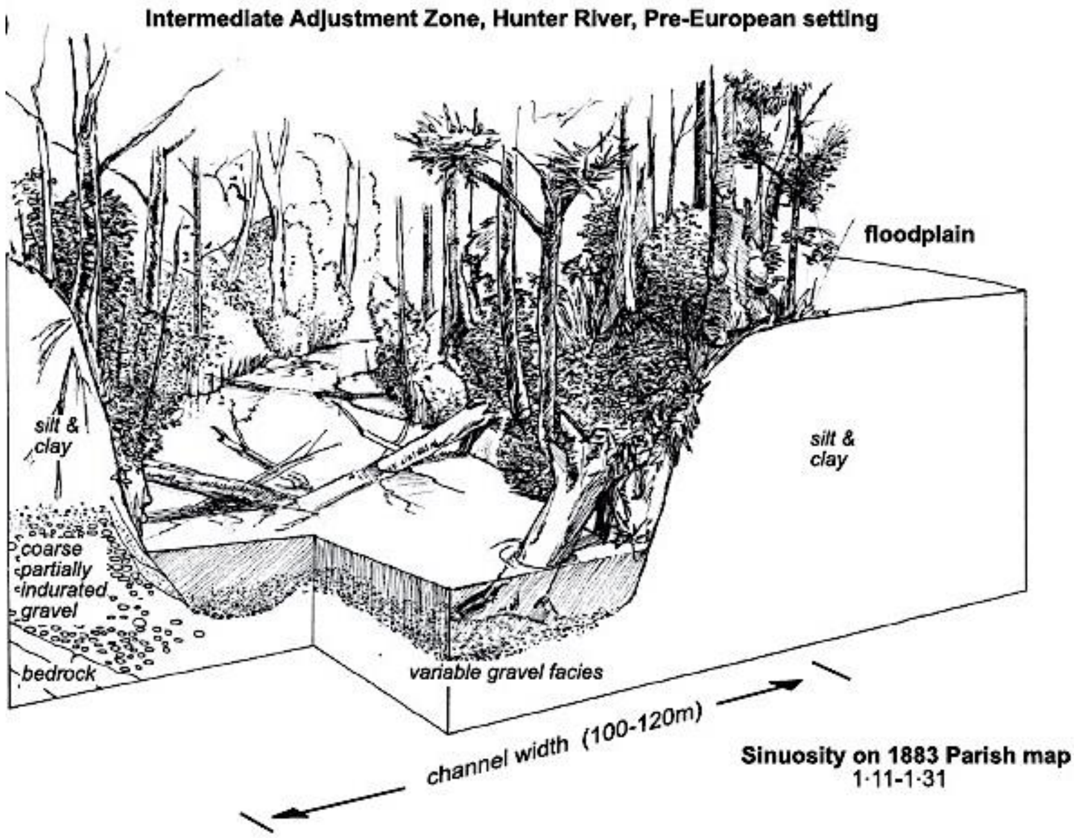


Figure 5 Conceptualised sketch of a channel prior to European disturbance, taken from Hoyle et al. 2008. Note the abundance of in-channel woody debris, riparian vegetation and the fining upwards succession of sediments observed on the floodplain.

Table 1 Post-European disturbance response associated channel change of south-east Australian rivers (Hughes 2014).

River	Source	Documented Change
Bega River (NSW)	Brooks & Brierley (1997)	1850-1920: 340% widening, with an increased sediment load
Wollombi Brook (NSW)	Page (1972) Erskine (1986)	100% widening of channel, downstream movement of a sediment slug
Illawarra Streams (NSW)	Nanson & Hean (1985)	Max cross section increase 230%-340% in steep upstream section with channel avulsion and floodplain scour
Cann River (VIC)	Erskine & Whitehead (1996)	1935-1995: 325% widening, depth increase 40%, chute cut-off and downstream build up of sediment slug
Cobargo Catchment (NSW)	Brierley *et al,* (1999)	50% sediment removed and 50% banks eroding in upper catchment
Tarcutta Creek (NSW)	Page & Carden (1998)	100-200% widening of channel. Incision of chain of ponds to continuous incised channel
Cann/ Thurra River	Brooks *et al,* (2003)	Comparison between highly altered Cann River and 'natural' Thurra River

Historical river changes have resulted in the need for increased understanding of river system functioning in order to implement effective management strategies (Hoyle et al. 2008; Brierley & Fryirs 2009). Historical river works have in cases failed to identify the primary causes of channel instability and as a result, rehabilitation and management programs have been inefficiently implemented (Hoyle et al. 2008). As such, work has been undertaken to understand the nature and causes of channel changes or channel metamorphosis (Spink et al. 2009): antecedent controls on channel stability (Hoyle et al. 2008), the role of woody debris in riverine environments (Brooks et al. 2003; Brooks et al. 2004) and the role of riparian vegetation on channel stability and recovery (Gurnell 2014). This work has provided an understanding of the detrimental impacts of many land use practices to the riparian and riverine environment. However, despite the prominence of stock on the floodplain and river environments, little work has been undertaken to address both the morphological and ecological impacts of stock in these environments.

Another major consideration for rehabilitation and management programs has been changing land use of the floodplain setting. Land use has changed through time with many past land use practices such as logging and forestry making way for contemporary land use practices such as urban space and vegetation reserves. However, some historical land uses such as mining, agriculture and grazing remain contemporary in the Hunter catchment. As such management techniques have had to account for the impacts on the riparian zone from each of these land uses.

2.3 RIVER MANAGEMENT IN SOUTH-EASTERN AUSTRALIA

River management is and has been an important aspect of New South Wales' environmental management plans over the last 100-200 years. The objectives and science behind the river and riparian zone management, however, have changed through time as the primary aims of river and catchment remediation have changed (Spink et al. 2009).

2.3.1 *Historical European river management in New South Wales (NSW)*

Rivers throughout NSW have had a recent history of human disturbance and interaction. This history can be divided into the various regimes that have occurred through time. In the period up to 200 years ago, the dominant human interaction was through the Aboriginal people and their fire management strategies (Dodson & Mooney 2002). Following the introduction of European land use practices there has been a fundamental shift in the character of Australian rivers (Brierley et al. 1999; Brierley et al. 2005).

The rapid introduction of European land use practices to NSW landscapes, resulted in the rapid land clearance and alteration of the catchment conditions. The desire to utilise the land for European style farming methods promoted the clearance of the catchment vegetation (Brierley & Murn 1997). The removal of riparian vegetation resulted in the reduction of bank strength and hydraulic resistance of rivers (Brierley et al. 1999). The introduction of stock and pests such as rabbits has resulted in the further degradation of Australian river systems through the destruction of understory riparian vegetation and the erosion of banks (Eyles 1977; Erskine et al. 2012). The removal of in-channel woody debris 'desnagging' has been undertaken on many major Australian rivers in an effort to improve the navigability of rivers and improve floodwater transmission (Brierley et al. 2005). Early river control programs sought to stabilise and straighten the channel through the introduction of sand dredging programs and water or sediment control structures (Spink et al. 2009). This sediment control has resulted in the loss of vast quantities of sediment from the upper reaches of many rivers to the lower reaches (Bartley & Rutherfurd 2005; Spink et al. 2009).

2.3.2 *The historical management of the Hunter River*

The Hunter River is characteristic of many south-east Australian rivers. It has experienced rapid degradation in the form of channel expansion, incision and morphological simplification due to European interaction (Brierley & Murn 1997; Erskine et al. 2012). These channel adjustments were the result of processes such as the catchment vegetation clearance, riparian zone vegetation removal, woody debris removal, artificial straightening of channels, the introduction of stock and the alteration of the sediment regime through dredging & damming (Erskine et al. 1985). The Hunter River, however, is unique as it has a long and dense history of river rehabilitation efforts primarily from the 1950's (Spink et al. 2009). The Hunter River underwent three periods of major channel adjustment over the past 150 years following European settlement (Spink et al. 2009). The implementation of river rehabilitation structures post-1950s in conjunction with construction of Glenbawn Dam in 1958 has seen a reduction in stream energy and a rapid reduction in the rate of erosion (Brierley & Fryirs 2009; Spink et al. 2009).

River management pre-1980s

Following a series of major floods throughout the 1950s, a catchment management authority termed the Hunter River Management Trust was established to manage river work programs (Spink et al. 2009). Rivers were managed with the objective of controlling bank erosion, sediment transport and to increase floodwater conveyance (Webb & Erskine 2003; Hoyle et al. 2008). Early river control structures tended to involve the introduction of heavily engineered wood and concrete structures to the channel (Spink et al. 2009). These hard engineering structures tended to address the issue on a local bend or straight scale as opposed to on a reach or regional scale. The implementation of such heavy engineering structures may have in fact caused downstream channel incision and erosion (Hoyle et al. 2008). During this paradigm of river management, native riparian vegetation was cleared from river boundaries to allow for floodwater conveyance and stock access (Spink et al. 2009). The removal of riparian vegetation resulted in the reduction of bank strength and the rapid development of steep banks. Exotic species such as willows (*Salix* species) and poplars (*populis* species) were planted to bring increase the geomorphic stability of channel bars, benches and banks (Webb & Erskine 2003; Hoyle et al. 2008). Exotic species were utilised for bank stabilisation work due to their ability to spread from cuttings, cost effectiveness and effectiveness at stabilising the bank (Webb & Erskine 2003).

River management post-1980s

Pre-1980s, the objectives of river management were focused on the construction and control of the river (Shellberg & Brooks 2007). Throughout the 1980s a change of the objectives and thus paradigm of river management occurred with a realignment of river management goals to match the scientific theory and research. Principles of geomorphology were introduced as a basis for river management programs and this resulted in a shift away from the use of hard engineering structures, towards vegetation based soft structures (Spink et al. 2009). Since then there has been a shift towards ecosystem management over a much broader scale than was addressed by the constructive regime pre-1980s (Spink et al. 2009). This period has been marked by an increase in the amount of vegetation-based remediation works with minimal structural works coincident with a reduction in the number of new hard engineering-based structures (Hoyle et al. 2008; Brierley & Fryirs 2009; Spink et al. 2009; Hubble et al. 2010). Vegetation was reintroduced into riparian zones to stabilise in-channel bars and benches, promoting depositional environments (Erskine et al. 2012). Initially the use of exotic species such as willows (*Salix species*) and poplars (*populis species*) was common (Webb & Erskine 2003; Mika et al. 2010). However, there has been a shift to discontinue the use of exotic species as well as non-endemic species for use in channel rehabilitation in order to preserve the genetic integrity of an area (Webb & Erskine 2003; Erskine et al. 2012). Historically remediation efforts along the Hunter River have been poorly focused with the application of techniques having little regard for the style of river or site conditions present at each location (Spink et al. 2009).

2.3.3 *Recent developments in river management*

Analysis of historical river management strategies has provided scope for recent management strategies, utilising results from both successful and unsuccessful studies (Brierley & Fryirs 2009; Brierley & Hooke 2015). As the objectives of river management have changed, the types of structures and the methods of river rehabilitation and control have also changed to become more catchment specific (Spink et al. 2009).

Past river rehabilitation programs have met the goals or objectives for that particular paradigm, however, a number of historical river management programs have failed (Webb et al. 1999; Spink et al. 2009). The failure to correctly identify historical river condition and its controlling variables has resulted in the non-specific application of rehabilitation methods (Spink et al. 2009). As such, contemporary rehabilitation programs will first be required identify the causes of the channel adjustment and the potential of each site to be successfully rehabilitated (Hoyle et al. 2008; Brierley & Fryirs 2009; Fryirs et al. 2009). In the case of the Hunter an understanding of the anthropogenic changes to the catchment conditions which has resulted in the incision, and expansion of the channel is essential for effective management (Brierley & Fryirs 2009). In the past many of the structures have been installed as a reaction to channel erosion and incision marked by bank collapse (Spink et al. 2009). The response mechanisms were typically non-specific and applied to a range of areas regardless of the type of adjustment or stream present (Spink et al. 2009). Areas of some south-east Australian rivers have become so fundamentally different to the pre-disturbance condition that their potential for rehabilitation to the pre-disturbance condition is essentially zero (Brierley et al. 1999).

The contemporary Hunter River faces a number of different or new rehabilitation challenges as a result of the past effectiveness of management programs. One of the major ongoing issues in the Hunter River is that of weed infestation and the dominance of exotic species over native species (Brooks et al. 2016). Current management actions undertaken by the Hunter Local Land services are greatly reduced from the peak of activities in the 1980s – 1990s where millions of dollars were spent on stabilising the river and flood mitigation (Brooks et al. 2016). Current river management action is undertaken with a few narrow goals in the Hunter River focused on the maintenance of historical river works assets, flood mitigation and channel stability. These goals have been achieved under the current management practices and resources however, may be more effective elsewhere in improving the health of the riparian zone (Brooks et al. 2016).

Brooks et al. (2016) proposed that investment should be made in maximising native in-channel vegetation. Historically revegetation programs implemented have failed due to intensive weed growth, low light intensities and grazing disturbance (Webb et al. 1999). Through a controlled weed management program involving assisted natural regeneration, strategic planting and the introduction of stock in a controlled fashion, riparian zone rehabilitation may be achieved (Brooks et al. 2016).

Another area of research is in passive remediation, allowing the riparian corridor to regenerate itself over time with minimal human input. This can be achieved through changes to disturbance factors, such as through fencing of the riverbanks denying stock access (Shellberg & Brooks 2007; Brierley & Fryirs 2009). This can be complemented with aggressive weed reduction measures, to allow native vegetation an opportunity to compete and colonise the riverine environment (Shellberg & Brooks 2007). Furthermore, seeds in the banks of river channels allow the colonisation of pioneer species when allowed to germinate and mature (O'Donnell et al. 2014; O'Donnell et al. 2015).

2.4 KEY CHARACTERISTICS OF RIVERS

2.4.1 Importance, value and role of riparian vegetation in stream health and ecosystem functioning

Riparian vegetation is an important component of the riverine ecosystem, which directly and indirectly controls the river morphology. Vegetation is able to increase the geomorphic stability of the channel banks whilst also supplying nutrients, organic matter and shading to the river helping to create diversity in aquatic habitats (Webb et al. 1999).

Riparian vegetation can directly increase the bank strength and hydraulic resistance of channels through their complex root systems (Gurnell 2014; Hooke & Chen 2016). This effect has been observed in a range of environments and is highlighted by the fact reaches with vegetation have much lower rates of lateral migration than non-vegetated reaches (Brierley et al. 2005). The impact of vegetation on bank stability decreases as bank height increases and root density decreases, unless the bank face is also vegetated (Shellberg & Brooks 2007). There is continued debate throughout the literature as to the exact role of vegetation on channel bank width. Evidence exists in support of vegetated banks being wider than non-woody vegetated banks (Gurnell 2014), however, other studies have suggested that vegetated streams are narrower than their non-woody vegetated counterparts (Huang & Nanson 1997; Brierley et al. 2005).

Where plants colonise channel bars, benches or the channel bed, there is an associated increase in flow resistance resulting in reduced flow velocities (Huang & Nanson 1997). The increased flow resistance from channel bed vegetation is associated with decreased erosive energy and local velocities along banks and channel beds (Shellberg & Brooks 2007).

Channel bed vegetation can, through the reduction of flow velocities, result in the reduction of sediment transport capacity of a stream (Huang & Nanson 1997). This results in the deposition and retention of fine sediment along with the stabilisation of channel bars and benches and initiating the contraction of the channel (Boulton et al. 1998; Brierley et al. 2005). This effect has been observed and recorded throughout many Australian rivers as they recover following catastrophic widening (Brierley et al. 2005; Shellberg & Brooks 2007; Erskine et al. 2012). Riparian vegetation also serves an important ecological function, as it is a source of organic matter and for stream temperature regulation (Webb et al. 1999). This highlights the important role vegetation has in nutrient cycling but also in the generation of aquatic habitats (Webb et al. 1999).

Riparian vegetation acts as a source of large woody debris (LWD) to the stream. LWD has an important role in the river ecosystem and to the river health (Brooks et al. 2004; Brooks et al. 2006). LWD is recruited to the channel primarily through tree mortality with minor contribution due to wind throw and bank erosion (Webb & Erskine 2003). The reduction in quantity of LWD in many Australian rivers is a result of a range of factors including; the direct removal or ‘desnagging’ of Australian rivers, as implemented by various river management strategies and the removal of riparian vegetation; the dominant source of LWD for streams (Webb & Erskine 2003; Brooks et al. 2006). LWD has an important role in providing resistance to flow, increasing bank strength, the creation of geomorphic complexity; initiating the development of scour pools and riffles and delaying downstream movement of leaf litter and sediment (Brooks et al. 2004; Mika et al. 2010). Where LWD has been removed from within channel there has been morphological simplification and other changes such as channel incision, expansion and increased sediment movement (Brooks et al. 2004). Where LWD has been reintroduced into river systems there has been an associated stabilisation of the river channel, slowing of sediment transport, increase in morphologic diversity, and increase in aquatic habitat diversity (Brooks et al. 2004; Mika et al. 2010).

2.4.2 Weed management in New South Wales

Invasive plant species are often able to rapidly propagate, outcompete and also suppress other plant species growth in disturbed environments (Lawes & Grice 2010; Osunkoya & Perrett 2011). Exotic species pose a threat to riparian zone biodiversity as they directly compete with native species. They also impact the aquatic ecosystem through altering catchment conditions and flow boundaries in conjunction with reducing water quality. Furthermore they impact the agricultural industry due the toxicity of some weed species to stock such as green cestrum (*Cestrum parqui*) and competition with pasture or crop species (HCCREMS. 2010).

Due to the threat invasive plant species pose to biodiversity, native species and crop species, various weed management strategies and policies have been introduced; notably the *Australian Quarantine Act 1908*, NSW *Noxious Weeds Act 1993*, the National Weeds Strategy 2007 and the Weeds of National Significance strategies (NSW Department of

Primary Industries 2015). These policies aim to reduce the introduction of new exotic species to the environment, reduce the potential of these species spreading and causing damage to local ecosystems and also to contain and eradicate weed species (NSW Department of Primary Industries 2015).

The implementation of weed management activities across Australia have traditionally been reactive and response driven however, have recently become more focused on a strategic model of weed control (HCCREMS. 2010). Weed management within NSW has four targeted goals, prevention, eradication, containment and asset protection (NSW Department of Primary Industries 2015). Weed species are classified depending upon the threat they pose to biodiversity, with weeds of national significance, noxious species and weeds of regional interest identified. A variety of techniques have been employed for weed management, namely the removal of weeds from a local environment including herbicide use, slashing, burning, mulching and through the use of goats. Goats in conjunction with stock can be useful in improving pasture condition and reducing weed density as part of a broader weed management program (NSW Department of Primary Industries 2015).

2.4.3 Importance of organic carbon and fine sediment retention in riparian environments

Organic matter is typically measured through organic carbon and plays an important role in the riparian zone ecosystem, influencing soil chemical and physical fertility (Grewal et al. 1991), whilst also functioning as a fuel to bacteria reducing nutrient loads such as nitrogen to the river (Woodman 2010). Nitrogen poses a significant detrimental risk to the aquatic ecosystem as excess nitrogen and nutrients may result in algal blooms and the eutrophication of the waterway (Woodman 2010). Where riparian zone vegetation has been re-established or increased, there have been decreased nutrient or nitrogen loads to the stream but also increased carbon sequestration in the soil (Mackay et al. 2016). Afforestation or the regrowth of vegetation has been shown to increase soil organic carbon in pasture or grasslands (Chen et al. 2016)

Riparian vegetation serves as an important source of organic carbon to the channel banks and aquatic river system. The removal of native riparian vegetation and introduction of exotic species has directly resulted in the change in the type of organic matter and temporal supply of this material to river systems (Mika et al. 2010). The removal of in-stream woody debris allows softer, less dense woody debris to pass through the system altering the cycling of nutrients and organic matter in the aquatic ecosystem (Mika et al. 2010). The introduction of a dam to a riverine system can also reduce the input and connectivity of organic matter and sediment downstream (Erskine et al. 1985).

Increased fine sediment loads to a river system present a number of issues and challenges in management. Detrimental impacts of this occurrence include the reduction of channel heterogeneity (Bartley & Rutherfurd 2005) and the inhibition of aquatic biota processes (Silver 2010). Fine sediment presents a number of potential issues to water quality. Increased quantities of fine sediment in the water column reduce the availability of light. This in turn has negative implications on the aquatic biota reliant on clear water and light, reducing diversity of aquatic biota. Increased fine sediment within the channel can reduce the oxygen availability and water exchange within the hyporheic zone in the channel (Boulton et al. 1998; Boulton 2007).

Creating sedimentary discontinuities such as a dam may result in the trapping and build up of sediment (Erskine et al. 1985; Mika et al. 2010). This hydrologic discontinuity also limits the availability of floodwaters for the reworking of bed sediments and the flushing of fine-grained sediments (Mika et al. 2010). Following the reintroduction of LWD into a river system it has been reported that there is an increase in variability of grain size, along with a significant fining of sediment at a reach scale (Brooks et al. 2004).

2.4.4 *The establishment of riparian zone corridors and the benefits on water quality*

The riparian zone or corridor is an area of land immediately adjacent to a river system. Establishing an effective buffer zone may restrict stock access or represent a break in the crop growing area to further promote the development of riparian vegetation (Shellberg & Brooks 2007). The benefits of riparian corridors or buffer zones are further being investigated and becoming better understood. Well-documented benefits of establishing a riparian zone corridor include channel stabilisation, increased bank stability, increased sediment retention (Shellberg & Brooks 2007) and increasing the diversity of the river ecosystem as a source of organic matter and woody debris (Gurnell 2014). The establishment of riparian corridors could begin the rehabilitation of many sites and help the geomorphic recovery of river systems (Shellberg & Brooks 2007).

Riparian corridors can be implemented to reduce the sediment load flowing into a river from surrounding agricultural land. Where riparian corridors have been appropriately designed and account for site conditions they have been over 90% effective at reducing sediment load to a river (Silver 2010). This has important water quality implications as increased sediment load to a river reduces water quality, lowering the productiveness of an aquatic habitat and reducing aquatic habitat diversity (Bartley & Rutherfurd 2005; Silver 2010).

Riparian corridors also prove useful at reducing the nutrient load, specifically phosphorus and nitrogen sourced fertilisers entering the waterways (Woodman 2010). Thus is important at improving or maintaining the water quality, as high nutrient levels promote the growth of algae and the eutrophication of the waterway, negatively impacting the aquatic ecosystem (Woodman 2010). The slowing of runoff allows greater time for infiltration of the water, this allows time for the de-nitrification process to be undertaken in the soils (Hunter et al. 2006; Woodman 2010). The bacteria which act to denitrify water, are supported in the riparian zone by high organic carbon content of the soils (Hunter et al. 2006; Woodman 2010)

These major functions of riparian corridors are controlled by a range of factors, namely vegetation type, density, width and spatial extent (Silver 2010). Woodman (2010) notes that if the spatial extent of the riparian corridor is not sufficient it will have minimal impact on reducing nutrient and sediment loads to the river (Woodman 2010).

2.4.5 The effects of grazing on the riverine and riparian environments with focus on water quality, organic matter content and fine sediment retention

Cows are important drivers of geomorphic change and as such have important management implications on riparian zones and their ecologic functioning (Trimble & Mendel 1995). Stock access to the riparian zone and channel banks has a number of negative implications for riparian zone and aquatic ecosystem health. Through grazing of the riparian zone cows reduce the bank stabilising effects that vegetation has on the bank. Physical compaction of the soil reduces the amount of infiltration, which can occur into the soil, causing more water to flow into the river as surface runoff (Trimble & Mendel 1995). Associated with this process is an increased amount of fine sediment being washed into the river with the run off, an increased nutrient load as the retentive properties of bank soil (e.g.

denitrification processes in the soil) are being bypassed. Cows may also play a role in decreasing organic matter of the soil, which is needed to power the denitrification process exacerbating the issue of increased nutrient load. This results in the decreased water quality of the river, which has detrimental effects on aquatic ecosystems. Chronic grazing of the riparian zone also promotes the prolonged degradation of the riparian zone as native vegetation does not have an opportunity to regenerate (Shellberg & Brooks 2007)

Stock management is an area of continued interest due to the associated release of sediment and reduction of water quality downstream (Bartley et al. 2014). Tufekcioglu (2013) found that the most effective way to increase stream water quality is to reduce grazing density in the riparian zone and by reducing stock access to the channel. Work by Webb and Erskine (2003) found that due to grazing, cows can reduce the density of weeds at a location. This grazing may promote the growth of native species, due to the reduced weed density competition for light and resources (Webb et al. 1999; Webb & Erskine 2003). Shellberg and Brooks (2007) found that restricting or eliminating stock access to riparian zones is an effective method to increase native riparian density, promote sedimentation and reduce stream bank erosion. Recent work from Brooks et al. (2016) suggests that stock can be used in controlled grazing regimes to reduce weed density in conjunction with strategic planting and revegetation of native species (Figure 6 & Figure 7).

Figure 6 Riparian Zone at Dart Brook Mine Site prior to controlled grazing (Image courtesy of Ron Connolly).

Figure 7 Riparian Zone at Dart Brook Mine Site post-controlled grazing. Note the vastly reduced density and concentration of weeds (Image courtesy of Ron Connolly).

2.5 KNOWLEDGE GAPS IN RIPARIAN ZONE MANAGEMENT

There have been numerous studies of both the river system and the riparian zone establishing the importance of riparian vegetation on river system functioning. As such the importance and benefits of riparian vegetation on rivers is well established and well known. Furthermore work has been undertaken describing the physical impacts of cattle or stock on the riparian zone and the river setting.

Some research questions, which the literature presents, include:

- The relationship between land use and organic carbon storage on bars and benches

- The physical impacts on bars of crash grazing (organic carbon and fine sediment retention)

- Best management practice for riparian zone grazing and weed management

- The importance of the riparian zone for carbon sequestration

3 Regional Setting

3.1 BACKGROUND TO THE STUDY SITES

The Hunter catchment is a large coastal catchment located on the central coast of New South Wales (Figure 8). This catchment drains approximately 22 000 km^2 with the upper Hunter catchment draining approximately 4500 km^2 (McVicar et al. 2015). Within the Hunter catchment there are 10 different styles of river with the dominant being partly confined valleys with bedrock-controlled discontinuous floodplain pockets (Brierley & Fryirs 2009). Three study sites have been selected over an approximately 10km stretch of the Hunter River between Aberdeen and Muswellbrook (Figure 9).

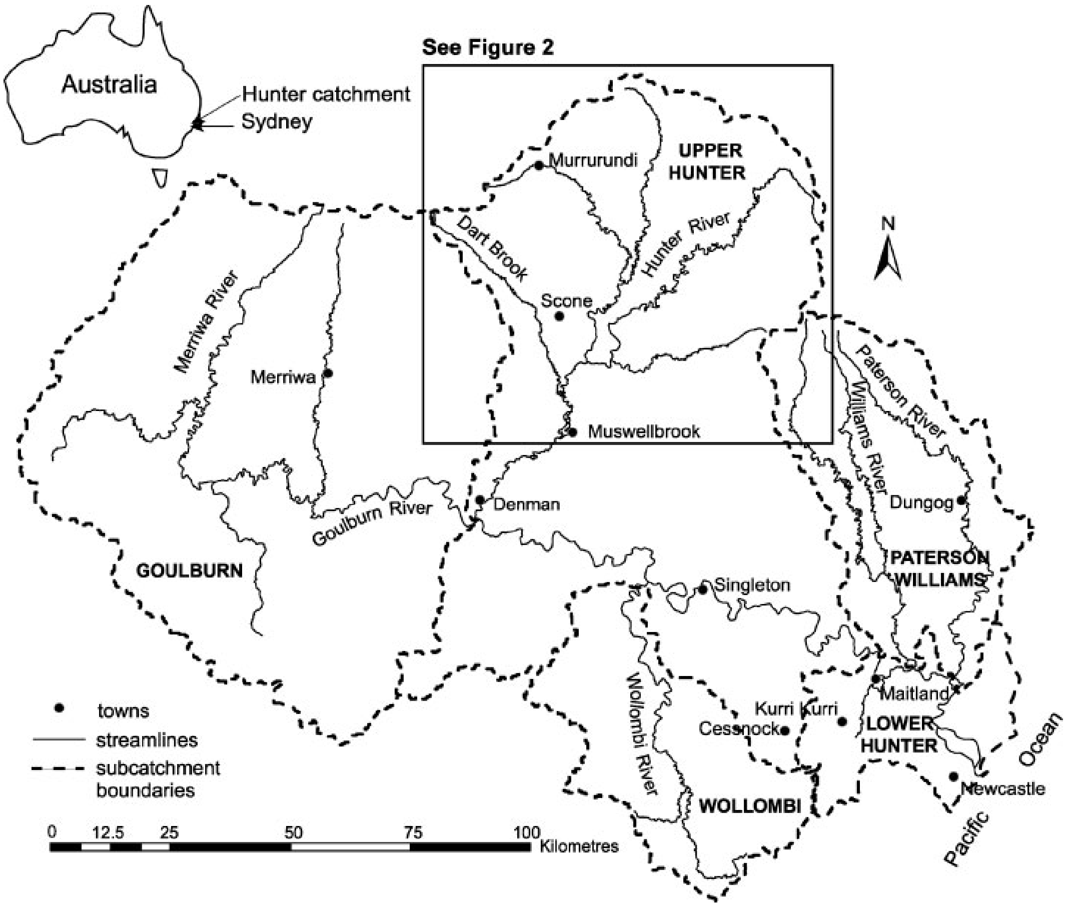


Figure 8 Spatial extent of the Hunter catchment. Taken from Spink et al. 2009.

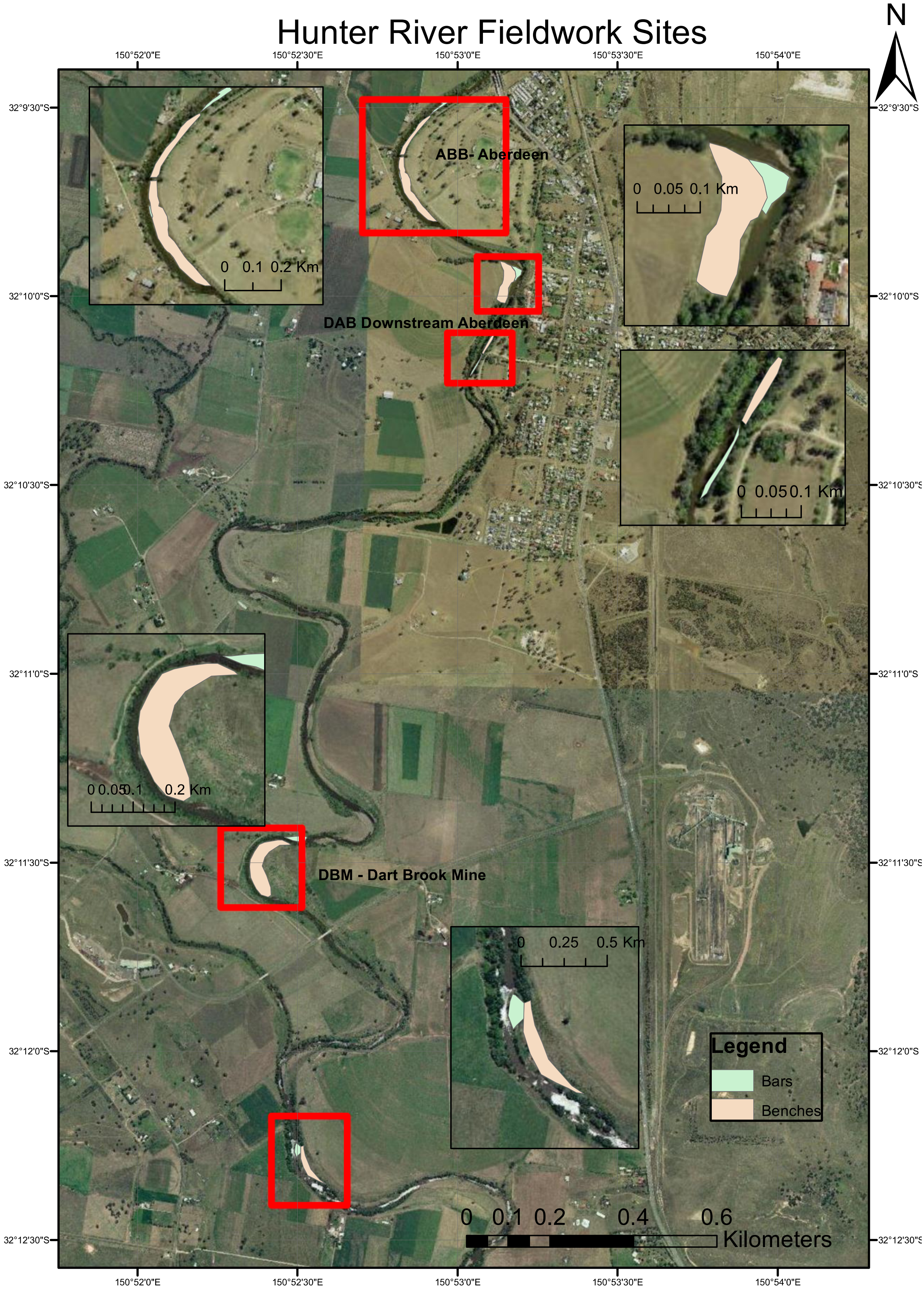


Figure 9 Study reach with Hunter River fieldwork locations between Aberdeen and Muswellbrook.

3.2 GEOLOGY

The Hunter catchment is an extremely large coastal catchment and is comprised of the northern most reaches of the Sydney Basin (Figure 11; McVicar et al. 2015). The Sydney Basin Group in the Hunter catchment is characterised by Permian sedimentary units overlain by Triassic sedimentary units (Spink et al. 2009). A large thrust fault, the Hunter-Mooki Thrust fault, runs north-west to south-east through the centre of the upper Hunter catchment (Figure 10; McVicar et al. 2015). The Hunter-Mooki Thrust fault separates the Sydney Basin from the New England Fold Belt (Carey & Osborne 1939).

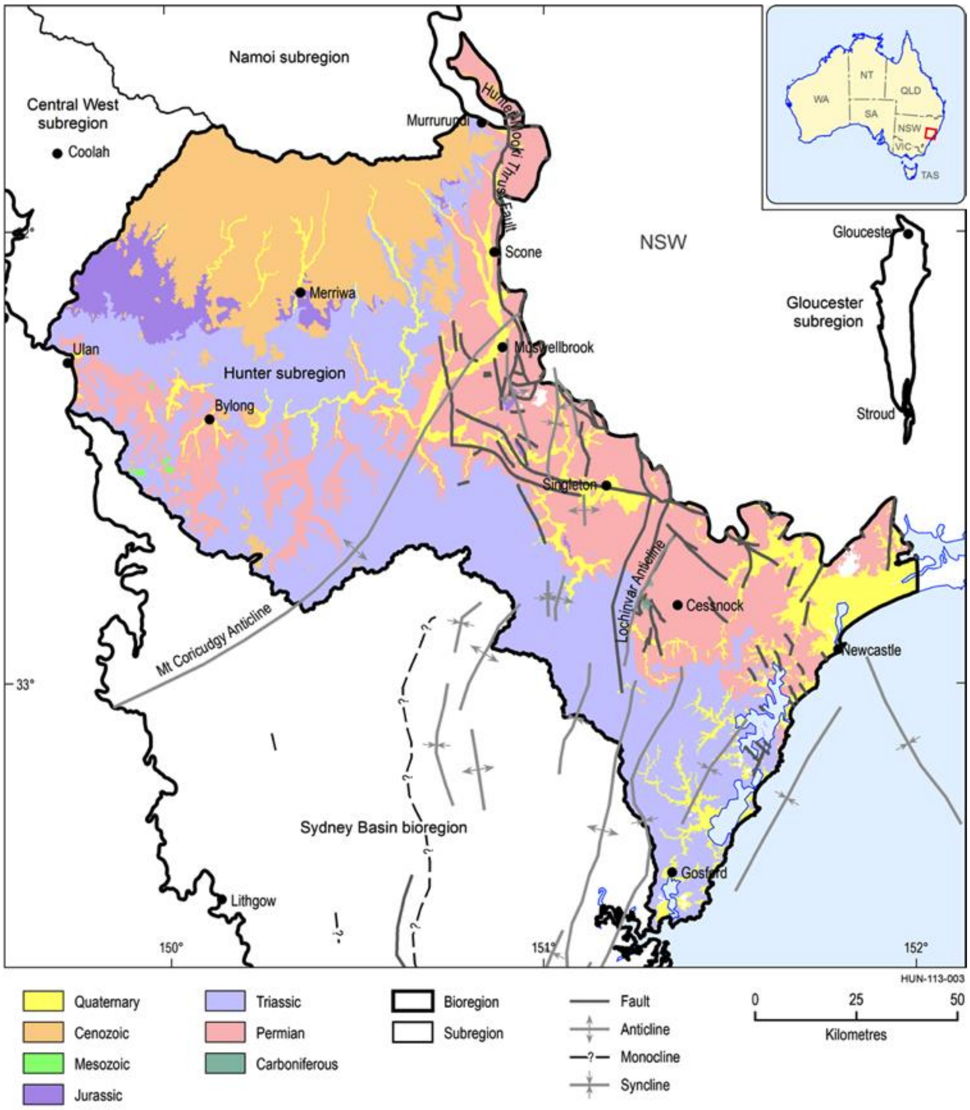


Figure 10 Structural map of the Hunter catchment; Note the Hunter-Mooki Thrust fault at the northeastern boundary of the unit. Taken from McVicar et al. 2015.

The New England Fold Belt is dominated by Carboniferous metamorphics and Cenozoic basalts. A series of Cenozoic basalt flows exist flowing to the northern reaches of the Hunter catchment (Erskine et al. 2012). Quaternary sediments have been aggraded throughout the valleys of the Hunter catchment, typically consisting of gravel, sands, silts and clays (Shellberg & Brooks 2007).

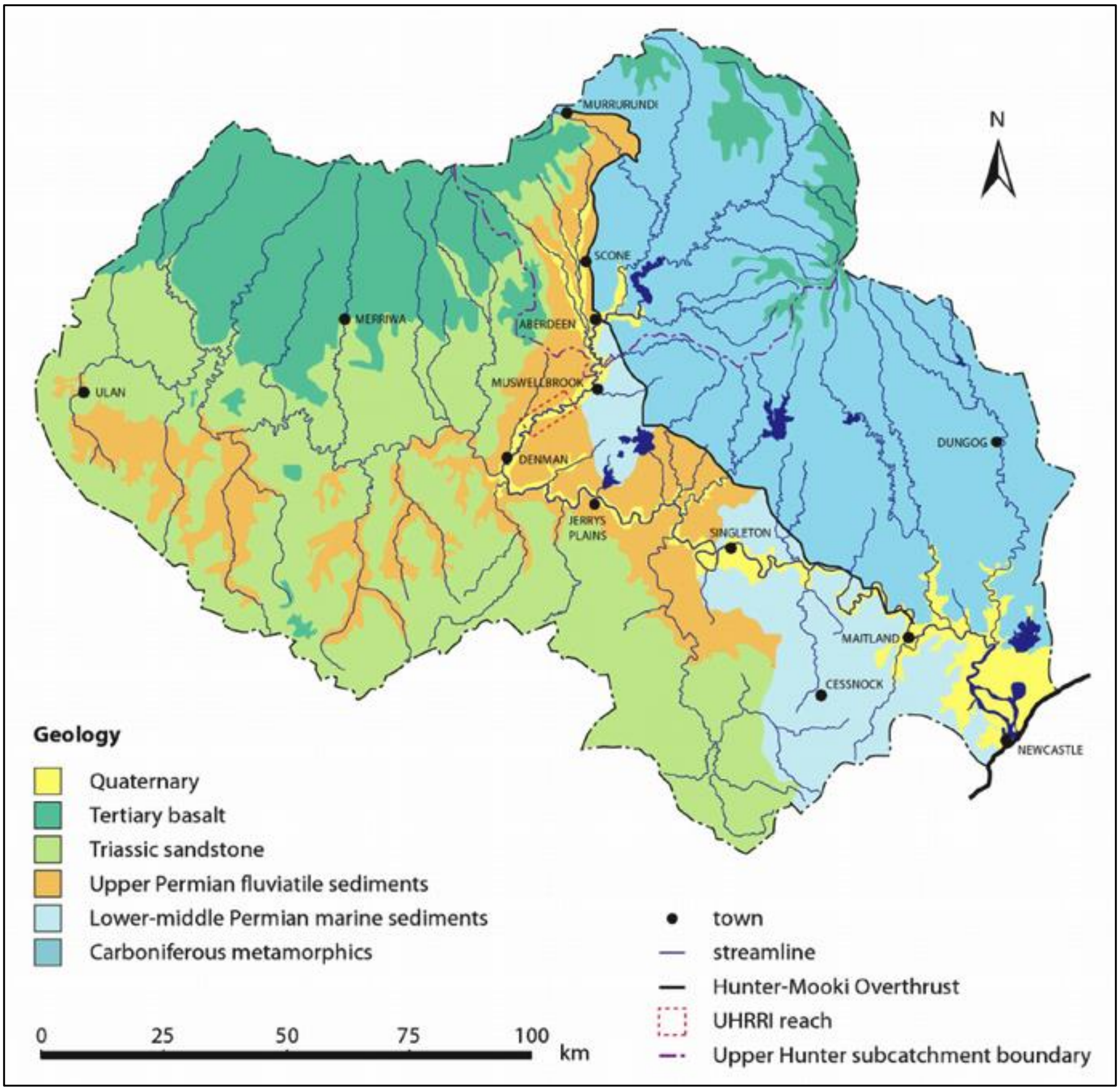


Figure 11 Detailed geologic map showing the contrast between the Sydney Basin Group and the New England Fold Belt rock strata. This is most apparent along the Hunter-Mooki Thrust fault. Image taken from Spink et al. 2009.

3.3 HISTORICAL AND MODERN LAND USE

The primary land uses within the Hunter catchment are grazed modified pastures (39.3%), nature conservation (22.6%) and minimal use land purposes (16.8%; McVicar et al. 2015). Mining has historically been an economically important practice through the Hunter catchment however, only occupies 1.1% of land (Figure 12). Much of the nature conservation land lies in the headwaters of the rivers, while the lowland regions of the catchment have been developed for primarily agricultural purposes (Shellberg & Brooks 2007).

Early Europeans utilised the floodplains for agricultural purposes, crops and pastureland and also the river for navigation and as a source of sand and gravel (Webb et al. 1999). The introduction of this European land use paradigm resulted in the systematic clearing of vegetation for the development of agricultural fields, pastures and mines (Shellberg & Brooks 2007; Spink et al. 2009).

The shift in land use paradigm resulted in the change from a largely forested catchment area with a diverse range of eucalypt and native plant species to the current situation where by almost all areas have experienced a decrease in vegetation cover and diversity, with some areas having lost almost 100% of historical vegetation cover (Shellberg & Brooks 2007). The introduction of roads and railroads to the areas has provided a pathway for exotic species of vegetation to spread throughout the catchment (Shellberg & Brooks 2007). Riparian vegetation extent has increased over the past 30 years as a result of changing land use (Brooks et al. 2016).

Europeans have also strongly influenced natural watercourses, directly and indirectly altering the watercourse through the introduction of water retention structures (e.g. Glenbawn Dam) and directly through the implementation of river training schemes and river straightening projects (Spink et al. 2009).

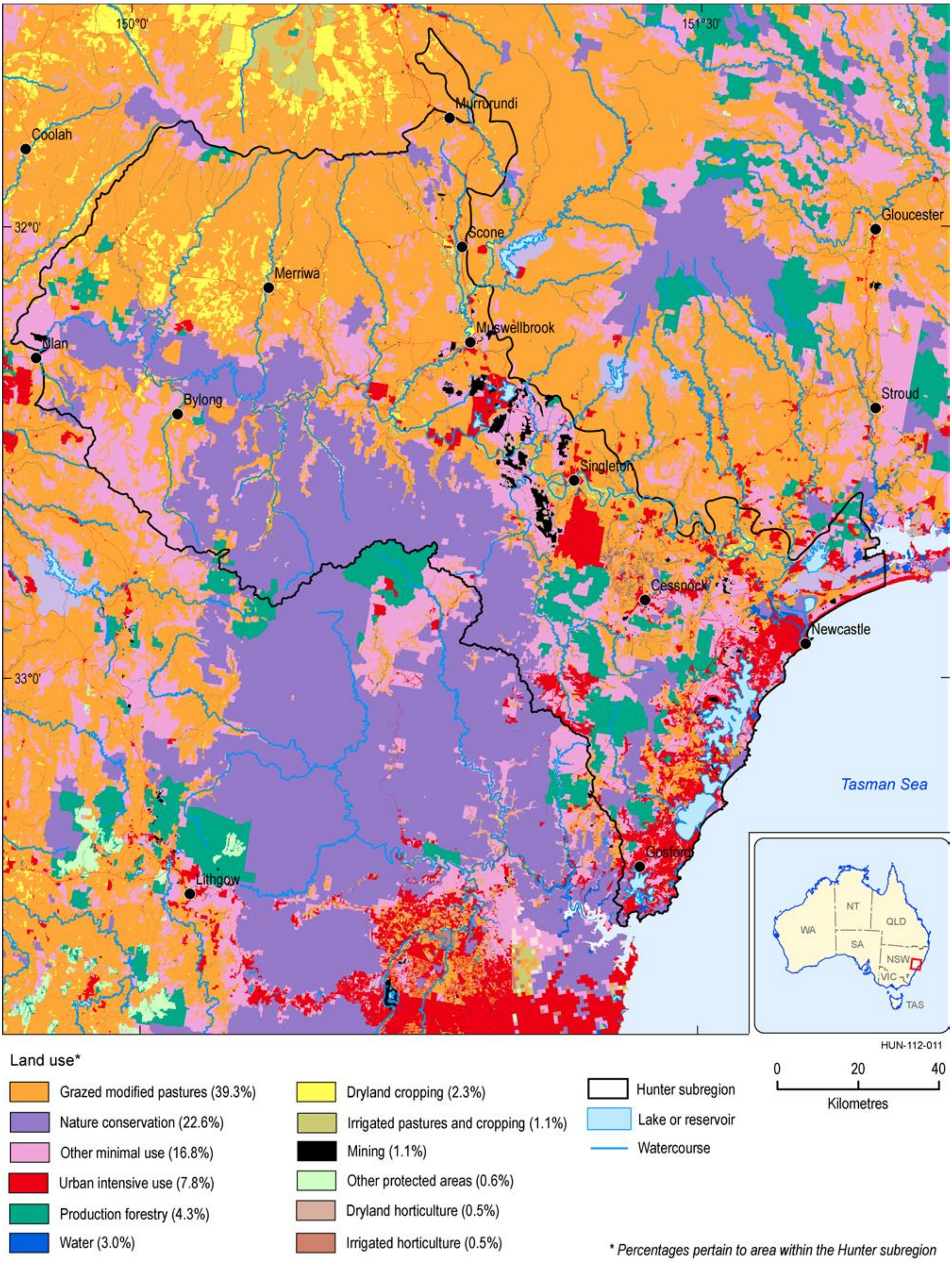


Figure 12 Contemporary land uses across the Hunter catchment. Taken from McVicar et al. 2015.

3.4 HYDROLOGY

The upper Hunter catchment has a number of both rivers and tributaries, which feed the Hunter River, notably the Pages River, Dart Brook and Rouchel Brook. At Muswellbrook the total upstream catchment area is approximately 4200km^2. Stream gauges are located at Muswellbrook (stn. 210002 & stn. 210008), Aberdeen (stn. 210056), Moonam Dam (stn. 210018) and Belltrees (stn. 210039).

The hydrologic conditions of the catchment have been dramatically changed over the past 100 years. The construction of Glenbawn Dam began in 1947 and was completed in 1957. This reduced the stage height of large floods, reduced the frequency of intermediate floods and regulated water flow to ensure a constant discharge (Erskine & Bell 1982; Shellberg & Brooks 2007). In the hydrologic regime prior to the construction of Glenbawn Dam the recurrence of larger floods was much higher (Figure 13; Hoyle et al. 2012). The sedimentologic and hydrologic impacts from the introduction of this barrier decrease in a downstream direction as more tributaries supply both water and sediment to the Hunter River (Shellberg & Brooks 2007).

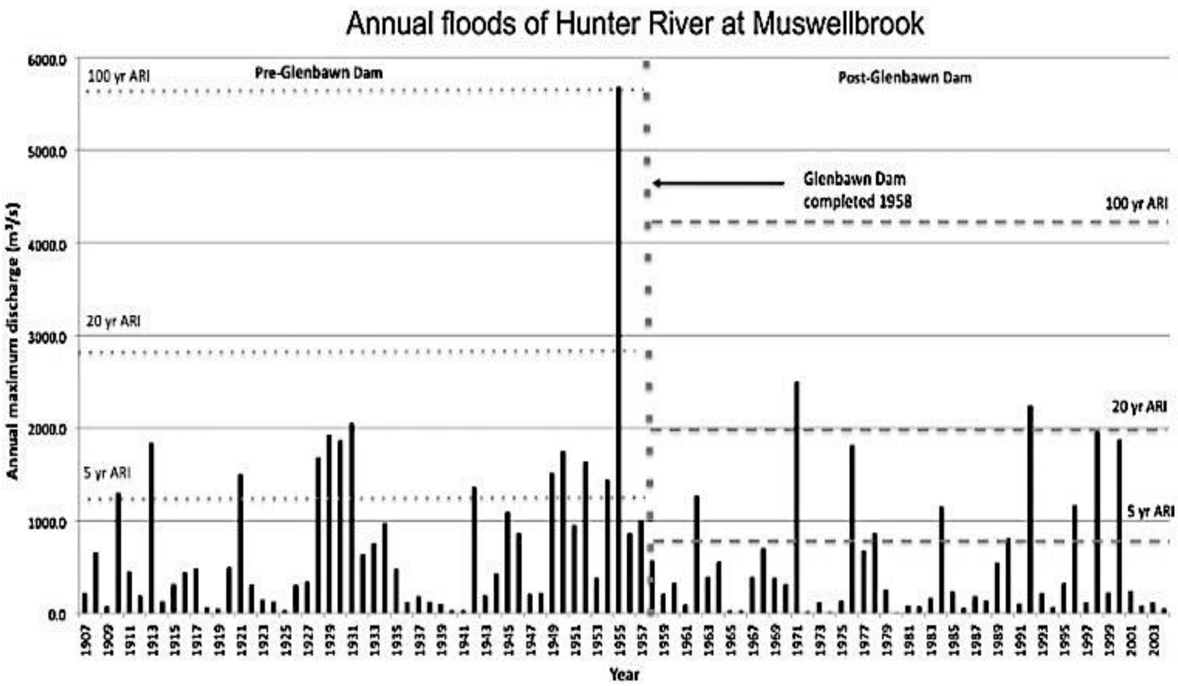


Figure 13 Annual flood of Hunter River at Muswellbrook 1907-2006. Data reconstructed from multiple gauges (stn. 210002 and stn. 210008 – 1 km apart) to improve data accuracy. Taken from Hoyle et al. 2012.

Discharge on the Hunter River prior to the closing and regulation of Glenbawn Dam in 1958 was seasonal with increased discharge on the cooler winter months (Figure 14). Following the completion of Glenbawn Dam, the discharge regime is significantly different and much more stable, as such flow is much more consistent even during drier or hotter months (Figure 14).

The largest recorded flood in the 109-year gauge history was the 1955 flood which recorded a discharge rate of approximately 5680m^3/s at Muswellbrook (stn. 210008; Hoyle et al. 2012). This event is considered a 1/100-year flood. Hoyle 2012 found that 90% of the time flow is less than 12 m^3/s and less than 1 m^3/s for 10% of the time.

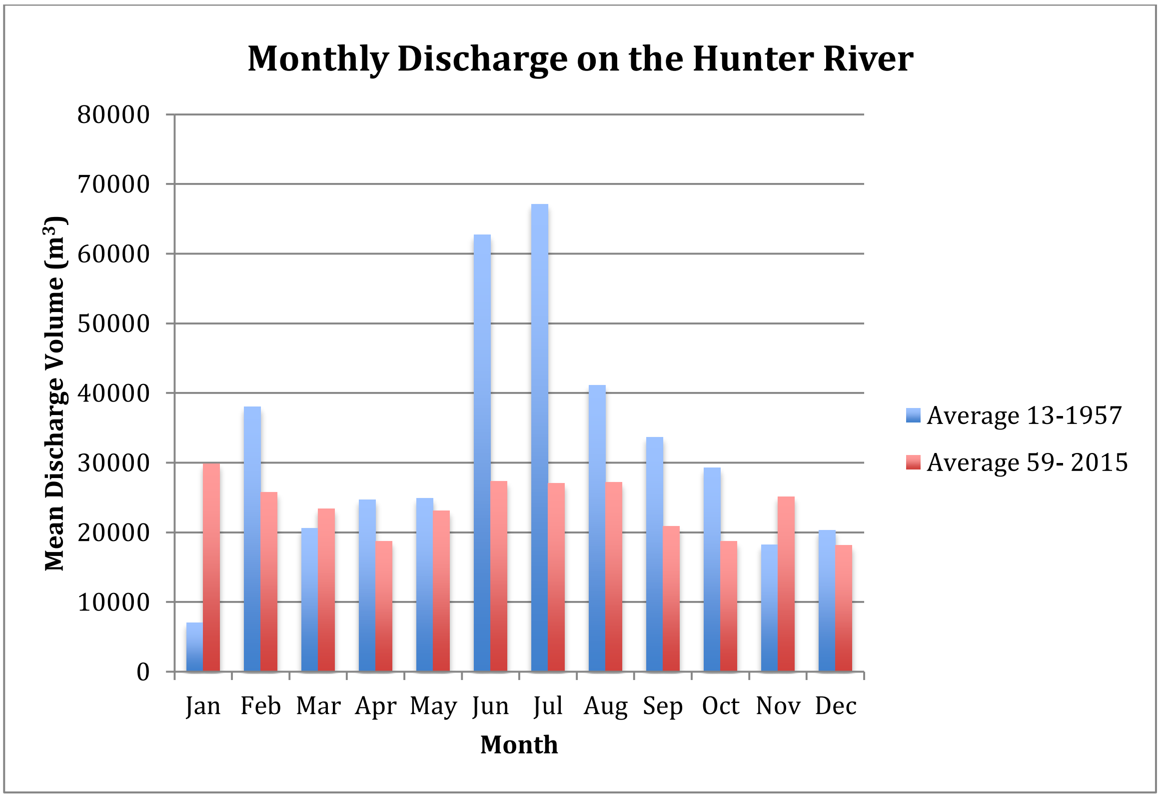


Figure 14 Mean monthly discharge on the Hunter River at the Muswellbrook stream gauges (stn. 210002 and stn. 210008) before (1913-1957) and after (1959-2015) the introduction of Glenbawn Dam.

Historical flow gauge records show that in recent years total annual discharge has been below 500 000 ML. The peak annual discharge was in 1950 (Figure 15) following the highest recorded annual rainfall across the Hunter catchment.

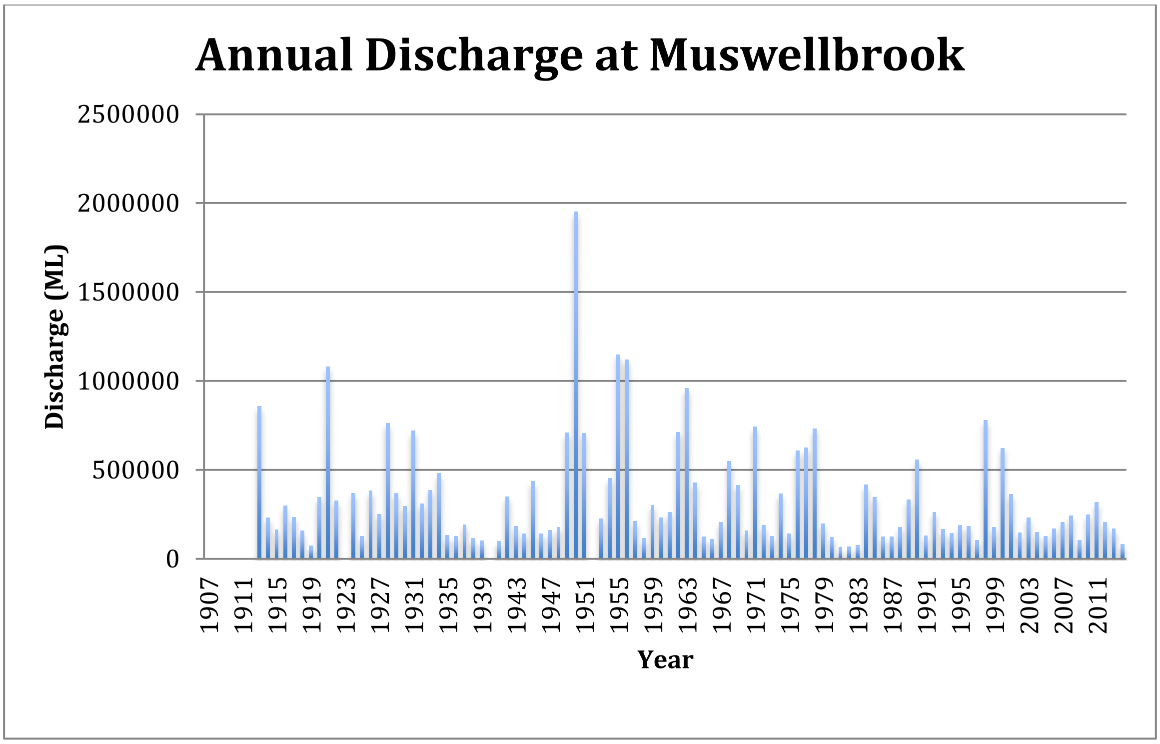


Figure 15 Total annual discharge at Muswellbrook (stn. 210002 and stn. 210008 composite).

3.5 CLIMATE

The Hunter catchment area experiences a warm temperate climate with climatic variability related to its large spatial extent (Scealy et al. 2007). The ocean acts to moderate the climate in the coastal reaches of the catchment, limiting extreme thermal variation and producing a more stable climatic regime (Shellberg & Brooks 2007). The climate of the inland areas of the Hunter catchment is moderated by continental conditions and thus has a more variable climate. Both coastal and mountainous regions of the Hunter catchment receive increased amounts of rainfall compared to low lying inland areas of the catchment (Webb & Erskine 2003). A strong precipitation gradient exists to the west, from the coast to the inland reaches of the catchment (Shellberg & Brooks 2007).

Temperature records over a 60 year period (1950-2016) at the Scone weather station (stn. 061089) in the upper Hunter catchment show an average monthly temperature range between 11°C - 24°C (Bureau of Meteorology 2016). The maximum daily temperature value was 43°C and the minimum recorded temperature was -3°C (Bureau of Meteorology 2016).

Rainfall records over a 120 year period from the Aberdeen rainfall gauge (Station 061000) show average annual rainfall is approximately 600mm/year. Seasonal rainfall is greatest in summer with the least rainfall occurring the winter months (Figure 16; Shellberg & Brooks 2007). Large rainfall events can occur over any season however, tend to be concentrated in the warmer summer months due to moist tropical air and increased temperatures producing intense convective precipitation (Shellberg & Brooks 2007).

Annual precipitation records of the Aberdeen station (061000) show a pattern of alternation between periods of increased rainfall and periods of below average rainfall (Figure 17). This annual variability is strongly linked to the alternation between periods of El Niño and La Niña as part of the El Niño Southern Oscillation (ENSO; Shellberg & Brooks 2007). This annual variation is reflected in the climatic records from other stations in the region at Muswellbrook and Scone.

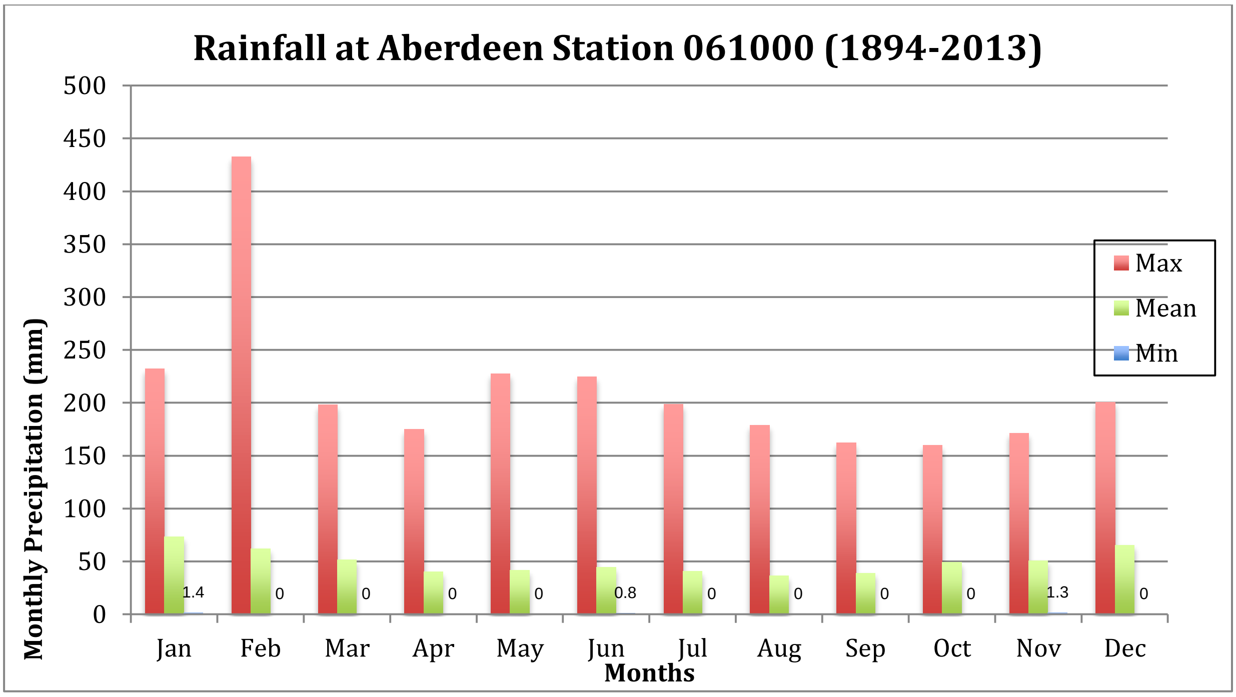


Figure 16 Long-term monthly precipitation statistics at Aberdeen (stn. 061000; Bureau of Meteorology 2016).

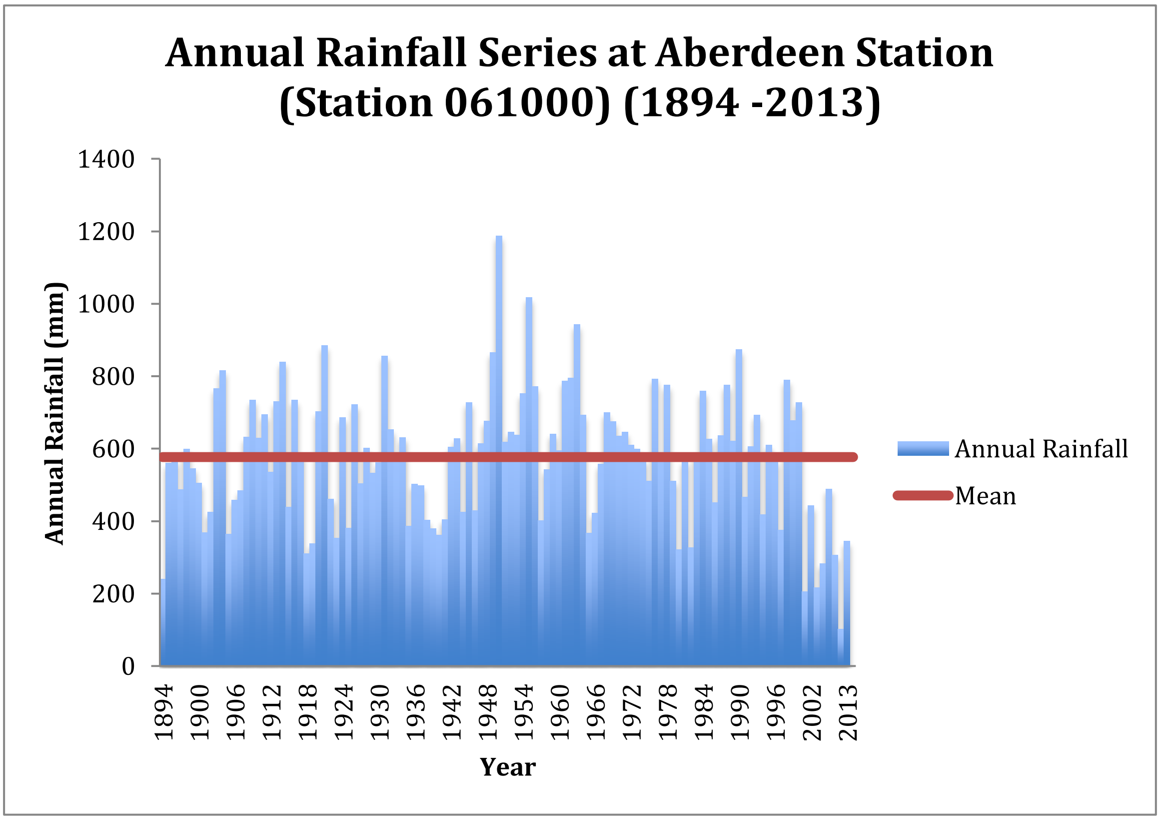


Figure 17 Long-term precipitation record from the Aberdeen Station (stn. 061000) in the upper Hunter catchment. Note the succession of above average rainfall events in the 1950's (Bureau of Meteorology 2016).

3.6 RIPARIAN VEGETATION ON THE HUNTER RIVER

Vegetation in the Hunter catchment has had an extremely disturbed history and as a result only pockets of original native vegetation remain (e.g. tree species such as river she-oak *Casuarina cunninghamiana*; Scealy et al. 2007; Shellberg & Brooks 2007). The catchment is dominated by dry sclerophyll forests where forested (41.8%; Figure 18). Anthropogenic influence has resulted in the removal of native riparian vegetation throughout the Hunter catchment (Brierley & Fryirs 2009). As native vegetation was removed, exotic species were introduced to manage erosion resulting from the removal of the initial riparian vegetation (Webb & Erskine 2003; Spink et al. 2009). This has resulted in the modern day riparian zone being dominated by exotic species such as willow (*Salix species.*), poplar (*Populus species*), giant reed (*Arundo donax*), castor bean (*Ricinus communis*), privet (*Ligustrum species*), Peruvian pepper (*Schinus molle*), fennel (*Foeniculum species*) and balloon vine (*Cardiospermum grandiflorum;* Shellberg & Brooks 2007). These weed species dominate native vegetation and reduce the ability for native species to recolonise (Webb & Erskine 2003). Whilst many of these weeds are not listed as weeds of national significance (WoNS), many are classified as noxious weeds under the *Noxious Weeds Act 1993* and careful management and care must be taken to limit the spread and propagation of these species (HCCREMS. 2010). Weeds of national significance include willows (*Salix species*) and blackberry (*Rubus furticosus*) however, weeds of regional significance in the Hunter area include green cestrum (C*estrum parqui)*, privet (*Ligustrum species*) and blackberry (*Rubus fruticosus*) (HCCREMS. 2010).

Since the 1950s the riparian vegetation has been recovering slowly and increasing the river's flow resistance and ability to trap sediment (Brierley & Fryirs 2009; Mika et al. 2010). Figure 18 highlights the cleared nature of the catchment especially in areas immediately abutting rivers. Approximately 35% of the modern Hunter catchment is cleared or dominated by exotic species (McVicar et al. 2015). Recent work has found that over the past 30 years, vegetation has increased between 43% across the Hunter catchment, with an average increase of 25% riparian woody projected foliage cover over the last 12 years (Brooks et al. 2016).

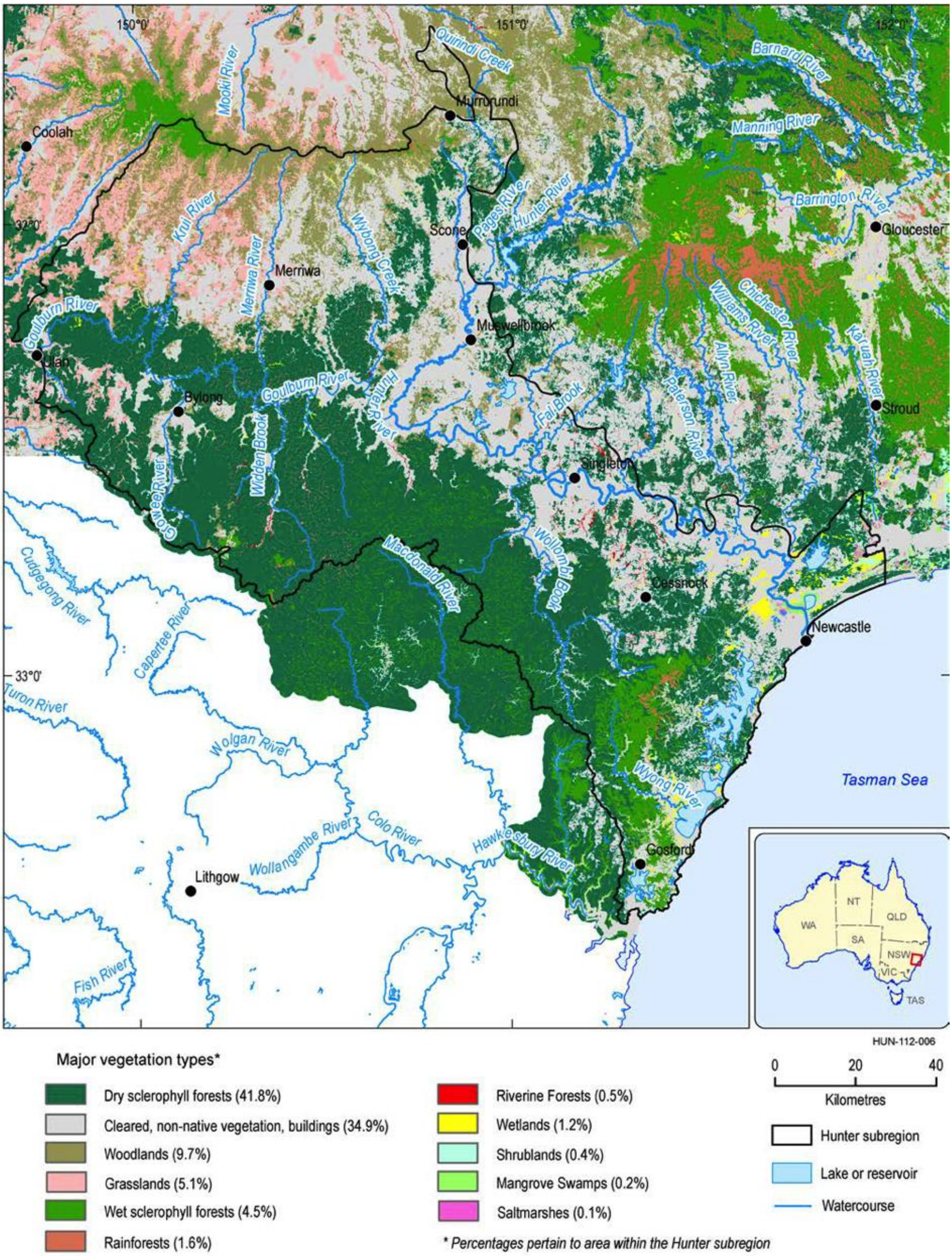


Figure 18 Vegetation classification across the Hunter catchment. Taken from McVicar et al. 2015.

3.7 CHAPTER SUMMARY

The upper Hunter River is a vastly altered river characterised by a low flow channel which adjusts between geomorphic features such as bars and benches (Hoyle et al. 2007). Typical structure of the river is to have a small low flow channel, in set bars, inset benches with a terraced floodplain (Hoyle et al. 2007). Within the study reach, much of the river channel is grazed with pockets of dense vegetation typically dominated by weeds and exotic species such as willow (*Salix species)*, poplars (*Populis species*) and giant reed (*Arundo donax*) with vines common such as balloon vine (*Cardiospermum grandiflorum*) in conjunction with some stands of river she-oak (*Casuarina cunninghamiana*; Shellberg & Brooks 2007). Vegetation is highly altered with almost 100% being removed at some point in time. Vegetation however has been regrowing and re-establishing along the Hunter River (Brooks et al. 2016). Flooding has been reduced following the introduction of Glenbawn Dam which acts to reduce low level flood events, as seen by less spikes in the hydrologic record (Hoyle et al. 2008).

4 METHODS

4.1 INTRODUCTION

This study aims to address a number of aims and objectives using a range of different methodologies both field and laboratory based. As such the aims are outlined with the selected methods and justifications below.

4.2 SPATIAL DATA METHODS

Investigate historical land use and vegetation changes and relate this to the climatic and hydrologic record

Establishing the land use history of the upper Hunter River was undertaken through the utilisation of historical aerial photography and modern satellite imagery. A series of images captures the study sites in 1938, 1952, 1955, 1972, 2009 and 2015. This was utilised to produce a time series that characterised major channel changes, adjustments and changes in land use and vegetation (Hoyle et al. 2008). Field photographs taken from both the ground and air utilising drone photography provided by Andrew Brooks (2016) demonstrating recent changes was also utilised for the purpose of this comparison.

Two additional raster datasets were sourced from Skorulis (2016) and the NSW Office of Environment and Heritage (2016). A normalised difference vegetation index (NDVI) dataset was provided by Skorulis (2016), which consisted of a statewide assessment of riparian zone change over a 28-year period using composite images from 1987-1991 and 2009-2015 in the spring. Temporal change was determined by subtracting the pixel values of the later dataset (2009-2015) from the earlier dataset (1987-1991; Cohen et al. 2016). This dataset was clipped to a 50 m buffer layer generated from a 2009 Department of Environment, Climate Change and Water (DECCW) Land Use: New South Wales dataset. This dataset contained two threshold values ± 0.1 and ± 0.2 as using an NDVI threshold < 0.2 likely represents bare land or pasture grass, whereas an NDVI threshold $0.2 \leq \text{NDVI} < 0.5$ may represent a mixture of high and low density vegetation (Cohen et al. 2016).

A seasonal composite fractional cover dataset produced by the NSW Office of Environment and Heritage (OEH) (2016) dataset was utilised to show seasonal changes in fractional cover throughout the study sites from 1988-2016. The dataset consisted of 4 bands or layers bare, green, non-green and model residuals. The spring data series was utilised to show the same season as in the NDVI dataset from Skorulis (2016). This fractional cover layer was clipped to the same 50 m buffer layer surrounding the channel as the dataset from Skorulis (2016). A polygon of the study area between Muswellbrook and Aberdeen was then used to clip the buffer layer to only show the region of interest. Band statistics were then calculated from the clipped fractional cover layer and exported to excel. The spring values were then calculated through time, and shown as each band or layer through time. These values were also plotted against spring seasonal discharge (stn. 210056) and precipitation (stn. 061000) over the same time period.

A series of five preliminary study locations were selected using satellite imagery from NSW Land and Property Information (Public Base Layer). This data layer was utilised of ARCGIS 10.2 to map and measure major geomorphic features such as bars and benches using the measure tool in order to develop a field sampling program. Further investigation in the field led to the final selection of sites most appropriate for the research questions for sediment sampling. Geomorphic feature area, shape and perimeter were also calculated using spatial data on ARCGIS 10.2 using the measure tool.

4.3 Hydrologic Data Methods

Investigate historical land use and vegetation changes and relate this to the climatic and hydrologic record

Hydrologic data was analysed for sites both upstream and downstream of Glenbawn Dam (Figure 19 & Table 2) utilising annual and monthly daily discharge but also maximum daily discharge. This was utilised to create a summary of historical flow conditions and relate historical vegetation change to the hydrological record.

Annual series flood frequency analysis was also undertaken at each gauging location. The annual maximum daily discharge was recorded and assigned a rank from largest to smallest (Cunnane 1978).

$$Flood\ recurrance\ interval = \frac{(N+1)}{M}$$

$$N = Total\ number\ of\ years\ of\ record$$

$$M = Rank\ of\ individual\ flood$$

Table 2 Summary of hydrologic datasets utilised and collected for analysis (Office of Water, 2016).

Station Number	Station Name	Catchment Area (km^2)	Date Started	Period of Time in Operation	Number of years	% Complete (Annual Discharge)	% Complete (Monthly Discharge)	% Complete (Max Daily Discharge)
210018	Hunter @ Moonan Dam Rd	764	1940	Continued-July 2016	77	77	93	93
210039	Hunter @ Belltrees	1180	1999	Continued-July 2016	18	83	90	96
210056	Hunter @ Aberdeen	3090	1959	Continued-July 2016	58	47	62	63
210002	Hunter @ MuswellBrook	4220	1907	Continued-July 2016	110	63	63	67
210008	Hunter @ MuswellBrook	4220	1918	1962	45	88	94	99

The hydrologic record was also utilised to calculate inundation rates for each bar and bench within the study locations. Field surveying was undertaken to establish the structure of each feature and the relative height of each feature to the water level at the day. This was level was then related to the water level on the day of surveying at the Aberdeen stream gauge (stn. 210056) making the assumption of similar cross sectional area. The height of the water was subtracted from the maximum height of the bar or bench to determine the addition height of water required to fully inundate the bar or bench. This difference value was then added to the stream height to give a stream height required to fully inundate the geomorphic features. The relationship between stream height and discharge rate was then established through plotting of stream height (m) against discharge rate (ML/day) for the last 16 years (2000-2016) and a quadratic curve was fitted. As the stream height (m) required to fully inundate a site was known, the corresponding discharge rate (ML/day) could be taken either from the equation of the line or from the curve directly. The discharge rate required to inundate the study sites was used with the annual flood recurrence intervals for Aberdeen (stn. 210056) to determine the frequency of inundation by matching discharge rate and reading the recurrence interval. The monthly average maximum and mean discharge rates were calculated for the Aberdeen Gauge. This was to determine the frequency of flows, which may inundate bars, and or the seasonality likelihood of inundation.

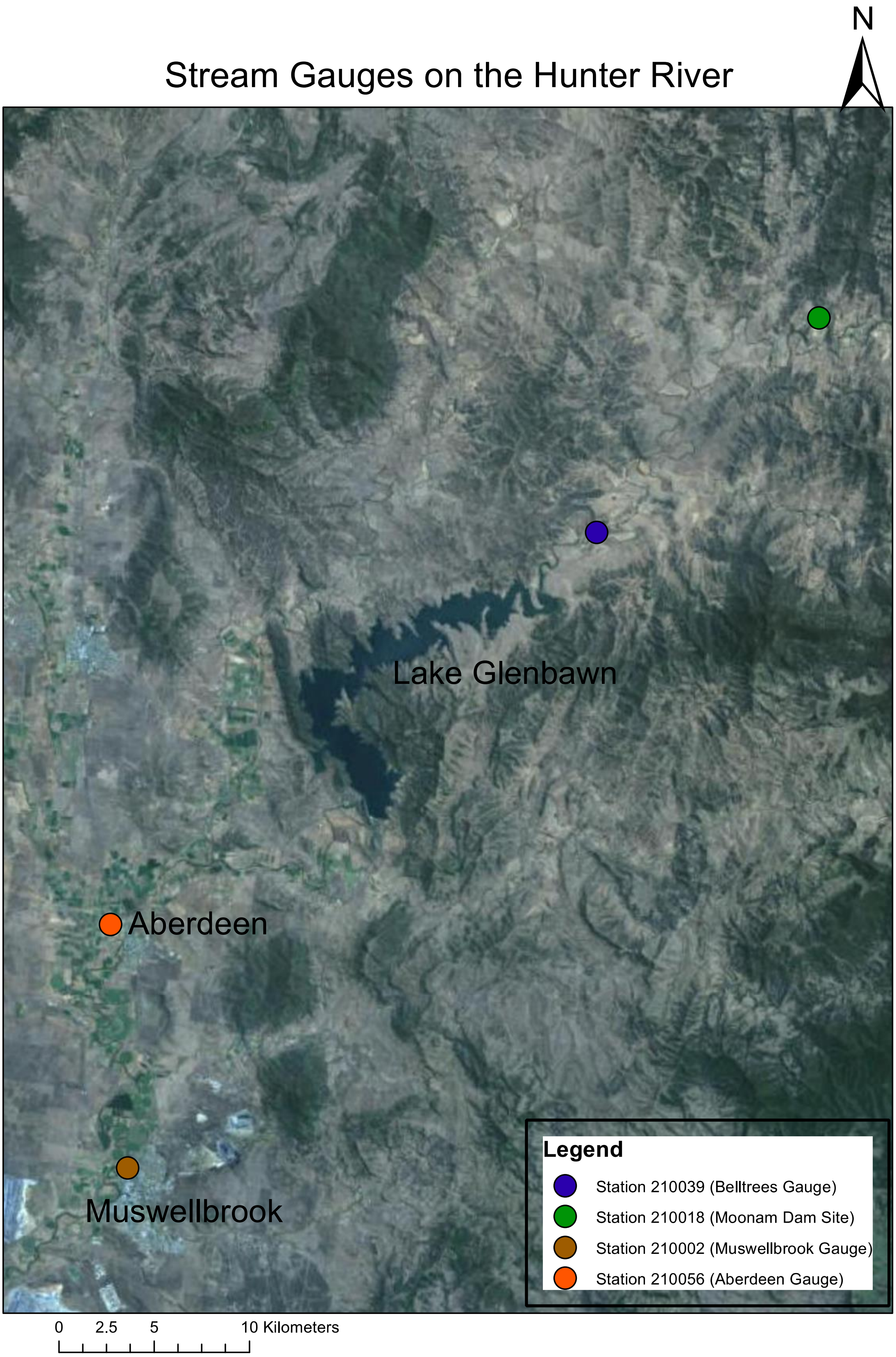


Figure 19 Spatial distribution of stream flow gauges utilised in the upper Hunter catchment.

4.4 Field Data Collection Methods

Assess the difference between of benches and bars of different land use regimes statistically in terms of sedimentological, geochemical and morphological parameters.

A series of six bars and six benches were analysed in paired type settings (Table 3 & Figure 9). As established earlier, three study locations were selected utilising aerial photography in conjunction with consultation with landholders to establish the historical and modern grazing regimes (Connolly R, personal communication 2016). A total of one hundred and eleven (111) soil samples were taken for the purpose of grain size analysis and organic carbon content. Locations for sediment sampling were kept at consistent points on each geomorphic feature with nine samples being taken as in Figure 3 (Hoyle et al. 2007). However, due to the variable spatial extent of each feature, no set grid or distance was established between each sample point. These samples were taken using an 8 cm internal diameter; 10 cm deep hollow stem auger to ensure the same depth and amount of sediment was retrieved. In conjunction with the fine smaller samples a bulk sediment sample was taken at the coarsest point on each geomorphic feature which was consistently point two (Figure 3; Hoyle et al. 2007).

Table 3 Site names and locations; ABB - Upper Aberdeen, DAB - Downstream Aberdeen & DBM - Dart Brook Mine site.

Non- Grazed Bar (Vegetated Bar)	Non - Grazed Bench (Vegetated Bench)	Grazed bar	Grazed Bench	Crash- Grazed Bar	Crash Grazed Bench
ABB1	ABB2	ABB3	ABB4		
DAB4	DAB3	DAB1	DAB2		
DBM3	DBM4			DBM1	DBM2

At each study location a vegetation transect was undertaken in conjunction with a topographic survey. This survey was undertaken at the mid-point of each bar or bench along the same pathway in which soil samples (4, 5 & 6) were taken (Figure 3). Data collected included the spatial distribution and structure of the riparian zone, bar and bench topographic profile, % canopy cover, % mid canopy cover, % ground cover as well as the vegetation species present. This data set was used in order to perform both statistical analyses and gain an understanding of the weed and exotic species diversity but also to relate the hydrologic record to conditions seen in the field.

4.5 Statistical and Laboratory Methods

Assess the difference between of benches and bars of different land use regimes statistically in terms of sedimentological, geochemical and morphological parameters.

Determining Organic Content of the Samples

Determining the organic carbon content of soils has traditionally been divided into two categories; weight loss on removal of organic matter or determination of a constant constituent of organic matter (Schulte 1995). Methods for the determination of organic carbon include the Walkley Black Method, oxidation with H_2O_2, ignition and ignition after decomposition of silicates with hydrofluoric acid (Schulte 1995). Loss on ignition (LOI) was selected as it is a useful and time efficient method for determining the organic carbon content of non-calcareous soils (Sutherland 1998). Other methods of LOI testing involve heating the samples to a higher temperature (850°C) for a shorter period of time (4 hours), however, this may cause the release of structural clay particles (Ball 1964). Ball (1964) found that results using the LOI method were strongly correlated with results found using the Walkley and Black method.

In order to prepare the sedimentary samples for LOI testing, samples were allowed to air dry before being sieved to less than 2 mm using a non-metallic sieve (Abella & Zimmer 2007). This size was selected as it is generally accepted that this is the size fraction containing most organic carbon (Sutherland 1998). Sediment was then ground using a mortar and pestle to a grain size to pass through a 150 micron sieve (Goldin 1987). The sample was then dried overnight in an oven at 105°C before it was placed in a muffle furnace at 375°C for 16 hours (Ball 1964). The samples were placed at 375°C as this allowed the burning of the organic carbon within the sample without the breakdown and release of structural clay particles (Ball 1964). Organic carbon was calculated using the following equation.

$$LOI\% = \frac{Ws - Wa}{Ws - Wc} \times 100$$

$Ws = Weight\ of\ container\ and\ sample\ post\ oven$ (105°C)

$Wa = Weight\ of container\ and\ sample\ post\ furnace$ (375°C)

$Wc = Weight\ of\ container$

Duplicate samples were taken on every 1 in 8 samples for the first 5 rounds of samples analysed (less than 10% deviation; Appendix A).

Measuring Fine Sediment Accumulation

Samples were allowed to air dry before being split into different size fractions. Sediment was sieved to less than 1.5 mm prior to analysis in the Malvern Mastersizer. The Malvern was used to analyse 111 samples measuring the grain size of particles and determining the relative proportion of particles of different sizes.

In addition bulk sediment grain size analysis was utilised to show major differences between locations. This analysis was performed by air-drying the 12 samples collected in the field, before dividing the sediment into three major groups. Sieving divided the group into samples larger than -4 phi, between -4 phi and -1 phi and sediment smaller than -1 phi. This rough division was utilised to show major differences in terms of grainsize.

Statistical Analysis

To determine significant difference between study sites, statistics using SAS JMP 10 software was undertaken. Outliers from the sample pool were excluded to meet the conditions of the statistical analysis. Samples were tested first for normality using the Shapiro Wilk W test (Abella & Zimmer 2007). Samples found to be non-normally distributed were tested using the Wilcoxon/ Kruskal Wallace (Rank Sums test). Where samples were found to be normally distributed, sample variance was tested to determine if the sampled had equal or non-equal variance using Welch's test. Samples with normal distribution and equal variance were then tested using a paired t test. Samples with normal distribution and non-equal variance were tested using a non-equal variance t test. The probability of wrongly rejecting the null hypothesis was set a power level of $\alpha = 0.05$ (Upson et al. 2016). Organic carbon values, mean fine sediment size (< 1.5 mm) and fine sediment proportions were all tested using the above method. Statistics were also used to correlate organic carbon and the relative vegetation canopy cover. This utilised the non-parametric multivariate Spearman's test against $\rho = 0.05$.

5 SPATIAL DATA ANALYSIS RESULTS

5.1 INTRODUCTION

This chapter presents the results from both spatial and hydrologic data analyses. This will convey an understanding of temporal changes to the physical catchment conditions in the study area. Datasets that have been utilised includes flow data from hydrologic gauges, historical aerial photography, field photography and satellite imagery.

5.2 HISTORICAL TIME SERIES RESULTS

The study sites in the Aberdeen area have a long photographic record, which is extremely useful in identifying major changes to the nature of both the Hunter River but also the adjacent floodplain. Photographs in conjunction with satellite imagery have been compiled to produce a time series at both study locations with six points through time; 1938, 1952, 1955, 1972, 2009, 2015.

The 1938 aerial photo imagery provides a useful baseline to assess morphological and vegetation changes that have occurred over the past 80 years at both the Aberdeen (Figure 20) and the Dart Brook Mine study sites (Figure 21). Riparian vegetation was discontinuous and disconnected in the 1938 imagery. The 1952 imagery shows a major morphological change on the Dart Brook Mine site with the development of a neck cut off and the formation of an oxbow lake between 1938 and 1952. Photographs following the 1955 flood were taken in 1955 across both study locations and show channel straightening, large regions of bank erosion and the development of large bars and benches (Figure 20 & Figure 21). The aerial photographs taken in 1972 show continued straightening of the river south of the oxbow lake at the Dart Brook Mine site (Figure 21). Across both locations there appears to be a trend of increasing riparian zone vegetation since 1972. The time interval between 1972 and 2009 is marked by increased channel stability, increased riparian vegetation and the colonisation of many bars and benches by vegetation across both study locations. Another trend, more pronounced in the Aberdeen area is the increased agricultural and urban development of the surrounding floodplains (Figure 20). The final 2015 image in the series shows the contemporary Hunter River which has a weed dominated discontinuous riparian zone interspersed between largely cleared agricultural land.

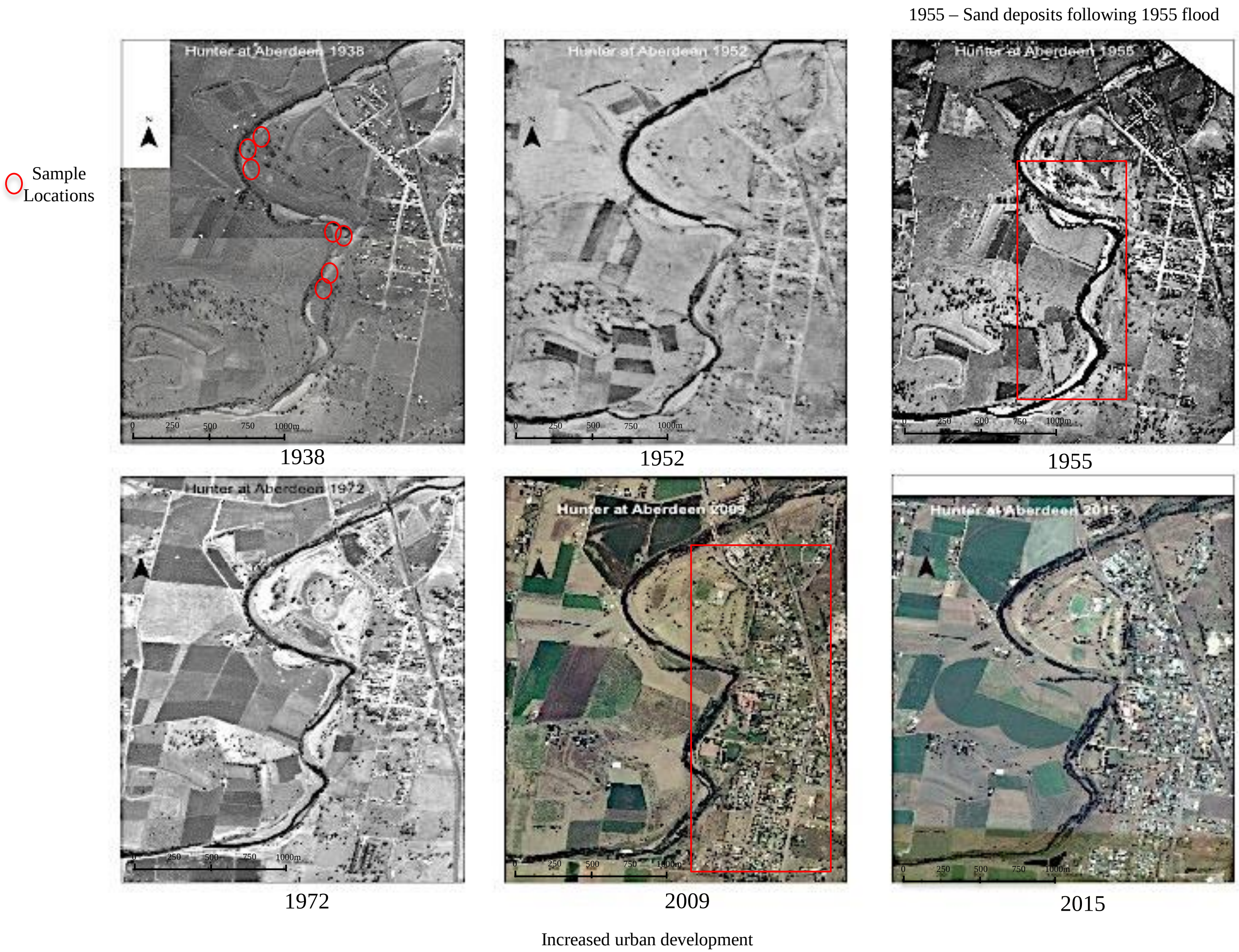


Figure 20 Historical time series showing channel change from 1938-2015 at Aberdeen. Flow is top to bottom. All imagery is georeferenced and orthorectified.

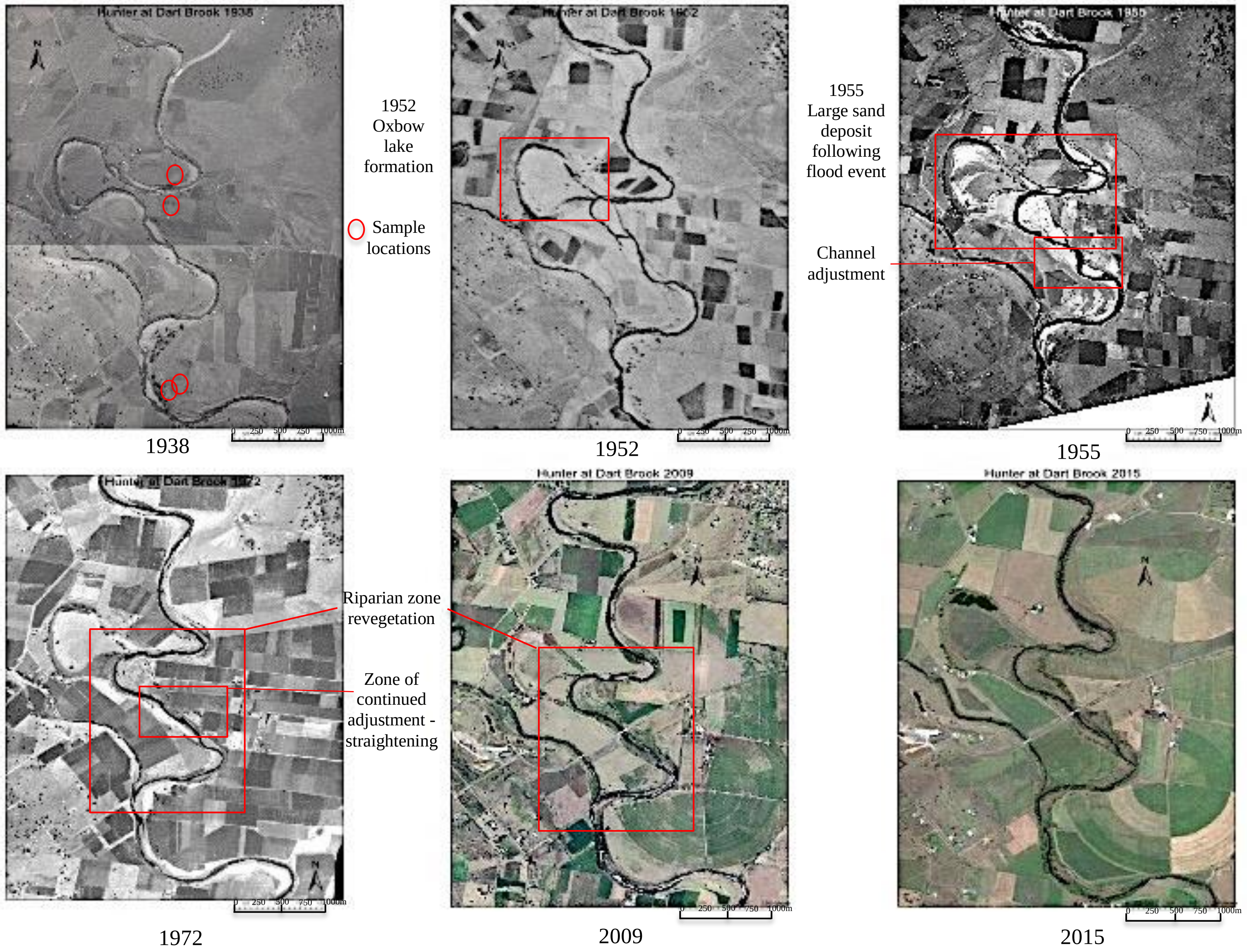


Figure 21 Historical time series of the Hunter River in the Dart Brook Mine area (1938-2015). Flow is top to bottom. Imagery is georeferenced and orthorectified.

Ground photographs taken in 1980 at various locations at Muswellbrook along the upper Hunter River show the extent and amount of vegetation change over 31 years to 2011 (Table 4). The Muswellbrook U/S photograph series shows the colonisation of the channel margins and a dramatic increase in vegetation density (Table 4). Other photographs in Table 4 show similar trends of both an increase in the extent of riparian vegetation but also an increase in the density of the vegetation (Muswellbrook downstream and Aberdeen gauges). More recent increases in riparian vegetation at Aberdeen on the Hunter River highlight the recent nature of some changes. It is interesting to note the prevalence of exotic species such as willow (*Salix species)* in the Muswellbrook downstream and Muswellbrook gauges photographs.

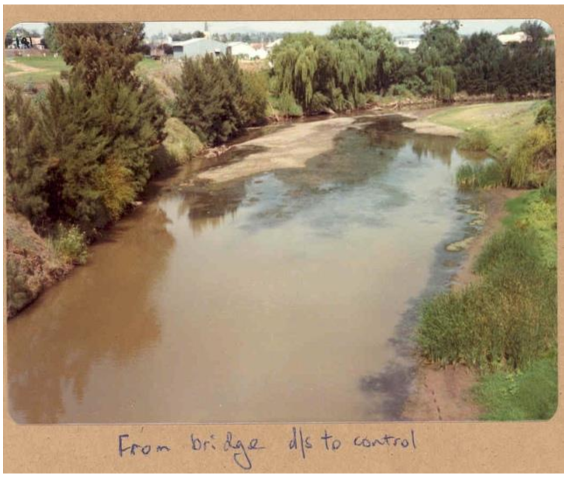
Table 4 Historical and contemporary photography showing areas of positive vegetation change at Muswellbrook and Aberdeen (Courtesy of Anthony Belcher, NoW).

Muswellbrook U/S 1980

Muswellbrook U/S 2011

Muswellbrook Gauges 1980

Muswellbrook Gauges 2011



Muswellbrook D/S 1980

Muswellbrook D/S 2011

Aberdeen D/S 2000

Aberdeen D/S 2011

Aberdeen Gauges 2000

Aberdeen Gauges 2011

5.3 REMOTE SENSING RESULTS

Remotely sensed imagery was used to assess the scale and nature of riparian change over the past 30 years, in conjunction with quantifying the spatial extent of geomorphic features across all study locations. This was achieved utilising spatial tools in ARCMAP 10.2 and data layers provided by Skorulis (2016) and the NSW OEH (2016).

NDVI data was utilised from Skorulis and was analysed at two separate thresholds, 0.1 and 0.2. These different thresholds both analysed the difference in vegetation in spring from two time periods 1987-1991 and 2009-2015 with a 50 m buffer around the river polyline in the 2009 DECCW Land Use: NSW dataset. Regardless of the threshold utilised, the dominant predicted response using the NDVI imagery was that of no change.

NDVI Threshold 0.1 – This threshold establishes changes in pixel value greater than 10% either positive or negative. As such it shows a great deal more predicted change than the NDVI threshold of 0.2. Figure 23 and Figure 25 show predominantly positive changes in pixel values indicating increases in vegetation where changes have occurred along the Hunter main stem. This is particularly highlighted in Figure 25 south of the channel confluence, where the area has experienced apparent significant vegetation increase. The Aberdeen sites and the upper Dart Brook Mine sites have experienced less significant apparent vegetation increase, with more area of the river experiencing no change or change less than 10% (Figure 23 & Figure 25). Contemporary ground conditions along the study sites are shown in Figure 22.

NDVI Threshold 0.2 – This threshold established changes in pixel value greater than 20% either positive or negative and is more likely to represent changes in woody vegetation (Cohen et al. 2016). Using this threshold, there is significantly less apparent change especially at the Aberdeen sites (Figure 24). A site of interest in the Dart Brook Mine site south of the confluence where there is predominantly positive vegetation change (Figure 26). However across both Figure 24 and 26 no change or changes with an NDVI pixel value less than 20% are dominant.

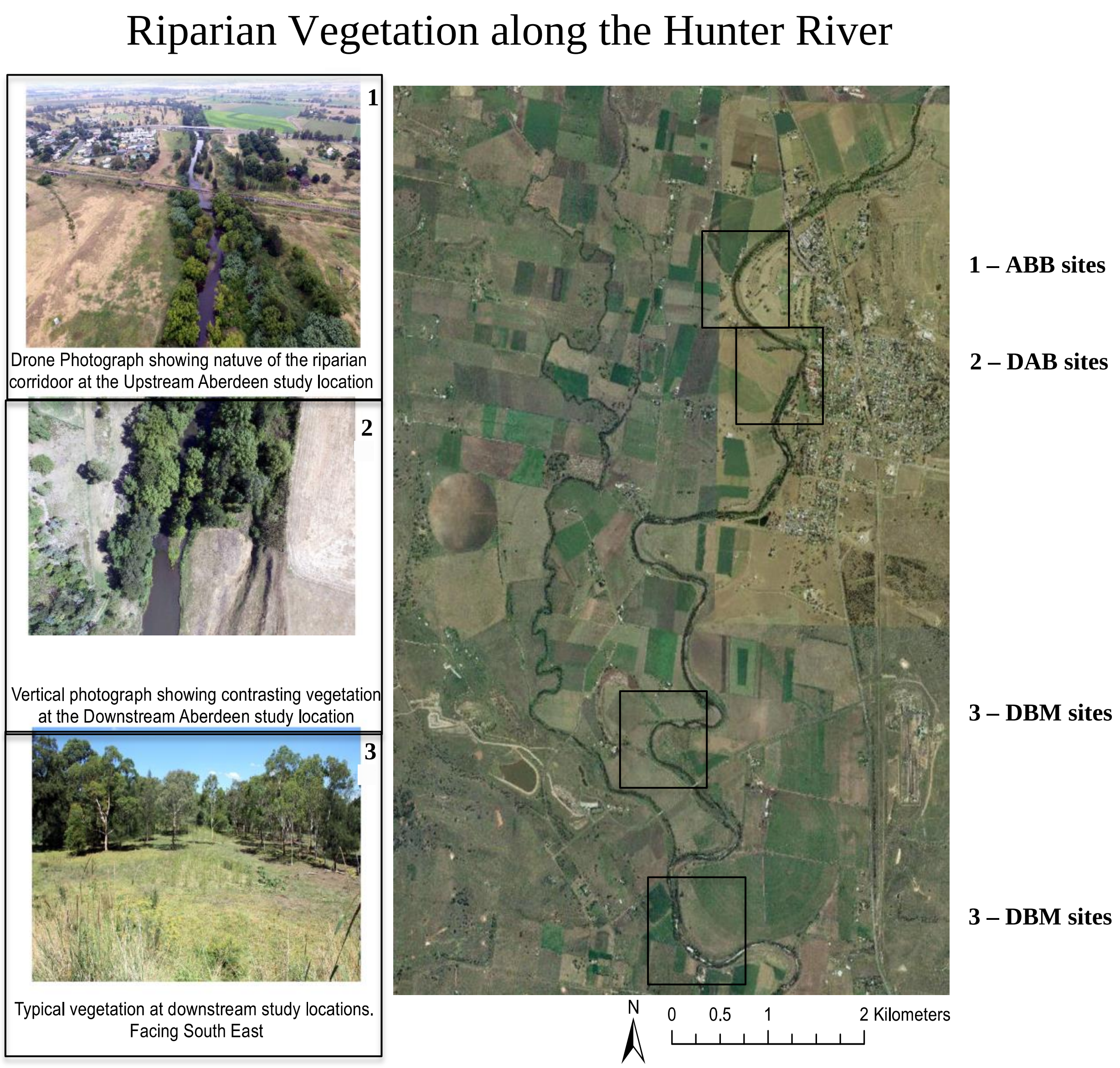


Figure 22 Spatial relationships of the study locations. (Inset) A combination of photographs showing the observed site ground conditions.

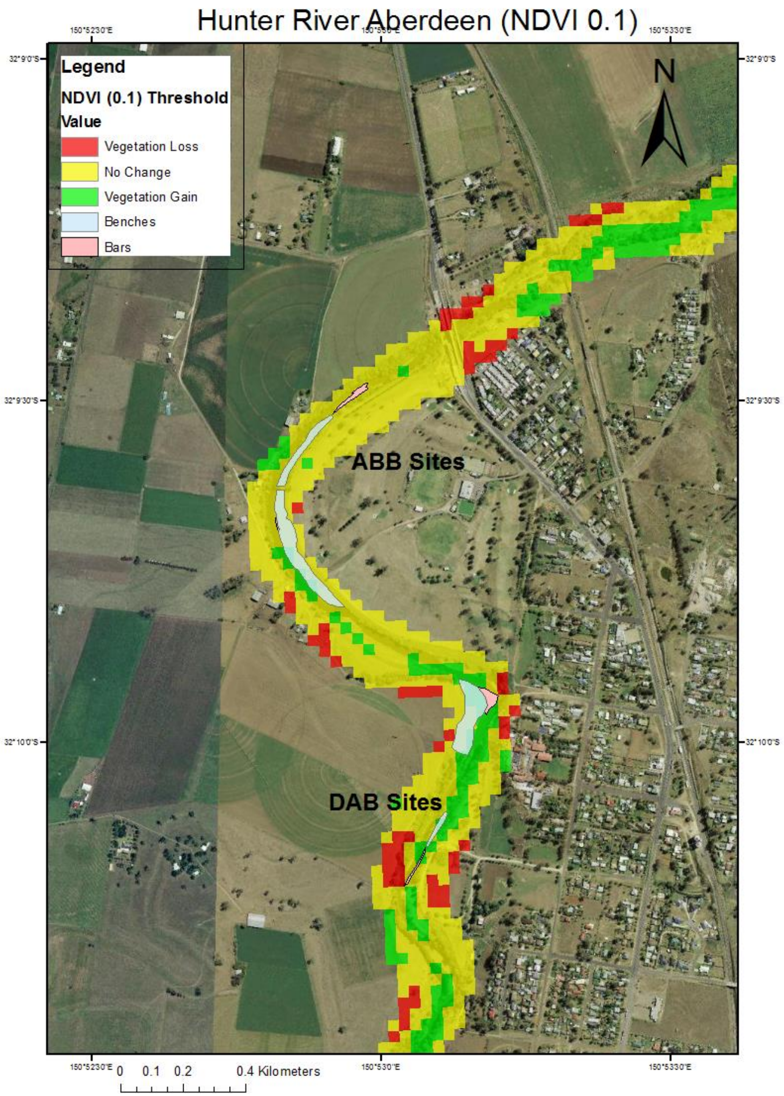


Figure 23 NDVI imagery of the Aberdeen study sites (0.1 threshold).

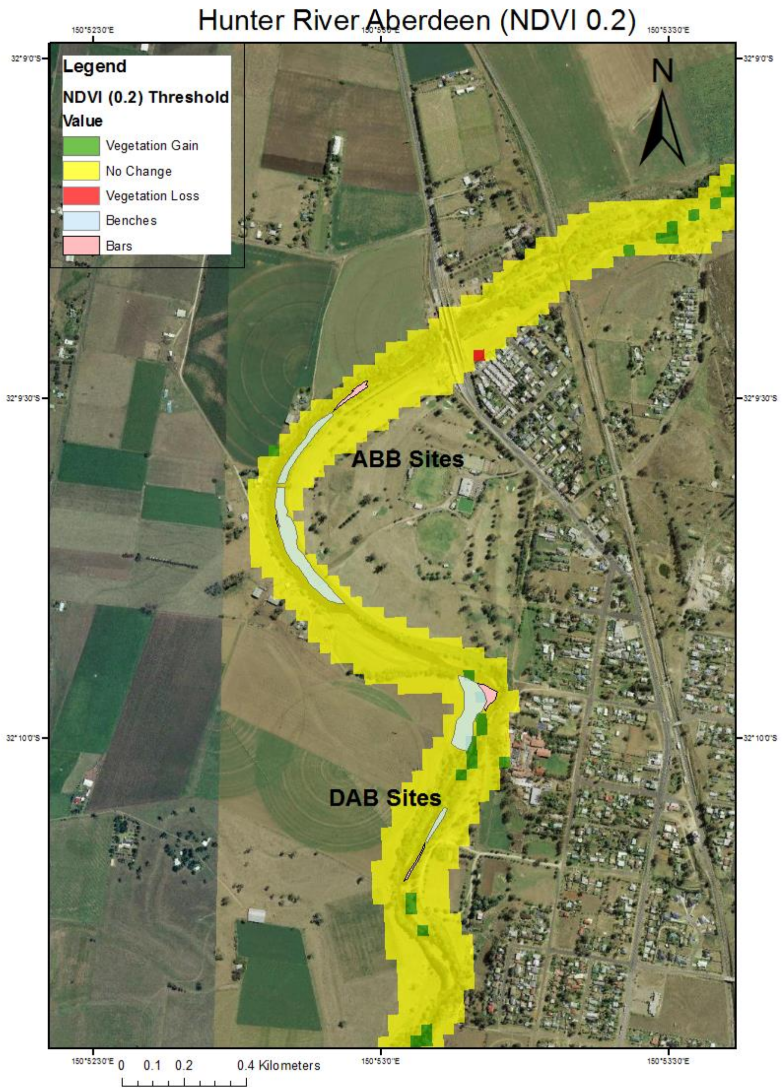


Figure 24 NDVI imagery of the Aberdeen study sites (0.2 threshold).

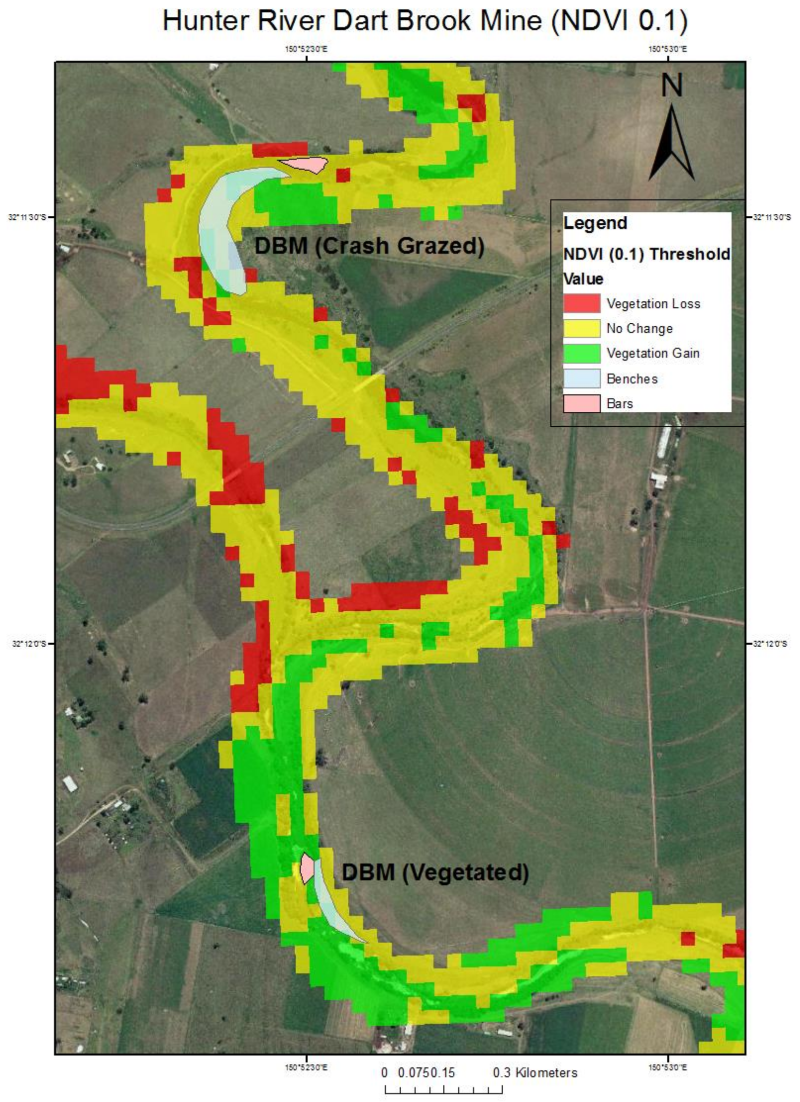


Figure 25 NDVI imagery of the Dart Brook Mine study sites (0.1 threshold).

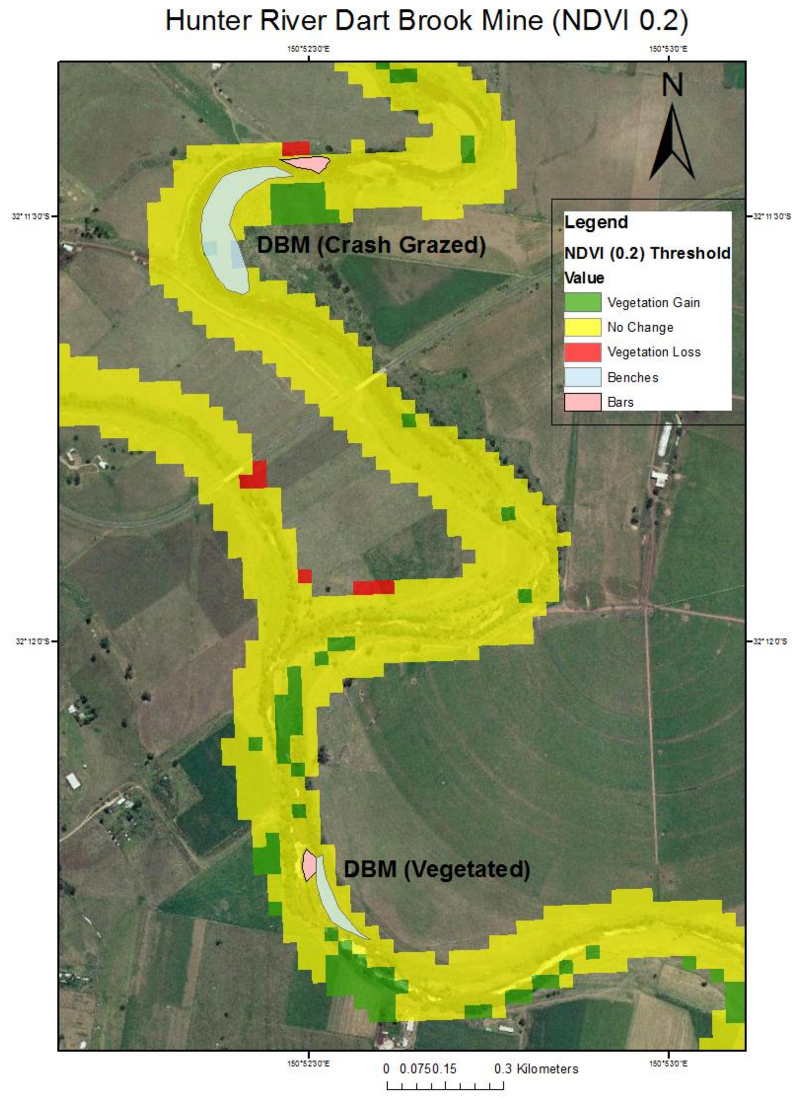


Figure 26 NDVI imagery of the Dart Brook Mine study sites (0.2 threshold).

The Office of Environment and Heritage Fractional Cover Change dataset consisted of 4 spectral bands or layers. Band one represents the bare ground fraction, band two represents green vegetation and band three represents non-green vegetation fraction. When this data set is plotted through there is a slight trend of increasing green vegetation (Band two) and a slight decrease in the fraction of bare ground (Band one; Figure 27).

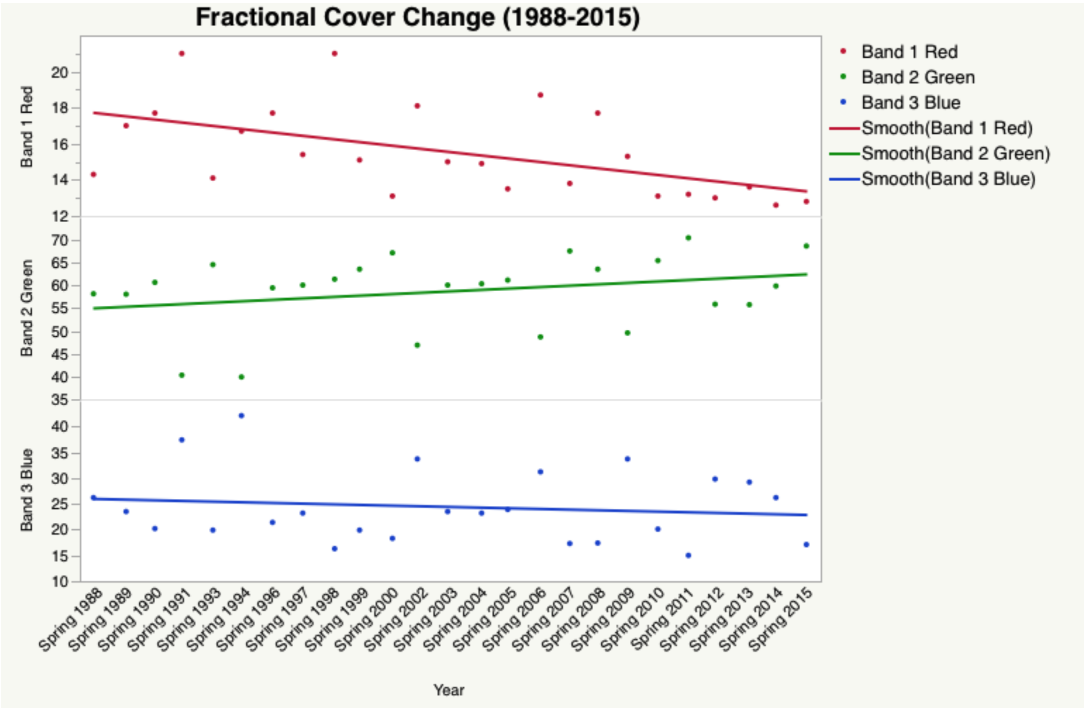


Figure 27 Spring seasonal fractional cover (1988-2015). Lines represent best fit and hold no mathematical significance.

When spring fractional cover was plotted against annual spring stream discharge at Aberdeen (stn. 210056) and against annual spring precipitation records at Scone (stn. 061089) there was no significant relationship or correlation (Appendix K).

5.4 HYDROLOGIC RECORD THROUGH TIME

The hydrologic regime plays an important role in determining the energy available for the morphological and sedimentological reworking of the channel bars and benches. High-energy flows have the capacity to perform dramatic amounts of geomorphic work, as seen in the 1955 flood (Chapter 5.2), and as such it is important to determine the frequency of these flows. Annual maximum series flood frequency analysis was undertaken at four stream gauges on the Hunter River; Muswellbrook (stn. 210002 & stn. 210008) and Aberdeen (stn. 210056) downstream Glenbawn Dam and at Moonam Dam Rd (210018) and Belltrees (stn. 210039) upstream from Glenbawn Dam. The flood recurrence interval was determined and used to produce a plot showing the relationship between discharge rates and flow recurrence for each location (Figure 28 & Appendix I).

The upstream gauges at Moonam Dam Rd (stn. 210018) and Belltrees (stn. 210039) both had reduced catchment area and thus maximum-recorded discharge relative to the downstream locations (Table 2). However, both recorded a similar 10 year recurrence interval discharge of approximately 40 000-50 000 ML/day (Appendix I).

The gauge at Muswellbrook had the greatest upstream catchment area and the largest recorded maximum daily discharge (ML/day). A one in ten year event would be expected to record a value of approximately 12 500 ML/day (Appendix I). The Aberdeen gauge is also downstream of Glenbawn Dam however, has a shorter recorded history of floods (Figure 28). The maximum flow rate recorded at the Aberdeen gauge was approximately 150 000 ML/day and may represent a 20-year flood event (Figure 28).

Survey data from each study site was recorded and related to the stream height recorded at the neaet gauge; the Aberdeen stream gauge on the day of observation (Appendix I). The discharge rates required to inundate the bars were calculated so that frequency of inundation could be determined (Table 5 & Appendix I). Figure 28 was used to relate the required discharge rate (ML/day) to the frequency or recurrence interval (years) from the annual series flood frequency analysis. Bars required lower discharge values to become completely inundated in contrast to the adjacent and elevated benches. In general all of the bars and benches studied would likely become completely inundated in the event of a 3-year flood (Table 5).

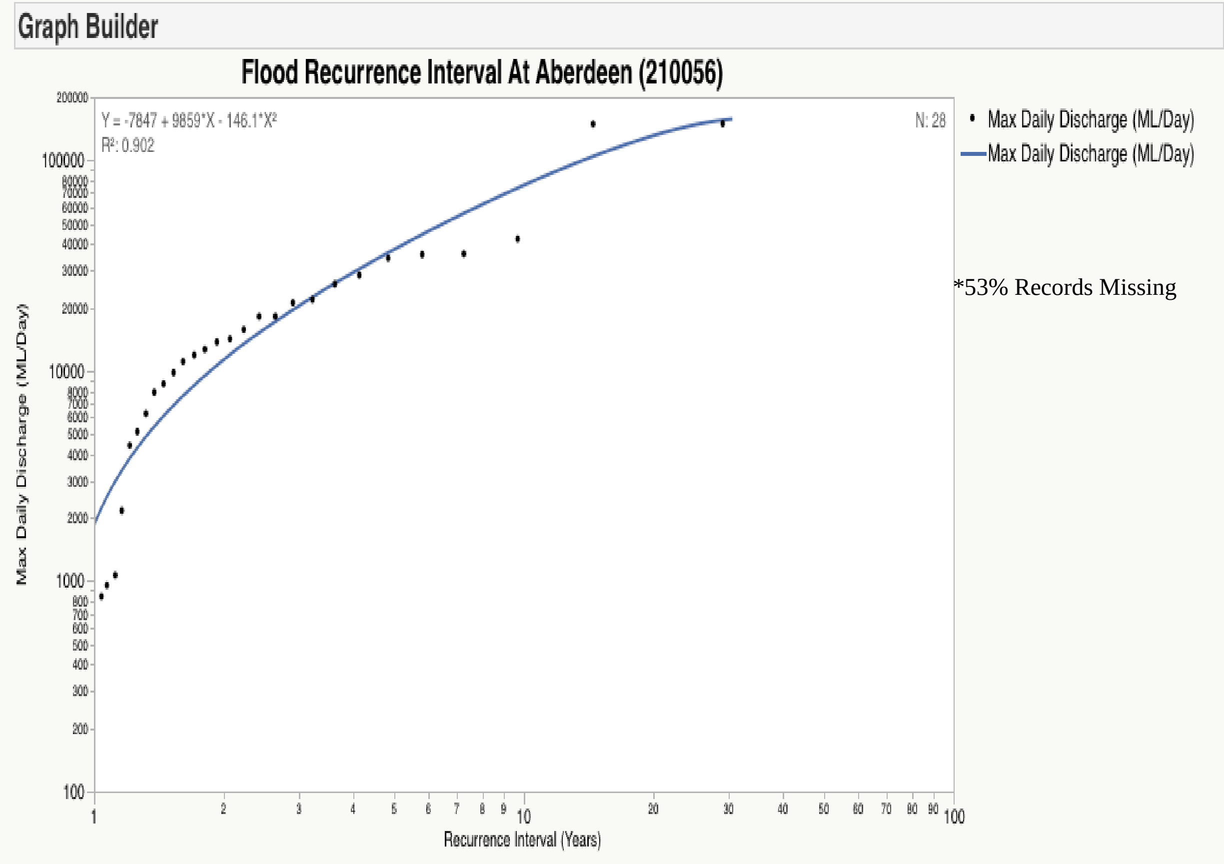


Figure 28 Annual series flood recurrence intervals for the 58 years of recorded data at the Aberdeen flow gauge (stn. 210056).

Table 5 Recurrence intervals of required flow rates and discharge rates to inundate the study locations (assuming the same cross-sectional area of Aberdeen Station (stn. 210056)

Site	Discharge (ML/Day) Required to inundate	Water Level (m) Required to inundate	Estimated Recurrence Interval	Date of last water level (m) required to inundate
ABB1	3306	2.662	1.2	26/08/2015
ABB2	2090	2.427	1.02	27/08/2015
ABB3	1835	2.369	0.996	27/08/2015
ABB4	16326	4.04	2.55	3/03/2013
DAB1	1234	2.212	0.934	27/08/2015
DAB2	5064	2.932	1.336	26/08/2015
DAB3	6517	3.12	1.49	26/08/2015
DAB4	5269	2.96	1.358	26/08/2015
DBM1	3134	2.632	1.133	26/08/2015
DBM2	11204	3.612	1.991	23/04/2015
DBM3	4800	2.895	1.308	26/08/2015
DBM4	14322	3.882	2.329	4/03/2013

Figure 29 shows the average minimum, mean and maximum monthly discharge rates for the flow gauge at Aberdeen (stn. 210056). Minimum average monthly discharge rates remain relatively constant, likely a factor of the upstream regulation. Average and maximum mean monthly discharge show a similar pattern of increased discharge in the summer months and decreased discharge rates in both spring and autumn months. As such bars and benches may be more likely to become inundated in the summer months where average maximum flows may exceed 10 000 ML/day.

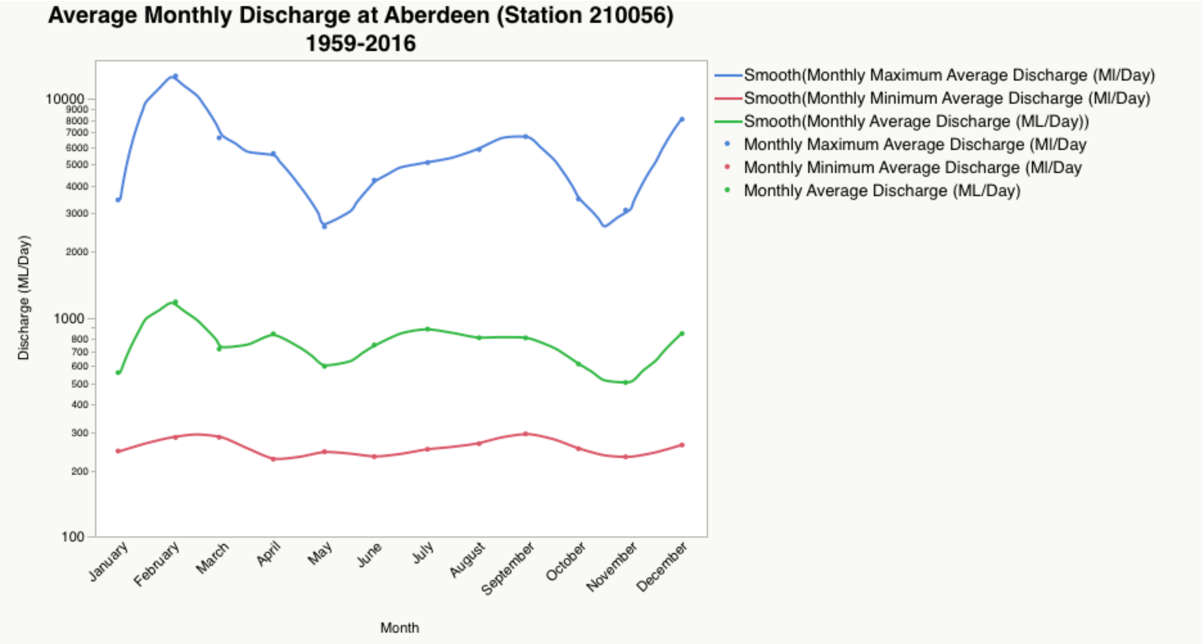


Figure 29 Monthly discharges at Aberdeen stream gauge (stn. 210056) from 1959-2016.

5.5 CHAPTER SUMMARY

Historical aerial photography and satellite imagery indicate that there have been periods of geomorphic instability and channel adjustment over the past 80 years concentrated in the first half of the record. Over the past 40 years there has been increasing riparian vegetation and a period of relative geomorphic stability with limited channel adjustment. The surrounding floodplain land has experienced significant development in the Aberdeen study reach, whereas the Dart Brook Mine site has been consistently dominated by agricultural land use practices. Utilising two different NDVI thresholds of 0.1 and 0.2 produces differing levels of predicted vegetation change, however, where change has occurred over both thresholds it tended to be positive. The OEH fractional cover dataset showed slight increase in the spring green value through time however, also showed to correlation with the spring seasonal discharge at Aberdeen (stn. 210056) or precipitation records at Scone (stn. 061089) suggesting other controls (expanded upon in the following chapter). Bars are more likely to become inundated than benches however, all study sites are expected to be inundated every 3 years. Glenbawn dams impacts small floods and also moderates average minimum monthly discharge in drier time periods (Figure 29; Erskine & Bell 1982).

6 EXPERIMENTAL RESULTS

6.1 INTRODUCTION

This chapter provides a summary of the key field and experimental results. This includes data obtained from using; loss on ignition (LOI) analysis, grain size analysis, bulk sediment sieving, statistical analyses and vegetation transect data. Results have been summarised to both individual sites and combined to common land use types (Table 6).

Table 6 Summary of site types and which bars fall into each category. Unvegetated refer to perennially grazed, vegetated refers to never grazed sites.

Crash Grazed Bar (CBAR)	Vegetated Bars (VBAR)	Un-vegetated Bars (UBAR)	Vegetated Benches (VBEN)	Un-vegetated Benches (UBEN)	Crash Grazed Benches (CBEN)
DBM1	ABB1	ABB3	ABB2	ABB4	DBM2
	DAB3	DAB1	DAB4	DAB2	
	DBM3		DBM4		

6.2 ORGANIC CARBON

Organic carbon content was analysed in 111 samples using the LOI method proposed by Ball (1964) outlined in Section 4.5 with multiple duplicates taken throughout the process (Appendix A). Figure 30 shows average organic carbon value for nine samples taken on each bar or bench. This highlights the variability in sediment properties along the 10 km study reach and the significant differences between sampling locations and land use.

The maximum organic carbon values were seen in vegetated benches and bars (ABB2 & DAB3) of 7.99% and 11.0% respectively (Figure 30 & Table 7). Whereas the lowest average organic carbon value (1.9%) was seen in unvegetated bars (DAB1) (Figure 30 & Table 7). Figure 31 further highlights the trend of grazed locations having lower organic carbon values than ungrazed or vegetated locations. The maximum organic carbon values (8.18%) were measured in samples from benches, which have never been grazed (VBEN). The lowest organic carbon values (1.90% & 2.11%) were found in perennially grazed bar samples (UBAR) and crash grazed/ partially grazed bench samples (CBEN).

Analysis of the organic carbon values shows that there are statistically significant relationships from this dataset. Significant differences are observed between the vegetated benches, which were significantly higher in organic carbon on average than any other land use type (Table 7 & Appendix C, D & E). Vegetated bars, crash grazed bars and un-vegetated benches were statistically similar in terms of organic carbon (Table 7). This may be a result of benches typically having higher organic carbon values than bars. Crash grazed bench samples and grazed un-vegetated bars consistently had the lowest organic carbon values with an average value of around 2% (Figure 31).

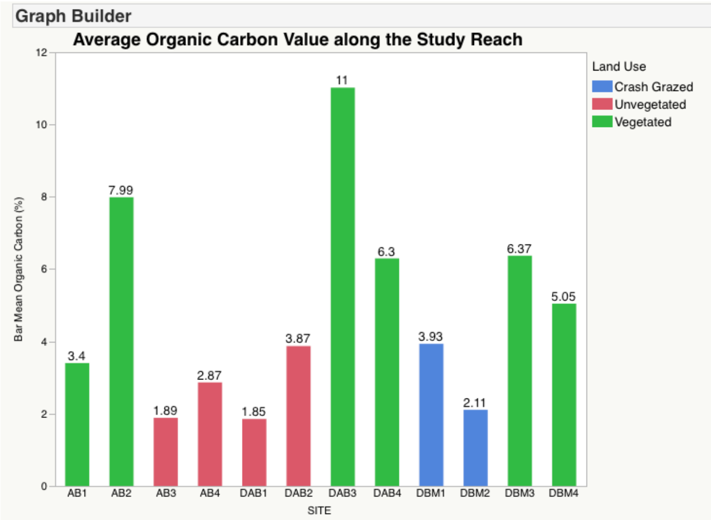


Figure 30 Average organic carbon values (%) from each bar and bench sampled with the study reach.

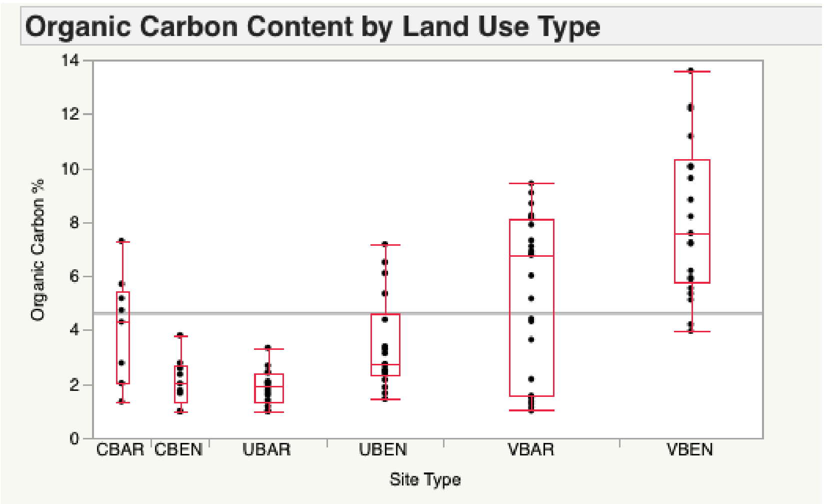


Figure 31 Average organic carbon values (%) from each land use type sampled within the study reach.

Table 7 Connecting letter report showing the statistical relationships between land use types and average organic carbon content of samples collected in the study reaches on the Hunter River.

Site type	Connecting report		letter	Mean (% Organic Carbon)	Standard Deviation
VBEN	A			8.18	2.86
VBAR		B		5.36	2.93
CBAR		B		3.93	2.00
UBEN		B		3.45	1.73
CBEN			C	2.11	0.90
UBAR			C	1.90	0.62

6.3 FINE SEDIMENT

Grain size analysis of 111 samples was undertaken on the < 1500-micron fraction, using the Malvern Mastersizer (Appendix B). Figure 32 shows that on average the perennially grazed sampling locations (UBAR & UBEN) tended to have larger particle size (508 μm & 245 μm) than the non-grazed locations (VBEN, 49 μm & VBAR, 168 μm). This is highlighted in Figure 33, which summarises the average grain size from each location from each land use type. The average grain size for the unvegetated bar DAB1 (597 μm) was statistically much larger than other study sites across all land use types.

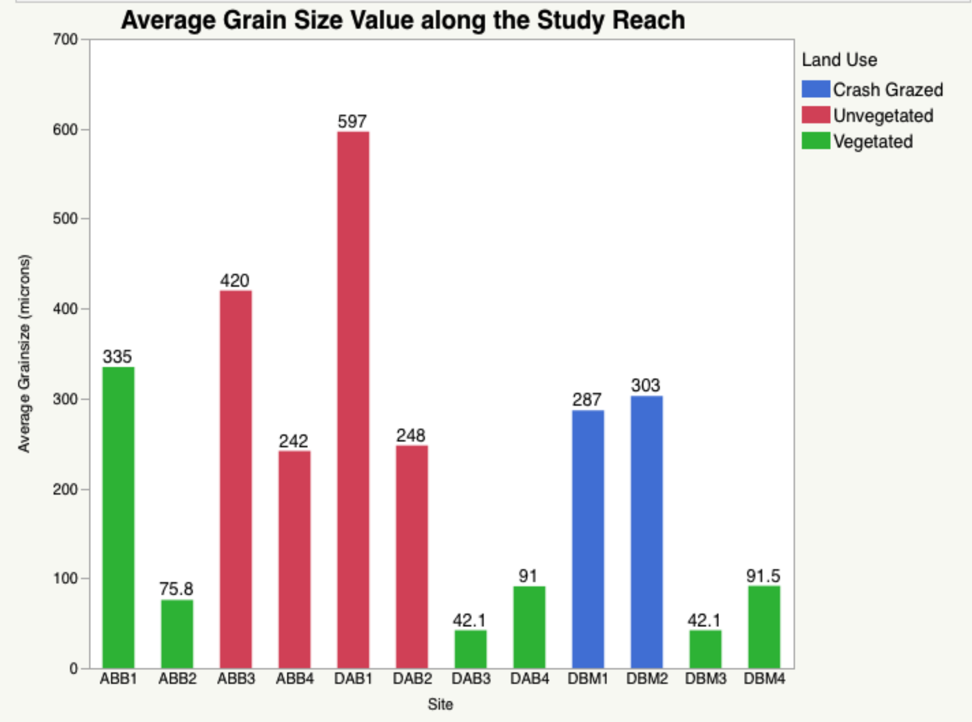


Figure 32 Mean grainsize from each bar and bench sampled within the study reach on the Hunter River.

Figure 32 shows the average grainsize across each land use type which highlights the fine grained nature of vegetated benches, which were significantly finer than any land use type. Perennially grazed study sites were significantly coarser than never grazed locations (Appendix C, D & E).

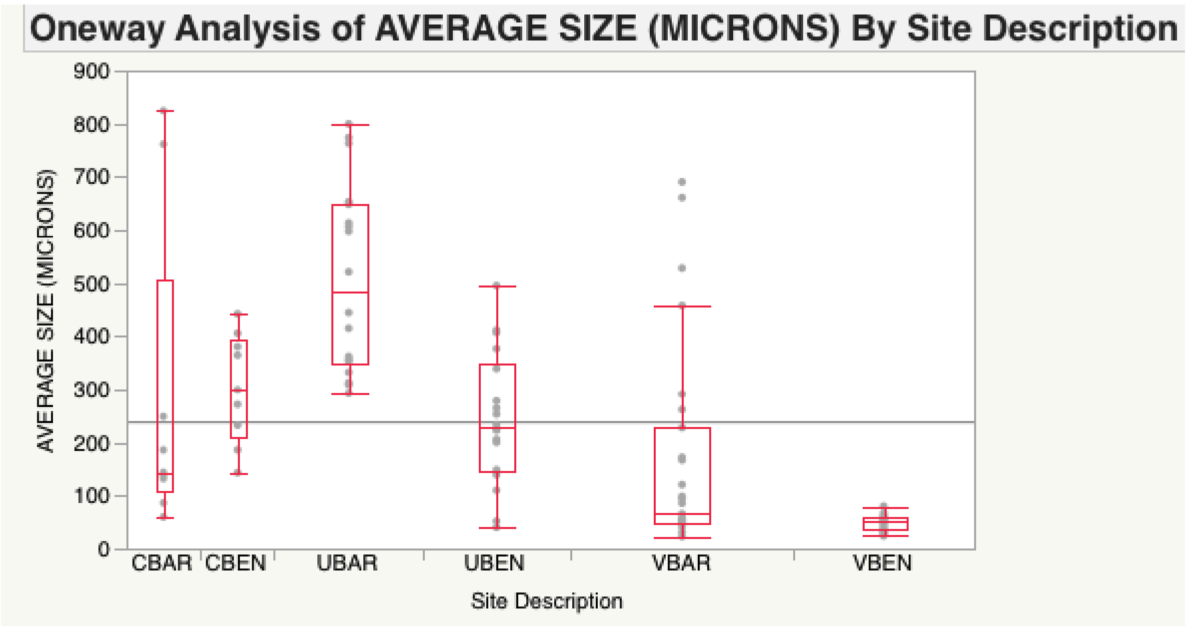


Figure 33 Average grain sizes by land use type throughout the study reach on the Hunter River.

The coarsest samples on average were collected on unvegetated bars (UBAR), with the finest samples collected on vegetated benches (VBEN; Figure 33). Unsurprisingly bars tended to be coarser than benches, which may be attributed to the hydraulic position and potential winnowing effect of water as it moves over the bar. Vegetated bars were on average the second finest group in terms of grain size. Perennially grazed benches and crash grazed bars and benches tended were all statistically similar and finer than perennially grazed bars (Table 8).

Table 8 Connecting letter report showing the statistical relationships between land use types and average fine sediment size of samples collected in the study reaches on the Hunter River.

Site type	Connecting letter report				Mean Size (Micron)	Standard Deviation
VBEN	A				49.38	14.35
VBAR		B			168.05	193.76
UBEN			C		244.52	125.12
CBAR			C		286.61	292.15
CBEN			C		362.64	102.91
UBAR				D	508.31	175.89

One of the key results observed was the relationship between organic carbon and grain size. This was an inverse relationship where an increased organic carbon value was associated with a decreased grain size value (Figure 34). This may be a factor of the majority of organic carbon occurring as fine sediment particles.

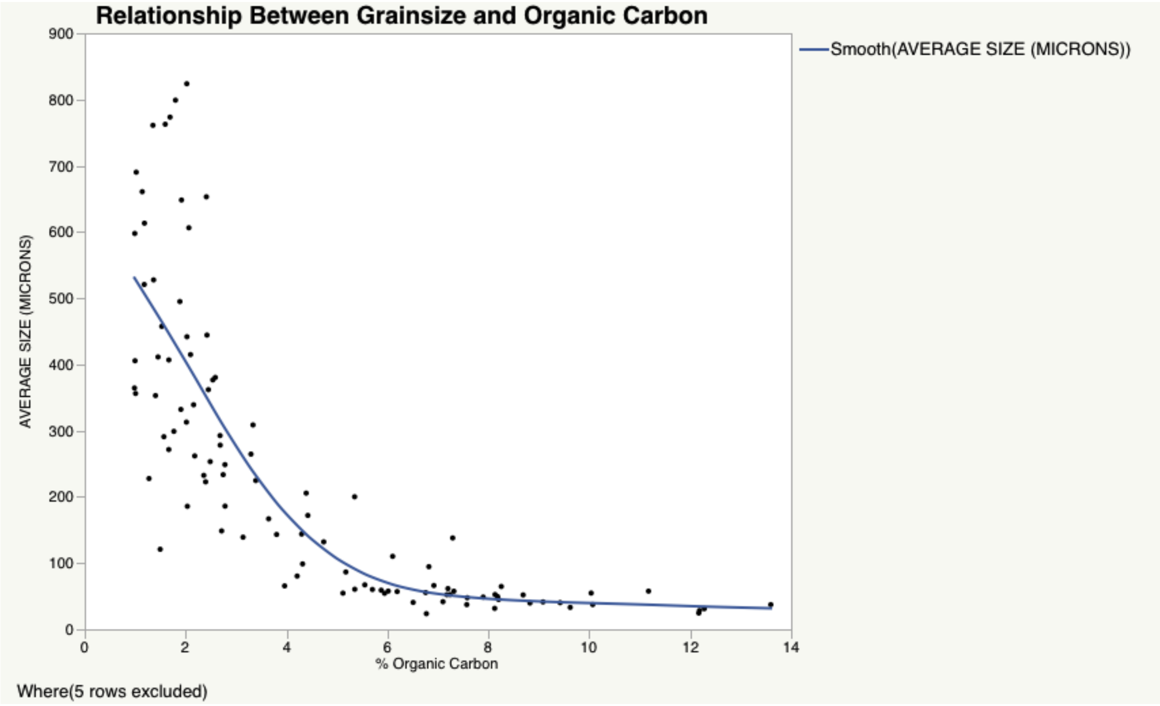


Figure 34 The inverse relationship between grainsize and organic carbon as observed through the analyses of sampled collected throughout the study reach on the Hunter River.

One trend that was observed across both grainsize and organic carbon was that of spatial variability. Samples proximal to the stream (1, 4 and 7) were reduced in organic carbon and had an increased average grain size relative to samples taken distal to the stream (3, 6 and 9; Figure 35).

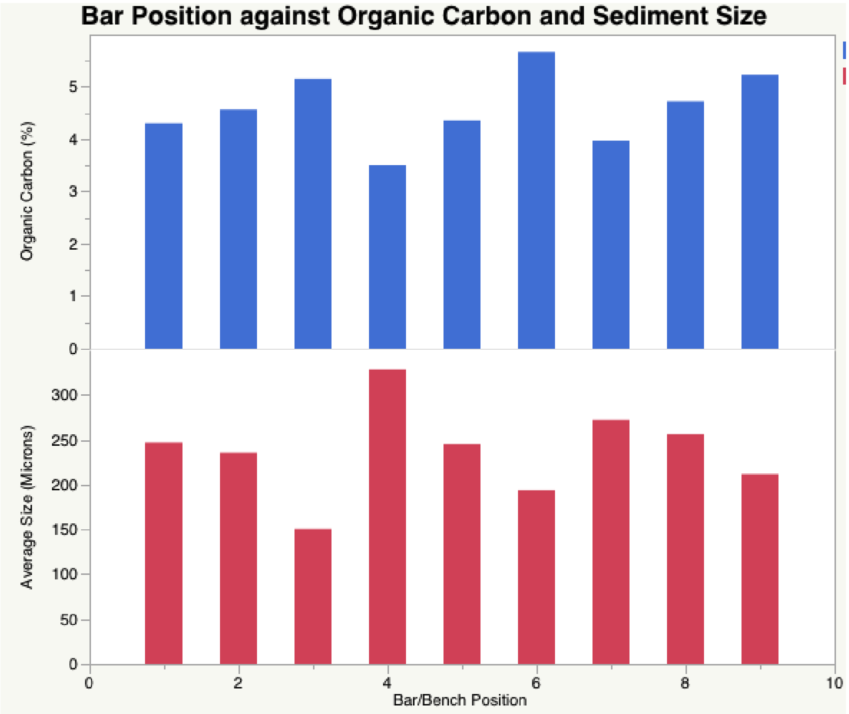


Figure 35 Spatial relationship between organic carbon and grainsize as observed from the sampling regime in Figure 3.

Another key characteristic of grain size is that of the sorting of particles. Figure 36 presents the overall fraction of each sample into sand (2 mm–62.5 µm), silt (62.5 µm–3.9 µm) and clay (3.9 µm–0.98 µm) particles. As previously established there appears to be a relationship between fine grain size and increased organic matter, therefore, soils with increased proportions of silts and clays may also have increased organic carbon. Vegetated bars (VBAR) and benches (VBEN) had increased proportions of silt and clay size particles relative to the other land use types (Figure 36 & Figure 37). Unvegetated bars and benches had the highest proportion of sand size particles (Figure 36 & Figure 37).

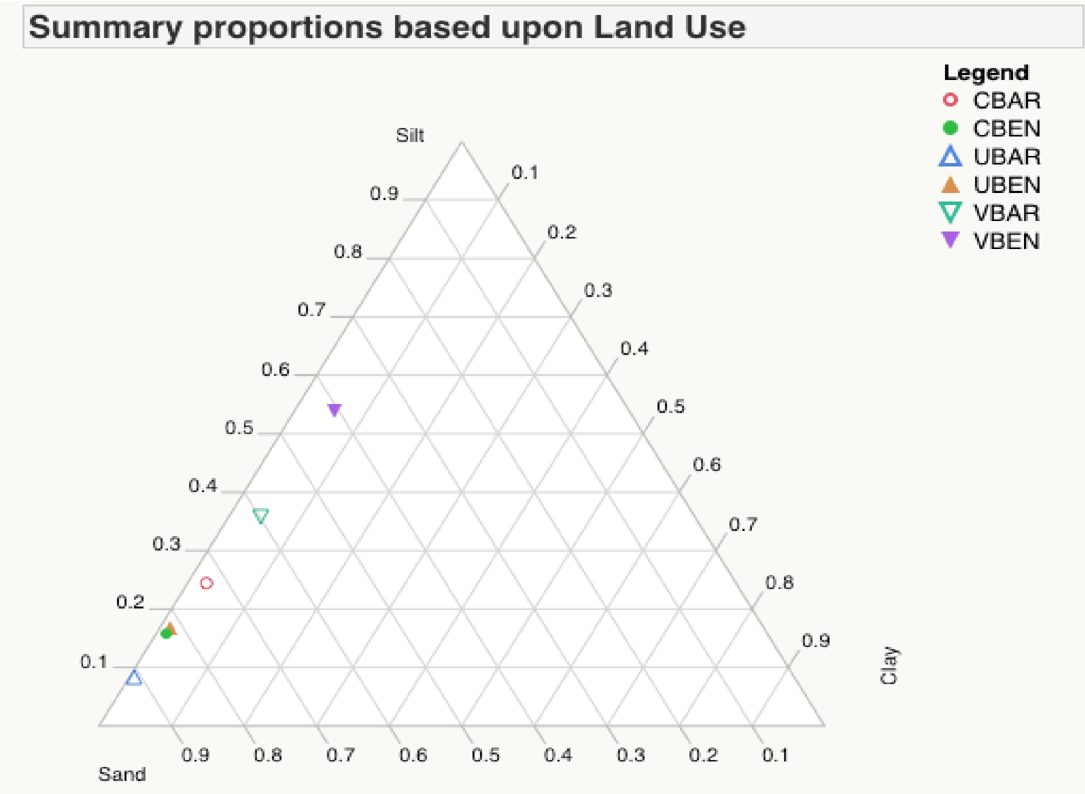


Figure 36 Average fine sediment proportions across land use types sampled.

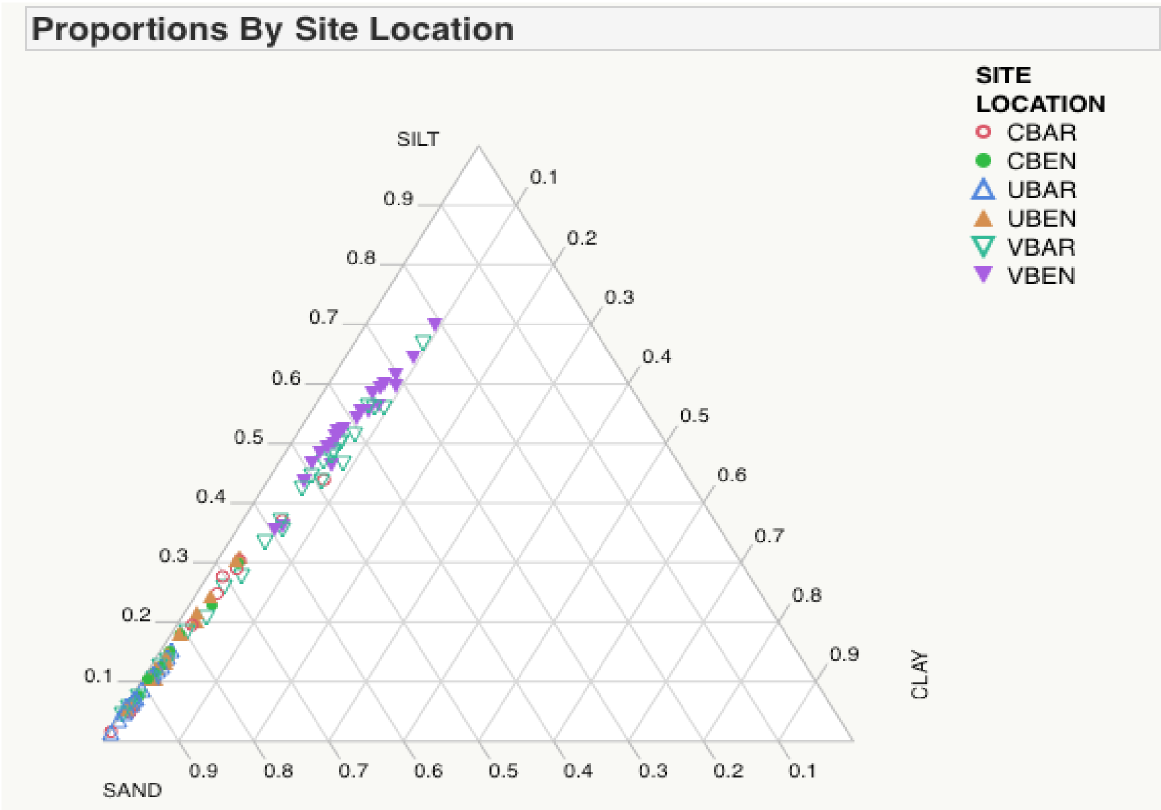


Figure 37 Complete summary of the proportions based upon land use type. Note the increased proportion of silt-sized particles in the vegetated land use settings.

6.4 BULK SEDIMENT

Bulk sediment samples were taken to compare the composition of the bars and benches. In general vegetated benches were dominated by finer fractions of sediment (DAB2, DAB4). However, it is apparent that many of these bars and benches are significantly different in sediment size proportions to each other (Figure 38). Figure 39 further highlights this difference with varied proportions of sediment sizes. One notable observation is that the crash grazed bar and unvegetated bar were among the two coarser grained settings.

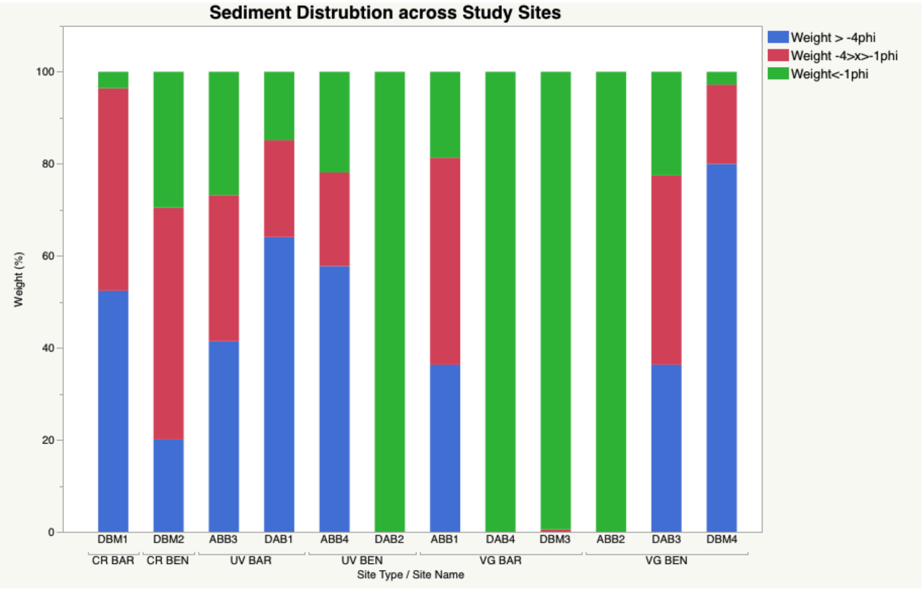


Figure 38 Bulk sediment sorting across each sample location within the study reach on the Hunter River.

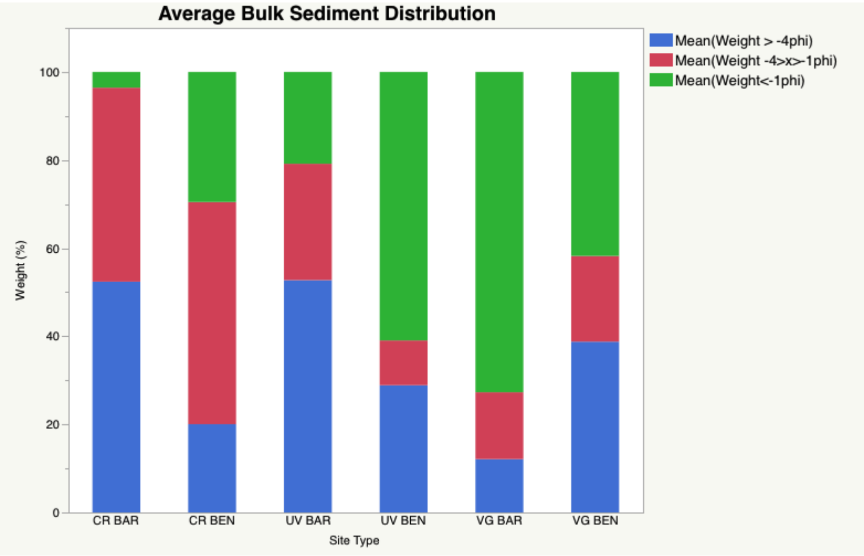


Figure 39 Bulk sediment sorting across each land use type within the study reach on the Hunter River.

6.5 VEGETATION STRUCTURE

Vegetation transects were undertaken at the midpoint of each bar and bench (Figure 41, Figure 42; Appendix H). Canopy density, mid canopy density, ground cover and species were identified and recorded along the surveyed transect (Table 9). Never grazed bars had much denser canopy cover than perennially grazed locations (Table 9).

Table 9 Vegetation transect values & organic carbon values across each bar and transect.

SITE	ORGANIC CARBON (BAR)	ORGANIC CARBON (4,5,6)*	AVERAGE CANOPY COVER	AVERAGE MID-CANOPY COVER	AVERAGE GROUND COVER
AB1	3.401	3.111	40	0	62.86
AB2	7.988	9.664	44	1	100
AB3	1.885	1.692	0	0	71.11
AB4	2.866	2.699	0	0	71.11
DAB1	1.854	1.851	0	0	45.63
DAB2	3.871	3.075	48.33	0	100
DAB3	11.02	9.583	48	2	60
DAB4	6.296	7.009	48	2	60
DBM1	3.933	2.561	10	0	55
DBM2	2.108	1.794	0	0	100
DBM3	6.371	6.159	60	0	100
DBM4	5.045	4.827	31.11	0	100
***4,5,6 WERE SAMPLED ALONG THE VEGETATION TRANSECT**					

There was a significant correlation (R^2=0.7338) between organic content of the bar and the density of canopy cover. Increased canopy cover was associated with increased organic carbon across the entire bar and the vegetation transect (Figure 40).

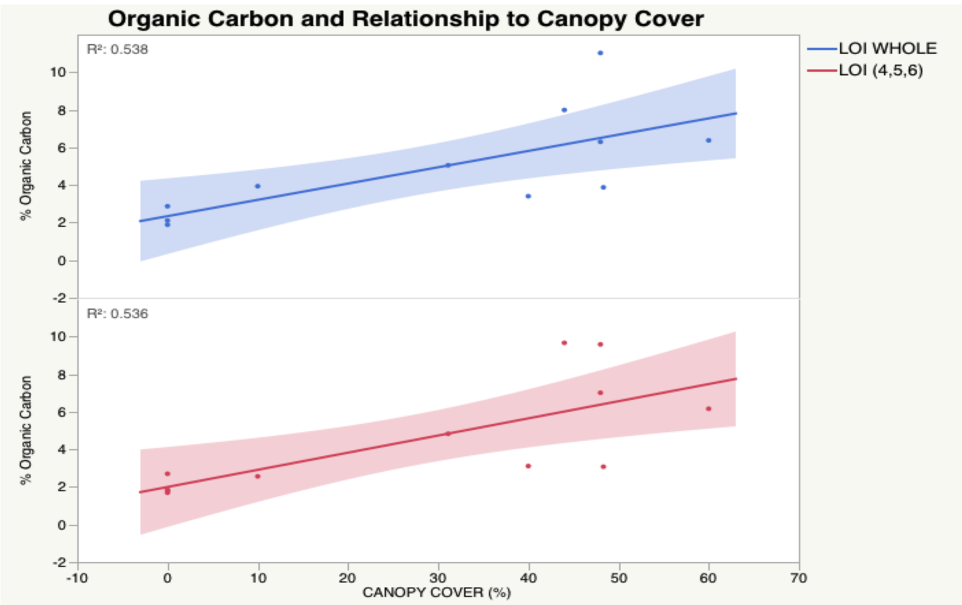


Figure 40 Positive-correlation between canopy cover (%) and organic carbon (%).

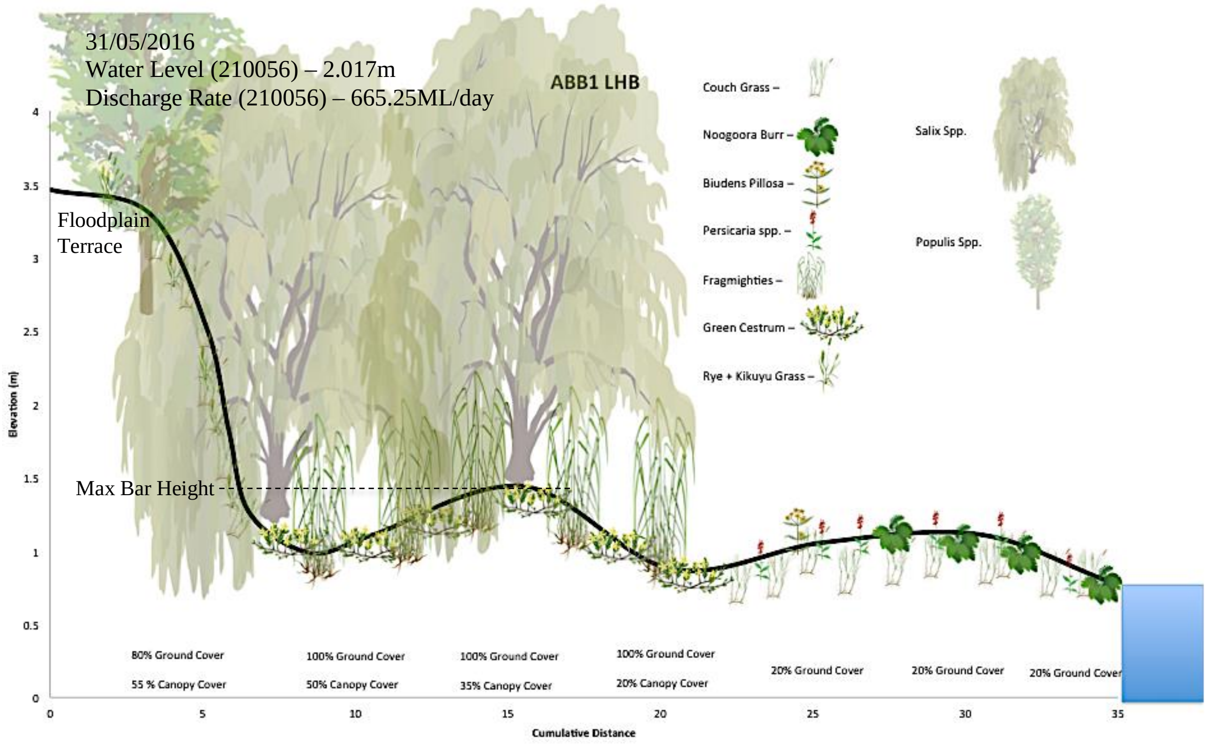


Figure 41 Example vegetation transect undertaken at the most upstream study site on the Hunter River (ABB1 - Ungrazed bar; Integration and Application Network 2016).

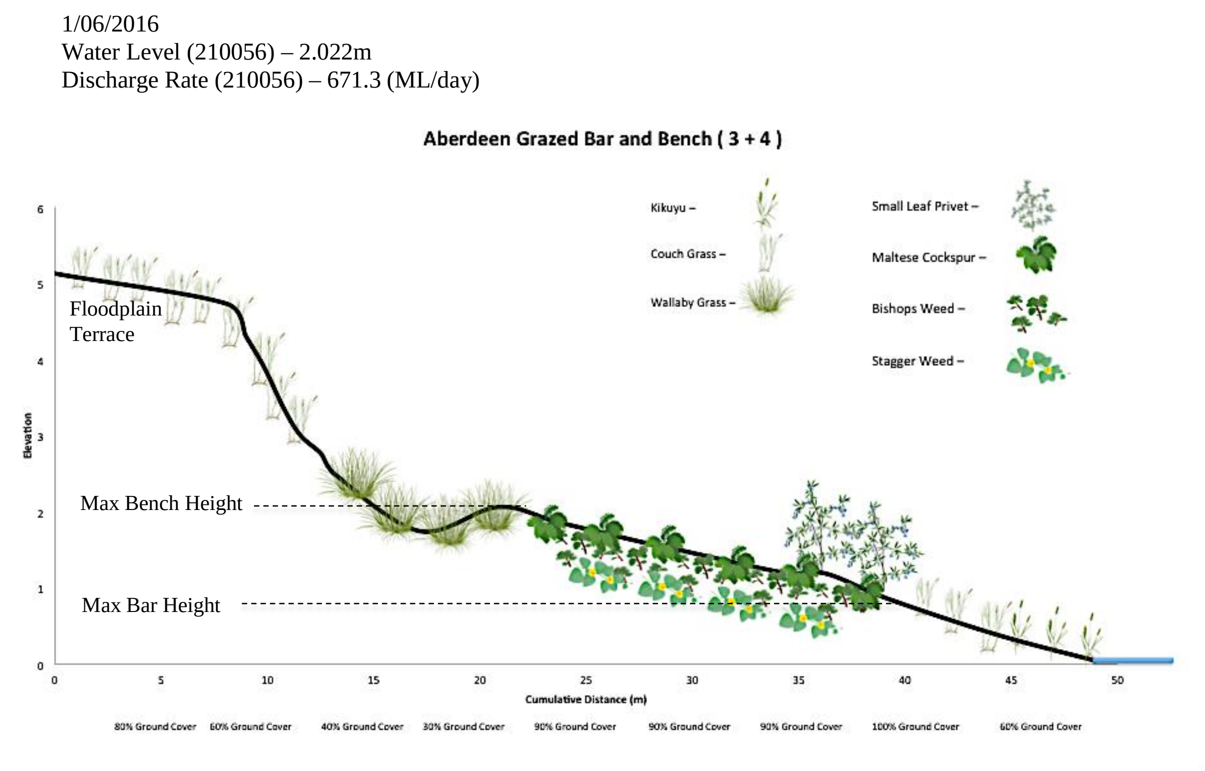


Figure 42 Example vegetation transect undertaken at the upper Aberdeen site of the grazed bar and bench setting (Integration and Application Network 2016).

6.6 CHAPTER SUMMARY

Samples collected in the field from three land use settings provide important insight about the relationship of organic carbon and grain size to land use. In general, benches tended to be composed of finer sediment than bars, which may be a function of their hydraulic position and potential winnowing effect of water flow. There was an inverse relationship between organic carbon and fine sediment size; as sediment size increased, the organic carbon content of the soil tended to decrease. As a result, benches tended to have increased organic carbon content as well as be dominated by the finer sediment fraction. Bars tended to be lower in organic carbon content with an increased average grainsize.

Key findings from this chapter were that of the significant differences in organic carbon and fine sediment size based upon land use types. Perennially grazed locations tended to have the lowest organic carbon values with increased average grainsize. This was contrasted by never grazed locations, which tended to have the highest average organic carbon values and the smallest average grainsize. These locations were also predominantly composed of finer grain sized particles. Of interest was the crash or partially grazed locations which, sat somewhere within the middle of these results both in terms of grain size and organic carbon composition.

There was also a strong correlation between vegetation canopy cover and organic carbon composition. This suggests that increased vegetation cover and density will result in increased organic carbon in the soils. Also of note were the distinct differences between study sites in terms of bulk bar composition. Many of the sampling locations were composed of different proportions of sediment size fractions.

7 DISCUSSION

7.1 INTRODUCTION

This chapter provides a discussion on the key results from this study and provides context to the experimental outcomes. In doing so, uncertainty and the limitations of the study will also be addressed.

7.2 DISCUSSION OF CHAPTER 5 RESULTS

Utilising spatial data such as aerial photography and satellite imagery is becoming an increasingly useful method for rapidly establishing the nature and timing of environmental change. Historical imagery of the study sites in the Hunter catchment has shown recent periods of geomorphic stability and vegetation increase (Brooks et al. 2016). Hydrologic analysis has shown the decrease in the discharge volume following the completion of Glenbawn Dam in 1958 (Erskine & Bell 1982).

In the period since the 1970s the Hunter main stem channel has been relatively stable with little in the way of dynamic lateral channel changes (Figure 20 & Figure 21). In general the photographic time series show little in the way of channel straightening and adjustment across both study locations, however local channel straightening is evident between 1955 - 1972 in response to the neck cut off at the Dart Brook Mine site (Figure 21). Factors that may influence this stability could include an increase in bank resistance or strength or a reduction in peak stream discharge.

Over the past 30-40 years there has been an increase in riparian vegetation of between 25% - 43% throughout the upper Hunter catchment (Brooks et al. 2016). This is in accordance to recent work by Cohen et al. (2016) suggesting that across eastern Australia, riparian zones have experienced a mean increase between 8% - 34% (NDVI thresholds 0.1 and 0.2). Across both study locations where change has occurred it tended to be positive regardless of the threshold of NDVI change used (Figure 23 – Figure 26). This increase in riparian vegetation is particularly prominent following the 1955 flood, which left large areas of floodplain bare (Figure 20 & Figure 21). Vegetation has colonised these bare areas increasing bank cohesion and resistance to erosion. Recent increases in riparian vegetation density and extent may be a major factor in the increased geomorphic stability experienced on the Hunter River following the 1955 flood.

Fractional cover changes since 1988 show a slight increase in green vegetation throughout the study reach however, do not show any significant relationship with spring stream gauge data or spring precipitation records (Figure 28; Appendix J). This indicates that another factor may be primarily responsible for the increased riparian vegetation. Anthropogenic management strategies from the 1980s have promoted the revegetation of the riparian zone for the purposes of river management and increasing channel stability (Spink et al. 2009). Management strategies over recent years have promoted the stock exclusion or reduction from the riparian zone to promote the development of riparian zone vegetation enhancing channel stability (Jansen & Robertson 2001).

Flow gauges in the upper Hunter catchment provide a record of the historical and contemporary discharge conditions. Flood recurrence intervals were determined for four gauges on this river in order to determine the predicted frequency and magnitude of large flow events. Flood events are important as they mobilise sediment and perform geomorphic work, with the potential for channel adjustment (1955 flood Hunter River; Figure 20 & 21). As expected the furthest downstream gauges had the largest discharge volume. The Muswellbrook gauge is particularly useful for investigating historical changes and determining annual recurrence intervals as the record extends over 100 years from 1907-present (Table 2 & Figure 13). Annual series flood recurrence intervals were calculated for the entire time period 1907 - 2016 but also 1907-1957 and 1959-2007 (Figure 13) to show the impact of Glenbawn Dam. Figure 13 highlights the decreased size of the contemporary floods following the completion of Glenbawn Dam (Hoyle et al. 2012). Erskine and Bell (1982) found that Glenbawn dam significantly reduced both annual runoff and flood peaks in the reaches downstream. The regulatory influence of dams decreases with distance, as such reaches proximal to the dam will be influenced more strongly than those further away (Erskine & Bell 1982). As such calculated flood recurrence intervals do not account (1907-2016) for this alteration to catchment conditions and the modern 100-year flood may be much reduced from the 1955 100-year flood.

Stream gauge data can also be utilised to determine the frequency of inundation of the river benches and bars. Through relating the stage height of the river and the height required to completely inundate the bars and benches to the discharge volume or rate. This rate may then be related to the annual series flood recurrence intervals (Figure 28) to determine the inundation frequency of each bar and bench. Inundation rates were calculated for each study site and found that all sites examined were expected to become inundated every three years (Table 5). Knowledge of the rates of inundation provide an understanding of the hydrologic conditions which have produced the soil conditions in both bars and benches (Graf-Rosenfellner et al. 2016), but also in understanding the timing and frequency of sediment reworking. Using the values from Table 5, it can be assumed that the most recent time all sites were simultaneously inundated was the 3rd October 2013 where the maximum stream height was recorded at 4.363 m at the Aberdeen stream gauge (stn. 210056; Table 5). The date of the last period of inundation represents the most recent period of sediment erosion or accumulation on each bar or bench (Table 5).

Historical alteration to the hydrologic regime has seen a reduction in the frequency of large flood events in the upper Hunter catchment (Erskine & Bell 1982). Hydrologic inundation may occur less frequently than in the past due to the decreased stream energy and discharge volumes. Reduced flows and flood frequency as a result of river regulation is a common occurrence to many Australian and world rivers such as the Murrumbidgee River (Ren & Kingsford 2014).

Results presented in chapter five demonstrate the changing nature of the Hunter River from an unstable high-energy river to the contemporary regulated stable system that it is today. Anthropogenic induced increases in vegetation have resulted in increased bank stability and resistance to erosion, whilst the completion of Glenbawn Dam has resulted in an altered hydrologic regime reducing stream discharge and power (Erskine & Bell 1982). The observations throughout the upper Hunter are consistent with regional trends across eastern Australia of increased riparian vegetation (Cohen et al. 2016) and a decrease in stream energy following the introduction of flow regulation structures (Ren & Kingsford 2014).

7.3 DISCUSSION OF CHAPTER 6 RESULTS

Field sampling and laboratory analysis has shown that grazed study sites were significantly coarser in grain size than un-grazed locations with a reduced organic carbon content. There were significant relationships between vegetation cover and organic matter observed on the study sites. Reduced organic carbon values in perennially grazed locations were likely the result of a number of factors. Organic carbon content was to be strongly correlated with canopy cover (Figure 40), and thus denser woody vegetation. In areas where riparian vegetation has been removed for agricultural purposes such as, perennially grazed study locations, lower organic carbon values may be expected as the nature and supply of organic carbon has been changed (Mika et al. 2010). Management practices, such as stock access, which result in a degraded or altered riparian zone may reduce the amount of carbon sequestered. Land use in this study focused on agriculture and grazing, and found that even a reduced period of stock access to the riparian zone resulted in a reduced amount of organic carbon stored in bar and bench sediment relative to ungrazed study locations. This may be a result of the direct and secondary influences stock have on bars and benches such as; consumption of saplings (Brooks et al. 2016), grazing of up to 80% of the riparian vegetation, mechanical abrasion and trampling of vegetation, destruction of channel boundaries and compression of the bar and bench sediment (Trimble & Mendel 1995). As stock impair the development of vegetation, an important source of organic carbon is removed from the system and thus not stored within the sediment, resulting in reduced organic carbon where there is no riparian vegetation or canopy cover (Figure 40, Appendix H; Mwendera & Saleem 1997). Whilst stock impair the ability of vegetation to develop, they also cause a disruption to the environment favouring the establishment of weeds and exotic species (Lawes & Grice 2010). Photography of the crash grazed locations shows the reduction in biomass, predominantly of exotic species (Figure 6 & Figure 7). This changes the nature and timing of the organic matter supplied to the soil but also to the river, and can impact on the aquatic ecosystem (Mika et al. 2010).

Where stock has permanent access to the riparian zone they compact the surface of the bars and benches altering hydrologic pathways and increasing both runoff and erosion (Trimble & Mendel 1995). Organic carbon and fine sediment stored in the upper portion of the soil profile may be stripped into the channel by surface run off or sheet flow as the ability of bar or bench to retain fine sediment is reduced. This results in both the increased average grain size and the reduction in proportion of fine sediment particles observed on grazed and crash grazed study sites. The crash grazed study locations have not been completely inundated following the trial grazing period however, sediment may have been removed through sheet flow over the bar. Secondary effects of grazing may further promote the erosion of the upper component of the soil, as vegetation that impairs waters ability to flow is removed through trampling and grazing by stock.

An interesting feature across both organic carbon storage and fine sediment retention results was the general trend of crash grazed locations having values between perennially grazed and never grazed locations. The major implication of this is that after a relatively short period of stock access both fine sediment retention and organic carbon content were significantly different to other land use settings. This indicates the rapid nature of changes to the sedimentary properties throughout the study sites. The crash grazed study locations went against the general trend of the study, that of benches having increased organic carbon and decreased average grain size. This inconsistency may be a result of increased grazing pressure on the benches than on the bars due to the steep gradient required to access the bars or abundant palatable food sources on the benches. This may also be due to more recent complete or partial sediment reworking of the bar through inundation than the bench.

Spatial patterns within each study site show a strong trend of winnowing, where areas more frequently inundated or subjected to higher stream energies i.e. sample sites proximal to the stream were reduced in organic carbon content but also displayed increased average grain size relative to the distal sample locations (Figure 35 & Table 10).

Table 10 Organic carbon % and grain size and sample position on bar or bench.

BAR POSITION RELATIVE TO STREAM	ORGANIC CARBON (%)	GRAIN SIZE (µm)
PROXIMAL (1, 4 & 7)	3.92	279.5
MID BAR (2, 5 & 8)	4.45	242.1
DISTAL (3, 6, & 9)	5.70	180.5

A major factor of both fine sediment retention and organic carbon storage in the upper component of the soils is in the timing of sediment reworking through flooding. Through calculating the inundation rate of the bars and benches, the average period of reworking period could be predicted indicating time periods for the accumulation of organic matter and fine sediment (Table 5). The average bar could be expected to be inundated every 1.15 years, whilst the average bench could be expected to be inundated every 1.79 years (Table 5). Hoyle (2007) found that bars were reworked at flow stages less than 1-2 year flood event, and that a larger flow event was required to rework the elevated bench sections on the Hunter River. Floods have higher than average stream powers and the ability to perform more ‘geomorphic work’ moving finer particles downstream, leaving the larger particles behind. As expected benches are less frequently reworked and inundated in part explaining the increased proportions of fine sediment relative to bars. Benches are also further away from the highest energy flows than bars, meaning there is less energy on benches than on bars to remove sediment. Lower energy flow as in the waning stages of a flood promote the deposition and retention of finer sediments, resulting in benches (218.7 μm) being finer than bars (320.99 μm) on average (Figure 32 & Figure 33; Fryirs & Gore 2013).

Spatial variability in sediment is a function of the various processes such as downstream fining of sediment as stream power is reduced, pool- riffle interactions causing deposition and erosion of sediment and small variations in bed topography which influences regional and local patterns of deposition and sediment reworking (Hoyle et al. 2007). The absence of any significant trend in the bulk sediment analysis may be a result of natural variation within the reach.

7.4 IMPLICATIONS OF THE STUDY

Riparian zone management has local, regional and global implications. As such there needs to be appropriate action and management at every stage to ensure the sustainability and health of the environment. Poor management of the riparian zone at any scale can result in a degraded environment, decreased water quality and the disruption of a potentially significant carbon store.

Riparian zone vegetation has the ability to retain sediment and increase bank resistance and strength (Hubble et al. 2010) has resulted in decreased downstream sediment load as riparian vegetation extent and density increases. This has a number of local implications, as fine sediment load to the river is reduced, water quality is increased. Locally, high fine sediment loads result in decreased light availability to the stream, impairing photosynthesis in aquatic organisms (Wood & Armitage 1997). This in turn results in decreased diversity in the aquatic invertebrate assemblage (Wood & Armitage 1997; Davies et al. 2016). Increased fine sediment load also impairs hyporheic zone functioning, blocking pores for the interchange of ground and surface water (Boulton et al. 1998). Where sites within this reach experienced grazing, the relative proportion of fine sediment was lower indicating that this sediment fraction has been transported or does not preferentially accumulate into the channel. Regional impacts of an increased sediment load include the accumulation of sediment downstream and increased sedimentation rates in the coastal and offshore zones (Bartley et al. 2014). As terrestrial sediment is lost to the offshore zone, it may be deposited onto fragile marine ecosystems (terrestrial sediment released Burdekin catchment may be deposited on the Great Barrier Reef (Lough et al. 2015). Due to the global nature of the agricultural industry and the prime agricultural land surrounding rivers, the appropriate management of the riparian zone is important to ensure downstream impacts are mitigated.

Carbon sequestration has become a prominent global issue due to the issue of global warming and climate change. Aquatic bed sediments may also play an important role in the global carbon cycle (Sutherland 1998). Vegetated riparian zone study sites stored significantly more organic carbon than unvegetated or grazed locations. As such the relationship established between vegetation and organic carbon is quite clear and vegetation is important in organic carbon sequestration.

Utilising average values from the study, an approximation can be made to determine the storage potential in the upper 10 cm throughout the 10 km study reach. A series of estimates produced a range of values for storage, with vegetated zones having the greatest potential for organic carbon storage (Table 11). Using an assumed bulk density of 1.6t/m^3 (Walling et al. 1996) the projected amount of organic carbon may be determined.

Table 11 Predicted carbon sequestration quantity over the study reach within the Hunter catchment.

Method	Locations	Organic Carbon Storage (m^3)	Organic Carbon Sequestration (tonnes)
1	Study Reach (10km)	3088.5	4941.6
2	Study Reach (10km)	3231.5	5170.5
3	Study Reach (10km)	3862.0	6179.2
4	Study Reach (10km)	4062.0	6499.2
5	Study Reach (10km)	5243.3	8389.2

*All methods use a bulk density assumption of 1.6t/m^3 as was used by Erskine (1996) on Wollombi Brook.

Method one – Uses the average organic carbon (OC) for each land use type and the measured distance over the 10 km study reach; grazed (2.68 km, 2.7% OC), ungrazed (5.92 km, 6.8% OC) and crash grazed (1.4 km, 3% OC). This method uses a 60 m riparian zone width and a 10 cm depth of sample.

Method two – Uses the average organic carbon (OC) for both grazed and ungrazed locations over the measured 10 km study reach; grazed (3.38 km, 2.7% OC) and ungrazed (6.62 km, 6.8% OC). This method uses a 60 m riparian zone width and a 10 cm depth of sample.

Method three – Uses the average organic carbon (OC) for each land use type and sample location over the 10 km study reach; grazed bar (1.87 km, 1.9% OC), grazed bench (2.68 km, 3.5% OC), crash grazed bar (0.64 km, 3.9% OC), crash grazed bench (1.4 km, 2.1% OC), ungrazed bar (1.66 km 5.4% OC) and ungrazed bench (5.92 km, 8.2% OC). This method uses a 60 m riparian buffer on benches and a 15 m buffer on bars with the same 10 cm depth of sampling.

Method 4 – Assumes the average organic carbon value (6.8% OC) for ungrazed study locations over the 10 km study reach. This method uses a 60 m riparian zone width and a 10 cm depth of sample.

Method 5 – Assumes the average organic carbon value for ungrazed bars (4.17 km, 5.4% OC) and ungrazed benches (10 km, 8.2% OC) of the entire 10 km study reach. This method uses a 60 m riparian buffer on benches and a 15 m buffer on bars with the same 10 cm depth of sampling.

These methods could be further extrapolated to show the potential storage throughout the entire catchment, given that there are approximately 14 500 km of streams, rivers and tributaries (Table 12). Using these assumptions, restricting stock access and grazing activity on the river margins and developing a vegetated riparian corridor may increase the amount of carbon sequestration between 26 – 36%. The 2015 Status of the worlds soils report found that conversion of tropical or temperate forest to grazing land may reduce the soil organic carbon (SOC) between 25 – 35% and that reversing this process may result in similar increases in SOC (FAO and ITPS 2015).

Table 12 Projected carbon sequestration volume throughout the entire Hunter catchment river network.

Method	Location	Organic Carbon Storage (m^3)	Organic Carbon Sequestration (tonnes)
1	Hunter catchment (14568km)	4499436	7199097
2	Hunter catchment (14568km)	4707777	7532442
3	Hunter catchment (14568km)	5626313	9002102

- All methods use a bulk density assumption of 1.6t/m^3 as was used by Erskine (1996) on Wollombi Brook.

See description of methods in Table 11.

Historical management practices across Australia have resulted in the release of large quantities of sediment, forming sediment slugs and reducing the heterogeneity of the channel (Bartley & Rutherford 2002). Where stock have access to the river channel, they may result in the collapse of the bank margins and the associated release of sediment (Trimble & Mendel 1995). Large amounts of sediment have been lost from the upstream reaches of many rivers following rapid channel expansion (Brierley & Murn 1997). Management practices, which promote the stabilisation of the channel margin through the development or regeneration of riparian vegetation such as stock exclusion, may result in increased water quality, normal aquatic ecosystem functioning and increased aquatic biodiversity in degraded riparian zones (Capon et al. 2016).

Recent land management practices throughout the upper Hunter catchment have promoted the restriction of stock access to the riparian zone (Shellberg & Brooks 2007). The removal of stock from the riparian zone through fencing has helped to promote regeneration and formation of a vegetated riparian buffer zone. The benefits of an effective riparian buffer zone include; increased fine sediment retention, decreased nutrient load to the river and increased organic carbon content (Osborne & Kovacic 1993; Silver 2010). Sedimentation and high nutrient loads from adjacent floodplains are considered a diffuse source of pollution and as such require a spatially extensive management system to prevent pollution entering the system and impacting the aquatic ecosystem. As vegetated riparian buffer zones can effectively surround a river, they may prove useful in mitigating this form of pollution. This improves local and downstream water quality for agricultural use but also improves diversity within the aquatic ecosystem, reducing the occurrences of algal blooms and the eutrophication of the waterway. Where stock have access to the riparian zone, increased sedimentation rates, and degradation of the riparian vegetation community is common (Trimble & Mendel 1995).

Annually weed species cost Australian farmers a total of $4 billion through weed management activities and lost agricultural production (Sinden et al. 2004). Aside from their economic impacts, exotic species also threaten biodiversity, due to their ability to outcompete native species in disturbed or degraded environments (Coutts-Smith & Downey 2006). Through this competition, exotic species reduce the diversity of species present and may result in the local extinction of native species (McKinney 2002). The reduction in biodiversity due to weeds has a number of negative implications on ecosystem functioning and health (Vavra et al. 2007). These negative functions include; reduced water quality, the displacement of native species, land degradation and the reduction in productivity in farm and forest land (HCCREMS. 2010)

There are 32 weeds of national significance throughout the entire Hunter catchment, with two species observed in the study reach riparian zone; willow (*Salix species*) and blackberry (*Rubus fruticosus*). A number of other exotic species were prominent, dominating areas such as balloon vine (*Cardiospermum grandiflorum)*, giant reed (*Arundo donax*), poplar (*Populis species*) and green cestrum (*Cestrum parqui*). Historical practices and channel works promoted the use of species such as willow (*Salix species*) along river channels to stabilise the channel boundaries. Due to the threat these exotic species pose to ecologic diversity, it is vital that any riparian zone management strategy includes a management plan relating to these exotic species. Current weed management practice in NSW consists of a number of goals; prevention, eradication, containment and asset protection (NSW Department of Primary Industries 2015). Practical approaches to weed removal are based around a number of techniques including: slashing, burning the use of herbicides, grazing, hand weeding, use of competitive natives and controlled fire usage (NSW Department of Primary Industries 2015). An example of current treatments for blackberry (*Rubus fruticosus*) includes a combination of physical control (continuous grazing by goats, bulldozing or slashing), herbicides and biological controls (Bruzzese et al. 2000). This study has observed the decrease in exotic species density as a result of managed stock introduction to the riparian zone (Figure 6 & Figure 7). Some limitations to the use of stock include the presence of noxious weeds such as green cestrum (*Cestrum parqui*), which has been shown to negatively impact the health of stock (Brooks et al. 2016). Recent research suggests that prescribed or controlled grazing may be useful as a targeted measure to reduce biomass and weed density of a study site as part of a larger management strategy (Brooks et al. 2016).

Riparian zones throughout New South Wales have experienced between 8% - 34% (NDVI 0.2 and NDVI 0.1) increase in woody vegetation since 1978 (Cohen et al. 2016). The Hunter catchment itself has experienced between 25% - 43% increase in woody vegetation since the 1980's (Brooks et al. 2016). The increase in vegetation has been attributed to changes in management practices and the alteration of the hydrologic regime (Cohen et al. 2016). The increase in vegetation has been seen in other countries such as England where there was a 23% increase in woody vegetation cover between 1984-2007 attributed to a change in management practices (Hooke & Chen 2016). Due to the relationship between carbon sequestration and vegetation, the increase in woody vegetation on a regional scale may play an important role in increasing the amount of carbon stored in the soils.

In order to preserve the functioning of the river systems and protect ecologic diversity appropriate river management strategies need to be implemented. Weeds pose a threat to ecologic diversity across many rivers of south-eastern Australia. As such, riparian zone management policies should address a number of issues including weed management, channel stability, sediment retention and organic carbon sequestration. Management strategies that incorporate the development of an effective riparian corridor through processes such as stock exclusion or reduction and the removal of exotic species may address the goals of river and riparian zone management.

7.5 LIMITATIONS OF THE STUDY

This study focuses on organic carbon storage and fine sediment retention across different land use settings present along the upper Hunter River. As such there are a number of inherent limitations and assumptions, which need to be considered when utilising these study findings.

This study was undertaken throughout a limited spatial scale and only addressed study locations with distinct differences in vegetation. As such the number of sites available for selection within the study region was limited. This reduced spatial scale may fail to account for the high levels of landscape and sedimentologic variability associated with river and riparian zone settings.

Due to the time constraints of the study, before and after data was unable to be collected on the grazing locations to establish a base level of organic carbon content and fine sediment. This has led to the assumption based upon known impacts of grazing that the organic carbon content has been reduced and the average grain size fraction increased. It has also led to the failure to quantify the degree or amount of change experienced. Following on from this, no ongoing sampling occurred following the initial sampling round to assess temporal changes in the fine sediment content and organic carbon content of the study sites.

This study reach has been heavily degraded and has had numerous river work structures and rehabilitation efforts to improve the health and stability of the system. As such this system is neither natural nor completely degraded. Historical rehabilitation structures may impact upon the stability of the stream in a fashion unique to each site and as such produce unique floodplain, bar and bench structures.

The study design assessed variations between land use and also accounted for within channel variability. However, due to the number of samples taken, only the upper component of the soil profile was examined. As such a complete profile of organic content within each bar and bench was not collected. The composition, size and shape of each bar was typically vastly different. Bulk sediment analysis from each study location showed high amounts of variability between study locations (Section 6.4), as with spatial analysis showing the size differences between study locations (Appendix J). This variability may suggest that the sites are different and character and comparison between sites should be undertaken with some degree of caution.

This study was further limited in the calculation of the study site inundation rate and frequency. The study sites were not at the same location as the Aberdeen gauge (stn. 210056) hence same stage discharge cannot be assumed. The potential difference in stage discharge may result in different inundation rates to the predicted inundation rate, however, the values produced in Table 5 likely remain within an order of magnitude and as such may be assumed.

7.6 FURTHER RESEARCH AND IMPROVEMENTS

This study captured an instantaneous snapshot of soil properties on gravel bars and benches in the upper Hunter River. The aim of this was to investigate the role land use, specifically the presence of grazing, plays upon the riparian zone. To gain a more complete understanding of this a series of research questions should be addressed.

In order to establish the temporal effects of grazing and crash grazing more specifically, further work should investigate the recovery or further degradation of study sites. This may consist of a further sampling round at the same study sites to assess vegetation type and density, organic carbon retention and fine sediment retention. Further value may be added to the literature through investigating the role of riparian vegetation in storing organic carbon in a range of different river styles and energy regimes. Further variables that may provide further value to the understanding of the relationship between organic carbon and the riparian zone include comparing the relationship between vegetated zones of predominantly exotic and native vegetation species. Organic carbon storage and grazing intensity could also be investigated through the comparison of study sites which have experienced different grazing intensities. In order to definitively understand the direct impact grazing and crash grazing has on riparian zone benches and bars, a before and after study may provide useful insights. Through establishing a baseline value, the increase or decrease in carbon sequestration may be related directly to grazing. This style of experiment may also be useful in determining the contribution of flood events to carbon sequestration and fine sediment retention. Answering these research questions would provide value to the literature and current understanding of best practice for riparian zone management.

8 CONCLUSIONS AND RECOMMENDATIONS

8.1 CONCLUSIONS

Riparian zone management is an ongoing issue in many catchments both in NSW but also globally. As pressure is placed on the global food market due to climate change, pressure from agriculture is also being placed upon rivers and their environments. In order to protect these environments, appropriate management strategies need to be implemented.

This project aimed to quantify the impacts land use has on carbon storage and fine sediment retention in the riparian zones of the upper Hunter River. Through field-based measurements these goals were met, showing significant difference in sedimentary properties between land use settings. This study also provided an account of temporal changes in vegetation, climate and the hydrological record. Through utilising literature, this thesis reviewed historical and contemporary river management strategies and in conjunction with field observations produced recommendations for riparian zone management.

This study has found that over the past 30 years, changes to management of the Hunter River have resulted in increased geomorphic stability and increases in riparian vegetation. Vegetation increases observed along the Hunter River have tended to be dominated by exotic species such as willow (*Salix species*), cottonwood (*Populus species*), giant reed (*Arundo donax*), green cestrum (*Cestrum parqui)* and balloon vine (*Cardiospermum grandiflorum*). As ecologic diversity becomes better understood and the role of native species clear, research has been required to investigate the best practice for managing weeds. Given the scale of the riverine corridor, a cost effective but environmentally sustainable approach is needed.

The role of stock and grazing in weed management is one of interest, as stock may prove useful in the initial removal of exotic vegetation. Grazing however, has been found to reduce the amount of organic carbon sequestered and reduce the fine sediment retention of the riparian zone and adjacent benches. This may have regional ramifications and cause a reduction in water quality. Despite these perceived negative implications, crash grazing presents a low cost opportunity to reduce weed density in previously unmanaged river reaches as part of a larger weed management program.

The riparian zone may be a globally important carbon sink that can be fully utilised through changing current management strategies. In order to fully understand the impact of cattle on the riparian zone further research and long-term studies need to be undertaken

8.2 RECOMMENDATIONS

Further research needs to be undertaken to fully establish the sedimentological impacts of intermittent grazing on bars and benches, but also how this may impact the aquatic ecosystem and the structure of riparian zone vegetation. This research should also investigate the role of the riparian zone as both an intermittent carbon store but also as a long-term store of carbon.

Practically, intensive perennial grazing of the riparian zone with high stock numbers should be restricted, with the goal of developing a riparian zone buffer. Riparian buffers have proven to be effective at increasing water quality and sediment and nutrient retention. One effective method for developing an effective vegetated riparian buffer is through passive remediation, where an area is fenced to stock and allowed to regenerate through time. Assisted recovery may prove more effective as this process incorporates the removal weed reducing competition for native species in conjunction with fencing of the riparian zone to prevent stock access.

In river reaches where weeds dominate the riparian zone, intervention needs to occur to ensure proper ecologic functioning. Intervention may include the introduction of a grazer, such as a small number of cattle over a limited time period to mechanically break apart and remove weeds. This process should be part of a larger weed management program, involving spraying, poisoning or burning of weed species. Where stock are introduced to a reach, the impacts they will have should be considered and controlled e.g. through the introduction of sediment fencing or riparian vegetation along the river margin to reduce the sediment load to the river.

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APPENDICES:

APPENDIX A – ORGANIC CARBON VALUES

Vegetated Bars		Vegetated Benches		Un-vegetated Bars		Un-vegetated Benches		Crash Grazed Bar		Crash Grazed Bench	
SITE NAME	% Organic Carbon	SITE NAME	% Organic Carbon	SITE NAME	% Organic Carbon	SITE NAME	% Organic Carbon	SITE NAME	% Organic Carbon	SITE NAME	% Organic Carbon
ABB1-1	1.021	ABB2-4 Duplicate	6.114	ABB3-2 Duplicate	2.179	ABB4-1	5.349	DBM1-1	2.023	DBM2-1	2.781
ABB1-2	1.365	ABB2-1	6.192	ABB3-1	1.008	ABB4-2	2.713	DBM1-2	5.702	DBM2-2	0.986
ABB1-3	8.689	ABB2-2	4.824	ABB3-2	2.016	ABB4-3	3.138	DBM1-3	4.737	DBM2-3	1.666
ABB1-4	1.140	ABB2-3	5.876	ABB3-3	3.335	ABB4-4	2.575	DBM1-4	1.352	DBM2-4	0.997
ABB1-5	1.274	ABB2-4	8.283	ABB3-4	2.682	ABB4-5	3.340	DBM1-5	2.034	DBM2-5	2.360
ABB1-6	7.120	ABB2-5	9.622	ABB3-5	0.992	ABB4-6	2.183	DBM1-6	4.299	DBM2-6	2.026
ABB1-6 Duplicate	6.719	ABB2-6	12.170	ABB3-6	1.403	ABB4-7	1.741	DBM1-7	5.175	DBM2-7	1.767
ABB1-7	1.527	ABB2-7	3.558	ABB3-7	1.906	ABB4-8	2.148	DBM1-8	2.779	DBM2-8	2.588
ABB1-8	1.569	ABB2-8	5.352	ABB3-8	1.596	ABB4-9	2.608	DBM1-9	7.293	DBM2-9	3.803
ABB1-9	7.100	ABB2-9	12.279	ABB3-9	2.453	ABB4-10	1.667				
DAB4-1	6.771	DAB3-1	8.824	ABB3-9 Duplicate	2.689	ABB4-11	4.389				
DAB4-2	8.125	DAB3-2	11.174	DAB1-1	2.016	ABB4-13	2.685				
DAB4-3	7.316	DAB3-3	10.037	DAB1-2	1.184	DAB2-1	6.509				
DAB4-4	6.015	DAB3-4	7.572	DAB1-3	2.423	DAB2-2	7.177				
DAB4-5	8.256	DAB3-5	7.581	DAB1-4	1.691	DAB2-3	6.103				
DAB4-6	6.757	DAB3-6	13.597	DAB1-5	1.799	DAB2-4	2.539				
DAB4-7	2.180	DAB3-7	10.068	DAB1-6	2.064	DAB2-5	3.390				
DAB4-8	6.821	DAB3-8	12.184	DAB1-7	1.180	DAB2-6	3.295				
DAB4-9	4.422	DAB3-9	18.148	DAB1-8	2.411	DAB2-7	1.886				
DBM3-1	3.645	DBM4-1	5.551	DAB1-9	1.918	DAB2-8	2.487				
DBM3-2	5.167	DBM4-2	1.897			DAB2-9	1.453				
DBM3-3	4.318	DBM4-3	4.210								
DBM3-4	1.496	DBM4-4	7.240								
DBM3-5	7.897	DBM4-5	3.279								
DBM3-6	9.083	DBM4-6	3.962								
DBM3-7	8.132	DBM4-7	8.203								
DBM3-8	9.422	DBM4-8	5.118								
DBM3-9	8.182	DBM4-9	5.943								

Sample Name	**Original Organic Carbon (%)**	**Duplicate Organic Carbon (%)**	**Difference**
ABB1-6	7.21	6.719	7%
ABB2-4	6.238	6.114	2%
ABB3-2	2.016	2.179	7%
ABB3-9	2.453	2.689	9%

APPENDIX B – SEDIMENT SIZE VALUES

Sample Name	sand	Silt	clay	Clay2um	Mean (micron)
ABB1-1 - Average	95.23	4.48	0.28	0	690.17
ABB1-2 - Average	88.28	10.57	1.15	0.14	527.59
ABB1-3 - Average	45.44	49.07	5.49	0.82	51.91
ABB1-4 - Average	93.88	5.6	0.53	0.01	660.75
ABB1-5 - Average	79.98	18.29	1.73	0.27	227.66
ABB1-6 - Average	52.82	42.62	4.56	0.72	66.13
ABB1-7 - Average	91.76	7.61	0.63	0.02	457.38
ABB1-8 - Average	86.46	12.51	1.03	0.11	290.77
ABB1-9 - Average	36.54	56.47	6.99	1.16	41.69
ABB2-1 - Average	44.78	50.35	4.87	0.84	56.98
ABB2-2 - Average	70.86	26.78	2.36	0.38	188.14
ABB2-3 - Average	46.9	46.94	6.16	1.01	59.03
ABB2-4 - Average	43.98	51.49	4.52	0.71	61.51
ABB2-5 - Average	30.86	62.02	7.12	1.25	33.1
ABB2-6 - Average	21.18	70.94	7.88	1.4	24.55
ABB2-7 - Average	76.42	21.83	1.75	0.27	167.64
ABB2-8 - Average	47.02	46.8	6.17	1	60.47
ABB2-9 - Average	31.6	60.43	7.97	1.42	31.16
ABB3-1 - Average	93.18	6.37	0.45	0	356.11
ABB3-2 - Average	88.38	10.75	0.87	0.1	414.79
ABB3-3 - Average	84.61	14.11	1.28	0.15	308.56
ABB3-4 - Average	87.71	11.35	0.94	0.1	292.52
ABB3-5 - Average	92.84	6.59	0.58	0.02	597.7
ABB3-6 - Average	86.16	12.52	1.32	0.2	352.92
ABB3-7 - Average	86.97	12.08	0.95	0.11	332.01
ABB3-8 - Average	93.05	6.28	0.67	0.04	762.59
ABB3-9 - Average	86.84	12.13	1.03	0.12	361.87
ABB4-1 - Average	80.83	18.03	1.13	0.14	200.11
ABB4-2 - Average	67.43	30.39	2.18	0.37	148.58
ABB4-3 - Average	66.57	31.18	2.25	0.38	139.09
ABB4-4 - Average	78.08	20.3	1.62	0.27	268.71
ABB4-5 - Average	73.75	24.47	1.79	0.31	184.08
ABB4-6 - Average	77.85	20.01	2.13	0.38	177.43
ABB4-7 - Average	93.19	6.29	0.53	0.01	409.35
ABB4-8 - Average	84.24	14.64	1.12	0.14	282.91
ABB4-9 - Average	85.02	13.68	1.3	0.21	267.9
ABB4-10 - Average	87.98	10.59	1.43	0.25	406.73
ABB4-11 - Average	77.78	20.08	2.14	0.36	205.63
ABB4-13 - Average	85.41	13.17	1.42	0.24	278.03
DAB1-1 - Average	83.44	15.25	1.31	0.17	312.8
DAB1-2 - Average	96.17	3.5	0.33	0	613.2
DAB1-3 - Average	90.64	8.73	0.62	0.02	444.22
DAB1-4 - Average	98.4	1.52	0.08	0	773.31
DAB1-5 - Average	94.94	4.74	0.32	0	798.9
DAB1-6 - Average	94.4	5.3	0.31	0	606.27
DAB1-7 - Average	92.1	7.26	0.64	0.02	520.66
DAB1-8 - Average	93.88	6.07	0.06	0	653.03
DAB1-9 - Average	92.27	7.28	0.45	0.01	648.19
DAB2-1 - Average	35.35	59.98	4.68	0.9	40.63
DAB2-2 - Average	38.98	57.68	3.34	0.57	52.26
DAB2-3 - Average	59.8	38.44	1.77	0.28	110.19
DAB2-4 - Average	86.64	12.43	0.92	0.12	376.57
DAB2-5 - Average	76.82	21.77	1.41	0.24	224.65
DAB2-6 - Average	80.9	18.07	1.03	0.12	264.5
DAB2-7 - Average	94.39	5.36	0.25	0	494.88
DAB2-8 - Average	86.99	12.32	0.69	0.03	253.19
DAB2-9 - Average	88.68	10.5	0.83	0.09	411.21
DAB3-1 - Average	35.38	59.06	5.56	1.04	39.7
DAB3-2 - Average	47.36	48.65	3.99	0.71	57.64
DAB3-3 - Average	43.31	52.33	4.36	0.8	54.72
DAB3-4 - Average	33.93	59.88	6.2	1.17	37.28
DAB3-5 - Average	42.3	52.88	4.82	0.89	47.71
DAB3-6 - Average	33.17	60.52	6.31	1.16	37.25
DAB3-7 - Average	35.74	56.97	7.29	1.33	37.36
DAB3-8 - Average	26.79	65.37	7.84	1.47	28.37
DAB3-9 - Average	37.33	56.11	6.56	1.2	38.98

DAB4-1 - Average	24.33	67.51	8.16	1.14	23.62
DAB4-2 - Average	35.03	56.71	8.26	1.35	31.64
DAB4-3 - Average	47.54	47.38	5.08	0.94	57.53
DAB4-4 - Average	49.64	44.18	6.18	1.04	57.68
DAB4-5 - Average	50.42	44.99	4.59	0.82	64.66
DAB4-6 - Average	44	50.55	5.45	1	55.49
DAB4-7 - Average	84.99	13.47	1.54	0.21	261.78
DAB4-8 - Average	58.41	37.23	4.35	0.71	94.55
DAB4-9 - Average	71.31	26.09	2.6	0.43	171.95
DBM1-1 - Average	98.23	1.6	0.17	0	823.71
DBM1-2 - Average	49.17	44.34	6.49	1.04	60.15
DBM1-3 - Average	68.1	29.1	2.8	0.46	132.04
DBM1-4 - Average	94.2	4.81	0.99	0.1	760.98
DBM1-5 - Average	72.77	24.91	2.32	0.41	185.72
DBM1-6 - Average	70.5	27.74	1.76	0.29	143.8
DBM1-7 - Average	58.07	37.31	4.61	0.75	86.53
DBM1-8 - Average	78.71	19.54	1.75	0.3	248.64
DBM1-9 - Average	66.97	30.5	2.53	0.42	137.95
DBM2-1 - Average	74.45	22.9	2.65	0.42	185.96
DBM2-2 - Average	83.79	15.12	1.09	0.14	364.34
DBM2-3 - Average	86.32	12.54	1.14	0.14	271.44
DBM2-4 - Average	91.53	7.65	0.83	0.1	405.46
DBM2-5 - Average	80.95	17.96	1.09	0.13	232.42
DBM2-6 - Average	88.93	10.44	0.63	0.02	441.76
DBM2-7 - Average	84.58	14.07	1.35	0.22	298.91
DBM2-8 - Average	87.55	11.55	0.9	0.11	380.27
DBM2-9 - Average	67.43	29.95	2.61	0.45	143.18
DBM3-1 - Average	76.37	20.68	2.95	0.44	166.85
DBM3-2 - Average	59.13	35.68	5.18	0.94	85.89
DBM3-3 - Average	62.23	33.72	4.06	0.67	98.72
DBM3-4 - Average	68.26	27.93	3.81	0.61	120.85
DBM3-5 - Average	43.61	50.87	5.52	0.99	48.68
DBM3-6 - Average	36.88	56.94	6.17	1.11	41.34
DBM3-7 - Average	46.1	48.29	5.62	0.69	52.51
DBM3-8 - Average	41.16	51.95	6.88	0.98	40.23
DBM3-9 - Average	45.29	47.12	7.59	1.21	49.45
DBM4-1 - Average	51.98	43.93	4.09	0.77	67.11
DBM4-2 - Average	82.19	15.06	2.75	0.59	301.38
DBM4-3 - Average	58.73	36.43	4.85	0.98	80.39
DBM4-4 - Average	43.25	52.16	4.59	0.9	52.46
DBM4-5 - Average	59.92	35.76	4.31	0.88	102.39
DBM4-6 - Average	49.28	47.02	3.7	0.72	65.56
DBM4-7 - Average	39.53	54.68	5.79	1.1	44.99
DBM4-8 - Average	45.9	49.7	4.4	0.84	54.6
DBM4-9 - Average	38.31	56.11	5.58	1.1	54.41

APPENDIX C NORMALITY TEST – SHAPIRO WILK W VALUES –

	% ORGANIC CARBON	MICRON SIZE	SAND	SILT	CLAY	CLAY 2UM
SITES	Prob < W (Shapiro Wilk W Test)	Prob < W (Shapiro Wilk W Test)	Prob < W (Shapiro Wilk W Test)	Prob < W (Shapiro Wilk W Test)	Prob < W (Shapiro Wilk W Test)	Prob < W (Shapiro Wilk W Test)
CBAR	0.6382	0.0018	0.7093	0.5566	0.3657	0.5409
CBEN	0.7245	0.7907	0.2699	0.3328	0.0115	0.0463
UBAR	0.6544	0.051	0.5981	0.591	0.3681	0.003
UBEN	0.0126	0.837	0.6146	0.5542	0.6001	0.2213
VBAR	0.004	0.0001	0.0655	0.0614	0.168	0.0745
VBEN	0.252	0.0001	0.9679	0.8889	0.0988	0.2364
	GREEN =NORMAL	GREEN =NORMAL	GREEN =NORMAL	GREEN =NORMAL	GREEN =NORMAL	GREEN =NORMAL
	YELLOW = NON NORMAL	YELLOW = NON NORMAL	YELLOW = NON NORMAL	YELLOW = NON NORMAL	YELLOW = NON NORMAL	YELLOW = NON NORMAL

APPENDIX D – VARIANCE TESTING VALUES

VARIANCE TESTING ON ALL RESULTS

		LOI (% Carbon)		Grain Size (Micron)		(Sand)		(Silt)		(Clay)		(Clay 2um)	
SITE	SITE	Prob > F (Welch's Test)	TEST USED	Prob > F (Welch's Test)	TEST USED	Prob > F (Welch's Test)	TEST USED	Prob > F (Welch's Test)	TEST USED	Prob > F (Welch's Test)	TEST USED	Prob > F (Welch's Test)	TEST USED
CBAR	CBEN	0.0295	T	0.1223	W	0.1167	E	0.1234	E	0.1221	W	0.1145	W
CBAR	UBAR	0.0158	T	0.0075	W	0.009	T	0.0088	T	0.0083	T	0.0018	W
CBAR	UBEN	0.6434	W	0.4105	W	0.0594	E	0.073	E	0.0154	E	0.0179	E
CBAR	VBAR	0.2075	W	0.0465	W	0.0926	E	0.099	E	0.0449	T	0.0856	E
CBAR	VBEN	0.0001	T	0.0001	W	0.0002	T	0.0002	T	0.0011	T	0.0002	T
CBEN	UBAR	0.4819	E	0.0008	T	0.0001	T	0.0001	T	0.0001	W	0.0001	W
CBEN	UBEN	0.035	W	0.2408	E	0.747	E	0.722	E	0.9375	W	0.07572	W
CBEN	VBAR	0.0137	W	0.0065	W	0.0001	T	0.0001	T	0.0035	W	0.0046	W
CBEN	VBEN	0.0001	T	0.0001	T	0.0136	T	0.0132	T	0.0101	W	0.007	W
UBAR	UBEN	0.0003	W	0.0001	T	0.0002	T	0.0002	T	0.0001	T	0.0006	W
UBAR	VBAR	0.0013	W	0.0001	W	0.0001	T	0.0001	T	0.0001	T	0.0001	W
UBAR	VBEN	0.0001	T	0.0001	T	0.0001	T	0.0001	T	0.0001	T	0.0001	W
UBEN	VBAR	0.06338	W	0.017	W	0.0001	T	0.0001	T	0.0001	T	0.0001	T
UBEN	VBEN	0.0001	W	0.0001	T	0.0001	T	0.0001	T	0.0001	T	0.0001	T
VBAR	VBEN	0.0085	W	0.0046	W	0.0002	T	0.0001	T	0.0197	T	0.0006	T

H0= THERE IS NO DIFFERENCE BETWEEN THE MEANS. SMALL H0 DISPROVES THIS
W = WILCOXON TEST
T = T TEST (UNEQUAL VARIANCE)
E = EQUAL VARIANCE T TEST

APPENDIX E – MEAN AND MEDIAN TEST P RESULTS

		LOI	Microns*	Sand	Silt	Clay	Clay 2UM
SITE	SITE	MEAN TEST	MEAN TEST	MEAN TEST	MEAN TEST	MEAN TEST	MEAN TEST
CBAR	CBEN	0.0295	0.1223	0.1167	0.1234	0.1221	0.1145
CBAR	UBAR	0.0158	0.0075	0.009	0.0088	0.0083	0.0018
CBAR	UBEN	0.6434	0.4105	0.0594	0.073	0.0154	0.0179
CBAR	VBAR	0.2075	0.0465	0.0926	0.099	0.0449	0.0856
CBAR	VBEN	0.0001	0.0001	0.0002	0.0002	0.0011	0.0002
CBEN	UBAR	0.4819	0.0008	0.0001	0.0001	0.0001	0.0001
CBEN	UBEN	0.035	0.2408	0.747	0.722	0.9375	0.07572
CBEN	VBAR	0.0137	0.0065	0.0001	0.0001	0.0035	0.0046
CBEN	VBEN	0.0001	0.0001	0.0136	0.0132	0.0101	0.007
UBAR	UBEN	0.0003	0.0001	0.0002	0.0002	0.0001	0.0006
UBAR	VBAR	0.0013	0.0001	0.0001	0.0001	0.0001	0.0001
UBAR	VBEN	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
UBEN	VBAR	0.06338	0.017	0.0001	0.0001	0.0001	0.0001
UBEN	VBEN	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
VBAR	VBEN	0.0085	0.0046	0.0002	0.0001	0.0197	0.0006
			*of sediment less than 1500 micron				
*** Small value rejects Ho**	* Green values fail to reject Ho		* Yellow Values reject Ho				

APPENDIX F – VEGETATION TRANSECT RESULTS

Vegetation Transects -

	Canopy Cover (%)	Mid Cover (%)	Ground Cover (%)
ABB1 Bar Average	40	0	62.86
ABB2 Bench Average	44	1	100
ABB3 + 4	0	0	71.11
DAB1 +2	0	0	45.63
DAB3 Bench Average	48.33	0	100
DAB4 Bar Average	48	2	60
DBM1 Crash Grazed Bar Average	10	0	55
DBM2 Crash Grazed Bench	0	0	100
DBM3	60	0	100
DBM4	31.11	0	100

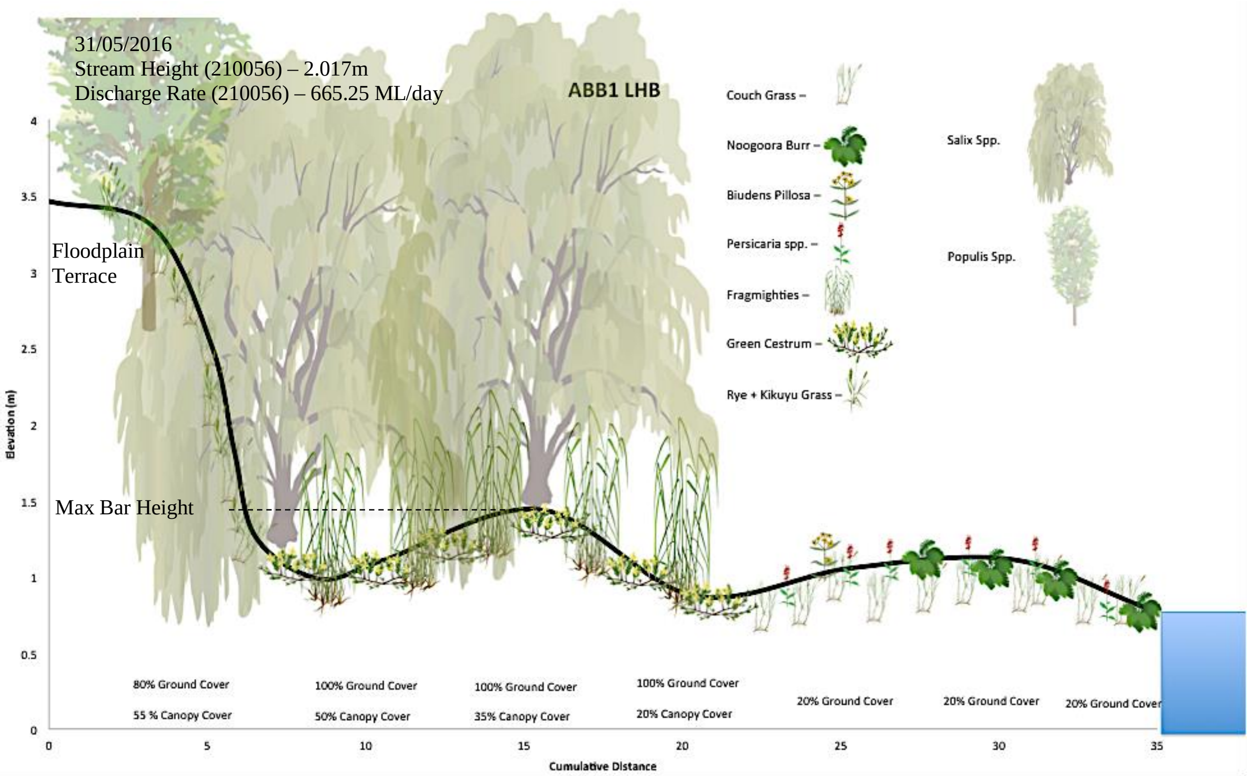
Sites	Bar Average Organic Carbon (%)	4,5,6 Average Organic Carbon (%)
AB1	3.401	3.111
AB2	7.988	9.664
AB3	1.885	1.692
AB4	2.866	2.699
DAB1	1.854	1.851
DAB2	3.871	3.075
DAB3	11.020	9.583
DAB4	6.296	7.009
DBM1	3.933	2.561
DBM2	2.108	1.794
DBM3	6.371	6.159
DBM4	5.045	4.827

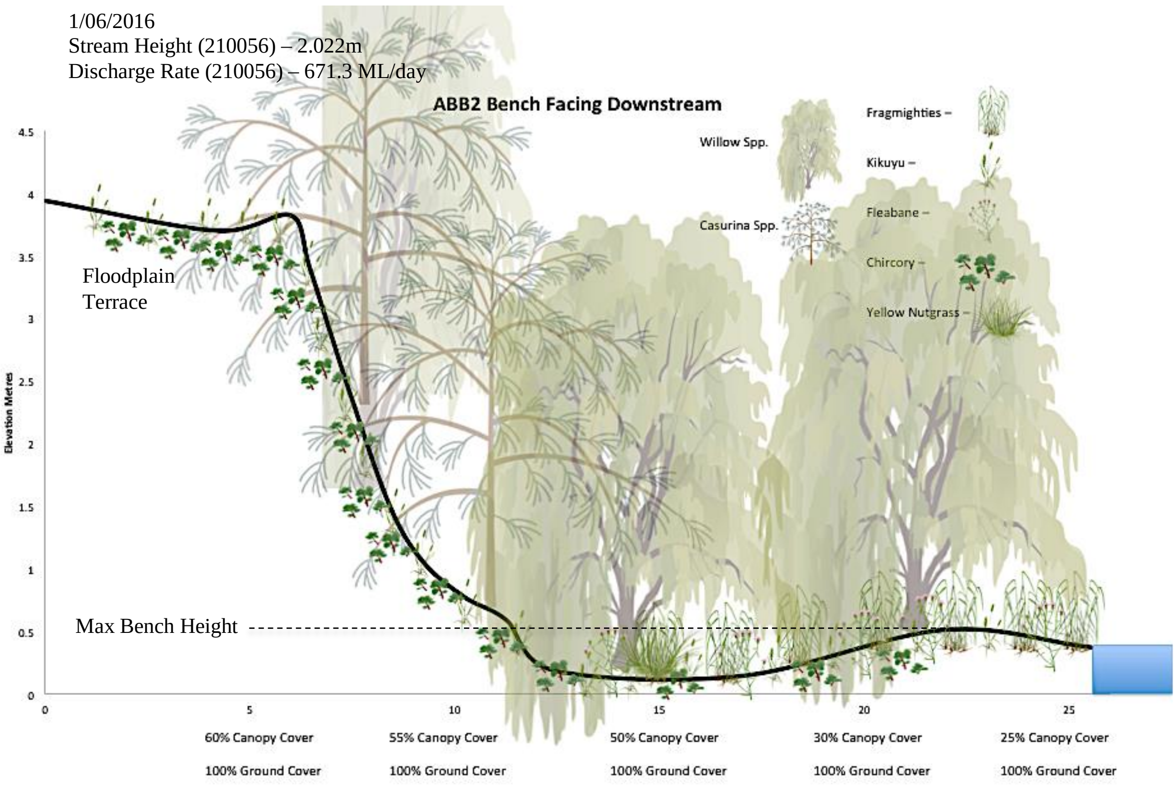
APPENDIX G – LAND USE TYPE SUMMARY VALUES

	LOI	LOI	Grain Size (Microns)		Sand		Silt		Clay		Clay 2UM	
	Mean	Standard Deviation	Mean	Standard Deviation	Mean	Standard Deviation	Mean	Standard Deviation	Mean	Standard Deviation	Mean	Standard Deviation
CBAR	3.93267	1.99967	286.613	292.153	72.9689	15.7164	24.4278	13.9741	2.60222	1.91117	0.41889	0.317232
CBEN	2.10822	0.89662	302.638	102.907	82.8367	7.6015	15.7978	6.9155	1.36556	0.74549	0.19222	0.147205
UBAR	1.89756	0.62464	508.314	175.894	90.8878	4.2328	8.435	3.8539	0.67833	0.4	0.05889	0.0679
UBEN	3.44878	1.72655	244.524	125.117	81.8083	7.7796	16.8489	7.2669	1.34278	0.59366	0.20333	0.128108
VBAR	5.35593	2.93319	168.054	193.755	59.8181	20.8295	35.8707	18.4817	4.31037	2.42996	0.6863	0.412694
VBEN	8.17973	2.85562	49.38	14.353	40.1888	9.35	53.1888	8.3259	5.62208	1.32639	1.02875	0.233374

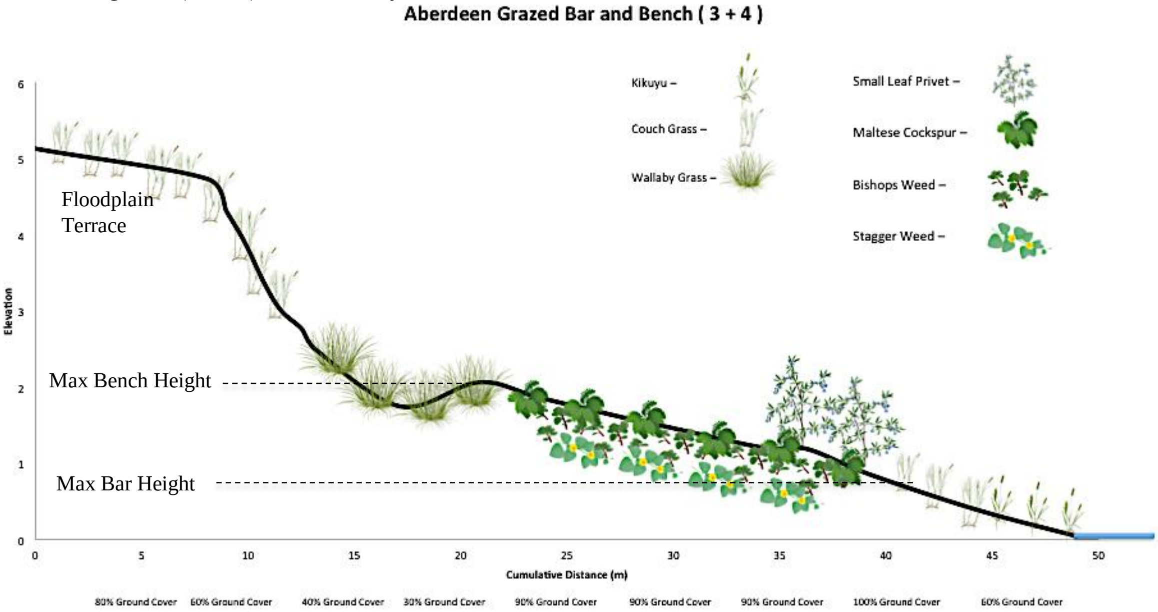
Grain size - sub sampled section all grainsize has been limited to a maximum of 1500 microns through a period of sieving

APPENDIX H – VEGETATION TRANSECTS

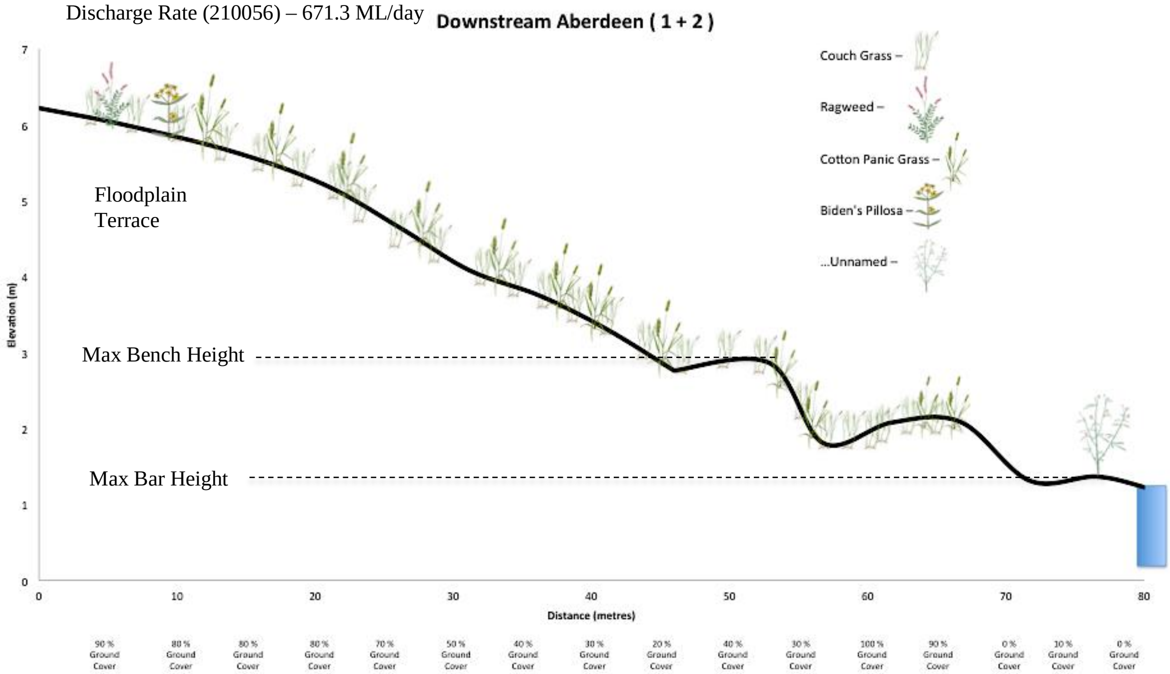


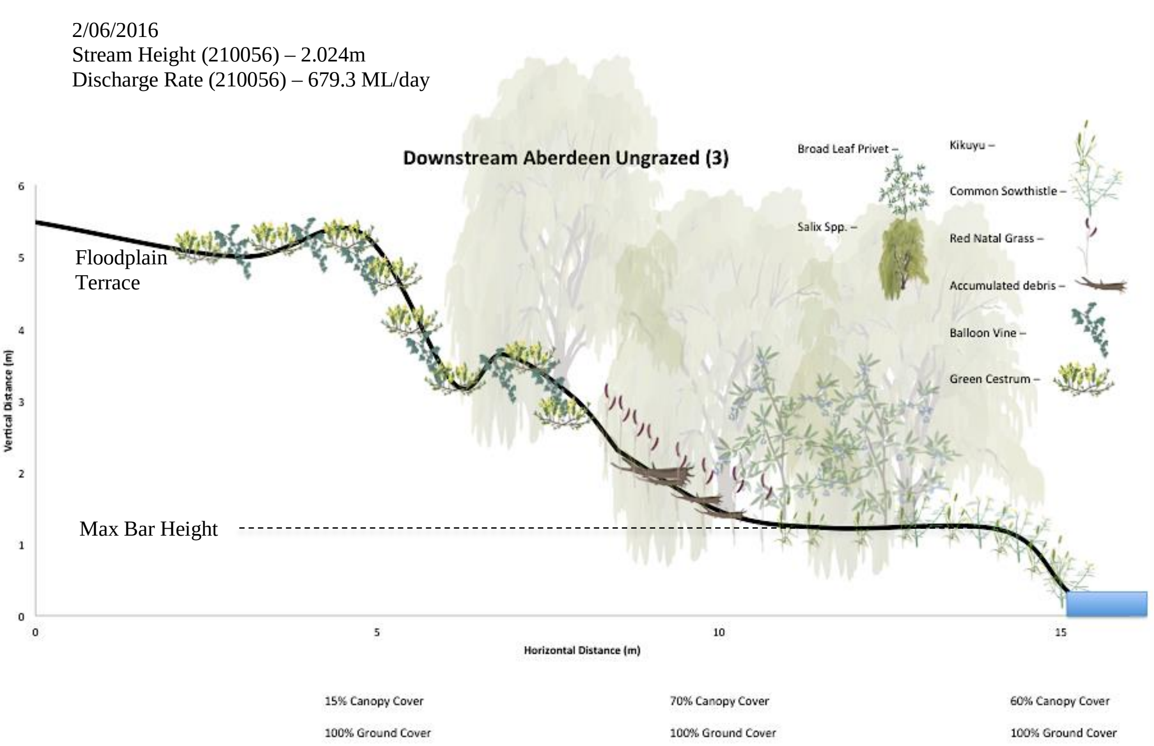


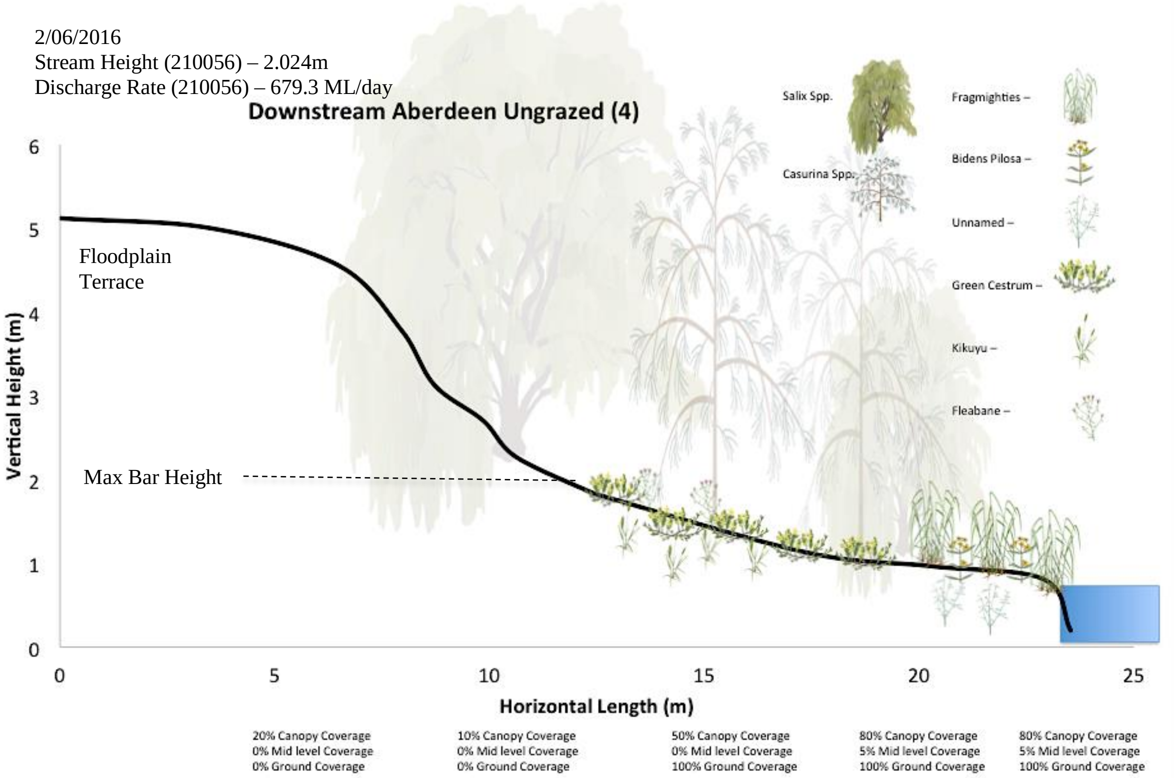
1/06/2016
Stream Height (210056) – 2.022m
Discharge Rate (210056) – 671.3 ML/day



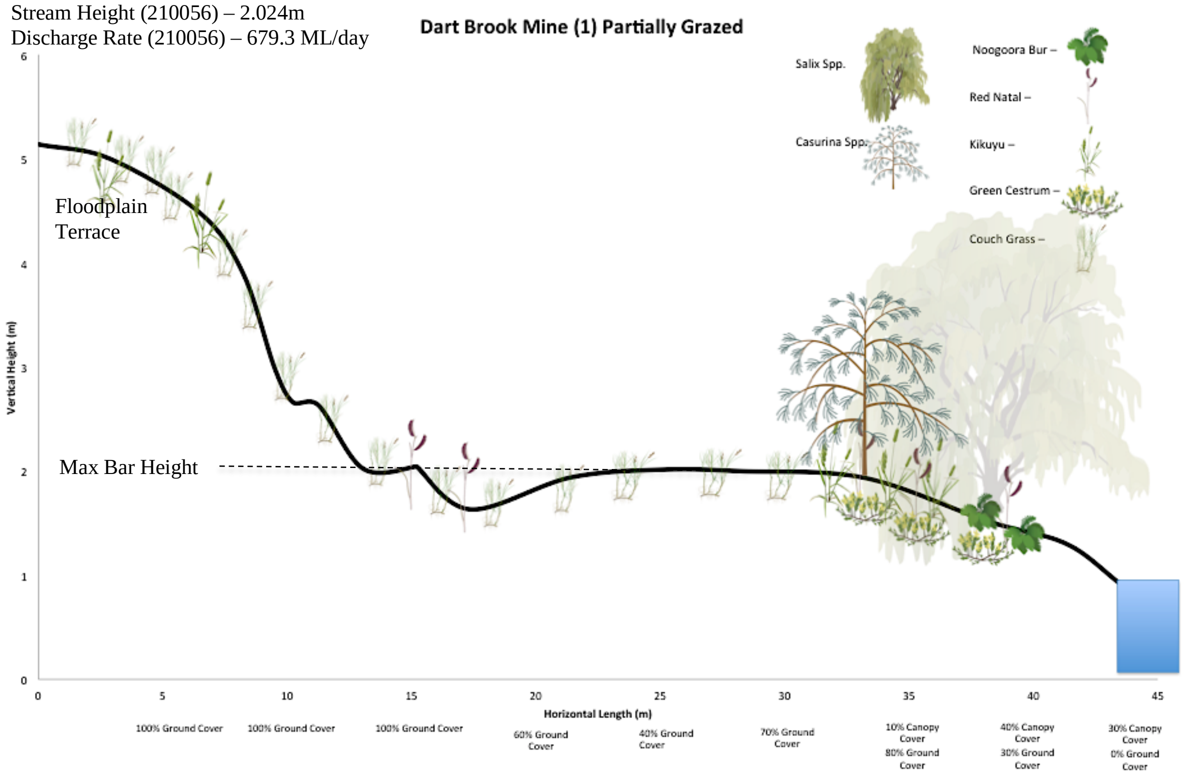
1/06/2016
Stream Height (210056) – 2.022m
Discharge Rate (210056) – 671.3 ML/day



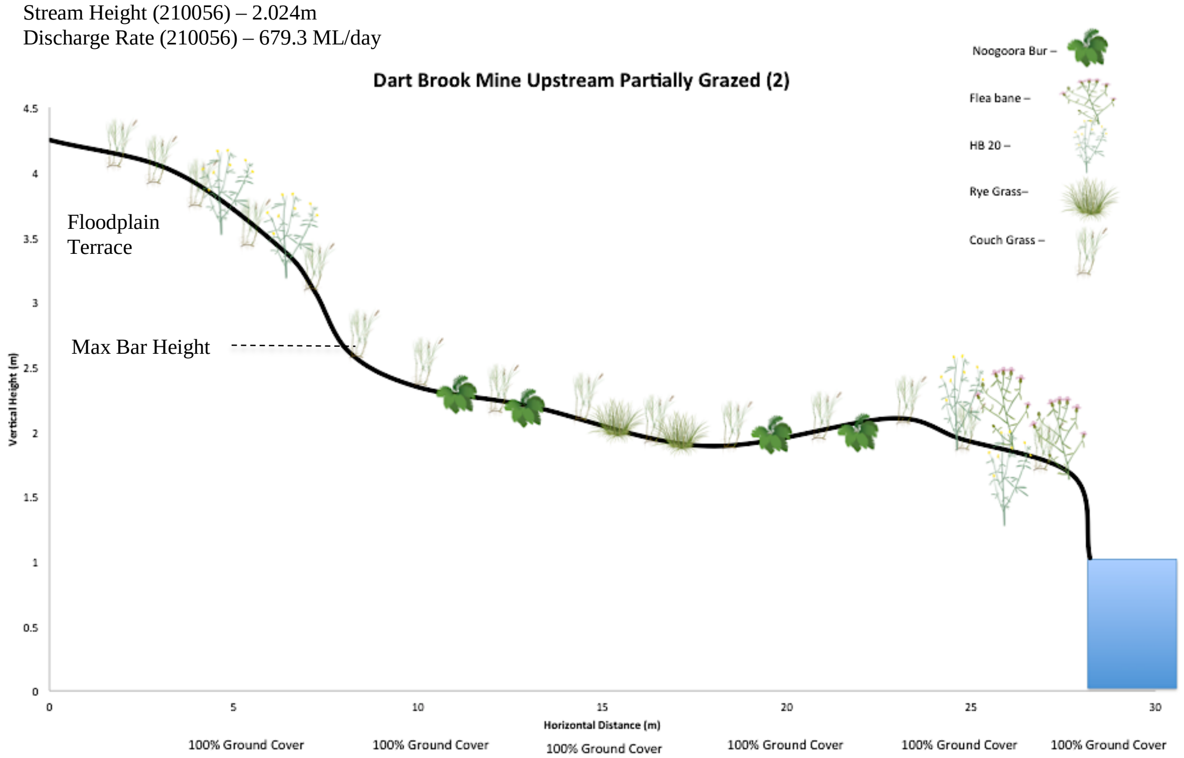

2/06/2016
Stream Height (210056) – 2.024m
Discharge Rate (210056) – 679.3 ML/day
Downstream Aberdeen Ungrazed (3)
Broad Leaf Privet –
Kikuyu –
Common Sowthistle –
Salix Spp. –
Red Natal Grass –
Accumulated debris –
Balloon Vine –
Green Cestrum –
Floodplain Terrace
Max Bar Height
Vertical Distance (m)
0
1
2
3
4
5
6
0
5
10
15
Horizontal Distance (m)
15% Canopy Cover
100% Ground Cover
70% Canopy Cover
100% Ground Cover
60% Canopy Cover
100% Ground Cover

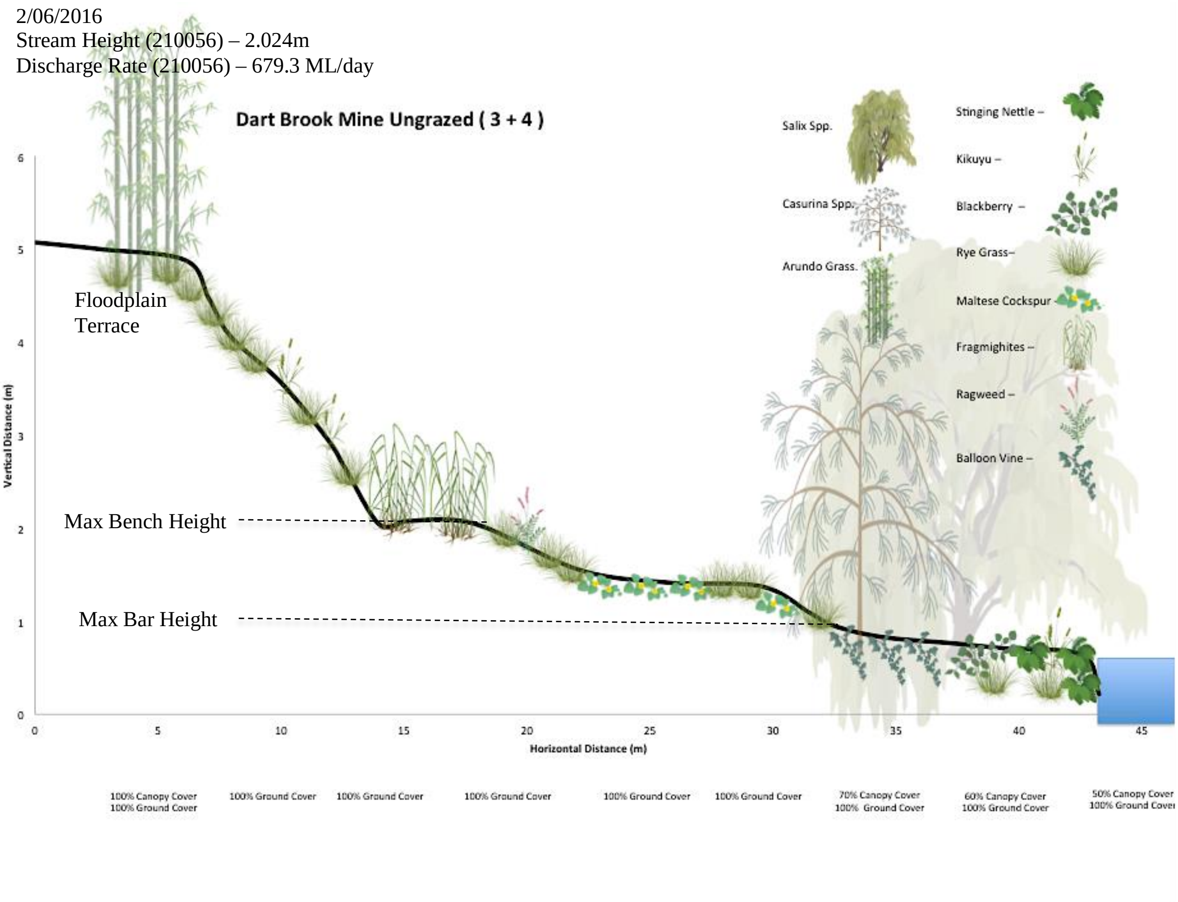

2/06/2016
Stream Height (210056) – 2.024m
Discharge Rate (210056) – 679.3 ML/day
Downstream Aberdeen Ungrazed (4)
Salix Spp.
Casurina Spp.
Fragmighties –
Bidens Pilosa –
Unnamed –
Green Cestrum –
Kikuyu –
Fleabane –
Floodplain Terrace
Max Bar Height
Vertical Height (m)
0
1
2
3
4
5
6
0
5
10
15
20
25
Horizontal Length (m)
20% Canopy Coverage
0% Mid level Coverage
0% Ground Coverage
10% Canopy Coverage
0% Mid level Coverage
0% Ground Coverage
50% Canopy Coverage
0% Mid level Coverage
100% Ground Coverage
80% Canopy Coverage
5% Mid level Coverage
100% Ground Coverage
80% Canopy Coverage
5% Mid level Coverage
100% Ground Coverage

2/06/2016
Stream Height (210056) – 2.024m
Discharge Rate (210056) – 679.3 ML/day



2/06/2016
Stream Height (210056) – 2.024m
Discharge Rate (210056) – 679.3 ML/day

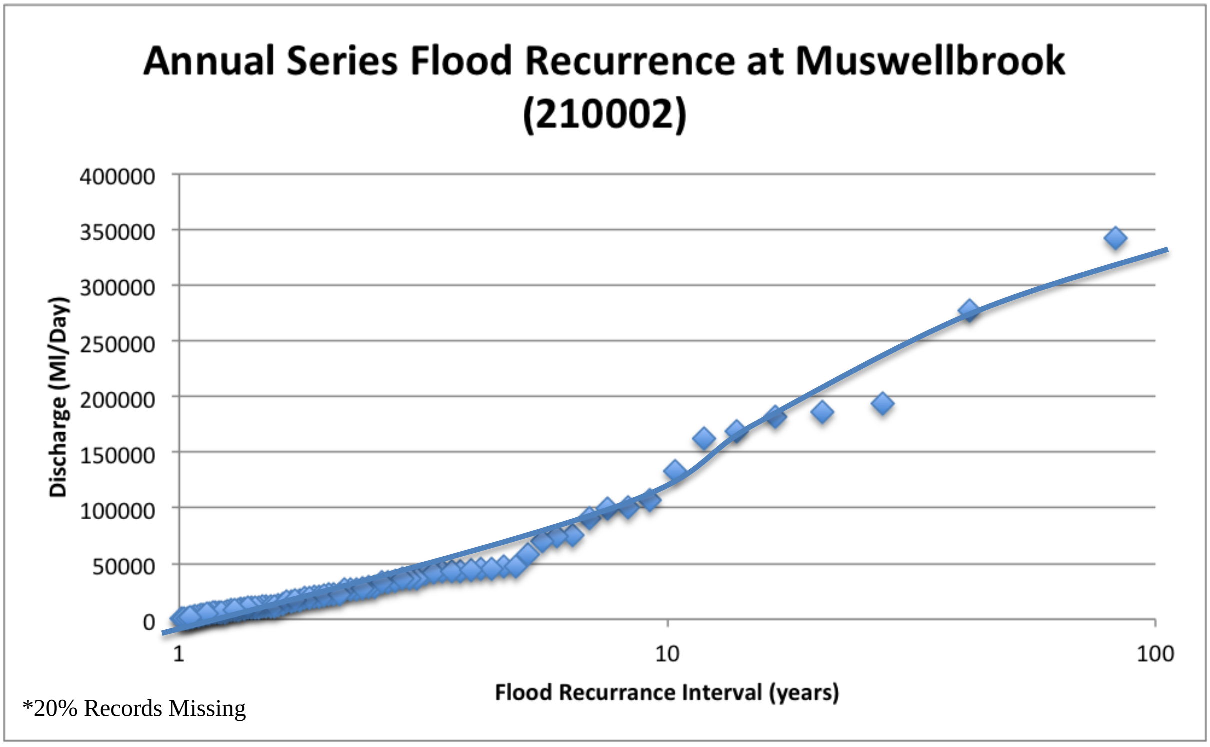


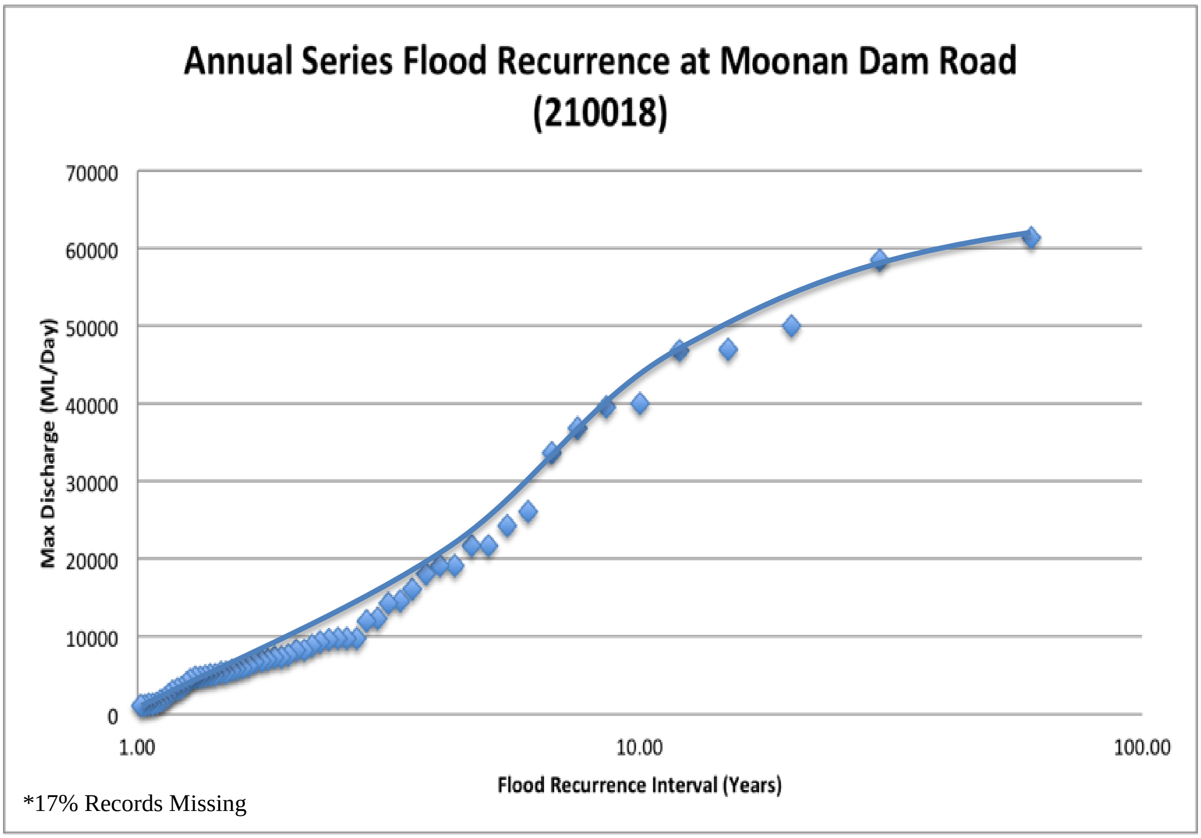


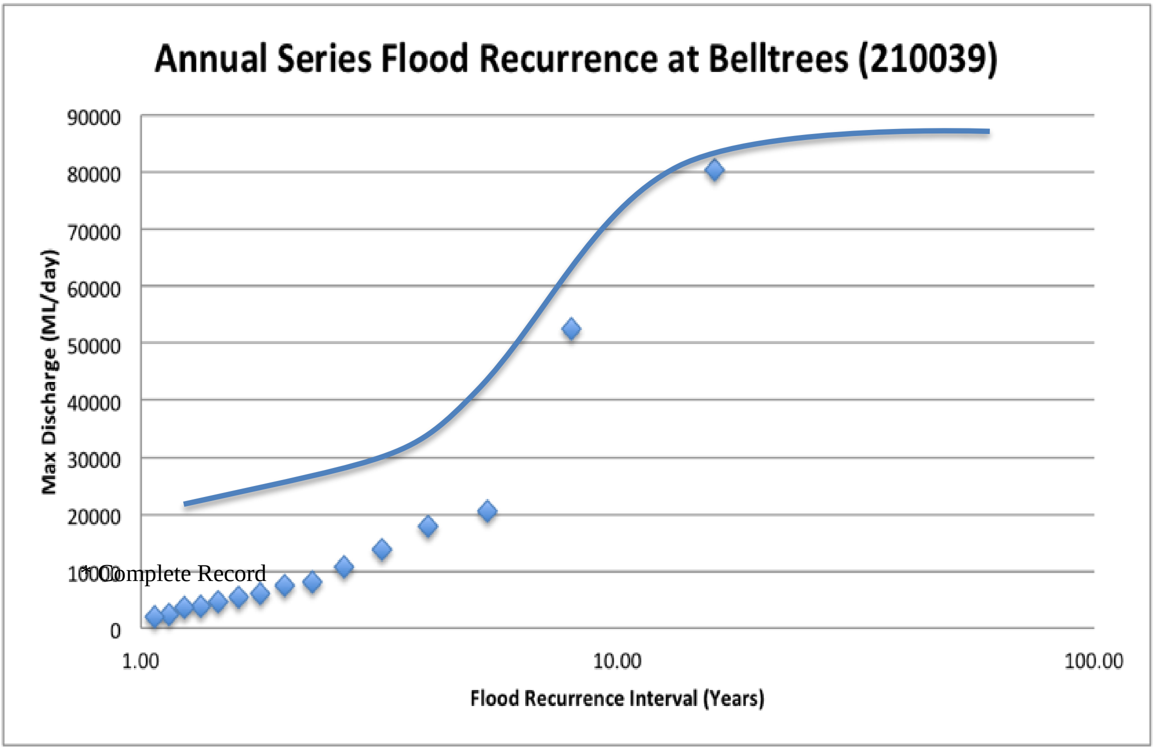
Acknowledgements –

Symbols Courtesy of the Integration and Application Network, University of Maryland Center for Environmental Science (ian.umces.edu/symbols/).

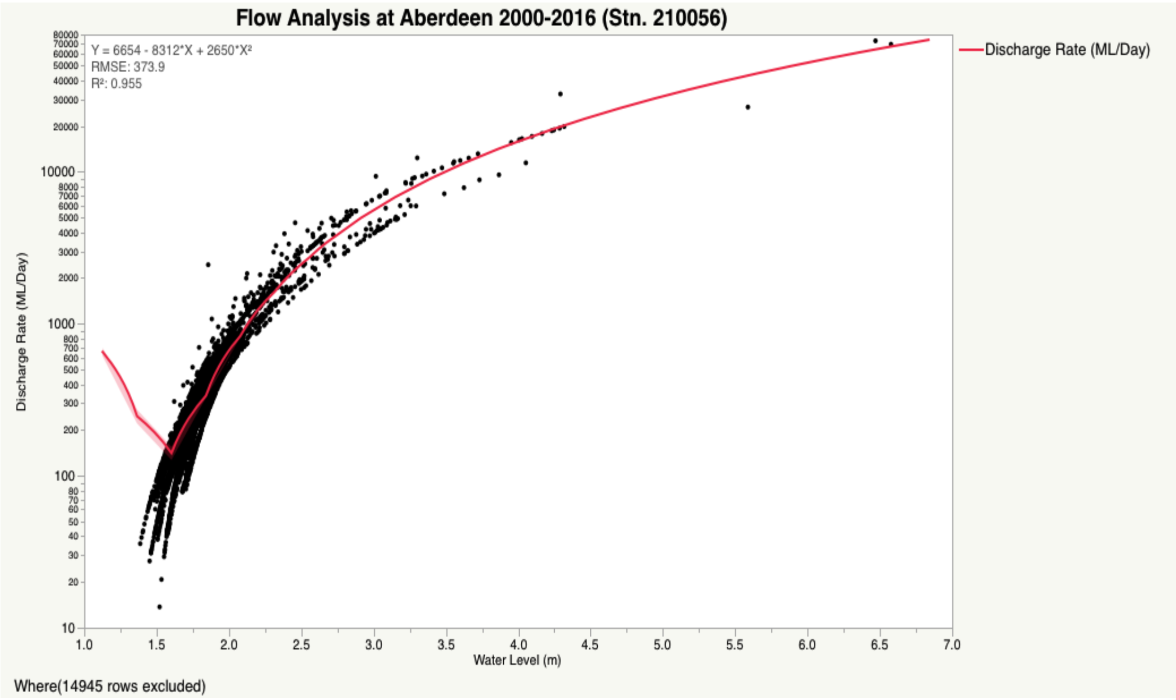
APPENDIX I – HYDROLOGIC STREAM GAUGE DATA –





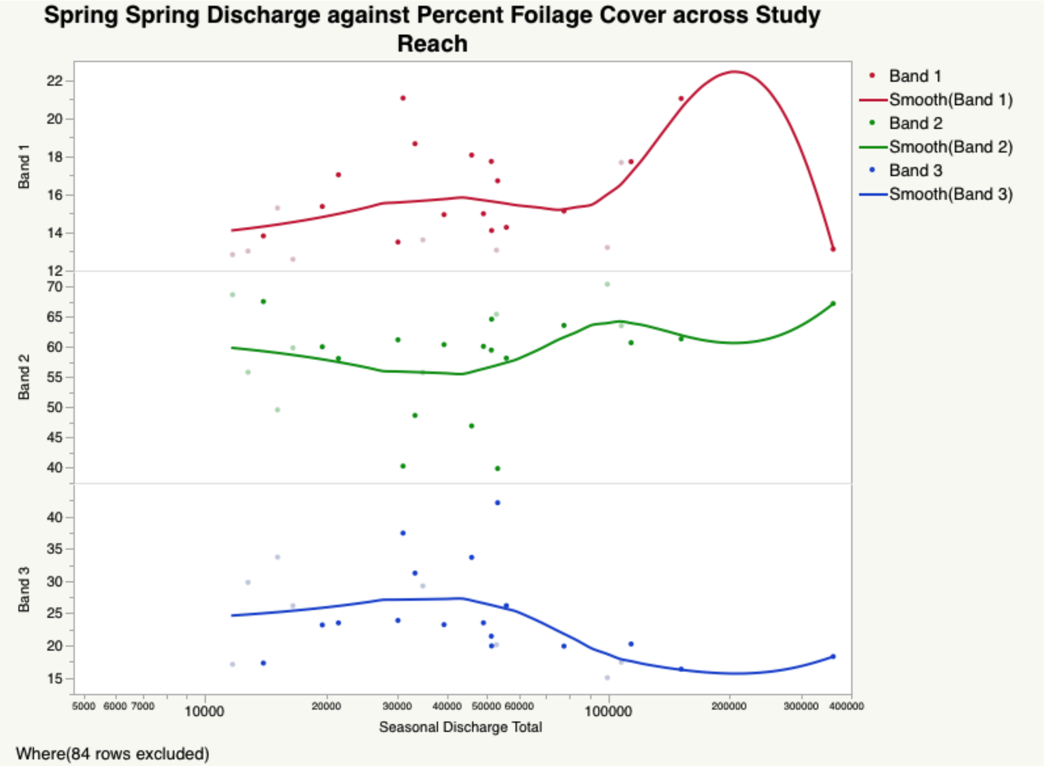


Flood Recurrence the relationship between discharge rate and stage height

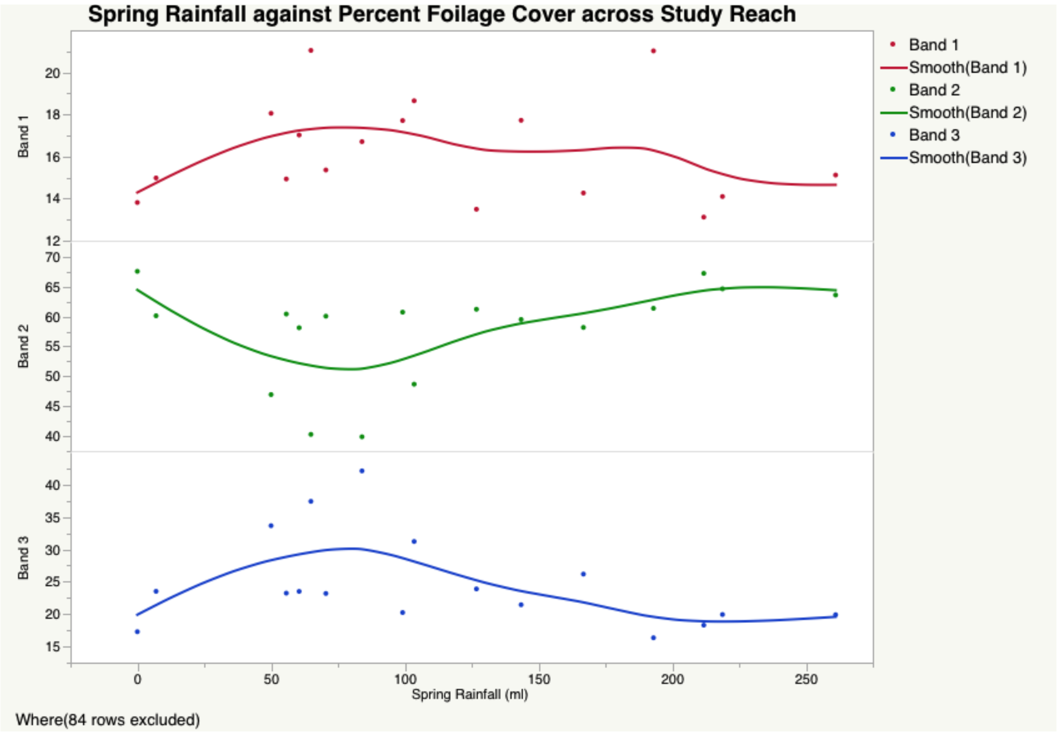


APPENDIX J – FRACTIONAL FOILAGE COVER

Discharge (ML/Day)



Rainfall (ml)



APPENDIX K – BAR GEOMORPHIC CHARACTERISTICS

Bar and Bench Characteristics of the Study Location

Site	Site Area (m^2)	Site Perimeter (m)
ABB1 Bar	2479	405
ABB2 Bench	7136.5	715
ABB3 Bar	306	112
ABB4 Bench	14831.5	944
DAB1 Bar	2805	316
DAB2 Bench	9678	616
DAB3 Bench	1162	234
DAB4 Bar	1027	215
DBM1 Bar	2595	284
DBM2 Bench	25866	1074
DBM3 Bar	2926	356
DBM4 Bench	15576	910