Suspended sediment transport and the implications on river channel breakdown: Northern Macquarie Marshes, NSW

“We never know the wealth of water til the well is dry” Thomas Fuller 1732, Gnomologia

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Abstract

The lower Macquarie River flows northwest from Burrendong Dam to its confluence with the Barwon River and forms part of the Murray – Darling Basin. Large-scale (i.e. climate and topography) controls determine the volume, energy of flow and the suspended sediment transport capacity down catchment. Unlike river systems that increase in size and capacity with distance down catchment towards coastal regions, the Macquarie River flows inland where decreases in capacity and size reflect the semi-arid nature of the climate and the lack of perennial tributaries. This study has identified that the small-scale controls of declining discharge, suspended sediment transport and in-channel vegetation promote channel breakdown in the distal reaches of the fluvial system.

The impact of declining discharge and in-channel vegetation blocking on the contemporary suspended sediment transport regime varies in both space and time in the lateral and longitudinal dimensions. Longitudinal and lateral hydrologic connectivity and suspended sediment transport were assessed using flood recurrence intervals, discharge, and total suspended solids data and channel corridor geomorphic units. Contemporary in-channel and floodplain sedimentation rates, using optically stimulated luminescence and unsupported lead-210, were investigated in the northern Macquarie Marshes. These variables were used as tools to assess the spatiotemporal variability of longitudinal and lateral hydrologic connectivity and suspended sediment transport down catchment.

Surface sediment accretion rates ranged from 2.43 g cm^{-2} yr^{-1} upstream of channel breakdown, 0.47 g cm^{-2} yr^{-1} within the zone of channel breakdown, and 0.077 g cm^{-2} yr^{-1} downstream of channel breakdown. Channel – floodplain hydrologic connectivity increases down catchment. The results show a discontinuity of suspended sediment transport through the northern Macquarie Marshes, promoting a positive feedback cycle between declining discharge and specific stream powers, enhancing in-channel sedimentation and vegetation growth. In-channel vegetation blocking and bed aggradation increases the recurrence of overbank flows and sustains the essential ecosystem services provided by dryland wetland systems.

Acknowledgements

This thesis provides another chapter in the investigation of form and process in the contemporary investigations of the geomorphology and connectivity of the Macquarie Marshes, New South Wales for which my supervisor, Dr Paul Hesse, has been working tirelessly with numerous students to develop a holistic understanding of this unique floodplain wetland system. I extend sincere thanks to Dr Paul Hesse as my supervisor has been very patient and understanding during my candidature and to Dr Kirstie Fryirs, my secondary supervisor, who was always involved and encouraging throughout my candidature.

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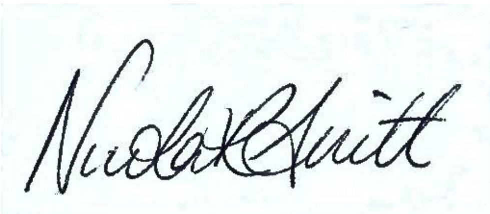
The results and conclusions presented in this thesis are based on fieldwork and analyses completed by the author. All work is original except where acknowledged and has not been previously submitted for a higher degree to any other university or institution.



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Chapter 1: Introduction

1.1 Introduction

Wetlands, marshes and peatlands often occur where channel breakdown is a key contributor. These have been variously called floodouts (Tooth, 1999a and 1999b; Brierley and Fryirs, 1999; Bird, 1982), terminal fans (Parkash et al, 1983; Kelly & Olsen, 1993) and alluvial fans (McCarthy et al., 1988; Ellery et al., 1990, 1993). River channel breakdown has been identified in a range of geomorphic environments globally (e.g. Eyles, 1977; Bird, 1982; Young, 1986; Parkash et al., 1983; Ellery et al., 1990; McCarthy et al., 1988, 1991; Assine and Soares, 2004; Assine, 2005). These features also form on the lower reaches of inland draining rivers in Australia (e.g. Tooth 1999a, 1999b, 2000; Ralph, 2008; Freeman, 2008; Yonge and Hesse, 2009; Ralph and Hesse, 2010; Ralph et al., 2012). It is the partial or complete collapse of channelised flow due to fluctuations in geomorphological and hydrological processes of the fluvial system that reduce the competency of the system to maintain streamflow and sediment transport, resulting in channel breakdown.

The controls that drive the collapse of a single channel to an area of channel breakdown often enhance or reduce sediment and water transfer (Tooth, 1999a). This can then impact on the level of lateral and longitudinal connectivity of the river and its floodplain over varied temporal and spatial scales (Fryirs et al., 2007a; Fryirs, 2013). Channel breakdown and the strength connectivity of sediment and water transfer within the channel and onto the floodplain control the type of vegetation and the growth patterns of vegetation and ensuing ecosystems. The movement of material between physical landscape compartments interacts with ecological communities to promote vegetation growth that filters water and regulates the speed of flow (Whiteoak and Binney, 2012).

The Macquarie Marshes form one of Australia's largest wetland areas and are listed under the Ramsar treaty. It is unknown what drives the lateral and reduced longitudinal (dis)connectivity or the impacts of these dynamics on the functioning of the floodplain wetland system. This research investigates controls on channel breakdown and how this affects spatial and temporal changes in lateral and longitudinal connectivity of the lower Macquarie River.

1.2 Channel breakdown and connectivity

The interaction of local small-scale processes resulting in morphological changes occurring within a reach are often connected with catchment-scale controls such as climate, geology and topography (Lane and Richards, 1997; Molnar et. al., 2002), which affect hydrology, bed material texture and calibre and landscape gradients. The channel geometry, planform, bed material size and composition, and the level of bed and bank stability are controlled by the flow regime and sediment supply (Gilvear et al., 2002). Unlike river systems that undergo increases in discharge and increases in channel size that flow from the headwaters to the sea (Ferguson et al., 2006), semi-arid inland-flowing rivers decrease in discharge and decrease in channel size (Sheldon et al., 2002). Semi-arid and arid rivers undergo complex interactions between discharge, slope, sediment transport, bank sediment composition, vegetation and patterns of tributary change, which result in a variety of patterns of channel change downstream (Tooth, 2000). One variety of channel change is channel breakdown.

Connectivity has been used empirically and conceptually to describe sediment, water and ecosystem process dynamics (Montgomery, 1999; Brierley et al., 2006; Fryirs et al. 2007a; Lexarta-Artza & Wainwright, 2009; Michaelides & Chappell, 2009) across different temporal and spatial scales. In river systems, vertical linkages of the hyporheic corridor with the river channel, and groundwater with the floodplain compartment are often areas of research for ecological studies of organism movement and bioproduction (Boulton and Lloyd, 1992; Standford and Ward, 1993). In geomorphology, connectivity is essentially assessed as the transfer of material, such as water, sediment and nutrients, across well-defined compartment boundaries (Fryirs et al. 2007a; Michaelides and Chappell, 2009; Lexarta-Artza and Wainwright, 2009; Jain and Tandon, 2010; Fryirs 2013). The focus is often on the longitudinal upstream-downstream and tributary-trunk connectivity of sediment transport, and the lateral connectivity of the channel and floodplain as sediment sinks. Connectivity within and between landscape compartments increases biodiversity and ecosystem health through healthy soils to support flora and wildlife such as invertebrates, waterbirds and fish to maintain a healthy food web (Standford and Ward, 1993; Montgomery, 1999).

There are three spatial dimensions of connectivity within a catchment that occur along the lateral, longitudinal and vertical planes. Longitudinal studies assess the transfer of material upstream to downstream or tributary to trunk. Lateral connectivity assesses the linkages between floodplains and channels or hillslopes and channels, and vertical connectivity assesses the linkage between channel-hyporheic zone and groundwater-floodplain (Poole et al., 2002; Brierley et al., 2006; Fryirs et al., 2007a). Temporal dimensions of connectivity can be assessed on short or long-time scales either within compartment (intracompartment) or between compartments (intercompartment) (Fryirs et al. 2007a; Jain & Tandon, 2010). Intercompartment and intracompartment connectivity of sediment and water movement are important for studies in fluvial process – form relationships. Discharge and sediment supply processes are drivers that govern the nature of morphological change within a fluvial system over long and short timescales (Lane et al., 1996).

Through identification of the controls on channel breakdown of a river system and the ensuing connectivity of suspended sediment transport, implications for ecosystem health (Arthington et al., 2006) can be assessed and the ecosystem services identified. Identification of the processes controlling channel breakdown and supporting wetland development can be used by riverine managers and local landholders to maintain good catchment and river management, and whole of ecosystem health (Lexartza-Artza and Wainwright, 2009). Connectivity has been defined for this project as the transport of suspended sediment longitudinally through the river corridor and laterally between the channel and floodplain, and the physical connection of landscape compartments within the river corridor.

1.3 Channel Breakdown of the Lower Macquarie River central-west New South Wales Australia

The lower Macquarie River, an inland flowing river and part of the wider Murray Darling Basin in southeastern Australia (Figure 1.1), undergoes intermediate riverine channel breakdown in its distal reaches. The channel remerges downstream of the area of channel breakdown as a single trunk channel. The area of channel breakdown is called the Macquarie Marshes, which has two distinct complexes, the (upstream) southern Macquarie Marshes and the (downstream) northern Macquarie Marshes.

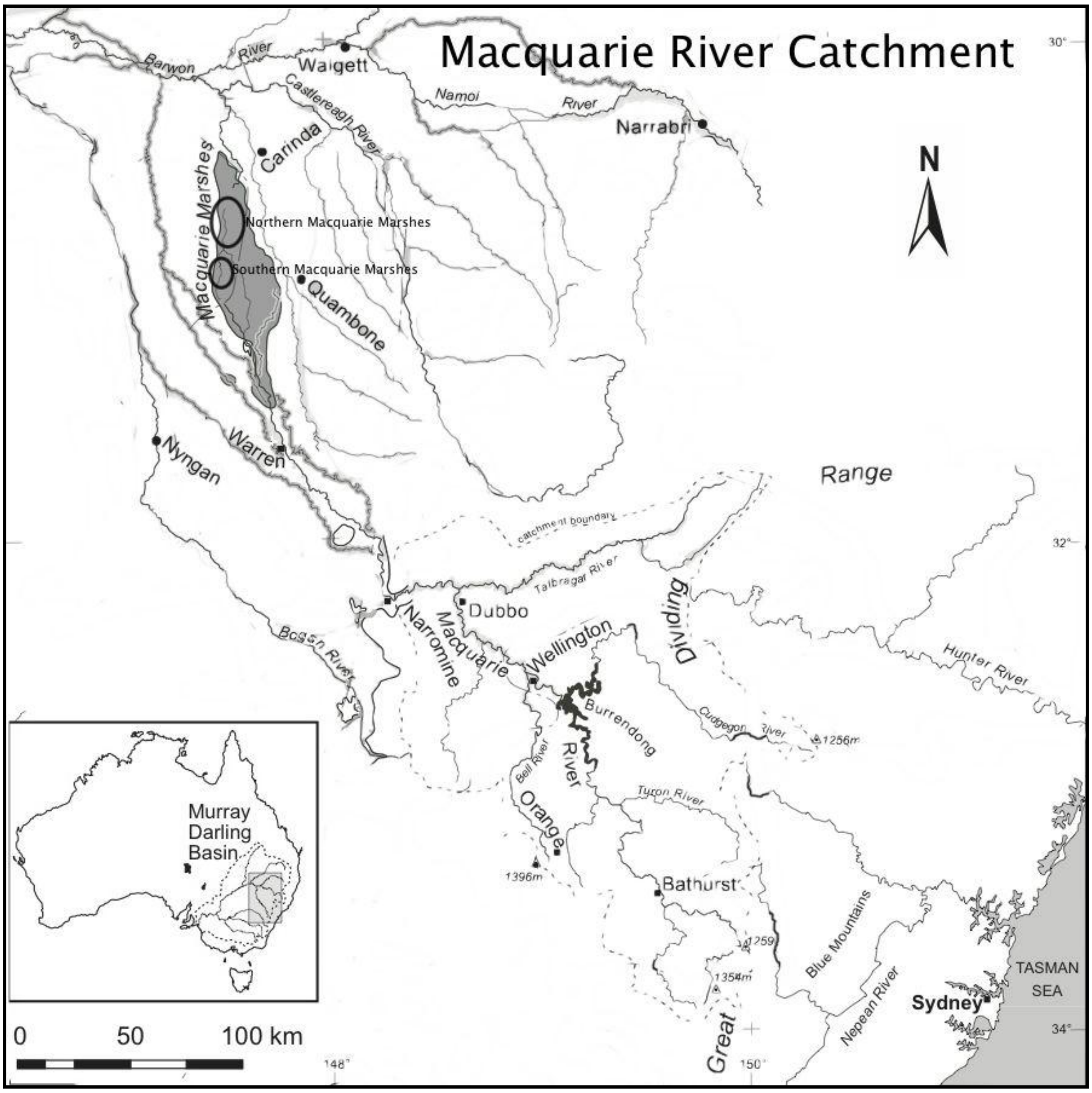


Figure 1.1 The Macquarie River Catchment, central west New South Wales

There has been previous geomorphological research undertaken by Ralph (2008), Yonge and Hesse (2009) and Ralph and Hesse (2010) on drivers of channel breakdown in the southern Macquarie Marshes and the sedimentation rates in-channel and on the floodplain. Their investigations also found evidence of an avulsive system, the driver of new channels within the southern Macquarie Marshes. Freeman (2008) undertook investigations into the northern Macquarie Marshes to determine if the same rate of sediment accumulation occurred on floodplains within the northern Macquarie Marshes. Yonge and Hesse (2009) and Ralph and Hesse (2010) have identified diminishing discharge and in-channel reed growth as dominant drivers of reducing sediment transport and decreasing fluvial efficiency leading to channel breakdown and bed aggradation. Bed aggradation drives avulsion processes in the south marsh complex. Freeman (2008) found very low floodplain sedimentation rates led to system stability of the north marsh complex with no evidence of avulsive processes. This data can be used to infer the strength and extent of lateral and longitudinal connectivity within the Macquarie Marshes.

The geomorphology of the Macquarie Marshes on the low gradient alluvial floodplains lends itself well to floodplain wetlands. The floodplain wetlands are sustained by periodic overbank flooding and support a range of ecological communities, which change with distance from channel (Arthington et al., 2006). Channel and floodplain wetlands provide an array of valuable ecosystem services both directly and indirectly to those living within the surrounding marshes or further afield within the region.

Each catchment is made up of a mosaic of biophysical systems performing different functions. The ecosystem services provided by the biophysical systems within the catchment adhere to the needs of the land use surrounding it. The Macquarie Marshes offer their own suite of wetland ecosystem services, which are a result of the behaviour and character of the lower Macquarie River system. By identifying the controls on channel breakdown, the connectivity of the system can be identified and therefore a determination of the type of ecosystem the physical system can support. The ecosystem services of the Macquarie Marshes are important for the diverse range of industries that make use of the area. It is also important for the local and non-local patrons who appreciate the recreational opportunities, appreciation of the biodiversity, the cultural and spiritual provisions, and regulation services provided by this system.

The ecosystem services of a river corridor are particularly important to the residents of the lower Macquarie River where varied land uses depend on a healthy and functioning river system to provide water, nutrients and sediment to support healthy soil formation, nutrient cycling and water to support both terrestrial and aquatic vegetative growth and wildlife health. Table 1.1 provides an overview of some of the specific ecosystem goods and services provided by the Macquarie Marshes.

Table 1.1 Examples of ecosystem services offered by the Macquarie Marshes, central west NSW.

Ecosystem Function	Ecosystem Processes & Components	Goods & Services
Provisioning services		
Water	Provision of water through the system	Water for consumption, irrigation and stock.
Food	Conversion of solar energy into edible plants and animals	Yabbies, fish, bush tucker
Regulating services		
Water filtration	Filtering water through in-channel and floodplain vegetation	Clean water for consumption, stock use and irrigation
Crop pollination	Habitat for pollinators	
Supporting services		
Soil formation	Role of vegetation in soil retention	Arable floodplains for agriculture through connected landscapes
Habitat to support primary production	Role of biota in storing and recycling nutrients to enhance habitat for primary production	Cotton, beef, sheep, dryland crops
Cultural services		
Recreational activities	Recreation potential of the Marshes	Pig shooting, bird watching
Provision of destinations for tourism	Tourism potential of the Marshes	Unique and scenic area with biodiversity value
Aesthetic values	Attractive landscape features	Personal enjoyment of the natural landscape
Provision of cultural values	Natural features with cultural value	Cooking mounds used by early indigenous tribes and artefacts left by early explorers
Scientific discovery	Variety of scientific and educational value	Providing education to various stakeholders through research and conservation. E.g. the geomorphology and waterbird breeding

Source: Modified from de Groot et al. (2002) and Whiteoak and Binney (2012)

1.4 Scope of this thesis

This study will investigate the downstream physical and hydrological patterns of the lower Macquarie River and the controls on riverine channel breakdown of the northern Macquarie Marshes. The strength and extent of lateral and longitudinal connectivity of the transfer of sediment through the northern Macquarie Marshes will be investigated. The results will be compared to the floodplain sediment accumulation rates identified by Freeman (2008) and the in-channel and floodplain sediment accumulation rates identified in the southern Macquarie Marshes by Ralph (2008). Investigations into the in-channel sedimentation rates will provide an understanding of whether the channels within the northern Macquarie Marshes will behave in a similar avulsive way as the channels in the southern Macquarie Marshes and whether avulsion is likely to have created the main channels of the contemporary northern Macquarie Marshes.

1.5 Research Aims and Hypotheses

The Macquarie River trunk channel exhibits a unique form of intermediate channel breakdown, identified as the Macquarie Marshes (Yonge and Hesse, 2009). This research thesis aims to investigate the patterns of suspended sediment transport how this is related to geomorphological variables and the processes involved in channel breakdown. It will then examine how these processes affect the hydrological connectivity and suspended sediment transport within the northern Macquarie Marshes, ultimately driving the type of vegetation growth and ecological communities this area of channel breakdown supports.

Recent geomorphological and palaeoecological research undertaken in the southern and northern Macquarie Marshes and identified differences in the geomorphic dynamics of the channel network and marsh complexes within the two systems with respect to sediment availability and the distribution of wetlands (Freeman, 2008; Ralph, 2008; Yonge and Hesse, 2009; Ralph and Hesse, 2010). The outcomes of research on the long-term geomorphic stability of the northern Macquarie Marshes has been based on the sediment accumulation rates of floodplain sediments at intervals from the main channel complex by Freeman (2008). Low floodplain accumulation rates raise interest in the rates of channel bed aggradation and ensuing channel stability.

Four hypotheses have been constructed for this research:

1. Suspended sediment transport increases from Burrendong Dam down catchment. Tributary inputs and bank erosion increase suspended sediment transport to the Macquarie River trunk channel. The suspended sediment transport greatly decreases through the northern Macquarie Marsh complex, because of 'filtering' by vegetation.

2. Sediment accretion rates of the in-channel zone and floodplain of the northern Macquarie Marshes are very slow in comparison to the sedimentation rates identified in the southern Macquarie Marshes. Sediment accretion rates are slowest downstream of the floodplain wetlands as a result of diminishing discharge and enhanced sediment deposition;

3. Processes controlling in-channel sediment deposition influence channel morphology and channel breakdown of the lower Macquarie River.

4. The area of channel breakdown enhances lateral connectivity and reduces longitudinal connectivity through changing channel morphologies and enhanced in-channel sediment deposition.

To test these hypotheses six key research aims have been developed:

1) Identify the patterns within the down catchment suspended sediment transport on a reach-by-reach basis by interpreting the distribution of in-channel erosional and depositional geomorphic units using aerial photographs, field observations and cross section surveys.

2) Identify longitudinal changes in channel morphology and capacity and compare to investigations of longitudinal declines of discharge and stream power and thus decline in the carrying capacity of suspended load

3) Investigate the longitudinal changes in total suspended solid concentrations down catchment and the connectivity of the Bell and Talbragar River tributaries in terms of suspended sediment supply to the Macquarie River trunk channel. A focus is placed on the total suspended solids entering into the northern Macquarie Marshes and exiting downstream of the wetlands.

4) Use flood return interval relationships to identify inundation of the floodplain and assess magnitude-frequency geomorphic effectiveness at selected sites

within the reaches identified of the lower Macquarie River, which will add to the reasons behind the patterns within the suspended sediment transport.

5) Characterise the character of sedimentation within the northern Macquarie Marshes and compare to the character of sedimentation of the floodplain of the northern Macquarie Marshes, and the in-channel and floodplain zones of the southern Macquarie Marshes.

6) Investigate the contemporary processes of in-channel sedimentation within three key areas of the Bora Channel in the northern Macquarie Marshes. Compare the contemporary in-channel rates of sediment accumulation with accumulation rates from adjacent floodplain sites of the northern Macquarie Marshes to establish whether bed aggradation is more dominant than floodplain accretion. Relate these findings to the in-channel sedimentation rates of the southern Macquarie Marshes.

1.6 Chapter Summary

Chapter 1: This chapter has outlined the objectives of this study focussing on establishing the processes controlling channel breakdown of the lower Macquarie River and the (dis)connectivity of the lateral and longitudinal transfer of material and its implications for ecosystem services. The focus is on the northern Macquarie Marshes and an investigation of sediment transport regime of this area of the Macquarie Marshes and the formation of floodplain wetlands. Furthermore, the utilisation of sedimentological, geomorphological, geochronological and hydrological techniques to establish fluvial connectivity has been outlined.

Chapter 2: In this chapter the literature on channel breakdown and the significance of geomorphic connectivity of a fluvial system is reviewed. The geomorphological and hydrological threshold controls on river channel breakdown are described and the role of geomorphic effectiveness and effective discharge on sediment transport.

Chapter 3: This chapter provides a catchment-scale assessment of physical characteristics of the Macquarie River valley as well as a review of the climate, hydrology, geology, land uses and biodiversity of the Macquarie catchment. Furthermore this chapter outlines the significance of the Macquarie Marshes.

Chapter 4: This chapter outlines the methods used to establish longitudinal and lateral physical and hydrological patterns of the lower Macquarie River. Also it outlines the field and laboratory methods used to establish the sedimentological characteristics and sediment accumulation rates of in-channel and floodplain cores at four sites in the northern Macquarie Marshes.

Chapter 5: This chapter provides the results of the geomorphological and hydrological methods established in Chapter 4. The results are presented for representative sites within reaches. Longitudinal and lateral patterns within the data are identified.

Chapter 6: This chapter provides the results of the geochronological and sedimentological methods established in Chapter 4. The results are presented for the four sites where the sedimentological and geochronological investigations were undertaken. Longitudinal and lateral patterns within the data are identified. The chapter closes with a comparison of sedimentation rates between the two geochronological techniques used.

Chapter 7: This chapter discusses the results in relation to the hypotheses established in Chapter 1. Furthermore, this chapter discusses the results relative to the outcomes established by previous research in the Macquarie Marshes and local and international literature on connectivity and the coupling of discharge and sediment supply. The chapter closes with the research being placed within the wider context of ecosystem services.

Chapter 8: This chapter compiles the main conclusions of this study and summarises the effectiveness of the techniques employed for this study and outlines the potential for further research.

Chapter 2: Controls on Channel Morphology and Connected River Corridors

2.1 Introduction

The processes that shape the fluvial environment are dynamic in space and time. This chapter reviews the literature on controls of riverine channel breakdown, including discharge, in-channel vegetation growth and sediment transport. Furthermore, it reviews the importance of the spatiotemporal variability in the longitudinal and lateral hydrologic and suspended sediment linkages in the fluvial environment. Furthermore, this chapter reviews the geomorphological and hydrological processes that influence channel breakdown and geomorphic connectivity.

2.2 Controls on River Channel Morphology and Channel Breakdown

2.2.1 Channel Breakdown

Channel breakdown is the complete or partial collapse of channelised flow in a river system due to changes in geomorphic thresholds. If the channel breakdown is terminal all discharge is lost, however if the breakdown is intermediate (Tooth, 1999a, 1999b) then flow rechannelises downstream of the breakdown. Channel breakdown can occur along any section of a channel where there are changes in geomorphic thresholds. It is most common to witness channel breakdown in its medial and distal reaches (Bird, 1982; Brierley and Fryirs, 1999; Eyles, 1977; Mabutt, 1977a; Young, 1986; Tooth, 1999a, 1999b; 2000). Channel breakdown has been well documented in different landscapes and of different varieties in the form of floodouts (Mabbutt, 1977a; Bird, 1982; Tooth, 1999a and 1999b; Brierley and Fryirs, 1999; Grenfell et al., 2009), terminal fans (Parkash et al, 1983; Kelly and Olsen, 1993), and can be in the form of alluvial fans (McCarthy et al., 1988; Ellery et al., 1990, 1993), wetlands (Bedford, 1996; Grenfell et al., 2009; Yonge and Hesse, 2009; Ralph and Hesse, 2010), marshes and peatlands (Watters and Stanley, 2006). These fluvial landforms are dominated by sediment deposition (Grenfell et al., 2009).

The controls on channel breakdown are geomorphological and hydrological thresholds and effecting thresholds have been documented for each case of channel breakdown. Thresholds of a river system are a shift from a point or phase that separates different modes of operation and promotes morphological changes within part of the river system (Bull, 1979). Threshold controls on river morphology have been classified by Schumm (1979), Bull (1979) and others as intrinsic or extrinsic thresholds. Thresholds within the system that instigate change only by the influence of an external variable are extrinsic thresholds (Schumm et al., 1984). External forcing is commonly the coarse scale control such that climate, geology and topography have a notable affect on small-scale processes (Montgomery, 1999).

Thresholds within a system that can affect change without the influence of an external variable are intrinsic thresholds (Schumm et al., 1984; Schumm, 1979; Brierley and Fryirs, 1999). Intrinsic thresholds gradually change channel morphology in the short term (Dollar, 2002) and on small spatial scales. Small-scale processes such as discharge, sediment transport and sediment calibre govern the adjustment of channel form (Rice and Church, 2001). Harvey (2002) showed sensitivity to change within a fluvial system is greatly governed by discharge and sediment supply thresholds. The adjustments within fluvial systems are complicated by the interrelation of the threshold with feedback mechanisms, which further enhance the threshold of change (Bull, 1979) such as in-channel growth of vegetation and its control on enhancing reductions in stream power and channel aggradation (Gradzinski et al., 2003; Yonge and Hesse, 2009).

2.2.2 External Controls on Geomorphological and Hydrological Thresholds of Channel Breakdown

Climate Change

Changes in climate influence thresholds extrinsically in river systems by influencing the hydrology of a catchment and sediment transport from hillslopes and through river systems. Climate change has a catchment scale effect on river systems twofold by either increasing or reducing the volume of water supplied to a catchment through precipitation and changing temperature ranges. Temperature ranges of the region effect the volume of discharge entering a system by fluctuating the volume of runoff and the type and density of vegetation growth (Bull, 1997). Bull (1979) found the optimal mean annual precipitation for the deposition of valley-fill by ephemeral streams ranges from 100 mm to 500. Less than 100 mm of precipitation annually is unable to support the growth of vegetation to effectively trap current sediment supply and encourage aggrading reaches (Bull, 1997). The average annual rainfall in the Markanda Fan region is 530 mm (Parkash et al., 1983). Climate variability in this region affects the volume of flow to the Fan and it is during the monsoon season that the Markanda Fan is inundated and the vegetation is rejuvenated. Floodouts located in areas of central Australia are in the precipitation gradient of 125 mm a^{-1} to 300 mm a^{-1} (Tooth, 1999a). This volume of precipitation is above the threshold of sediment transport capacity described by Bull (1979, 1997), promoting aggradational reaches. Mires are an example of channel breakdown occurring in regions of low gradients and high precipitation. A climate-controlled mire has formed on the Woronora Plateau of NSW where the annual precipitation is 1500 – 1600 mm annually (Young, 1986). The yearlong swampy conditions and the decaying organic matter in the mires increase the water retention capacity (Young, 1986). Continuous swampy conditions support the growth of in-channel vegetation and reduce the scour and erosional forces of higher flows.

Climate, on a short-term scale, affects the reach through seasonal variations and determines the volume of discharge lost to evaporation and evapotranspiration. In humid, wetter environments, less discharge is lost to the atmosphere than in a semi-arid to arid climate. Terminal fans that develop in many rivers are under fit streams that occupy much larger river valleys that developed during a wetter climate (Kelly and Olsen, 1993). Increased humidity and a wetter climate throughout the Pleistocene/Holocene initiated the transmission of abundant volumes of sediment through the river system promoting sediment deposition to the Pantanal of Brazil (Assine and Soares, 2004). The increase in sediment deposition promoted channel aggradation throughout the forming fan system. The hydrological threshold of the system was modified during the increase in sediment flux promoting channel avulsions and the infilling of old channels. The Pantanal region of Brazil remains in a state of channel breakdown. The current drier climate and the topographic subsidence caused by neotectonics, permits inundation of the floodplains and aggradation during periods of higher flows (Assine and Soares, 2004).

Neotectonics

In regions of active tectonics controls of thresholds are extrinsically driven in the long-term and can lead to channel breakdown via a disruption in longitudinal and lateral connectivity by the production of natural barrier to flow (Fryirs et al., 2007a). It is the tectonic movement that can establish long-term changes in channel morphology (Dollar, 2002). Neotectonics can cause back tilting or basin subsidence and initiate a reduction in stream gradients, increased channel sedimentation, flow dislocation and avulsion (Bul, 1979; Nanson and Knighton, 1996). Tectonic movement in west-central Brazil has caused the Pantanal depression in the landscape. A series of alluvial fans have formed in the Pantanal region because of increased sedimentation, the Taquari fan being the largest (Assine and Soares, 2004). Extensive swamp surfaces throughout the Pantanal are actively constrained by faults and the low topographic gradients (Assine and Soares, 2004). The Okavango fan in Botswana is another example of a depositional fan affected by neotectonics. The fan is contained in a graben-like structure caused by the fault system (McCarthy et al., 1988; Smith et al., 1997) of which aggradation, avulsion and anastomosis are all linked.

Topography

Landscape confinement is an extrinsic influence on geomorphic thresholds by defining the style of a reach and the way in which bankfull and overbank discharges will behave (Brierley and Fryirs, 2005). Where there are no confining features of landscape compartments such as alluvial terraces, aeolian sand dunes or bedrock valley margins and outcrops, higher stages of flow are able to breach levees and extend out over floodplains in splay or sheet flow. In periods of overbank flow vertical accretion of low gradient floodplains occurs, and splays and sheet flow (Brierley and Fryirs, 2005) can lead to formations of distributary channels, such as in floodouts and terminal fans (Yonge and Hesse, 2009). Discharge is lost across the floodplain and stream power is reduced. Floodout zones show the changing nature of flood flows from a channelized form at the apex of the floodout to largely unchannelised forms (Tooth, 1999a). The nature of flow can be attributed to the un-confinement of the reach where the area of channel breakdown often occurs after the emergence point (Tooth, 1999a), past the point of channel, terrace or bedrock confinement. There is a marked decrease in discharge and stream power as flow moves from the apex of the floodout to the unchannelised distal floodout zones. Splays and distributary channels develop beyond the emergence point, reducing the channel capacity of the trunk stream, initiating floodout formation (Tooth, 1999a). Sediment deposition is promoted through changes to the hydrological threshold of such river systems arising from a decline in capacity for transport because of diminishing discharge and the barrier effects of vegetation, bedrock or aeolian barriers (Tooth, 1999a). Channel breakdown occurs by diminishing discharge and stream power as flow becomes unchannelised and energy dissipates

(Tooth, 1999a). A reduction in discharge is common of all floodouts and it is hydrologic, alluvial, structural or aeolian barriers that disrupt the longitudinal connectivity of material transfer and determine the geographical location of the floodout (Tooth, 1999a). The absence of confining landforms allows for a greater number of splays to develop, decreasing flood discharge and increasing floodplain width and severely increasing infiltration losses to floodplain alluvium (Tooth, 2000).

2.2.3 Intrinsic Geomorphic and Hydrological Thresholds

Channel gradient

Channel bed slope is an intrinsic threshold that greatly influences the stream power and velocity of discharge and its erosive or accretive potential. Patton and Schumm (1975) explain the relationship between drainage-basin area (discharge data was unavailable) and critical threshold slope. The larger the drainage-basin area and the lower the slope, the more likely it was to be an aggrading system. Low slopes enhance infiltration through bed and banks by decreasing discharge velocity. Consequently, low gradient landscapes coupled with discharge decrease stream power stimulating aggradation of the channel (Bedford, 1996). Watters and Stanley attributed low gradients (< 0.0004 m/m) and low discharge volumes (0.13 and 0.25 $m^3 s^{-1}$) to the very low stream power (< 1 W m^{-2}) in peatlands in Wisconsin to promoting a depositional environment and channel breakdown. Tooth (1999a) established slope gradients of the floodout zones in central Australia to be very low, ranging from around 0.0014 m m^{-1} to 0.0006 m m^{-1}. The Markanda terminal fan formed in a flat, low gradient region with low stream powers promoting bed aggradation and distributary formation leading to the formation of the terminal fan (Parkash et al., 1983). Changes in grain size and sedimentary structures with depth from samples of the Markanda fan indicate deposition by decelerating flows as discharge diminishes downstream of tributaries and is lost to evaporation and infiltration initiating rapid sediment deposition (Parkash et al., 1983).

Low gradients and shallow channels of the Taquari Fan cause flow to anabranch and form numerous distributary channels reducing discharge (Assine, 2005). Discharge lost to distributary channels usually disappears by infiltration or evaporation, or flows into unconfined wetlands. The Okavango fan in a semi-arid climate in Botswana has developed in a low gradient landscape with low slopes of 0.00036 m/m (McCarthy et al., 1988; Stanistreet and McCarthy, 1993; McCarthy et al., 1991). This low gradient landscape is conducive to fan formation and channel breakdown by diminishing discharge and stream power and their influence on sediment deposition.

Discharge and sediment transport coupling in river systems

In a fluvial system, flow has been described as the initiator of patterns and processes. The flow regime of the fluvial system influences the nature and form of fluvial sediments (Sheldon et al., 2002). The eternally changing channel morphology amid changes to the flow and sediment regime affects the physiology, abundance and distribution of organisms and the dynamics of river – floodplain ecosystems. The driver of channel change is the interrelation of discharge and sediment supply (Gilvear, 1999) and the hydraulic geometry of the channel is often the result of both a function of sediment availability and discharge that ultimately modify channel geometry and slope. The dynamics of discharge and sediment supply are controls on erosion and deposition as channel morphologies respond to changes in these two variables (Lane et al., 1996) and is dynamically tied to stream power and the ability transport sediment. As a driver of channel change, sediment supply is determined by patterns of erosion and deposition up catchment and by locally supplied sediment of reach bed and banks. The relationship of sediment supply with daily fluctuations in discharge is reflected in the transportable sediment supply from upstream and is modified by the interaction of discharge, sediment supply and patterns of erosion and deposition in that reach (Lane and Richards, 1997). Bull (1979) examined the threshold of critical power as being one of the most important geomorphological thresholds of separating reaches of net aggradation and net degradation and its use in understanding the relationship between process and form.

The critical power threshold separates the modes of erosion and deposition within the channel that is dependent on the magnitude of power required to move the sediment load and the stream power available to transport it (Bull, 1979). Bull (1979) identified stream power and critical power as the two important components of the threshold of which discharge and slope are important drivers. Stream power has been shown to have an important influence in channel form characteristics, channel pattern, bedload transport rate and the geomorphic effectiveness of flood discharges (Costa and O'Connor, 1995; Knighton, 1999). An important factor of the critical threshold framework is that channels establish the minimum slope required to transport sediment (Bull, 1979) and when the channel slope increases or decreases it affects the stream power, however in the reaches of lower Macquarie River channel gradient is constant from Dubbo (Ralph and Hesse, 2010) and hence fluctuations in discharge drives the available stream power. Discharge in any river system is highly variable and linked with climate change, runoff and infiltration in which hydrological connectivity of surface water and the channel network is dependent on the lateral connectivity of the channel and hillslopes and the influence of vegetation (Lesschen et al., 2009) and other buffers (Fryirs et al., 2007a) in disrupting connectivity.

Discharge fluctuations, its link with stream power and the ability to exceed the critical threshold to transfer sediment are additionally important in understanding the concept of geomorphic effectiveness. Geomorphic effectiveness is the force exerted on a system followed by system change due to flow properties, such as stream power, flow velocity and depth, shear stress and turbulence; and by the resistance of the fluvial system to change, such as the critical threshold of sediment motion, roughness and geology (Bull, 1979; Molnar et. al., 2002). Alluvial channels respond to changes in surrounding physiology, hydrology and sediment load by an adjustment to their hydraulic geometry and river pattern (Pickup, 1976a; Nanson and Knighton, 1996). The channel geometry of a reach can widen or deepen, increase in shallowness and narrow, and change to the current threshold conditions depending on system sensitivity.

Geomorphic effectiveness has often been associated with the effective or dominant discharge, which has been described as flow of bankfull or near bankfull (Wolman and Leopold, 1957; Harvey, 1969; Brunsden and Thorne, 1979; Nash, 1994; Tooth and Nanson, 1995) and is governed on the 'geomorphic work' it delivers within the fluvial system. Geomorphic work as defined by Wolman and Miller (1960) is the rate of sediment movement through the system. The magnitude – frequency analysis of effective sediment transport and associated morphological change was introduced by Wolman and Miller (1960). After their assessment of four streams in the United States of America they determined that bankfull or near bankfull discharge was the most geomorphically effective in terms of sediment movement and modification of the channel surface form, associated floodplain and had recurrence intervals of one to two years or less (Wolman and Miller, 1960). The frequency of geomorphically effective events has been disputed by many authors (Nash, 1994; Costa and O'Connor, 1995) and especially in regards to eastern Australian rivers (Pickup, 1976a; Pickup and Warner, 1976; Tooth and Nanson, 1995). It is now generally accepted that bankfull and near bankfull conditions act as dominant discharge and control channel morphology on short temporal scales (Harvey, 1969) and have recurrence interval frequencies dependent on regional climate and the hydrological regime, which can have recurrence intervals of one to two years of less or decades and greater (Pickup, 1976a; Pickup and Warner, 1976; Nash, 1994). At bankfull conditions sediment transport is partly governed by the hydraulic geometry of the channel and at overbank flows this hydraulic geometry changes, therefore affecting the relationship between discharge and sediment transport (Leopold and Maddock, 1953; Harvey, 1969). However, the processes associated with high magnitude – low frequency events need not be the same between locations (Wolman and Gerson, 1978) as external controlling factors and bed material exert some influence on how the reach will behave during high magnitude – low frequency events. Furthermore, the response of the system to the imposed processes of different magnitude events is dependent on how the reach was 'conditioned' by previous events and this determines the response of the reach to further imposed processes (Lane and Richards, 1997; Fryirs et al., 2007a).

'Effective discharge' is essentially the discharge or range of discharges most effective in the long-term sediment transport and similarly 'dominant discharge' is identified as the discharge of a natural channel determining its characteristics and principal channel dimensions (Harvey, 1969; Nash, 1994). Pickup (1976a) identifies dominant discharge as the mean discharge or magnitude – frequency flows and the associated channel conditions the dominant discharge creates and Lane and Richards (1997) suggest that no dominant discharge can be defined because there are multiple discharge and sediment supply combinations available to a reach that can induce channel change. Wolman and Gerson (1978) and Costa and O'Connor (1995) discuss the events of geomorphic effectiveness as formative events because of the sediment transport and morphological changes of in-channel geomorphic units. Formative events both destruct and restore in-channel features during different stages of the event with most destruction occurring in the build up of stream power and bankfull discharges and the restoring and building processes occurring during waning stages of formative events and the time between the next formative event (Wolman and Gerson, 1978). The initiation of change within the fluvial system occurs by internal or exogenous disturbances, which instigates two types of formative events: 'Pulsed inputs' and ‘ramped inputs’ (Brunsden and Thorne, 1979). Pulsed inputs are low frequency – high magnitude formative events, which impact the form of features in river systems differently dependent on climate controls and landscape setting (Brunsden and Thorne, 1979). ‘Ramped inputs’ refer to the forcing of exogenous controls such as climate change, vegetation cover, land use and tectonics and that they are equally important in changes to long-term sediment transport (Brunsden and Thorne, 1979). Harvey (1969) identifies the duration of floods at a given frequency are as important as the frequency of dominant discharges. The duration of dominant discharge is the total time in which the discharge is in excess of a given value and is distinct from flood discharge which is established by return period of discharge at or above a given value (Harvey, 1969).

Costa and O’Connor (1995) identified a number of different factors working together as the determinants for a geomorphically effective discharge, such as flow duration, flow magnitude and frequency, resistance of the land surface, stream power and the restorative and recuperative processes between formative events. When assessing the effectiveness of flood discharges the channel and floodplain resistance to scouring at different flow stages need also be considered (Costa and O’Connor, 1995). Channel and floodplain surfaces are more easily scoured in bedload reaches and erode at greater rates because of the abrasive nature of sand and gravels compared to the cohesive resistance of channels and floodplains of fine-grained mud (Nanson, 1986) or well-vegetated channels and floodplains (Zimmerman et al., 1967). A key advance on the initial description of processes of effective discharge events and magnitude – frequency analysis of channels is the variable of flow duration and its influence on the type and amount of geomorphic work done within a channel (Costa and O’Connor, 1995). Although peak stream power of high magnitude – low frequency events can determine the competence of related discharges it is not the only factor in evaluating the geomorphic effectiveness of flood discharges (Harvey, 1969; Costa and O’Connor, 1995). The duration of stream powers above a certain value is important in producing channel changes by a number of different factors: duration is required to saturate channel banks and enhance bank failure; long durations aid wetting of bank sediments and enhance channel expansion (Costa and O’Connor, 1995); long duration stream powers can breakdown in-channel and floodplain vegetation, reducing resistance and increasing erosive potential (Zimmerman et al., 1967). However, it is the frequent capacity of a channel that maintains the reach by a balance between aggradation and erosion

(Harvey, 1969).

Discharge acts on the channel margins in a river system where its dimensions are balanced between erosive forces scouring bank, bed and geomorphic units, and aggradational processes are depositing materials back into the channel (Harvey, 1969). The effective discharges must be large enough to exert enough force to scour and transport sediment and frequent enough to maintain channel morphology and continual sediment transport (Harvey 1969). Discharge as a driver of channel breakdown changes in channel morphology are described by the following examples: Tooth (1999a) addressed floodout formations in central Australia and explored the reasons for changes in geomorphic thresholds affecting the hydrology of the system and leading to channel breakdown. Floodouts usually occur in arid or semi arid systems and usually along ephemeral rivers well beyond tributary inputs from the headwaters (Tooth, 2000). Consequently there is usually a marked reduction in discharge and stream power compared with upstream reaches (Tooth, 1999a). Floodout zones are typically characterised by a series of small distributary channels or unchannelised floodplain. The channelised flow and bedload transport gradually cease, ultimately onto a broad, low-gradient, alluvial surface (Tooth, 1999a, 1999b). Assine (2005) found decreases in discharge and stream power in the Taquari fan of Brazil modified channel morphology by promoting sediment deposition leading to the narrowing and shallowing of fan channels. The channel fans are located where there is a gradual increase in base level and the single channel feeds distributary channels, which deviate further into sheet flows (Bull, 1997).

Distributary channels that have been identified in areas of channel breakdown (Bull, 1997; Tooth, 1999a, 1999b, 2000; Ralph, 2008; Freeman, 2008; Yonge and Hesse, 2009) are the product of reductions in stream power, and spatially and temporally fluctuating discharge (Kelly and Olsen, 1993; Parkash et al., 1983). Distributaries can form from blockages in-channel causing flow resistance (Alam and Mustafa, 1986) where flow diverts and often does not re-join the trunk channel. They can also form as a result of breaches in levees by crevasse splays in periods of bankfull and overbank flow. Almost all discharge of the distributaries of the Markanda fan of India is lost before it reaches the distal reaches of the fan, except for monsoon season when sheet flooding of the fan occurs (Parkash et al., 1983). Bed and bank composition has an influence on the hydrological threshold as it determines the volume of transmission losses that occur vertically to the hyporheic zone and laterally through infiltration of channel banks. Transmission losses can occur quite rapidly downstream especially in arid and semi-arid ephemeral systems (Kelly and Olsen, 1993) through surface losses and evapotranspiration reducing the overall volume of discharge and decreasing stream power. For example the infiltration of discharge in the Markanda fan is due to lateral infiltration through the sandy layer and the lower clay layers of channel banks (Parkash et al., 1983). A bank composition of peat is easily infiltrated by discharge because of its extreme porosity (Watters and Stanley, 2006). In areas of Wisconsin in the United States peat lands are located in areas where overland flow is often rare and the regional surface hydrology is often driven by groundwater discharge, where groundwater derived base flow can be greater than 90 % of total stream flow (Watters and Stanley, 2006). Overbank flooding is rare in the Okavango fan as erosion resistant peat extracts discharge vertically from channels, reducing the volume and velocity of discharge (McCarthy et al., 1988). Only 2% of the volume of discharge entering the Okavango system exits at the base of the fan into a trunk channel (Stanistreet and McCarthy, 1993) because of the flow infiltration into the peat banks and evapotranspiration.

Reductions in fluvial efficiency and channel aggradation in channel breakdown zones are exampled in the development of terminal fans where sediment-laden streams decrease in size and vanish due to transmission losses, evaporation and sediment deposition (Kelly and Olsen, 1993). It is usually in semi-arid and arid (Parkash et al., 1983; Kelly and Olsen, 1993) environments that such processes occur where the climate does not contribute ample runoff and tributary inputs are scarce. Terminal and alluvial fans usually occur in dry environments on low gradient plains with ample sediment supply, where discharge and stream power continue to decrease downstream, depositing sediment from sediment-laden flow. An example of major deposition by vertical accretion occurs in the distributaries and inter-distributary channels in the Markanda terminal fan (Parkash et al., 1983).

2.2.4 In-channel vegetation

Watters and Stanley (2006) identify in-channel vegetation growth as a biological force just as important as physical drivers of discharge and sediment supply in understanding the channel breakdown of streams. Just as ecosystem are affected by geomorphic processes, biological processes such as in-channel vegetation growth can in turn act as key controls on physical processes (Montgomery, 1999), such as sediment deposition. In-channel vegetation has been identified as a natural promoter of channel bed aggradation (Bull, 1997) and in cases avulsive processes lead to new channel formation (Gradzinski et al., 2003; Yonge and Hesse, 2009). Interactions of in-channel vegetation and hydrology act to modify bank erosion and deposition processes by altering bank hydrology, geotechnical properties and boundary shear stress (Dollar, 2002; Hickin, 1984; Ellery et al., 1990; Nanson and Knighton, 1996). Vegetation increases bank stability in depositional environments by increased bank shear strength due to root support (Abernethy and Rutherford, 1998). Gradzinski et al. (2003) demonstrated the role of in-channel vegetation in the Narew River in Poland as forming an erosion resistant peat layer within the channel. The in-channel vegetation promoted bedload aggradation and infrequent channel avulsion by reducing flow velocities (Gradzinski et al., 2003). The way in which in-channel vegetation acts to enhance the rate of threshold change within channels is a self-enhancing feedback system by increasing hydraulic roughness, reducing the reach stream power, increasing the critical threshold and promoting sediment deposition (Bull, 1979; Gurnell and Gregory, 1995; Yonge and Hesse, 2009).

The type and size of vegetation is an important factor in understanding the dynamics of its affect on hydrology and sediment transfer of a reach. A field study by Prosser and Slade (1994) identified different types of vegetation are less susceptible to shear stress and create more resistance than others. They identified sedges and tussock grasses as the dominant types of in-channel vegetation that could withstand greater shear stress values and provide most resistance (Prosser and Slade, 1994). Aquatic plants exhibit a five times lower resistance threshold and were more affected by shear stress (Prosser and Slade, 1994) and reeds, rushes and sedges are a common type of in-channel vegetation that enhances channel roughness. Depending on the stem density of the vegetation, they can increase resistance and the drag coefficient, although not independently of channel slope (Dollar, 2002). Yonge and Hesse (2009) identified the common reed and bulrush as the dominant in-channel vegetation responsible for enhancing sediment deposition. In-channel large woody debris, fallen wood and the growth of woody vegetation has a particular hydro-geomorphic significance in the channel zone of low gradient alluvial rivers as increasing flow resistance by increasing channel roughness, reducing flow velocities and acting as an obstacle for sediment or vegetation accumulation (Eyles, 1977; Ellery et al., 1990; Ellery et al., 1993; Graeme and Dunkerley, 1993; Gurnell and Gregory, 1995; Dollar, 2002).

Vegetation in upland regions are also effective at colonising the in-channel zone and promoting in-channel wetland development as observed by Zierholz et al. (2001) in the Jugiong Creek catchment in southeastern NSW. The catchment experienced extensive gullying after European settlement in Australia and the introduction of modern agriculture (Zierholz et al., 2001). Emergent macrophytes began inhabitancy within the gully network of Jugiong Creek after 1940 and have since promoted sediment deposition, channel narrowing and further in-channel vegetation growth. The in-channel vegetation at Jugiong Creek has since created continuous dense in-channel wetlands (Zierholz et al., 2001). This pattern in identified by Wakelin-King and Webb (2007) at the floodout of Fowlers Creek, Australia. The floodout is a self-enhancing process in which the low gradient enhances infiltration, supporting vegetation. The density of the vegetation promotes infiltration, prohibits erosion and induces sedimentation, all of which maintain the low gradient landscape, continuing the cycle.

Vegetation as a factor of reducing hillslope-channel connectivity of sediment supply has been identified in a number of studies (Walling, 2005; Smith and Dragovich, 2008; Lesschen et al., 2009). The role of in-channel vegetation as a biological driver of channel change is coupled with its role as a natural barrier (Fryirs et al., 2007a) disrupting the connectivity of material transfer longitudinally and laterally within a river system. In cases where vegetation enhances channel breakdown of terminal floodout features (Wakelin-King and Webb, 2007) and intermediate channel breakdown (Yonge and Hesse, 2009) there is a full scale or temporary disruption in the transfer of water, sediment or both. In-channel vegetation growth as a driver of (dis)connectivity is evident in many forms of channel breakdown (McCarthy et al., 1992; Gradzinski et al., 2003; Assine, 2005; Wakelin-King and Webb, 2007; Yonge and Hesse, 2009), however longitudinal connectivity coupled with in-channel vegetation in not commonly addressed in the literature.

2.3 Connectivity of River Corridors

The term connectivity can be defined in different ways dependant on the focus such that it encompasses geomorphology, hydrology or ecology (Brierley et al., 2006; Michaelides and Chappell, 2009; Jain and Tandon, 2010). Traditionally, connectivity refers to the movement of materials, that is the continuity of water, sediment and nutrients, between landscape compartments (Poole et al., 2002; Hooke, 2003; Fryirs et al., 2007; Bertoldi et al., 2009; Lesschen et al., 2009; Jain and Tandon, 2010). The importance of the concept of connectivity is reflected in the demand for transfer of sediment, water and nutrients between landscape compartments to support greater geomorphic and ecosystem functions (Stanford and Ward, 1993; Poole et al, 2002; Sheldon et al., 2002; Brierley et al., 2006; Jain and Tandon, 2010; Wainwright et al., 2011; Hudson et al., 2012; Hudson et al., 2013).

Physical linkages of discharge and suspended sediment within the channel corridor determine ecological connectivity, the productivity of the ecosystem (Poole et al., 2002) and therefore, ecosystem services. The connectivity between landscape compartments or within landscape compartments can be assessed by different spatial and temporal relationships of material transfer between physically connected or disconnected features (Brierley et al., 2006; Jain and Tandon, 2010). The nature and pattern of sediment flux between landscape compartments has long been the focus of geomorphic studies of drainage basin connectivity as sediment flux largely governs landscape interaction and geomorphic processes within a landform (Jain and Tandon, 2010). Assessments of connectivity can also be used to understand the variation in sediment yield within a drainage basin where there are no changes to external forcing (Jain and Tandon, 2010).

2.3.1 Hydrologic connectivity

Hydrologic connectivity of the river corridor is simply the transfer of water between landscape compartments (Hooke, 2003). Hydrologic connectivity, and sediment entrainment and transport are often coupled within river systems, and heavily mediated by large-scale controls such as climate (i.e. hydrology) and landscape (i.e. channel gradient and confinement) (Chiverrell, et al., 2008). In low gradient meandering river valleys, hydrologic connectivity is fundamental between low gradient meandering alluvial rivers and their floodplains, supporting a number of floodplain ecosystem services (Hudson et al., 2012). Lateral hydrologic linkages and suspended sediment transport through overbank inundation is important for floodplain building processes and to dissipate energy of floods over their surface (Gilvear, 1999), an important ecosystem service.

Although hydrologic connectivity by infrequent high magnitude events is rather straight forward (Phillips, 2011), connectivity along many floodplains is dominated by low magnitude events that overtop the channel banks at different points along the river valley (Hudson et al., 2013). In areas of channel breakdown, overbank flows laterally connect the channel to floodplains and floodplain wetlands over variable spatial scales and for differing periods of time (Sheldon et al., 2002).

Sheldon et al. (2002) characterise arid and semi-arid reaches (dryland) as having varying degrees of hydrological connection, due to varying degrees of streamflow and high spatiotemporal degrees of ecosystem heterogeneity, driven by the uncertain nature of streamflow in these dryland environments. The degree of variability in overbank hydrological connectivity coupled with suspended sediment transport in low gradient dryland Australian ecosystems is a determinate for the spatiotemporal variability of floodplain sedimentation rates (Amos et al., 2009).

2.3.2 Buffers and barriers to linkages

The interrelationships between river planform, profile and cross section and connectivity occurs across three-dimensional spatial scales are responsible for whole catchment response (Poole et al., 2002; Gilvear, 1999; Jain and Tandon, 2010) and assessed over the vertical, longitudinal or lateral transfer of materials (Stanford and Ward, 1993; Poole et al., 2002; Jain and Tandon, 2010). Vertical connectivity is the coupling the channel and hyporheic zone or floodplain and groundwater (Gilvear, 1999; Brierley et al., 2006; Jain and Tandon, 2010).

Lateral connectivity is the coupling of channel and floodplain or hillslope and channel and drives sediment supply to channels (Brierley et al., 2006). The transfer of materials between channel and floodplain are dependent on the temporal and spatial variability of inundation (Thompson et al., 2011). Longitudinal connectivity is the coupling between the headwaters and river mouth with upstream impacts having downstream consequences, or between tributary and trunk channels. However, features can restrict connectivity and have been classified as barriers, buffers and blankets (Brierley et al., 2006; Fryirs et al., 2007a). Longitudinal hydrologic connectivity does not always coincide with sediment transport rates. Such is the case where in-channel barriers such as woody debris and in-channel vegetation, and changes in specific stream power and bed material texture, affect the sediment transport (Benda and Dunne, 1997).

Buffers and barriers disrupt longitudinal linkages within the channel (Fryirs et al., 2007a). An example of a buffer is a levee, which is a structure that can disconnect the channel with the floodplain and restrict natural floodplain building processes and inhibit the transfer of water and nutrients to support vegetation growth (Thompson et al., 2011). As the channel banks increase with height, the magnitude of flow must increase to breach the levee (Thompson et al., 2011). Levees largely disconnect the lower Missouri River from the floodplain wetlands and require flooding to restore the lateral connectivity (Galat et al., 1998). Landforms such as wetlands can act as buffers to suspended sediment transport along the channel network Brierley et al., 2006; Fryirs et al., 2007), and in-channel and floodplain vegetation can temporarily disrupt movement of streamflow and sediment transport, thus acting as a barrier (Brierley et al., 2006; Fryirs et al., 2007).

Blankets disrupt the vertical movement of water and nutrients (Fryirs et al., 2007). For example, fine sediment can blanket the channel bed as it is deposited between the interstices of gravel beds, reducing the permeability and hence, reducing the riverine recharge or discharge of hyporheic waters (Gilvear, 1999; Fryirs et al., 2007a; Jain and Tandon, 2010). Longitudinally, sand slugs can also act as a barrier to sediment movement down catchment (Thompson et al., 2011). Longitudinally, vegetation can act as an important buffer and obstruct sediment transfer in many low gradient systems (e.g. McCarthy et al., 1988; Zierholz et al., 2001; Gradziński et al., 2003; Ralph, 2008; Yonge and Hesse, 2009), resulting in channel bed aggradation.

Jain and Tandon (2010) outline system types in relation to their physical contact and the transfer of material between the lateral, longitudinal and vertical linkages. Connectivity is usually referred between compartments assuming physical contact, however compartments can be physically connected with no transfer of sediment and likewise can be physically disconnected with episodic connections of sediment transfer (Jain and Tandon, 2010). There are four linkages determined on their physical contact and the transfer of material so that; Type 1 is an active connected system where there is both physical contact and the transfer of materials; Type 2 is an inactive connected system where there is a physical connection but no transfer of material over determined time-scales; Type 3 is a partially active connected system where compartments are not physically connected by there is episodic movement of materials between them (either by rare events or wind); Type 4 the disconnected system where compartments are physically disconnected and there is no transfer of materials between them (Jain and Tandon, 2010).

Jaeger and Olden (2012) assessed longitudinal connectivity in an ephemeral system quantitatively by recording the continuity of streamflow through time and the longitudinal connectivity through space with the assistance of electrical conductivity sensors located in the channel bed sediment in ungauged areas. Electrical conductivity sensors in this semi-arid dryland environment could potentially provide quantitative data on the spatiotemporal variability of hydrological connectivity of the Macquarie Marshes. Hudson et al. (2013) makes a valid argument that cross sections have the potential to underestimate the flood stage required to engage lateral hydrological connectivity and floodplain inundation because of variations in channel bank height and the distance between along meandering river floodplains. Another aspect drawn by Hudson et al. (2013) is the differences in elevation between the natural levee surfaces relative to the floodplain bottoms.

The fluvial system involves the complex interaction between four components: the channel, the floodplain, the alluvial aquifer and riparian vegetation (Poole et al., 2002). As river systems are dynamic in space and time the interconnectedness of the complex systems that comprise the fluvial environment highlight the dependency of each component on each other and the importance of connectivity. For example, the geology, geomorphology, flow regime and plant communities together within a catchment influence the geomorphic and hydrologic characteristics of the fluvial system (Lane and Richards, 1997; Poole et al., 2002). Slopes and stream networks are often decoupled in landscapes that are tectonically stable, particularly Australian landscapes (Collins and Walling, 2004). Lowland fluvial systems with wide continuous floodplains are an example of such a landscape. In these systems it is often in-channel erosion that is dominant in suspended sediment loads (Collins and Walling, 2004).

2.3.4 Time and Space Scales of Connectivity

Longitudinal and lateral patterns and processes are recognised as a fundamental features of river systems (Stanford and Ward, 1993). Viewing them as an integrated fluvial system emphasises their independent nature and highlights the importance of their connectivity and system response to changes to external variants such as climate change, tectonics and land use (Jain and Tandon, 2010) and the implications for system management (Brierley et al., 2006). Lateral and longitudinal intercompartment and intracompartment linkages can be enhanced or disrupted by barriers, buffers and blankets (Fryirs et al., 2007a) that can occur at different spatial and temporal scales. An effective in-channel barrier is in-channel vegetation and its influence on local thresholds by reducing stream power and the fluvial efficiency of sediment transport (Yonge and Hesse, 2009). In periods of increased stream power, the influence of the vegetation can be worn down during long flow durations and increased sediment transport longitudinally is restored (Costa and O'Connor, 1995).

Buffers disrupt the lateral and longitudinal fluvial system of suspended sediment transport in the form of terminal or intermediate floodouts, absent water courses (Fryirs et al., 2007a) or low-sloped alluvial plains (Page and Nanson, 1996; Fryirs et al., 2007). Longitudinal linkages can commonly be affected by barriers through their effect on base level or the channel bed profile (Fryirs et al., 2007a), such as sediment slugs, which can act as a blockage to the downstream transfer of suspended sediment (Fryirs et al., 2007a; Thompson et al., 2011). Another barrier to sediment movement in a longitudinal linkage of regulated rivers are dams and weirs that obstruct the transport, particularly of bedload and to an extent the suspended load of the system, preventing the transfer of sediment down catchment (Fryirs et al., 2007a). These barriers and buffers alter the lateral and longitudinal linkages between compartments on different spatial and temporal scales. In some cases these obstructions or disruption can be overcome by high magnitude low frequency events, where re-working of geomorphic units can occur by effective discharges (Wolman and Miller, 1960; Harvey, 1969, Nash, 1994).

Floodplains are typically considered as the sediment sinks within a catchment and where sedimentation is dependent on the inundation of overbank flows (Thompson et al., 2011). The rate of deposition decreases with distance away from the channel (Asselman and Middelkoop, 1995; He and Walling, 1998) and the duration of overbank flow. Connectivity of sediment transfer between channel and floodplain is also dependent on vegetation type, density and proximity to the channel. Channel constriction by vegetation can lead to backflooding (Yonge and Hesse, 2009) sending flow overbank and increasing the rate of deposition upstream of the channel constriction (Thompson et al., 2011) and affecting the distribution of suspended sediment supply to the floodplain surface. Spatially, floodplain formation is influenced by the position of the reach within the catchment (Brierley and Fryirs, 2005) and temporally, is affected by overbank flows, either through floodplain building processes or stripping processes. Differences in channel bank heights along a meandering river can vary up to 0.8 metres, as was the result along the lower Mississippi River (Hudson et al., 2013). Variations in channel bank heights affect the temporal and spatial variability of floodplain inundation and the lateral hydrological connectivity. The areas along the channel bank of the lower Mississippi River where troughs were located are associated with meander bend cutoffs and weak spots along the upper channel banks affected by erosive flood processes (Hudson et al., 2013). It is worth considering the potential of the lower Macquarie River system to be hydrologically connected laterally during 'non-flood' stages of flow (Hudson et al., 2013).

Fluvial system studies on small space-scales and short time-scales aid the understanding of longer-term aspects of landscape behaviour and change (Lane and Richards, 1997). To acknowledge how a system behaves and changes, is through understanding the physical independence of 'internal' distributions of form and process which couple within-compartments and manifest as spatially distributed feedback (Lane and Richards, 1997) and a matter of changing time and space scales. Short time-scales and small space-scale processes matter and contribute to the overall understanding of longer-term landscape behaviour as small changes in the system trajectory may have effects in overall system evolution (Lane and Richards, 1997).

2.4 Chapter Summary

Longitudinal and lateral connectivity of fluvial landscape compartments can be physically connected or disconnected and still permit the transfer of material across well defined compartment boundaries. The longitudinal and lateral transfer of dominant discharges and the ability of the available specific stream power to convey sediment loads through the system. Channel gradient and discharge determine are two key controls on specific stream power and its ability to transfer materials between compartments.

The geomorphic effectiveness of magnitude – frequency events in a river system greatly determines the effective discharge and the interrelations with stream power and the capacity to transport sediment effectively down system. These events also support lateral connectivity of water and sediment transfer between channel and floodplain compartments in periods of overbank flow. Most importantly, longitudinal linkages of sediment transfer down catchment in arid and semi-arid environments are due to lack of effective discharge and often low-gradient landscapes. In-channel vegetation has been shown to be an effective enhancer of the positive feedback mechanism driving critical power to exceed stream power and assist in channel breakdown.

Chapter 3: The Macquarie River Catchment and Site Selection

3.1 Introduction

This chapter outlines the climate, hydrology and geology of the Macquarie River catchment and briefly describes catchment land use and common ecosystems. A particular emphasis is placed on the northern Macquarie Marshes, as it is the focus of this study. The Macquarie River is one of many inland draining river systems forming part of the extensive river network of the Murray Darling Basin in eastern Australia.

Furthermore, this chapter provides an overview of previous research of the Macquarie Marshes. The contemporary geomorphology will be outlined in this section to describe the system in its entirety in conjunction with the contemporary hydrological regime of the lower Macquarie River. Finally, the chapter outlines general geomorphology of the southern Macquarie Marshes and compares the channel and floodplain characteristics to the broad scale geomorphology of the northern Macquarie Marshes. The chapter closes by outlining the motives of site selection for this study, site morphology and the sampling strategy.

3.2 Regional Setting

The Macquarie catchment is located in semi-arid central west New South Wales and drains the western flank of the Great Diving Range from the Bathurst region. It flows for approximately 960 km in a northwest direction between latitudes 30–34 °S. and longitudes 147–150 °E. The origin of the Macquarie River is located upstream of Bathurst at the confluence of two tributaries, the Campbells and Fish Rivers. The Macquarie River flows through confined upland reaches through to unconfined alluvial reaches to its confluence with the Castlereagh River and shortly thereafter its confluence with the Barwon River near Brewarrina (Figure 3.1).

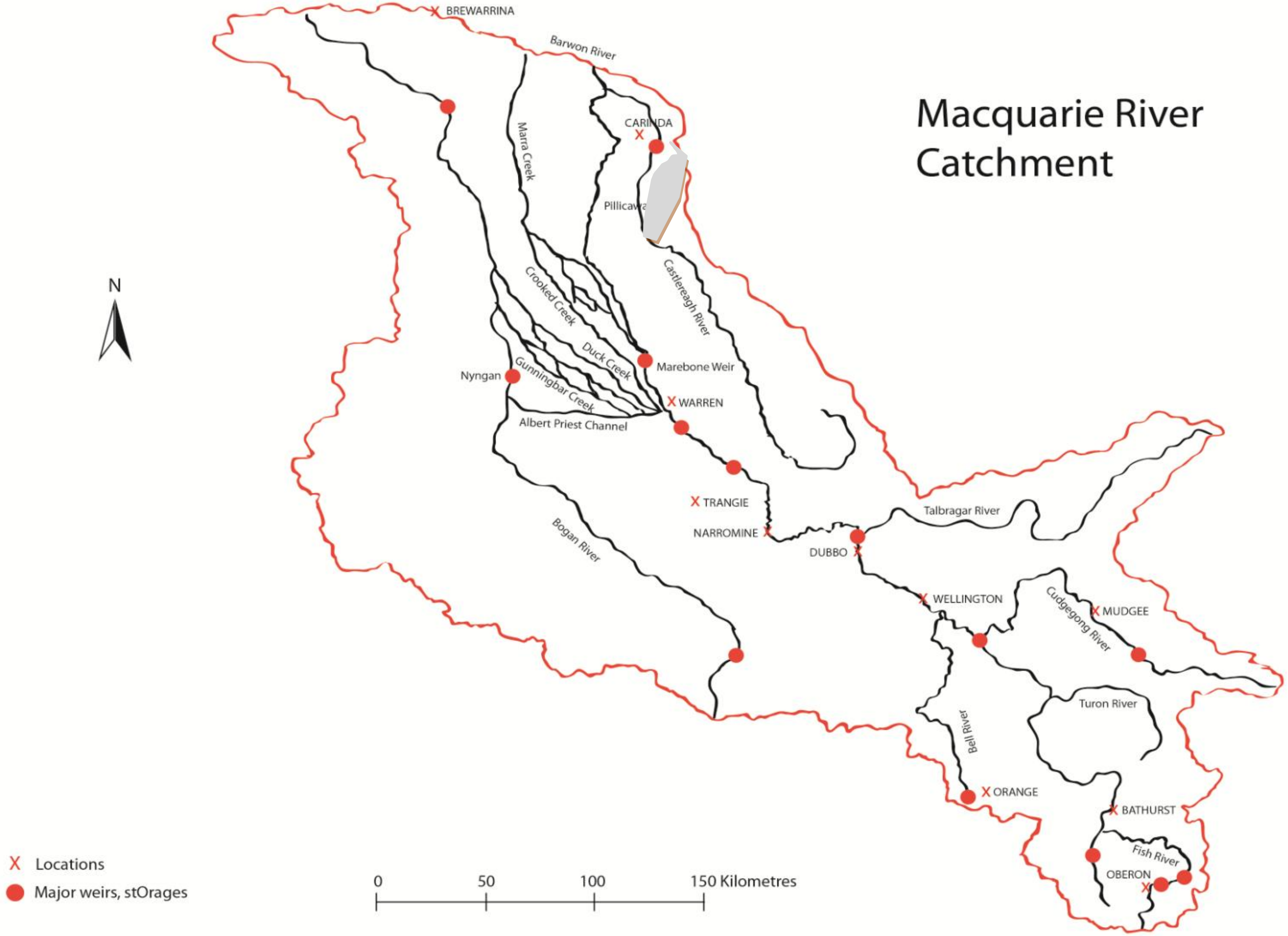


Figure 3.1 Map of the Macquarie River catchment with major weirs and storages. The shaded area near Pillicawarrina is the Macquarie Marshes.

The contributing area of the Macquarie catchment covers an area of more than 26,000 km^2 with notable tributary inputs from the Turon River, Cudgegong River, Bell River and receives its last tributary inputs from the Talbragar River at the town of Dubbo. The trunk channel of the Macquarie River remains as a sinuous single channel until it breaks down to a multi-channelled anabranching network with associated permanent and semi-permanent wetlands in its distal reaches to form the Macquarie Marshes. The Macquarie Marshes begin approximately 50 km downstream of Warren (Jenkins et al., 2005) and are divided in two complexes, the southern Macquarie Marshes and the northern Macquarie Marshes. Areas of both complexes are designated as nature reserves totalling approximately 19,990 ha and monitored by New South Wales National Parks and Wildlife. All adjoining land is privately owned, with the total area of more than 200,000 ha designated as the Macquarie Marshes. The major channels of the Macquarie Marshes are displayed in Figure 3.2.

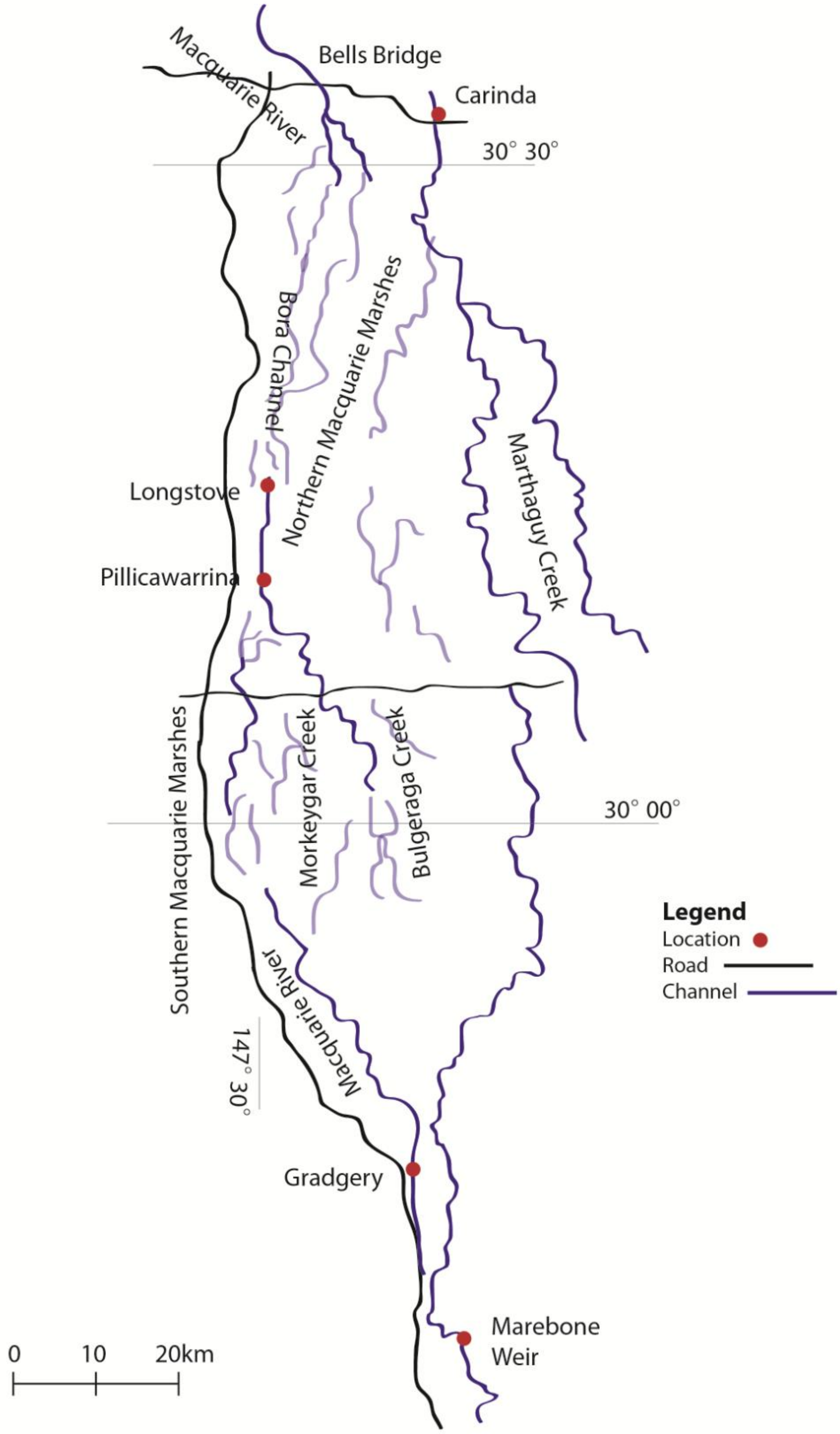


Figure 3.2 Map of the Macquarie Marshes from Marebone Weir (reach 5) to Bells Bridge Carinda (reach 7).

3.2.1 Significance of the Macquarie Marshes

The Macquarie Marshes are recognised for their national and international ecological importance and their important at a local scale for the communities of the Macquarie River catchment in the provision of wetland-derived ecosystem services (Finlayson, 2005). The recognition under the Ramsar Convention in 1986 designated the Macquarie Marshes as an important habitat for migratory species of waterbirds that are recognised under international agreements between Australia – Japan and Australia – China (Kingsford & Auld, 2005). The Ramsar site is comprised of the Macquarie Marshes Nature Reserve (~19,990 ha) and a currently functioning wetland on private land on the property Wilgara, approximately 20 km east of the reserve (Green et al., 2011).

The Macquarie Marshes are geomorphically and geologically unique (NPWS, 1993). They are an active inland multi-channelled system and one of the largest remaining inland semi-permanent wetlands (NPWS, 1993). The Macquarie Marshes depend on lateral connectivity in the form of inundation from overbank flows of the Macquarie River and other tributaries (NPWS, 1993) as well as the dry periods between floods to maintain the wetland ecosystem and diversity (Kingsford, 1995). The biodiversity of the Macquarie Marshes has adapted to the seasonality of flows.

Overuse of some of the main ecosystem goods and service, which broadly fall under the headings of *maintenance of essential ecological processes and life support systems* and *provision of natural resources* (de Groot et al., 2002), of the Macquarie River have impacted on other major ecosystem services. Degradation of ecosystem services has occurred beneath the broad headings of *providing habitat and living space for wild plant and animal species* and *providing opportunities for cognitive development* (de Groot et al., 2002). The drivers of overuse and degradation have occurred through water allocation, water diversion and off-site storage for urban consumption, and the reduction of flooding downstream and irrigation along the length of the Macquarie River (Morrison, 2002). The Marshes directly suffer the effects of grazing and irrigation. The effect that Burrendong Dam, with a capacity of 1,190,110 ML, has had on the Marshes since its development in 1967, has been detrimental to water quality, water flow, seasonality of flow and biodiversity and ecosystem function of the marshes (Kingsford, 1995).

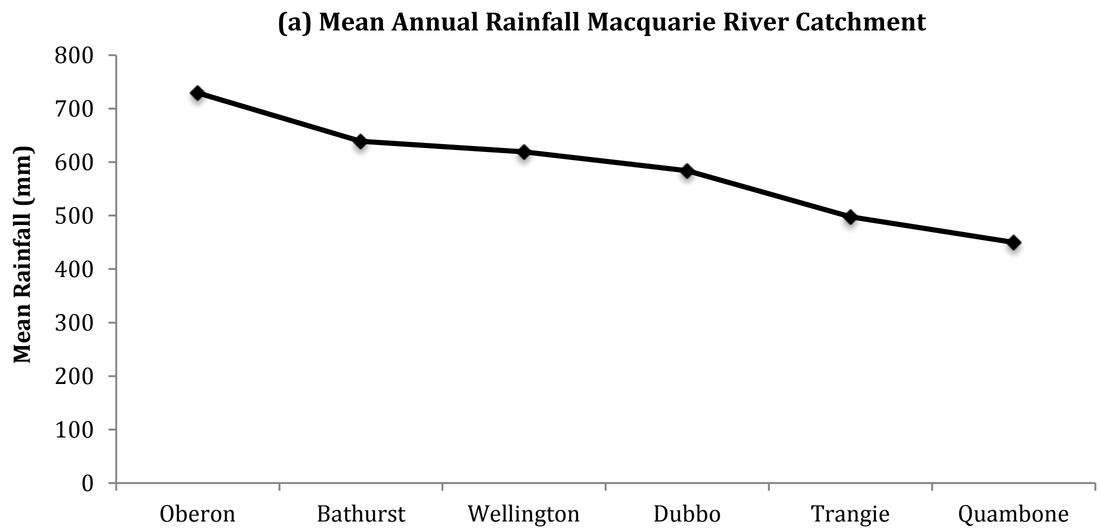
3.2.2 Geology and Catchment Topography

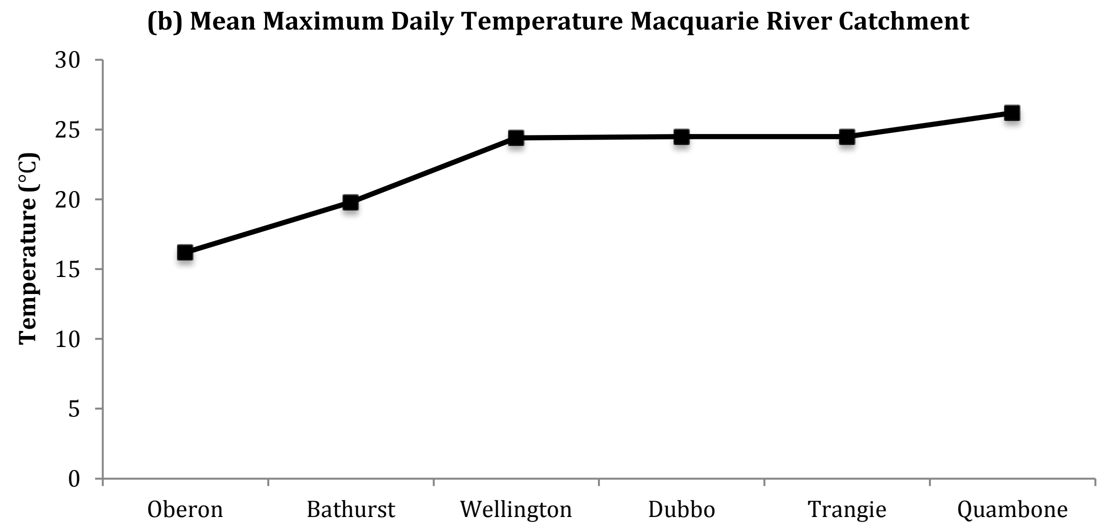
The Macquarie-Bogan catchment is a mosaic of landscapes from the confining bedrock uplands, bedrock confined and partly confined alluvial valley, to the lowlands of flat and expansive alluvial plains. The ranges in catchment elevation extend from 1,300 metres above sea level on the Great Dividing Range in the catchment headwaters to below 100 metres above sea level near Brewarrina (Green et al., 2011).

The highly variable geology of the catchment is formed of Palaeozoic volcanic, sedimentary and intrusive rocks of the Lachlan Fold Belt in the south (Tomkin & Hesse, 2004). The geology in the north and northwest of the catchment are Mesozoic sediments of Triassic Ballimore Formation and Jurassic Pilliga Sandstone. North of Narromine, Neogene and Quaternary sediments fill the alluvial valley and riverine plain (Tomkins and Hesse, 2004; Watkins & Meakin, 1996).

3.2.3 Climate and Hydrology

The Macquarie catchment is classified as a temperate climatic zone (Bureau of Meteorology (BoM), 2012), however the catchment is segmented by the intensity of summer temperatures and incidence of summer rainfall. The Macquarie catchment is in the transition between zones of winter dominated rainfall in the south and summer dominated rainfall in the north (DWE, 2008). Annual rainfall patterns show a decrease in rainfall down catchment and reveal the conceivable extent of runoff entering the system. The mean annual rainfall for the catchment decreases from 730 mm y^{-1} at Oberon to 430 mm y^{-1} measured at the closest site to the Macquarie Marshes, Quambone, shown in Figure 3.3. The mean maximum daily temperatures range from 4°C in the headwaters during winter to 35°C in the Macquarie Marshes during summer (BoM, 2012). The mean maximum daily temperature as reported by the Bureau of Meteorology for Oberon are 16.9°C and 26.2°C at Quambone located on the eastern side of the Macquarie Marshes. Daily pan evaporation data is not available for all stations, but is reported for the stations at Bathurst and Trangie and show a marked increase in daily pan evaporation from 3.7 mm at Bathurst to 5.8 mm at Trangie. Interannual and interdecadal climatic trends related to ENSO and IPO affect the seasonal and annual variability of discharge of the Macquarie River (Jenkins et al., 2005; Ralph & Hesse, 2010), Figure 3.3.


(a) Mean Annual Rainfall Macquarie River Catchment
Mean Rainfall (mm)
800
700
600
500
400
300
200
100
0
Oberon
Bathurst
Wellington
Dubbo
Trangie
Quambone


(b) Mean Maximum Daily Temperature Macquarie River Catchment
Temperature (°C)
30
25
20
15
10
5
0
Oberon
Bathurst
Wellington
Dubbo
Trangie
Quambone

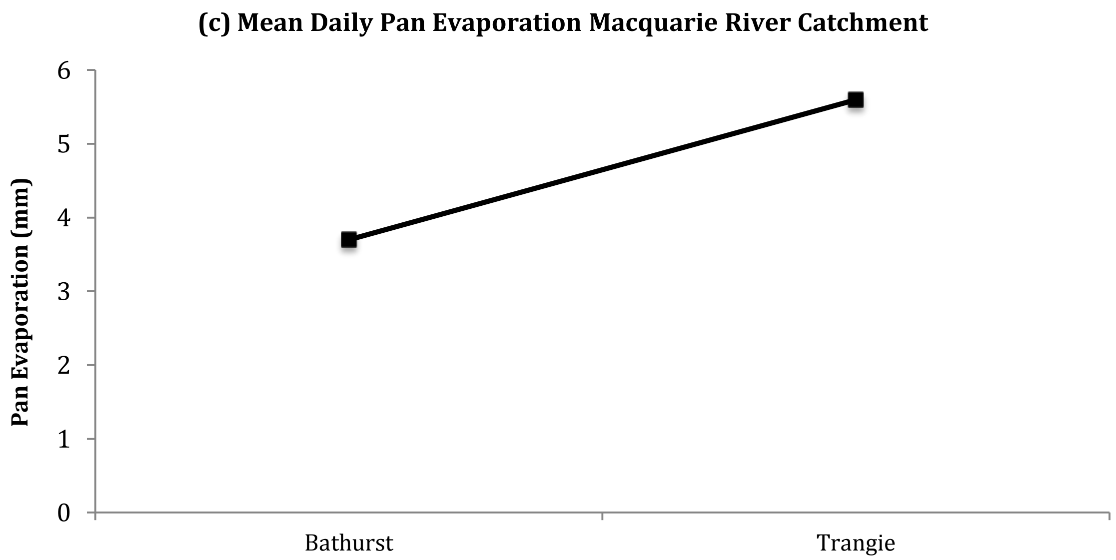

(c) Mean Daily Pan Evaporation Macquarie River Catchment
Pan Evaporation (mm)
6
5
4
3
2
1
0
Bathurst
Trangie

Figure 3.3 The mean annual rainfall (a), maximum daily temperature (b) and daily pan evaporation measurements (c) taken from the stations within the Macquarie River catchment at Oberon, Bathurst, Wellington, Dubbo, Trangie and Quambone (Source, BoM 2012).

Similar to many inland flowing rivers of the Murray-Darling Basin, flow of the Macquarie River decreases with distance downstream. Decreases in channel capacity and diversion of flow for irrigation, stock and domestic water supply, evaporation, groundwater recharge, and a number of effluent channels reduce the mean daily flow from over 3,000 ML/day at Dubbo to less than 900 ML/day upstream of the Macquarie Marshes (Green et al., 2011). The recorded mean daily flow at Carinda, downstream of the Macquarie Marshes, is less than 400 ML/day (Green et al., 2011). The changes in mean daily flow for the main gauges of the lower Macquarie River are indicated in Table 3.1. The rise in mean daily flow at Wellington is a result of the input from the Bell River tributary upstream of the gauge, and the Talbragar River tributary input upstream of the gauge at Dubbo further increases the discharge.

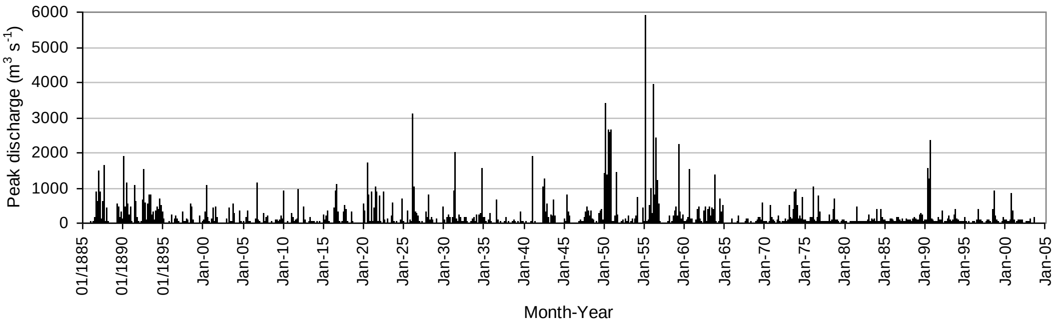
Table 3.1 Mean daily flow for selected gauges along the lower Macquarie River

Gauge Site	Catchment Area (km^2)	Mean Daily Flow (ML)	Period of Record
Macquarie River at Bruinbun (upstream Burrendong Dam)	4,500	1,162	1947-2009
Macquarie River at Wellington	14,130	2,712	1909-2009
Macquarie River at Dubbo	19,600	3,250	1885-2009
Macquarie River at Warren Weir	26,570	1,873	1901-2009
Macquarie River at Oxley (upstream Macquarie Marshes)	n/a	868	1943-2009
Macquarie River at Carinda (downstream of Macquarie Marshes)	30,100	388	1926-2009

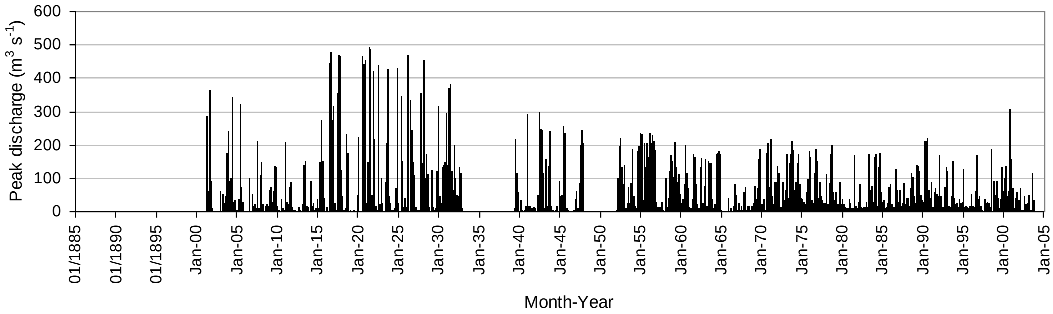
Source: NSW Office of Water Real Time Data - Rivers and Streams, 2011

The Macquarie River is highly regulated with the largest structure, Burrendong Dam, built to mitigate flood discharge and reserve water for human consumption and use. Burrendong Dam, completed in 1967 to provide water storage for town water, irrigation, and stock and domestic requirements (Green et al., 2011), captures approximately 88% of streamflow and releases more than half of the water captured for irrigation (Jenkins et al., 2005). The commission of Burrendong Dam introduced significant flood mitigation capabilities of the lower Macquarie River from flood events in the upper catchment (Green et al., 2011). Other impacts include: reduced large flows and flood peaks; low flows that erode channel beds and increased periods of no flow; and reduced seasonality (Kingsford, 2000), visible in Figure 3.4. Figure 3.4 shows the hydrographs of peak flood discharge at Dubbo, Warren and Carinda over a 120 year period. Groundwater is also an important source of water supply for irrigation, stock, domestic and town water supply for the Macquarie River valley and accounts for 11% of the total groundwater use of the Murray-Darling Basin (CSIRO, 2008).

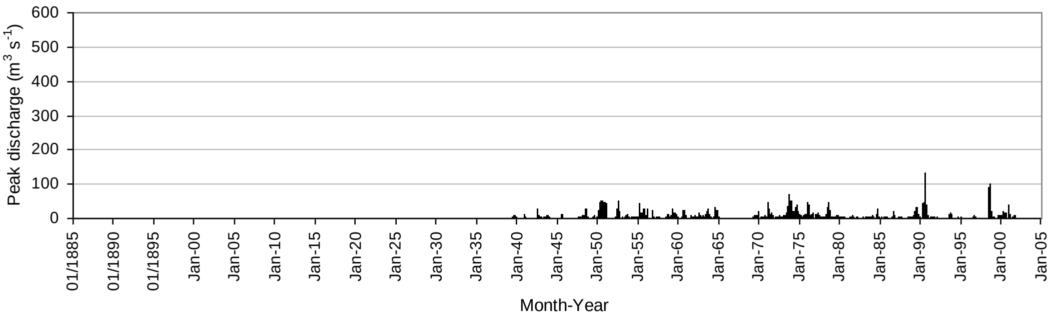
(a) Macquarie River peak monthly discharge at Dubbo



(b) Macquarie River peak monthly discharge at Warren



(c) Macquarie River peak monthly discharge at Carinda



(d) Macquarie River peak monthly discharge March 1960 - December 1962

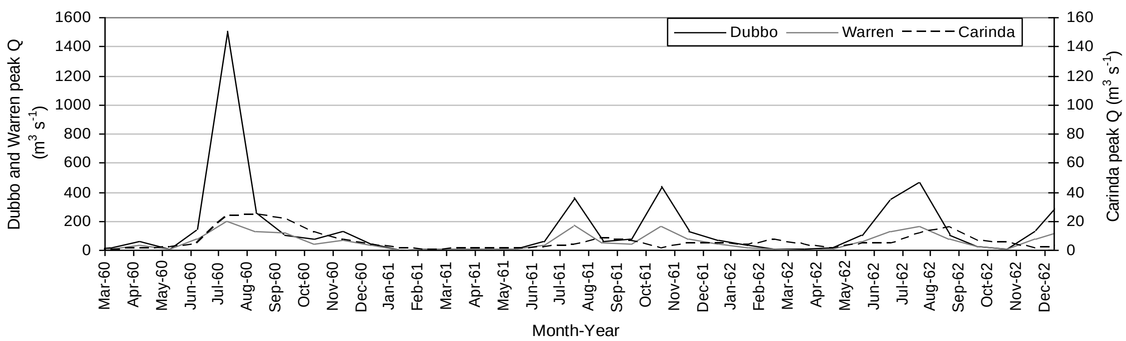


Figure 3.4 Hydrographs of Peak Monthly discharge at Dubbo, Warren and Carinda 1885 - 2005 illustrates variability in the flow regime of the Macquarie River. Declining discharge and a lag down catchment between Dubbo, Warren and Carinda illustrate the nature of flow through the Macquarie Marshes (Source: Ralph, 2008).

Five major weirs regulate the flow of the lower Macquarie River: Dubbo, Narromine and Gin Gin weirs are ponding structures providing pumping pools for irrigation; the weir at Warren controls flow diversion to Gunningbar Creek from which further regulators supply Duck Creek, Crooked Creek and the Albert Priest Canal (man-made); Marebone Weir upstream of the Macquarie Marshes supplies water to Marra Creek and the Bulgeraga Creek (Green et al., 2011). An 18 km bypass channel was excavated in 1972 to skirt around the eastern edge of the northern Marshes to deliver streamflow directly into the Macquarie River after the reformation of the trunk channel for the users downstream of the Macquarie Marshes in drier times.

In the Macquarie Marshes, fluctuating degrees of overbank flow were predicted to occur naturally every 1.07 to 1.8 years dependent on the distance from the channel. Every 1.07 years there would be flooding of the immediate floodplain, every 1.44 years flooding of the woodland floodplain and every 1.8 years the distal floodplain inhabited by coolibah woodland would receive overbank flows (Brereton et al., 2000). Increases in river regulation have slowly diminished the occurrence of overbank flows on the floodplains of the Macquarie Marshes. Since Macquarie River regulation, discharge is less variable; there has been a reduction in flood frequencies by 25 – 30% and a shift in the seasons of flooding, from winter – spring to spring – summer (Brereton et al., 2000). Constant low flows have increased, diminishing the flood – pulse regime of the floodplain wetland system and the extent of flooding has lessened by 40 – 50% (Kingsford & Thomas, 1995; Kingsford & Auld, 2005). The constant low flows have led to some areas of the Macquarie Marshes becoming wetter (Sheldon et al., 2000).

3.2.4 Human Impacts

The Macquarie catchment supports a large variety of industries including: agriculture, agribusiness, viticulture, mining and tourism. Land use changes since settlement has changed the vegetation on the floodplains and along the channel banks, and altered the hydrological regime. The agricultural industry supports irrigated and dryland crop production, and grazing. The increased use of land for agriculture has led to widespread land clearing on the floodplains and channel banks with only a thin veneer of one to two trees for the riparian zone. A decrease in vegetation on the channel banks and floodplain, and grazing cattle and sheep within channels, increases the sediment load into the channel. Irrigated crops such as cotton have led to land clearing and intense water use. Cotton production uses 90 % of irrigation water (Finlayson, 2006). In the years 1985 – 1995 the area planted with cotton tripled (Herron et al., 2002). Large-scale land clearing, water regulation and subsequent degradation have reduced the size of the original size of the Macquarie Marshes to 40-50% (Kingsford, 2000; Keith, 2004). Table 3.2 indicates the proportion of the catchment dedicated to each of the land use areas. Note that the largest proportion of the catchment is dedicated to grazing, only 1.6% to irrigated agriculture and 1.2% to conservation.

Table 3.2 The proportion of catchment area dedicated to the main land use categories of the Macquarie-Bogan catchment.

Land Use Category	Area (km2)	Proportion of Catchment (%)
Grazing	61,037	81.6
Dryland cropping & horticulture	6,954	9.3
Native landscapes	1,986	2.7
Forestry	1,841	2.5
Irrigation	1,182	1.6
Conservation	872	1.2
Residential	540	0.7
Wetlands	275	0.4
Lakes, rivers, dams	117	0.2
Mining	5	<0.1

Source: 2001/02 Land use mapping of Australia, Bureau of Rural Sciences (Green et al., 2011)

3.2.5 Biodiversity of the Macquarie Marshes

In the Macquarie Marshes one of the most extensive stands of river red gum woodland existed on the floodplains of the Macquarie Marshes and some of the largest reed beds (Kingsford, 2000). Up to 42,448 ha of river red gum forest existed in 1949 before the regulation of the Macquarie River (Kidson et al., 2000 a, b). The vegetation associations with different geomorphic units of the Macquarie Marshes include: river red gum woodland on the banks and immediate floodplain; water couch grasslands on the inundated floodplain regions; coolabah and black box woodlands on the distal floodplains; lignum swamps, reed swamps, cumbungi and river cooba in the channel and on the wetland floodplains of the area of channel breakdown (Paijmans, 1981; Brock, 1998; Jenkins et al., 2005; DEWHA, 2009). The Coolibah-Black Box Woodland is an endangered ecological community on the floodplain on lower reaches of the Macquarie River and suffers the direct effects of land clearing, fragmentation, overgrazing, weed invasion and alteration to food regimes (Green et al., 2011). The Macquarie Marshes support a diversity of fauna including 211 bird species, eight species of native mammal, 15 frog species, 24 native fish species and 56 reptile species (DEWHA, 2009).

3.3 The Contemporary Geomorphology of the Macquarie River

The broad geomorphic characteristics of the Macquarie River are initially outlined in this section. The fluvial sediments of the Murrumbidgee, Gwydir, Macquarie and Namoi provide a broad indication of the high-energy fluvial systems and landscape evolution in the late Quaternary (Watkins and Meakin, 1996; Pietsch, 2005; Yonge and Hesse, 2009; Young et al., 2002; Page et al., 1996). Yonge and Hesse (2009) used optically stimulated luminescence (OSL) and AMS ^{14}C to date sedimentary cores of the southern Macquarie Marshes with returned ages of the underlying coarse sediments between 8.4 ± 0.08 ka and 59 ± 10 ka. Dating indicates the formation of the contemporary fine-grained fluvial system since less than approximately 8 ka.

The change in climate in the Holocene reduced the size of flood peaks in the rivers of the Riverine Plain, which greatly diminished bedload transport from the upper catchment and resulted in the contemporary highly sinuous suspended load rivers (Page & Nanson, 1996).

3.3.1 The Macquarie River Corridor

Through a desktop study and further field assessment, the Macquarie River has been split into ten reaches of similar characteristics and behaviour, one reach style repeated (8 & 10). The broad reach boundary marks the transition of the reach between different types or styles and is based on the framework by Brierley and Fryirs (2005). Figure 3.5 shows the reach boundaries along the Macquarie River and Figure 3.6 describes the features of each reach type. The reach types indicate the confinement of the channel, the position within the landscape, sinuosity, bed material, and gradient and geomorphic units. The Macquarie Marshes are developed in reach 9 showing no valley confinement of the channel and a cohesive mud bed material texture.

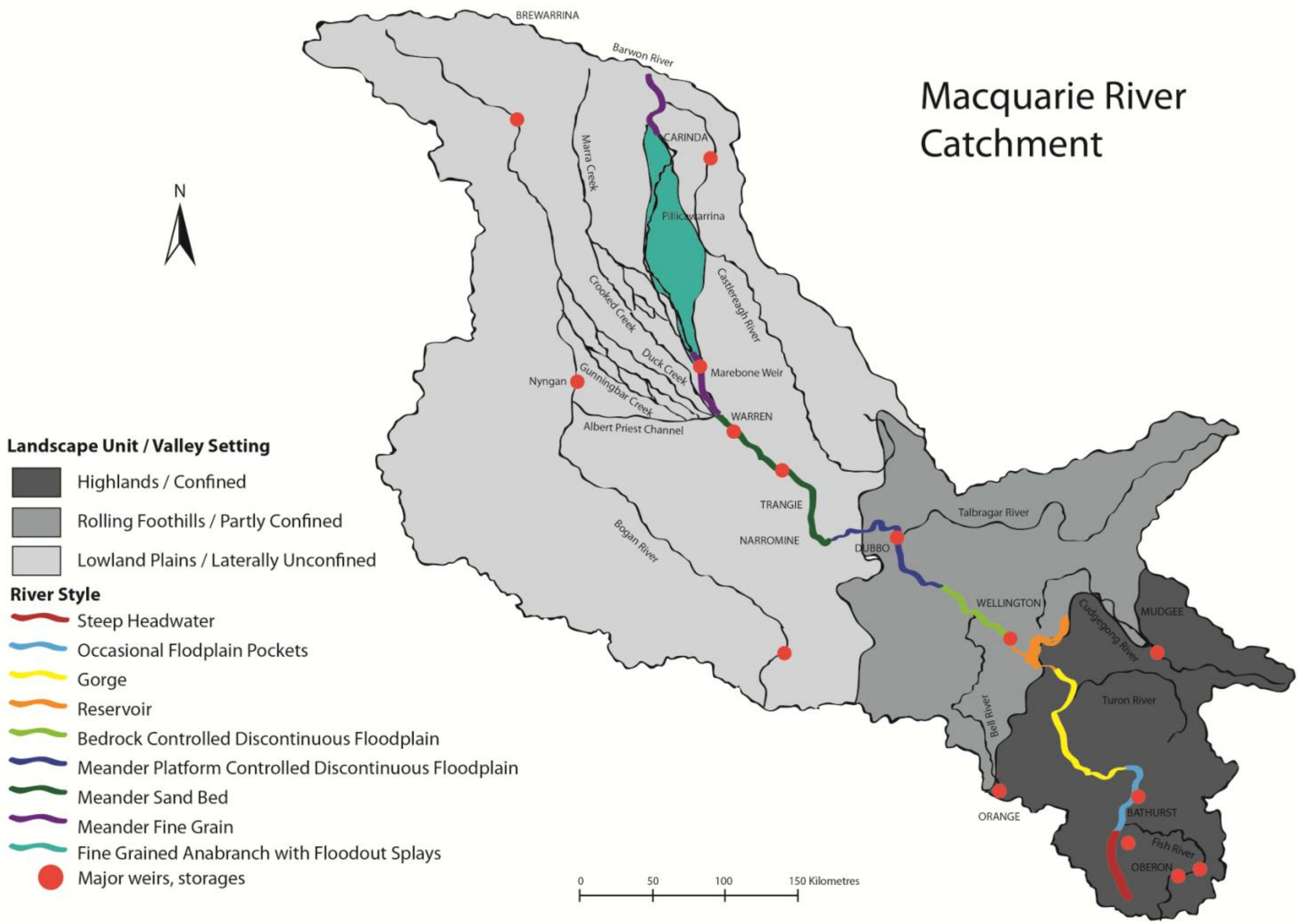


Figure 3.5 Map of the Macquarie River divided by reach boundaries.

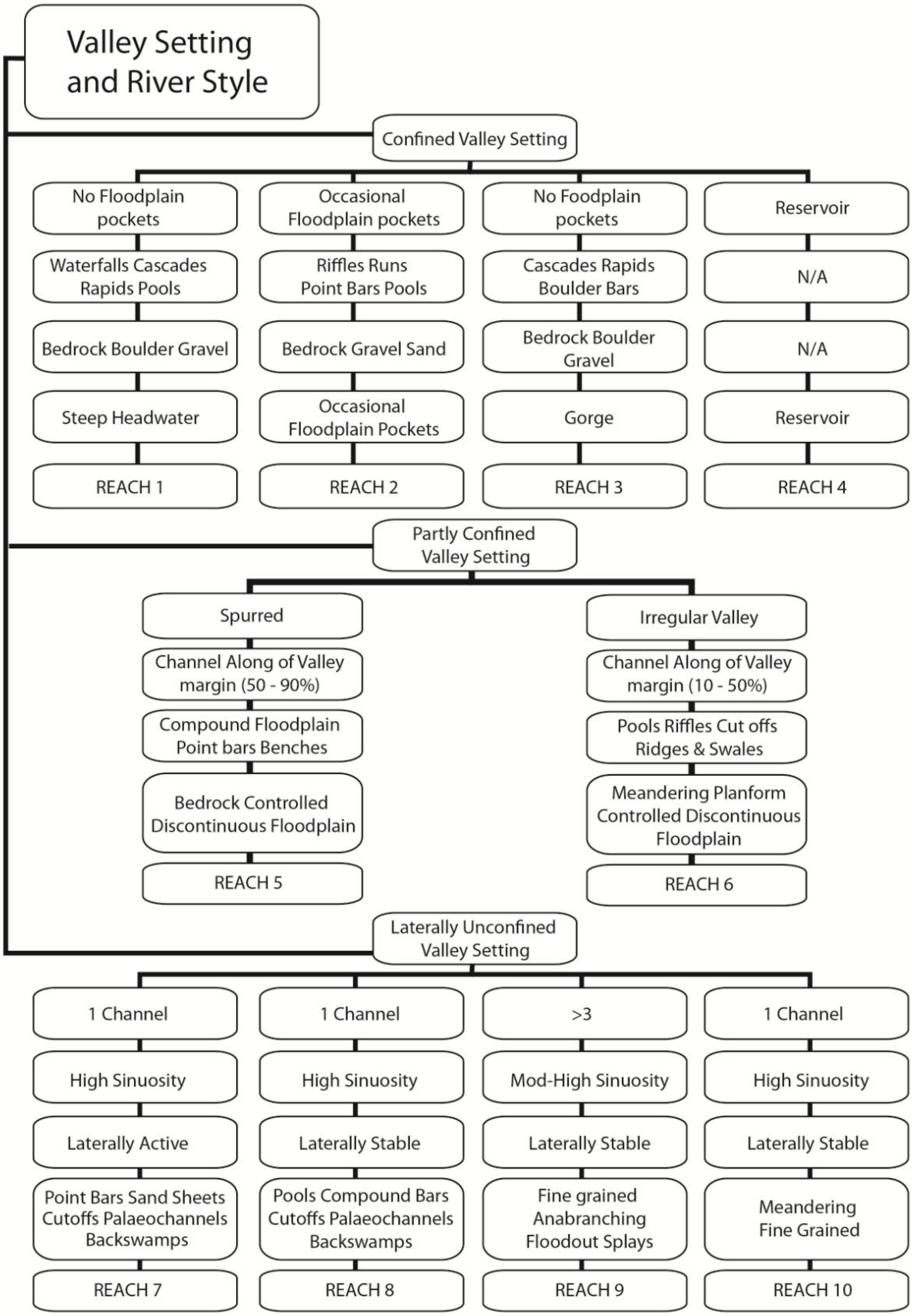


Figure 3.6 Valley settings and reach styles of the Macquarie River, southeastern New South Wales

3.3.2 Geomorphology of the Southern Macquarie Marshes

Yonge and Hesse (2009) identified three types of channels and four different floodplain units within the southern (upstream) Macquarie Marshes (Table 3.3). The three channel types include a trunk channel, primary distributaries, and marsh channels. The characteristics and vegetation associations are included in Table 3.3. Ralph (2008) and Yonge and Hesse (2009) identified four floodplain units within the southern Macquarie Marshes. The floodplain units include depositional floodout splays, impounded marshes, unchannelised floodplain and gilgai floodplain. Gilgai formation occurs on the floodplain by the shrinking and swelling of the marsh clays during the natural wetting and drying cycle and contributes micro-relief to the distal floodplain (Paton, 1974; Knight, 1980; Yonge and Hesse, 2009). Floodplains experience vertical accretion with some lateral accretion of the floodplain associated with the meandering trunk streams. The characteristics of the floodplain units are identified in Table 3.4.

Table 3.3 Characteristics of the three channel types in the southern Macquarie Marshes. Source: Yonge and Hesse (2009).

Channel Type	Sinuosity	W:D	Cross Sectional Area (m^2)	Floodplain Style	Levees	Distributary Channels	Riparian Vegetation
Meandering trunk streams	1.3 - 1.5	1 - 23 variable	12 - 36 decreasing downstream	Vertical and lateral accretion features	Yes	Well established large meandering channels with lateral accretion features including cutoffs, point bars and cut banks	Bed and banks largely unvegetated. Woody vegetation on channel margin including River Red Gum and River Cooba.
Primary Distributary Channels	1.1 - 1.2	3 - 25 highly variable, decreases downstream	< 15 decreasing downstream	Vertical accretion, no lateral accretion features	Yes	Straighter first order distributaries of meandering trunk streams or meandering trunk streams diminishing in capacity and effectiveness in their lower reaches	Reeds in channel margin in upper reaches, in combination with frequent in-channel reed growth in mid to lower reaches
Floodplain Marsh Channels	1.1 - 1.2	10- 14	< 5	Vertical accretion, no lateral accretion features	No	Distributaries bifurcating from primary distributaries. Often discontinuous and terminate. Can have reticulate pattern. Form contributory networks downstream of unchannelised floodplains	Banks and beds colonised by dense reeds and aquatic grasses.

Table 3.4 Characteristics of four floodplain units in the southern Macquarie Marshes. Source: Yonge and Hesse, 2009; Ralph, 2008.

Marsh Type	Floodplain Style	Description	Riparian Vegetation
Unchannelised Marsh	Vertical accretion	Permanently inundated floodplains, lotic wetlands, with no definable bed or banks. Act as unconfined conduits of flow that transmit discharge between channelised reaches and are characterised by dissipated discharge over large areas	Dense, continual colonies of reeds with aquatic grasses
Floodout Splays	Vertical accretion	Fan shaped, fine-grained depositional features with radiating distributary and marsh channels resulting in lotic wetlands and sediment accretion on the floodplain. Floodout splay morphology exists on a number of scales ranging from smaller units in singular lobes with central or multiple distributary channels to larger complexes of serial splay formation	Areas of River Red Gum, Box and Coolibah woodland or water couch pasture
Impounded Marshes	Vertical accretion	Lentic swamps and lagoons, concave basin morphology that retain semi-permanent or permanent water. Often develop as a result of isolation of a distal portion of the floodplain, or palaeochannel by vertically accreting trunk stream or primary distributary channel	Aquatics
Gilgai Floodplain	Vertical accretion	Ephemeral floodplain gilgai morphology develops on floodplain surfaces in areas removed from permanent saturation, through wetting and drying processes. The floodplains are broadly flat but have irregular, hummocky surface relief characteristics with deeply cracked depressions and elevated mounds when dry. The gilgai produce a high density pattern of reticulating drainage that is often discontinuous and directed by micro-relief	Box or Coolibah woodlands and patches of aquatics in depressions

3.3.2 Geomorphology of the Northern Macquarie Marshes

The northern Marshes cover the largest area of channel breakdown of the Macquarie Marshes, an area of approximately 200 km^2 with roughly 121 km^2 protected as a nature reserve. The vast floodplains of the Macquarie Marshes are confined to the west by palaeo-alluvial ridges of an old meandering palaeochannel. The Macquarie River bifurcates at 'the Willows' on the private property of 'Longstowe'. Flow merges again as a single trunk channel downstream of Duck Swamp, 22 km downstream of 'the Willows' (Figure 3.2).

The northern Macquarie Marshes is a fine-grained anabranching system with floodout splays that channel streamflow across large tracts of floodplain. Dense reed beds distinguish the areas of floodout splays. Two channel types represented within the northern Macquarie Marshes are similar to those identified in the southern Macquarie Marshes. The meandering trunk stream as identified by Yonge and Hesse (2009) characterises the Macquarie River as it enters the northern Macquarie Marshes but soon bifurcates to an anabranching system, before reforming as a meandering trunk channel downstream of Duck Swamp.

The other channel type, similar to that described by Ralph (2008) and Yonge and Hesse (2009), are floodplain marsh channels. Marsh channels take on both a distributary and contributory function within the northern Macquarie Marshes. They fracture the floodplain and are often discontinuous. The distributaries channel flow to the point of channel breakdown and also reform downstream of unchannelised floodplain to form a tributary network of marsh channels, re-emerging to a single trunk channel. The primary distributaries as described by Ralph (2008) and Yonge and Hesse (2009) in the southern Macquarie Marshes do not entirely correlate to channels of the northern Macquarie Marshes. The Bora Channel downstream of the bifurcation of the Macquarie River displays some of the characteristics of a primary distributary (Table 3.3) but soon undergoes numerous bifurcations as the start of the anastomosing network of marsh channels.

The floodplain units are generally the same as described by Ralph (2008) and Yonge and Hesse (2009). However, two key variables usually associated with channel avulsion, levees and primary distributaries, are not identified within the northern Macquarie

Marshes. Unchannelised marsh is identified within the central northern marshes and characterised by extensive dense reed beds and a lack of channelised flow. Floodout splays are evident in the northern Macquarie Marshes: most distributary marsh channels conduct flow across marsh floodplain, channel capacities and cross sectional areas diminish into depositional floodout splays. Anastomosing marsh channels also skirt around the edge of the floodout, channelling water through the Bora Channel complex or on to the distal floodplain. Whole-scale breakdown occurs on the eastern side of the northern Macquarie Marshes where lentic lagoons have formed as slight depressions within the landscape and retain water after high flows. Gilgai floodplain characterises the distal floodplain of the northern Macquarie Marshes. Each floodplain unit supports different vegetation associations. Gilgai floodplain supports semi-permanent water retention, woody vegetation, and lignum and chenopod shrubs. The vegetation association with the marsh floodplain is predominantly classified as low open River Red Gum woodland and pockets of reeds. Unchannelised marsh supports the growth of predominantly common reed and cumbungi. The lentic lagoons support reed, cumbungi and lignum growth and sparse woody vegetation.

Freeman (2008) investigated the historical change of the Macquarie Marshes. The outcome showed the downstream reformation of the meandering trunk channel of the Macquarie River approximately 4.5 km further upstream than the present day channel, close to where the bypass channel re-enters the system on the eastern side of the northern Macquarie Marshes. A small area of wetland is present on a parish map (1884-1910) that does not appear in the 1991 aerial photos (Freeman, 2008). Only the main channel was noted on the parish maps, the smaller marsh channels were not recorded. Marsh extent corresponds to contemporary marsh units and there is no evidence, as a result of the comparison between parish maps and aerial photos from 1991, of channel avulsion, indicating a relatively stable system over short temporal scales (Freeman, 2008).

3.4 Chapter Summary

The Macquarie River is an inland-flowing semi-arid perennial system within a catchment contributing to the larger Murray Darling Basin. It transects confined, partly confined and laterally unconfined alluvial plains in its distal reaches. Discharge, channel width, gradient and channel capacities decrease down catchment. Decreasing discharge, sediment calibre and confinement lead to the formation of a sinuous meandering cohesive fine-grained reach. The last tributary inputs into the lower Macquarie River system are the Talbragar River at Dubbo. Channel breakdown occurs in the distal reaches of the Macquarie River. The Macquarie Marshes are formed by a multi-channelled anabranching distributary, marsh channels and floodout splays over the low gradient floodplain. The Macquarie Marshes are typical in form of the floodplain wetlands associated with the inland flowing rivers of the Murray-Darling Basin with diminishing channel capacities.

The Macquarie Marshes are two distinct complexes: the southern and northern Macquarie Marshes. The significance of the Macquarie Marshes is recognised in the Ramsar listing of the wetlands for international bird migration and the ecosystem services it provides for tourism and agriculture. As the Macquarie Marshes are a dynamic system it is difficult to distinguish natural from artificial changes because of decreases in discharge by river regulation, removal of native vegetation and changing land uses.

Chapter 4: Surface and sedimentary sample collection and analysis methodologies

4.1 Introduction

This chapter outlines the desktop, field and laboratory methods used to gather data to establish the primary controls on channel breakdown and the implication of connectivity on the spatial area of channel breakdown. The geomorphic characteristics, channel morphology and connectivity of the lower Macquarie River with a focus on the northern Macquarie Marshes were established through data analysis of water samples, velocity measurements, and cross-sections used for channel measurements and discharge modelling. Furthermore, the chapter outlines the methods of investigation into the sedimentary characteristics and sediment accumulation rates of four cores extracted from the northern Macquarie Marshes.

4.2 Surface data collection and analysis

This section provides an outline of the methods used to collect and analyse surface data of the lower Macquarie River. Surface data was collected for channel cross sections, reach analysis, vegetation blocking of the in-channel zone, water samples for total suspended solids and velocity measurements. The lower Macquarie River was split into six reach types, with one repeated (reach 5 and 7). Data was collected at an accessible and representative site for each reach, with a greater number of sites closer to the Macquarie Marshes, particularly the northern Macquarie Marshes. Reach type determination exercised the framework detailed in Brierley and Fryirs (2005).

4.2.1 Desktop Study

A desktop study was undertaken to loosely split the lower Macquarie River into reach types and identify the type of geomorphic units, sediment type and calibre, and confinement of the channel. The desktop classification of each reach was used to evaluate the contemporary style of the reach and predict the controls defining river reach behaviour and character. The characteristics of the reach established through the desktop study were then confirmed through fieldwork.

A desktop study was the initial form of investigation into establishing reaches based on the River Styles® framework detailed in Brierley and Fryirs (2005). Aerial photographs (scales 1:50000, 1:40000, 1:25000, 1:15,000, and 1:5000), topographic maps (scales of

1:250,000 and 1:50,000), and published research were used to establish landscape confinement of the lower Macquarie River, the sediment load, energy, and the boundaries between reaches. Topographic maps were used to develop the long profile and the valley width of the changing landscape settings downstream along the Macquarie River, focussing on the Macquarie Marshes. The desktop study established public access areas to each of the pre-determined reaches, which became the representative sites for each reach. Subsequent fieldwork verified, modified or provided additions to the desktop study data. Clumping of characteristics was used for the trunk channel of the Macquarie River analysis due to the broad scale of evaluation; there was no minimum length requirement of a reach. Splitting occurred when there were notable changes between physical characteristics.

4.2.2 Collection of Field Data

Field samples and data for a number of variables were collected at each site. Some variables were used to establish downstream patterns of the lower Macquarie River and other variables collected to use in modelling flood discharges with Geomorphic Assessor developed by Adolphe Parfait (formally DIPNR, Muswellbrook). Observations of channel and floodplain roughness were collected for the modelling program using Table 4.1 as a reference. Photos at sites and observations were used to determine the percentage of the channels blocked by vegetation from reach 1 to reach 7.

Table 4.1 Manning's n coefficient of roughness.

Channel Type	**Range**
Small Channels (width <30 m)	
Low Gradient Streams	
Unvegetated straight channels at bankfull stage	0.025 – 0.033
Unvegetated winding channels with some pools and shallows	0.033 – 0.045
Winding vegetated channels with stones on bed	0.045 – 0.060
Sluggish vegetated channels with deep pools	0.050 – 0.080
Heavily vegetated channels with deep pools	0.075 – 0.150
Mountain Streams (with steep unvegetated banks)	
Few boulders on channel bed	0.030 – 0.050
Abundant cobbles and large boulders on channel bed	0.040 – 0.070
Large Channels (width >30 m)	
Regular channel lacking boulders or vegetation	0.025 – 0.060
Irregular channel	0.035 – 0.100

Source: **Based on data in V.T. Chow (1964)**

Floodplain gradient was used for Burrendong Dam (reach 1) to Marebone Weir (reach 5) using the distance between contours and the differences in elevation from topographic maps. Floodplain gradients between Burrendong Dam and Narromine were calculated from a topographic map with a scale of 1:250,000 with an error of ± 0.179 m/m. The sites between Narromine and Marebone were calculated from a topographic map with a scale 1:50,000 with an error of ± 0.2 m/m. The length of reach the slope was derived from is included in Table 4.2. Channel gradients from Marebone Weir (reach 5) to Bells Bridge Carinda (reach 7) were calculated from airborne LiDAR-derived DTM (1 m grid) provided by the Department of Environment and Climate Change (DECC). LiDAR could not resolve the ground surface where the channel bed or floodplain surface was covered by dense reedbeds or water. The error associated with the elevation data was evident in some transects below 2 cm of elevation (Hesse, 2009). The channel slope was extracted from the LiDAR data over at least one kilometre.

Table 4.2 Length of channel the slope was derived from between contours on a topographic map

Reach	Reach Length (km)
1	9
2	115.5
3	52.5
4	69.5
5	55.5
5	9.5

Cross section data was obtained for four cross-sections (Burrendong Dam, Ponto Falls, Minore Falls and Warren) from the Department of Land and Water Conservation (DLWC). All other cross-sections were measured using the Leica TCR 705 total station. There were instances where the channel was the only section of the site surveyed, attributable to private land boundaries directly at top-of-bank level. The total station attaches to a tripod and was set up on the left bank of the channel when possible. The laser from the total station is directed to the centre of a reflector prism, which needs to be visible at all times. The target height and the instrument height above the ground are required to work out the distances and changes in elevation using Pythagoras's theorem with the data from the total station. The Leica TCR 705 User Manual states that the laser on the instrument is viable to 3500 metres and has accuracy to 5 cm over that distance. Cross-section data was used in discharge modelling, downstream changes in channel shape, width-depth ratio and channel cross sectional area calculations. Within the Macquarie Marshes, cross-sections were taken at each site a suspended sediment sampler was installed to determine the height of the inlets above the channel bed (see section 4.2.2.1).

4.2.2.1 Water Sample Collection – Turbidity and total suspended solids

Water samples were collected, either by grab samples or in situ suspended sediment samplers, and analysed for turbidity and total suspended solids (TSS) at numerous sites between March and July 2008 to June and September 2009 during variable flow regimes. Samples were collected at bankfull during March 2008 in the northern marshes and well below bankfull during July 2008 and June and September 2009. Sampling sites were located downstream of Burrendong Dam to the Macquarie River gauge at Carinda. Sampling sites were concentrated throughout the southern and northern Macquarie Marshes. In the Macquarie Marshes samples were collected upstream and downstream of extensive reed beds and located where there was either an input or output of flow (i.e. tributary input or distributary output) (Appendix 2). During sampling in July 2008, water samples were collected at the location where suspended sediment samplers were deployed (Appendix 3). Water samples were collected in one litre new or reused clean acid washed plastic bottles from the channel thalweg. Before sample collection the bottle was rinsed with channel water and the sample collected at arms length with the mouth of the bottle facing upstream. The entire water column was sampled by gently moving the sample bottle up and down through the water column until the bottle was full. Figure 4.1 is a map of the suspended sediment sampling sites of the lower Macquarie River.

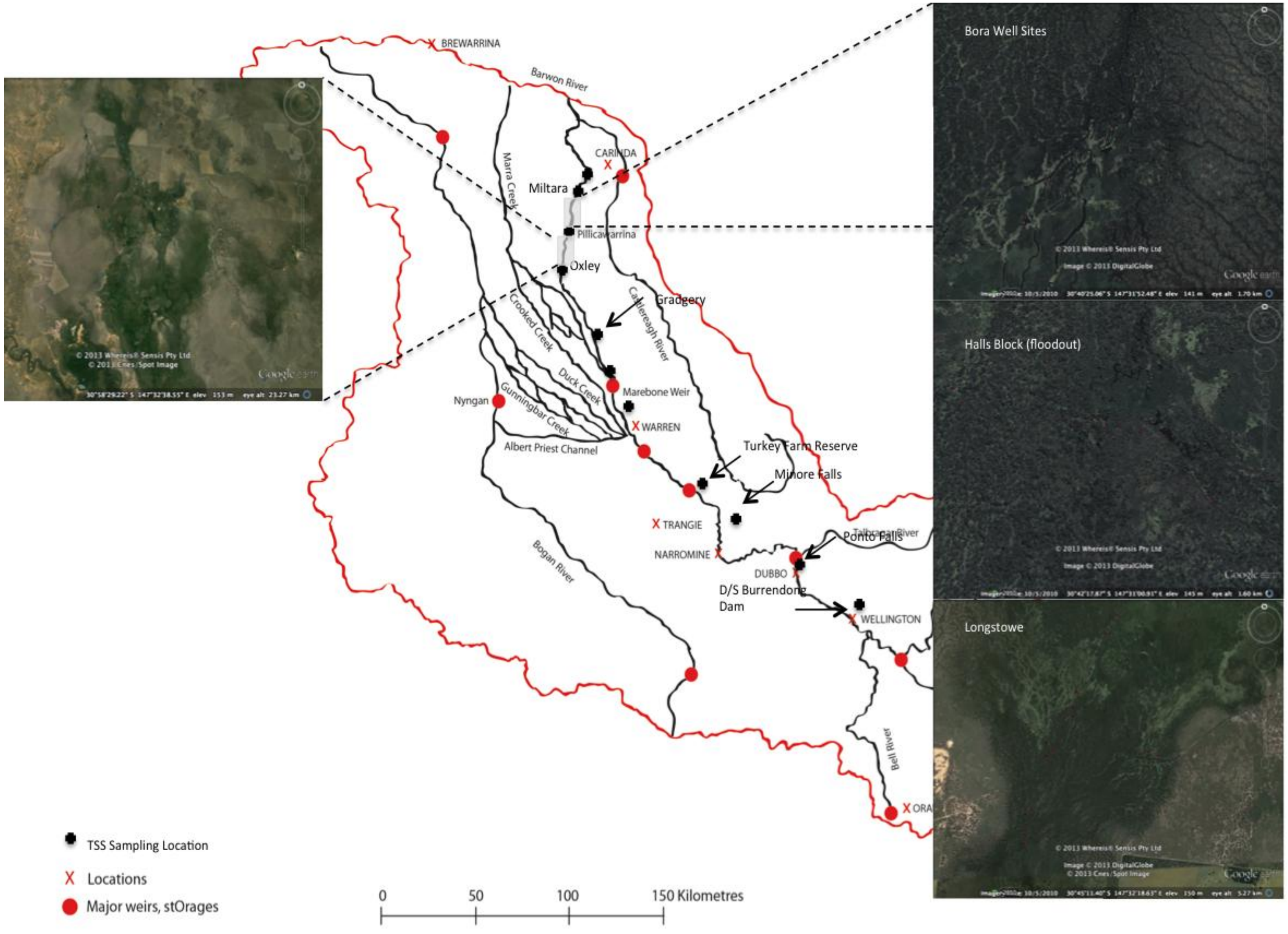


Figure 4.1 Suspended sediment sampling sites of the lower Macquarie River. The image on the left is for the southern Macquarie Marshes and the image on the right are the locations in the northern Macquarie Marshes.

Turbidity and total suspended solids

To establish downstream patterns and connectivity of suspended sediment transport, turbidity and total suspended solid (TSS) were analysed from the water samples to establish an understanding of the energy and sediment storage or erosion of a site. Both measures of particles in the water column were used to determine if there was a strong relationship between the two. Spectrophotometer measurements of total suspended solids are labour intensive and require the samples to be chilled and analysed on return to the field station, whereas the turbidity meter was portable and the sample could be analysed directly. The turbidity meter expresses results in nephelometric turbidity units (NTU), whereas the spectrophotometric TSS of a water sample is expressed in SI units (mg L^{-1}).

TSS analysis was undertaken using a HACH spectrophotometer, which measures the light absorption properties of the water to determine the mass of suspended particles per unit of water. Both methods of measurement were used during primary sample collection to determine if a correlation was present between the two methods. The turbidity (NTU) of the water sample was measured in the field directly after sampling with a Hanna portable turbidimeter. Three measurements were made of each sample, the average value calculated, and used to determine patterns and trends within the data. The water samples were chilled away from light, and refrigerated immediately on arrival at the field station. The avoidance of light and heat prevents algal growth and flocculation's forming (Droppo, 2001) that have the ability to alter the TSS measurements. Three to four TSS measurements of each sample were taken, the average value calculated, and the data used to establish a correlation with the turbidity data.

Taking the approach of collecting both sets of data provided a comparison and correlation between the data sets. The average turbidity and TSS values were plotted against each other and fitted with a linear regression to determine whether there was a good correlation (R^2 value), Figure 4.2. A good correlation (high R^2 value) indicated turbidity measurements could be used with confidence and later converted to the quantitative measurement of TSS.

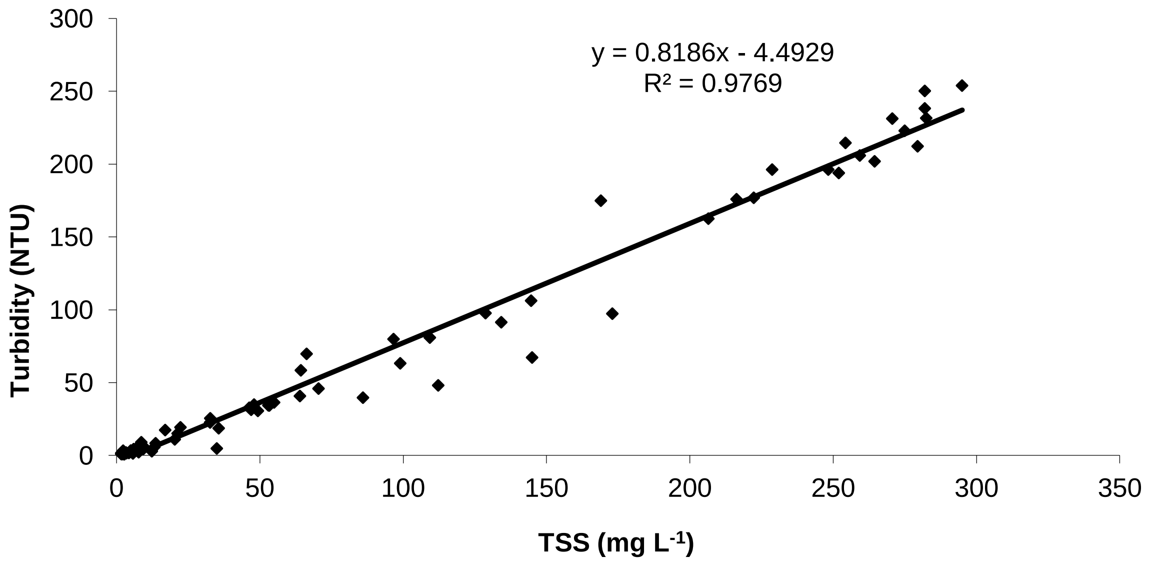


Figure 4.2 The correlation between the variables of suspended sediment measurement, turbidity and total suspended solids. The good correlation (R^2 = 0.98) is an indication that turbidity can become a proxy measurement for total suspended solids.

Turbidity and TSS measurements from 21 gauge stations along the lower Macquarie River recorded by Department of Water and Energy (DWE) were used in addition to the field-collected data. Turbidity data was converted to TSS using the equation of the line of best fit established in Figure 4.2. These additional datasets cover the period from 1977 to 2008 though not continuously. Sediment yield was calculated at the five gauge sites surrounding the Macquarie Marshes (Marebone, Oxley, Pillicawarrina, Miltara and Bells Bridge) using the gauge discharge data and the mean total suspended solids calculated at each site from gauge data. The yield in milligrams per day was calculated and then calculated to come to a final figure of tonnes per annum and mean discharge in megalitres per annum.

Suspended Sediment Samplers

A convenient method of suspended sediment sample collection is collection by suspended sediment samplers, also known as 'single-stage' or 'siphon samplers' (Graczyk et al, 2000; Diehl, 2007). The installation of such samplers in periods of dry conditions enables sample collection of different stages as the channel fills. This is particularly useful when the field site, such as the Macquarie Marshes, is an eight-hour drive from Sydney. Mackay and Taylor (2011) applied a modified siphon sampler design of Graczyk et al. (2000) in the remote upper Leichhardt River catchment in northwestern Queensland. The Leichhardt River is ephemeral which led Mackay and Taylor (2011) to seek a design of suspended sediment capture which could be installed into the dry channel and collect samples of different stages of flow when the monsoonal rains initiated river flow. Forty-six suspended sediment samplers were constructed in July 2008 and deployed in the same month in the southern and northern Macquarie Marshes. There are two sampler designs, one suitable for shallow channels and the other design suitable for deep channels. The shallow channel sampler is a modified design of Diehl (2007). The deep channel sampler is modified from the design of Graczyk et al. (2000).

The simple design of the deep channel siphon sampler allows for its simple operation. During the rise in stream stage, the elevation of the surface reaches the intake level; refer to Figure 4.3 (a). Water enters the 8 mm diameter plastic tube. Water continues to move through the intake tube as flow rises. A siphon is created once the water levels rise past the intake tube and the sample bottle begins to fill. The height difference between the stream stage and the discharge end of the intake tube is the hydraulic head. This drives the flow rate of water into the sample bottle. Filling is completed once the bottle is full with an air lock between the water height in the bottle and the rubber stopper. An airlock is established in the loop in the exhaust tube after the flow height reaches the exhaust. This airlock terminates further filling of the bottle (Grazcyk et al., 2000).

Changes in the water level after this point do not significantly affect the contents in the bottle. The modified deep channel sampler has two stage sampling heights. One at 20 cm and the other at 40 cm refer to Figure 4.3 (b). Essentially the theory of the design is the same, however, instead of one stage sampler these were constructed as two stage samplers. Flow height does not affect the deep channel samplers, but does affect the shallow channel samplers if stage height exceeds the height of the exhaust outlets. If stage height exceeds the exhaust outlets, water will continuously flow through the system, affecting the volume of suspended sediment collected in the sample.

The deep channel samplers were constructed using 100 mm diameter polyvinyl chloride (PVC) piping which formed the casing of the sampling system. 100 mm diameter PVC caps were used to cap both ends of the PVC pipe before installation in the field. The tubing used is Moss 8 mm diameter clear vinyl tubing and Moss 5 mm diameter clear vinyl tubing. The bottles used for suspended sediment collection in the samplers were wide mouth 500 mL Azlon (polypropylene). Rubber stoppers were used to seal the mouth of the Azlon bottles, which had two holes large enough to place the 5 mm and 8 mm vinyl tubing through. Clip Twist garden ties were used to tie the tubing in the correct shape to form the siphon and stay in the correct position in the cylinder. Plastic/silicone sealant was used to seal any gaps between the tubing and the stopper, and the tubing and the PVC pipe. Cloth tape was used to fasten the tubing in shape to the inside of the PVC pipe and to seal the PVC cap on the PVC tube when deploying it in the field. UV resistant 300 mm x 4.8 mm cable ties were used to fasten the mouth of the bottle to the inside of the PVC pipe to prevent movement and keep the bottles in an upright position. The casing lengths of 100 mm diameter PVC were 800 mm. Two Azlon bottles were fastened vertically in side the casing. Figure 4.3 was a modified design of the original design by Grazcyk et al. (2000). The sampler modified for the Macquarie Marshes contained two 500 mL bottles with the same design but different lengths of tubing.

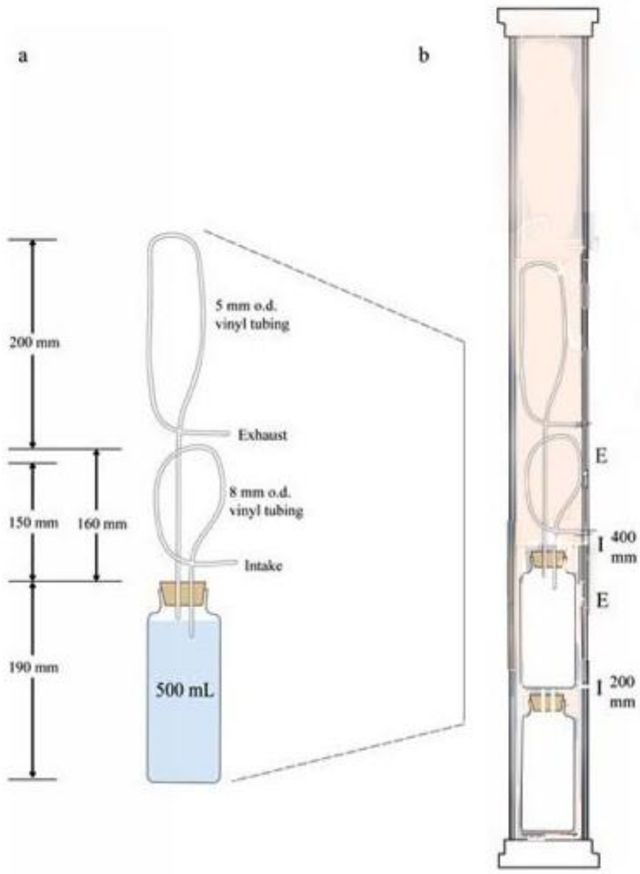


Figure 4.3 Graphic representation of the modified siphon sampler from the original design by Graczyk et al. (2000). The siphon samplers deployed in the Macquarie Marshes housed two 500 ml bottles with an intake tube at 200 mm and 400 mm. The photograph depicts a siphon sampler deployed in the Macquarie River reach at Bells Bridge near the township of Carinda.

A design by Diehl (2007) was used to construct the shallow channel samplers, shown placed in the field in Figure 4.4. The following materials were used: 50 mm diameter

PVC pipe was used as the skeleton of the shallow water samplers. 50 mm diameter PVC caps were used to cap both ends of the 50 mm PVC pipe. 100 mm diameter PVC pipe pieces were halved and used as a shield facing directly into the oncoming flow. The tubing used is Moss 6 mm diameter clear vinyl tubing. The bottles used for suspended sediment collection in the samplers were wide mouth 500 mL Azlon (Polypropylene). Wire was used to fasten the units of bottles and plywood to the 50 mm PVC pipe stand. The bottle lids were fastened to small sheets of plywood, which provided a shield and a way of keeping the bottles horizontal. Silicone sealant was used to seal any gaps between the tubing and the lids, tubing and the plywood, plywood and the lids, and the tubing and the PVC pipe shields. UV resistant 300 mm x 4.8 mm cable ties were used to fasten the tubing to the extent of the 50 mm PVC pipe stand. The skeleton lengths of pipe are 1 m. The bottles are placed at 10 cm and 15 cm from bed or bank height. Two bottles are used at each height as neither of them fill to 100 % because of their horizontal placement. This style of sampler is affected at a greater rate by evaporation as it is not encased within PVC cover.

Figure 4.4 Modified shallow channel sampler from Diehl (2007). A site within the Macquarie Marshes a shallow sampler was located. Intake tubes are located at the front of the sampler. Water fills the bottles as the air is released through the vents at the top of the sampler.

The shallow and deep-water samplers were attached to six foot steel star pickets with wire and fastened in two places (Figure 4.4). An insect repellent was sprayed into the opening of each part of tubing to prevent nesting in the tubes. A desk stop study was completed before installation of the samplers to identify the most appropriate locations. Unfortunately a flow had been sent through the system at the time of deployment, preventing the installation in the thalweg of the channel. Consequently the samplers were installed on either bank of the channel at the low flow mark and surveyed into a channel cross section.

4.2.2.2 Velocity and modelling for flood return interval discharge and overbank flow

The velocity at each site was measured at the time of sampling at three points of the water column (surface, mid column and channel bed) in the channel thalweg using an Enviroflow propeller-type flow meter in metres per second (m sec^{-1}).

The PINNEENA database (DWE, 2008) is a surface water archive of the Department of Water and Energy (DWE) for NSW (now Office of Environment and Heritage, 2011). The database contains information of daily stream flows, stream heights, storage levels, rainfall data, conductivity, water temperature, turbidity, pH and wind data. To determine the discharge volume of flood recurrence intervals of a 1 in 1, 2, 5, 10, 25, 50 and 100 years, log Pearson data was generated in and extracted from the PINNEENA database for each gauge location. The database contains information of daily stream flow from approximately 19 gauges currently servicing the Macquarie River catchment. DWE recognise that some data are of poor quality by the Data Quality Assurance Statement that appears in Appendix 1. Gauge data was not used unless there was at least 10 years of continuous measurements, as PINNEENA could not process a number of gauge station data for log Pearson calculations due to invalidities and missing data sets. The stage heights from the gauges of the lower Macquarie River for the dates January 2008 to December 2009 were used for the periods of suspended sample collection and suspended sediment sampler collection during field trips conducted in 2008 and 2009. Stage height for the period of suspended sampler use assists with inferring the loose time period the samplers filled.

Modelling river discharge over different return periods benefits both an investigation into understanding downstream patterns of channel capacity and specific stream power, and can assist in identifying the temporal scale of lateral connectivity for a given cross section of a reach. The software used to model discharge for this analysis was Geomorphic Assessor (Parfait, 1999). This program makes use of a variety of variables such as Manning's n coefficient of roughness, channel bed slope, the surveyed cross section, the specific weight of water, and a discharge (m^3s^{-1}) volumes for each return interval derived from calculations of data from the PINNEENA database.

4.3 Sedimentological and Geochronological Methods

Two geochronological dating methods were used to investigate the rates of sediment accumulation and sediment availability in the northern Macquarie Marshes, specifically optically stimulated luminescence (OSL) and the decay profile of unsupported lead-210 ($^{210}Pb_U$). Three in-channel cores were extracted along the primary channel of the northern Macquarie Marshes, the Bora Channel, and one core from the floodplain adjacent to the in-channel core in the northern Nature Reserve. The sites are from the Bora Channel on the property of Longstowe (LC), one in-channel site on Bora Channel within the Northern Macquarie Marshes Nature Reserve (NNRC) and one adjacent floodplain site (NNRFL), and one in-channel site at Bora Well (BWC), Figure 4.5. Three cores were extracted at each of three sites located within the channel, and on the floodplain adjacent to an in-channel site.

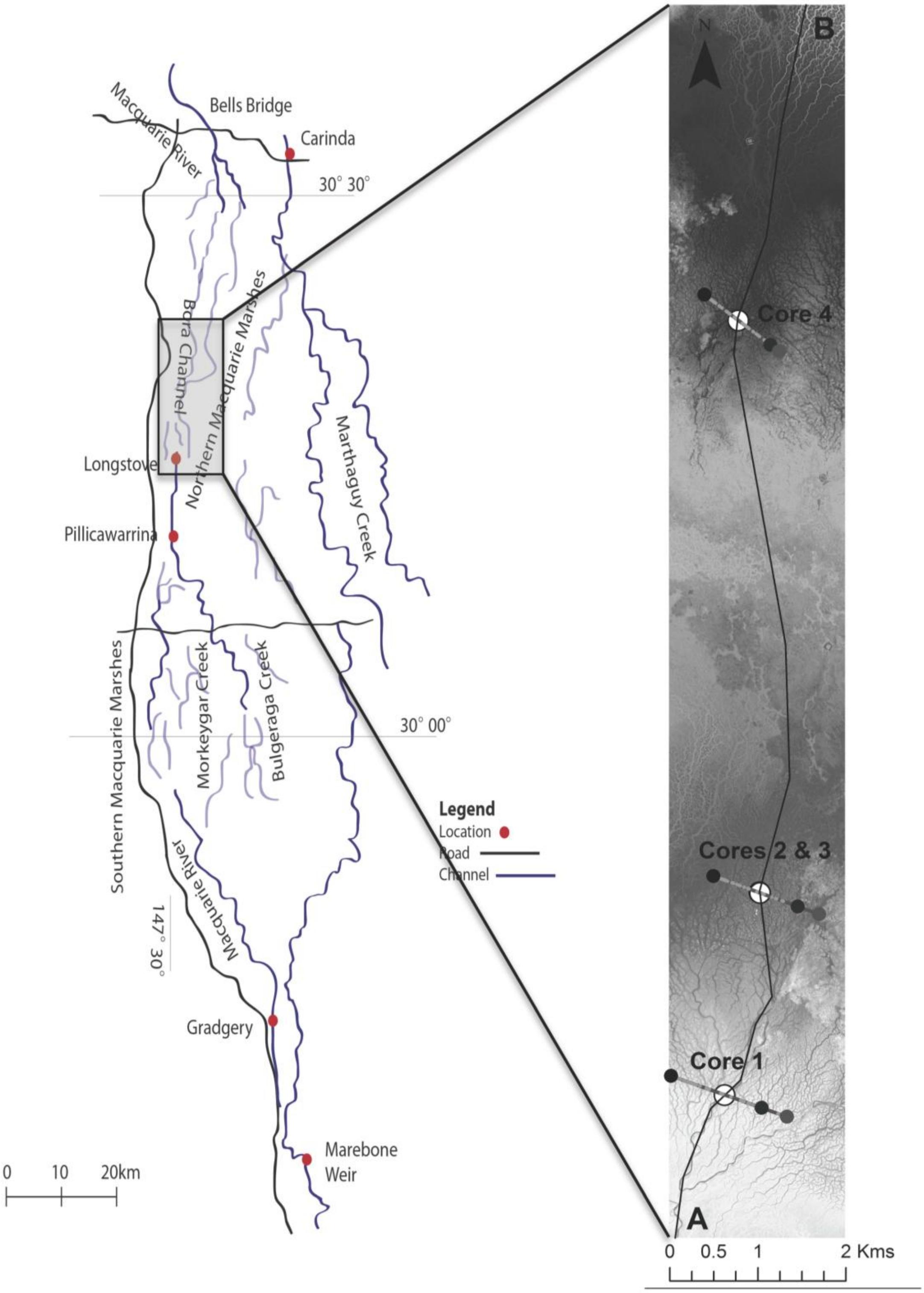


Figure 4.5 Coring sites of the northern Macquarie Marshes downstream of Pillicawarrina. The shaded area near Pillicawarrina is the Macquarie Marshes, the area of channel breakdown.

Three cores were extracted from each site with the material from each being used for various sediment dating and sedimentology applications. The maximum core depth achieved was at the floodplain site to a depth of 120 cm. The heavy clays of the in-channel cores prevented depths over 70 cm being recovered with the manual corer being used.

Sedimentological analysis of material from each site provided essential information regarding the sedimentary environment, sedimentary layers and characteristics at each site and supported a comparison between sites. The decay profile analysis of $^{210}Pb_U$ using alpha-spectrometry was applied to all cores to determine the maximum depth of $^{210}Pb_U$ activity. Freeman (2008) analysed the floodplain samples of the northern Macquarie Marshes using alpha-spectrometry on homogenised bulk material, which was additionally used for gamma-spectrometry inventory samples. Ralph (2008) used fallout ^{137}Cs technique to corroborate the ^{210}Pb radionuclide technique. However, according to Ralph (2008), ^{137}Cs was nearly always unsuccessful in the southern Macquarie Marshes because of low concentrations in the material, thus low activity. OSL and AMS ^{14}C were techniques used by Ralph (2008) as supplementary techniques to establish contemporary sedimentation rates and long-term sedimentation rates respectively, and support the findings of the radionuclide dating. For the purposes of continuity and comparison of techniques and models used by Ralph (2008) in the southern marshes, Freeman (2008) used similar techniques on floodplain sediments in the northern Macquarie Marshes. Freeman (2008) had limited success with AMS ^{14}C because of the low preservation rate of organic material in the northern Macquarie Marshes. Following the successful use of OSL and alpha-spectrometry $^{210}Pb_U$ by Ralph (2008) in the southern Macquarie Marshes and by Freeman (2008) in the northern Macquarie Marshes, this study used the OSL dating method in conjunction with alpha-spectrometry $^{210}Pb_U$.

The decay profiles for a core from each site within the northern Macquarie Marshes was established and the profile was normalised for dry bulk density. The data was used in the accretion models CIC and CRS for $^{210}Pb_U$, after Ralph (2008) applied lake and floodplain radionuclide accretion models to channel and floodplain sediment of the southern Macquarie Marshes. The central age and minimum models were used for the OSL data and as a result the more conservative MAM was used.

Outlined in this section are sediment characterisation methods applied to the cores extracted at four sites within the northern Macquarie Marshes. This section outlines the methods used for dry bulk density, loss on ignition, particle size, and soil moisture and core sedimentology. Furthermore, this section outlines the methods for OSL sample preparation and analysis, and outlines the methods of $^{210}Pb_U$ sample preparation and sample analysis.

4.3.1 Reference Condition and Contemporary Flux in the Macquarie Marshes

Reference sites associated with the region of the study and independent of contemporary catchment flux concentration are used to quantify the catchment-derived component of $^{210}Pb_U$ in the channel and floodplain sediments. Ralph (2008) and Freeman (2008) both compared their findings to a reference site in the southern Macquarie Marshes that is not impacted by inundation of catchment-derived inputs to determine the local fallout component independent of contemporary flux concentrations. Ralph (2008) established the site on the western edge of the southern Macquarie Marshes. Ralph (2008) collected and analysed a number of rain, dust and suspended sediment samples around Monkeygar Marsh to determine radionuclide concentrations in contemporary catchment derived inputs.

Freeman (2008) used Ralph (2008) reference sites for a comparison of catchment-derived flux for floodplain samples of the northern Macquarie Marshes. Ralph (2008) reference site will be used also for this study. The reference site is approximately 18 – 26 km south of the site at 'Longstowe' and 26 – 34 km south of the site at Bora Well (Freeman, 2008) and the data is provided in Table 4.3.

Table 4.3 Reference atmospheric inventories for $^{210}Pb_U$ for the Southern Macquarie Marshes. The data shows a large range or variability and low catchment derived concentrations. Data Source: Ralph (2008).

Reference Inventories	Mean Atmosphere Derived Inventories (mBq/cm^2)	Range (mBq/cm^2)	Standard Deviation (1δ)	Reference Flux	Catchment Derived Concentration (mBq/g)
Bulk $^{210}Pb_U$ (α)	281.8 ± 35.9	98.1±7.09 –534.23± 24.63	133.25	Flux $^{210}Pb_U$ (α)	20.8 ± 2.2

4.3.2 Sediment Sampling

Samples were collected in the Macquarie Marshes for luminescence and radionuclide dating during September 2009. During collection and preparation of OSL samples light must be excluded to avoid light contamination of the sample. Light contamination of the sample can affect the exposed grains by 'bleaching' them (emptying traps of stored electrons) and resetting the accumulated dose, potentially to zero. Unrealistically young ages can arise from light contamination of the sample. Thus, sample collection requires opaque, light-excluding core barrels or sample collection bags, completely preventing light penetration to the sample. Both OSL and radionuclide methods require the sample to remain in perfect stratigraphic order.

Samples from the Macquarie Marshes were collected as vertical cores, using a steel core barrel with opaque PVC liner. The steel core barrel includes a cutting shoe, which also collects 2 cm of core beyond the PVC liner. The core barrel inner liner is a 50 mm internal diameter opaque PVC pipe, cut to a length of 160 cm. Although it is possible to take deeper cores, by repeatedly inserting the barrel down the open hole, this was not necessary for this study.

The penetration depth of the core barrel and the recovered core length were measured and compared to establish whether there was sample compaction occurring or simply the core barrel was unable to accept any more sample ('driving'). This can occur when the friction of the damp clay core is too great to slide further into the liner. The top of each core was stuffed with newspaper to prevent any light penetration and reduce the movement of the sediment within the core tube. The cores were capped at both ends using a tight-fitting black plastic cap and securely adhered to the PVC pipe.

The cores were kept sealed under refrigeration to minimise light exposure and prevent drying of the sediment until sub-sampling. The three cores were extracted at each site and were sub-sampled for different analyses. Core one was used for optical dating; core two was used for $^{210}Pb_{ex}$, dry bulk density and particle size; and core three was used for soil moisture, loss on ignition of organics and carbonates, pH using a basic soil pH kit combining a dye indicator and barium sulphate and Munsell (2000) colour chart to assist with sedimentary interpretation. The core liners were opened using a handheld Dremel 300 series. The cores were sliced in half with a paint scraper under red light (darkroom) conditions for the OSL core.

4.3.3 Sediment Particle Size Analysis

Particle size affects the physical properties, including drainage and the ability to hold water, and the chemical characteristics of sediment (Rowell, 1994). Effects on chemical properties of particle size include flocculation, water and oxygen diffusion (hence redox condition). Sub-samples were taken at the same depths as samples for $^{210}Pb_U$ analysis (see below) from each of the four Macquarie Marshes cores. The sub-sample was oven dried at 105° C for 24 hours and weighed. Hydrogen peroxide (H_2O_2) was added to the dried sub-sample to remove organic matter and was heated to 60° C to stimulate the reaction. A 10% H_2O_2 solution was initially added to determine the extent of the reaction of each sub-sample. Following the first initial reaction, a 25% H_2O_2 solution was added to each sub-sample and re-administered if necessary, until the reaction ceased. The sediment was rinsed three times with Milli-RO water in the Spintron GT-20 centrifuge at 2000 rpm for 15 minutes to remove salts. The fine particulate nature of the sediment produced a cloudy supernatant. The supernatant was discarded after each run into a beaker, dried, weighed, and the mass added to the < 2 μm fraction mass for calculations. Following salt removal 10% sodium hexametaphosphate $(NaPO_3)_6$ and Milli-RO water were added to a volume of 200 ml to disperse the fine particles. The sub-sample bottle was placed in a Branson 8510 ultrasonic bath to disperse the heavy clay samples. The sub-samples were in the ultrasonic bath for 60-minute intervals. The sub samples remained in the ultrasonic bath until the heavy clays were well dispersed. Following dispersion, the sub-sample was wet sieved at 62.5 μm. The > 62.5 μm fraction and the fraction < 62.5 μm were dried at 65° C and weighed. Milli-RO water was added to the dried < 62.5 μm sub-sample with 0.2 ml of 5% Triton X - 100 dispersant to a volume of 50 ml and placed on a magnetic stirring plate with a magnetic stirring rod at high speed for one hour. The 5% Triton X – 100 and high energy stirring motion of the rod permits consistent dispersion and suspension of the sediment. The entire sub-sample was transferred directly to the mixing chamber of the Micromeritics SediGraph III 5120 for particle size distribution measurements of the < 62.5 μm fraction. The measured particle size diameters were 70 μm to 0.2 μm. The dried > 63 μm fraction was re-weighed and dry sieved at 200 μm and both fractions weighed. The original dry sample weight divided by the fractional weight produced a relative percentage for each size fraction.

4.3.4 Soil Moisture, Loss on Ignition and Dry Bulk Density

The soil moisture content of field-collected samples is dependent on the soil properties and antecedent weather and flow conditions. Soil moisture is measured by taking the wet weight of a sample and reweighing it after oven drying at 105° C. Sediment mass analyses are usually taken relative to the overall dry mass (Rowell, 1994). Core material was sub-sampled from half of a core from each site for soil moisture and loss on ignition (LOI%) at depth intervals beginning at the surface and in each consecutive 2 cm interval within the first 10 cm. One sample was taken between 10 – 15 cm and 15 – 20 cm and one sample each 10 cm interval thereafter. A 1 cm wide and 5 cm long slice was extracted from the middle of each sample interval and weighed. The sediment was oven dried at 105° C and re-weighed for a measure of the soil moisture content of the sample.

Loss on ignition (LOI%) is a technique used to determine the percentage of the total mass of a sediment sample contributed by organic and calcium carbonate by sequential heating at 550° C and 950° C (Dean, 1974; Rowell, 1994; Heiri et al., 2001). The LOI mass is expressed as a percentage of the initial dry weight as per Equation 4.1 and 4.2 (Heiri et al., 2001).

Equation 4.1 $$LOI_{550} = ((DW_{105}-DW_{550})/DW_{105})*100$$

Where LOI_{550} represents LOI at 550°C as a percentage, DW_{105} is the dry weight in grams of the sample after heating at 105°C and DW_{550} is the dry weight in grams of the sample heated at 550°C.

Equation 4.2 $$LOI_{950} = ((DW_{550}-DW_{950})/ DW_{105})*100$$

Where LOI_{950} is the LOI at 950°C and presented as a percentage. The DW_{550} is the dry weight of the sample after organic material combustion in grams, DW_{950} is the dry weight of the sample after carbonate combustion at 950°C in grams and DW_{105} is the dry weight of the sample after heating at 105°C in grams.

Following soil moisture content analysis, the organic matter and calcium carbonate content of the sediment sub-sample was measured using the LOI % method. The oven-dried (105° C) sediment is weighed in a crucible. In the first reaction, the sediment sub-sample is heated to 550° C for 24 hours in the Lindberg Blue M furnace, oxidising the organic carbon. The sample is allowed to cool to room temperature in a desiccator and re-weighed for LOI_{550} %. In the second reaction, the sediment sub-sample is heated to 950° C and kept at this temperature for at least 4 hours. Carbon dioxide is released from the sample leaving oxide, thus the LOI weight loss of $CaCO_3$ was multiplied by 1.36 by assuming the weight of carbon dioxide is 44 g mol^{-1} and the weight of calcium carbonate is 60 g mol^{-1} (Heiri et al., 2001). The sample is allowed to cool to room temperature in a desiccator and re-weighed for LOI_{950} %.

The dry bulk density (DBD) is a measure of the sediment mass per unit volume and is used as an indicator of soil porosity (Rowell, 1994). The DBD allows for a sedimentation date to be calculated in the form of grams per square centimetre per year. The core material for DBD was sub-sampled using a cylindrical container with a volume of 6.315 cm^3. The container weight was recorded before use. The matching half of the core used for soil moisture and LOI% was used for DBD sampling. The container was pushed in vertically to the middle of the sub-sample depth that was equivalent to depth intervals used for soil moisture and LOI. The sample was oven dried at 105° C and weighed. The DBD is the value of the dry mass divided by the known volume of the container and expressed in g cm^{-3}.

4.3.5 Core Sedimentology Interpretation

The sedimentology of each site was resolved by analysing one of three cores extracted from each site within the northern Macquarie Marshes. Half of the core was used for Munsell colour, sediment texture, and pH. The remaining half of the core was used to construct a stratigraphic diagram of the stratigraphy from the surface to the deepest sample point. The stratigraphic diagram included organics, calcium, manganese, and iron nodules, changes in layers, and lenses throughout the layers.

4.3.6 Sample Preparation for Optically Stimulated Luminescence Dating

The OSL method measures the release of energy or luminescence of a particle. Energy builds up within the defects of the grain's crystal structure during burial and releases the energy when it is exposed with heat or sunlight (Duller, 2004). This can be replicated in the laboratory and the energy released measured. Luminescence dating can be used to estimate the time since burial of the sample in question; effectively its last exposure to daylight (Aitken, 1998; Olley et al., 1999; Murray and Olley, 2002; Duller, 2004). The OSL method measures the time since last burial through the charges from light sensitive traps in crystal defects of quartz and feldspar grains are effectively released (Murray and Olley, 2002; Duller, 2004). Signal resetting, known as bleaching, by light is more rapid and complete than by heat, establishing optical dating as the more appropriate technique for dating sedimentary grains.

Australian quartz has been widely observed to exhibit high luminescence intensity and sensitivity: characteristics making it ideal for OSL dating (Pietsch et al., 2008; Fitzsimmons et al., 2010), in particular its suitability to the single-aliquot regenerative-dose protocol. The SAR protocol was used to determine the equivalent dose of the northern Macquarie Marsh samples. The two variables required to estimate an age of the sediment are the equivalent dose (D_e) measured in grays (Gy), which is the laboratory beta radiation necessary to stimulate a luminescence signal equal to that which the sample had acquired since burial (Aitken, 1998); and the dose rate, which is the dose per unit of time the sample had received during burial, measured in grays per thousand years (Gy ka^{-1}). The equivalent dose was divided by the annual dose estimation to produce an age estimate using Equation 4.3 (Aitken, 1998).

Equation 4.3 $$\text{Age (a)} = \text{Equivalent dose (Gy)} / \text{Dose rate (Gy a}^{-1}\text{)}$$

4.3.6.1 Sample preparation for equivalent dose

It is a requirement that sample preparation for luminescence must take place in a dark room using a subdued red light, thus the cores were opened in the luminescence lab under subdued red light. Dry or wet sieving of the sample is required, dependent on the desired mineral size fraction. The Macquarie Marsh samples were sieved into > 300 µm, 212 – 300 µm, 180 – 212 µm, 125 – 180 µm, 90 – 125 µm, and < 90 µm size fractions. The 90 – 212 µm size fractions are used for analysis and required further treatment.

The sub-samples were placed in 10% hydrochloric acid (HCl) to remove any carbonate particles. Samples are left in 10% HCl until all reactions cease. Treatment with 10% HCl is repeated until there is certainty the sample does not contain carbonates. Once the samples are dried they are treated with 10% H_2O_2 to remove organic matter within the sample. Treatment of the sample with 10% H_2O_2 should continue until reactions cease and the organics have been completely removed.

Following acid treatment and subsequent drying of the sub-samples, heavy liquid or density separation is required to separate a sample into heavy mineral and light quartz/feldspar fractions. Density separations can also remove heavily iron-coated quartz grains, which are likely to be less well bleached and therefore contain a poor luminescence signal (Singhvi et al., 1986). Another density separation is required to separate the quartz/feldspar fraction into their respective fractions. The heavy mineral and quartz/feldspar fractions of the sub-sample are separated using sodium polytungstate at a density of 2.70 g cm^{-3}. The second separation to separate the quartz/feldspar fraction is undertaken using polytungstate at a density of 2.56 g cm^{-3}.

Etching the quartz grains with a 40 % hydrogen fluoride (HF) solution removes the outer 10 μm rinds of the quartz minerals and removes the unstable, easily bleached layers of the grains (Aitken, 1998). Etching with HF also removes the alpha-irradiated portion of each grain (Rendell, 1995). Etching with HF should completely remove any feldspar minerals contaminating the quartz sample. The samples are covered with HF and remain in solution for no longer than 45 minutes. The samples were rinsed three times with water before two treatments with 10 % HCl to remove acid soluble fluorides. The sample was rinsed with water three times and then twice again with Milli-Q RO water. Samples were oven dried at 40°C. Dried samples were transferred to light-excluding vials.

The quartz samples are run through the RISØ TL-DA-20 automated single-aliquot reader with a Sr90 beta source, U340 7 mm filter and photomultiplier (PM) using blue diodes to stimulate the grains in each aliquot on a 0.5 millimetre mask for the shallow samples and a three-millimetre mask for the deep samples. Before running the northern Macquarie Marshes samples for an equivalent dose (D_e), exploratory runs on the RISØ were undertaken to determine a suitable dose rate and preheats for the samples. 24 aliquots were analysed at a shallow depth and a deeper depth at each site. The depth at which the excess ^{210}Pb was found to cease then established the shallow depth range sampled for OSL from each site. The deeper depth range at each site was taken 10 cm from the bottom of the core. Single aliquots were used for sample analysis because single aliquots or single grain analysis is the standard method of sample size for incompletely bleached samples (Murray and Olley, 2002). Initially a three-millimetre mask was used for the shallow samples.

The single-aliquot regenerative-dose or SAR protocol as outlined by Murray and Wintle (2000) was used for each aliquot. The aliquots were given five regenerative doses; regenerative dose point one and regenerative dose point five are the regenerative dose points and receive the same dose. The dose rates (Gy min^{-1}) calibrated for the RISØ at Macquarie University by K. Westaway and T. Cohen in April 2010 are processing-day-dependent for each sample. The dose rates corresponding to the processing day of each sample are listed in Table 4.4.

Table 4.4 Dose rates (Gy min^{-1}) as determined by RISØ calibration at Macquarie University in April 2010. The dose rates correspond to the sample processing dates.

Sample	**Processing Date**	**Dose Rate (Gy min^{-1})**
LC/03/03	29 March 2011	7.691439
LC/03/55	29 August 2011	7.614154
NNRC/03/15	17 March 2011	7.697534
NNRC/03/65	25 August 2011	7.616164
NNRFL/03/08	29 March 2011	7.691439
NNRFL/03/90	29 August 2011	7.614154
BWC/01/08	17 March 2011	7.697534
BWC/01/65	25 August 2011	7.616164

The irradiation was followed by a preheat of 260 °C and a heating time of 10 seconds, followed by an IR wash (removal of any infrared signal) of 50 °C for 100 seconds, followed by OSL stimulation at 125 °C for 100 seconds, followed by the test dose, a standard beta irradiation value for each sample, a preheat temperature of 160 °C, another IR wash, OSL stimulation and finalised with a hot optical wash at 240 °C for 100 seconds before moving on to the next dose point to remove any signals emitted by feldspar contamination. Sequence Pro (RISØ DTU 2008) was used to write the SAR sequence for each of the 48 positions in the RISØ carousel. The dose rates and the test doses were the only differences between each sample.

The program used to analyse the aliquot data for each sample was Luminescence Analyst Software Version 3.24 (written by Geoff Duller for RISØ, 2007). The Analyst Software enabled SAR to be calculated for each aliquot, provided the data for each dose point and a dose response curve for each aliquot. Each aliquot was carefully scrutinised to determine whether it fitted the rejection criteria detailed in Jacobs et al. (2006). The rejection criteria used by Jacobs et al. (2006) was developed on artificially irradiated grains, ensuring all grains were irradiated. However, the criteria can be applied to naturally irradiated grains although there are greater complexities and uncertainties associated with natural radiation and variable environmental conditions (Jacobs et al., 2006). It is commonly found that grains from fluvial environments such as the Macquarie Marshes have not received a full resetting of the OSL signal before burial due to factors within that environment which prevent the grains full exposure to sunlight (Jacobs et al., 2006). Following the application of each outlined rejection criterion by Jacobs et al. (2006), the removal of the rejected grains drastically reduced the calculated over-dispersion (OD) value from 12.1% to 7.0%. The rejection criteria as outlined by Jacobs et al. (2006) are shown in Table 4.5.

Table 4.5 Rejection criteria for aliquots and single grain as outlined by Jacob et al. (2006).

	Rejection Criteria	**Reason**
1.	L_N/T_N	The aliquot is rejected if the values of L_N/T_N do not intersect the dose response curve.
2.	Signal intensity	The aliquot is rejected if the signal of the test dose following the first OSL measurement is less than three times the background (T_N < 3 x BG). Removal of these grains reduced the OD value.
3.	Sensitivity correction – recycling ratios	The aliquot is rejected if the recycling ratio (R5/R1) is less than 0.9 or exceeds 1.1 (> 10%). This further reduced the OD value.
4.	OSL IR depletion ratio	The aliquot is rejected if there is evidence of feldspar contamination and the aliquot fails the IR depletion ratio test. This greatly reduced the OD value.
5.	Recuperation of the OSL signal	Recuperation of each aliquot can be assessed using the L_X/T_X ratio of the zero dose regeneration point. Minor reduction in the OD value.

Sample preparation for dosimetry measurements included drying the sample at 105°C, powdering the sample using a mortar and pestle, and then weighing the sample. The samples were sent to the Australian Government's Department of Sustainability, Water, Population and Communities Supervising Scientist (SSD) for measurement. The dosimetry or concentrations of ^{238}U, ^{235}U, ^{232}Th and ^{40}K in the powdered sediment samples were measured by high-resolution gamma-ray spectrometry. Gamma spectrometry determinations were performed by a SSD in-house method based on IR76 (Marten, 1992). Samples were pressed and measured for radionuclides after an ingrowth period of three weeks for radon progeny, to determine ^{226}Ra from the ingrown ^{214}Pb and ^{214}Bi.

4.3.6.2 Sediment age and sedimentation rate determination

The central age model (CAM) was initially used on the aliquots of each sample to determine the central age, the error and the scatter or over dispersion (OD) of values. Over dispersion (OD) in a D_e distribution is a quantitative measure referring to the standard deviation of a distribution of single aliquot D_e values from a central D_e value, after the estimation of the statistical error (Jacobs et al., 2006). The CAM data was used to generate radial plots, which display the data in such a way that it is easier to locate populations or multiple populations and discriminate between aliquots. The radial plot shows each aliquot in respect to the standardised error allowance for each sample. An OD of 20 % or less shows a normal distribution of bleached grains whereas an OD greater than 20% alludes to either partial bleaching or two populations of grains. The most rigorous models for incompletely bleached samples are the minimum age model and the finite mixture model (Galbraith et al., 1999; Thomsen et al., 2007). Due to the high value of OD using the CAM, the data was used in Minimum Age Model (MAM). The MAM was used following the results of the CAM. The MAM uses the aliquot that represents the minimum age of the sample with the best accuracy and precision. The MAM is the most conservative approach to data that is displaying multiple populations, large errors and high degree of scatter. The dose rate and error calculated by the MAM is used in estimating the final age of the sediment using the Final Age Model (FAM). The following data for each site was entered into the FAM to calculate an estimation of the final age: the data from the dosimetry results; MAM calculated value and error at one sigma; field water content and estimated range of water contents; the cosmogenic value as determined by the depth of the sample; shielding and the latitude and longitude.

The sample depth interval and the corresponding age, estimated using OSL, of each sample was used to derive an estimate of the sedimentation rate using Equation 4.4.

Equation 4.4 Interval Depth (cm) / Age Interval (years) = Sedimentation Rate (cm yr^{-1})

The sedimentation rate is averaged over the depth from the surface to the shallow luminescence depth and again averaged between the surface and the deepest luminescence depth.

4.3.7 Sample Preparation for Radionuclide Dating

Fluvial applications of the $^{210}Pb_u$ method contribute to identifying the geomorphology and evolution of floodplains (He and Walling, 1996) and the erosion and sediment delivery processes within a fluvial system (He and Walling, 1996b). Accurate chronologies of the sediment of these environments can be undertaken with the isotopic method of ^{210}Pbu geochronology (Noller, 2000). Age estimation using ^{210}Pbu geochronology is based on the radioactive decay of radium-226 (^{226}Ra) to its daughter isotope, the gas radon-222 (^{222}Rn) and then to ^{210}Pb in the ^{238}U decay series. The difference between unsupported and supported ^{210}Pb is explained further in the next section. $^{210}Pb_u$ radionuclide dating is an ideal method for dating recent sediments, especially in established carbon poor sediment. The ^{210}Pbu radionuclide technique yields a sediment age/depth relationship for modern sediments with an age range of 0 – 150 years BP (Brenner et al., 1994; Appleby, 2001).

The excess or unsupported ^{210}Pb method of dating to establish a sedimentation rate for the northern Macquarie Marshes using alpha spectrometry was chosen because of its successful use in dating other Macquarie Marshes sediments (Ralph, 2008; Freeman, 2008) and the failure of other methods such as AMS ^{14}C dating (Ralph, 2008) in marsh sediments. The first stages of sample preparation were undertaken at Macquarie University. The remaining stages of sample preparation and sample analysis were completed at the Australian Nuclear Science and Technology Organisation (ANSTO) at Lucas Heights in Sydney, Australia.

Alpha spectrometry was used to determine the activity of $^{210}Pb_U$ of the Macquarie Marshes sediments. The research of sediment accumulation rates in the Macquarie Marshes by both Ralph (2008) and Freeman (2008) directed the in-channel $^{210}Pb_U$ of the northern Macquarie Marshes to be measured by alpha spectrometry in preference to gamma spectrometry. Alpha spectrometry measures the alpha radiation emitted by polonium-210 (^{210}Po), the granddaughter product of ^{210}Pb decay (Appleby, 2001). Alpha spectrometry is more sensitive than gamma spectrometry and most suited to determine the activity of $^{210}Pb_U$ in small samples of very low activity (Appleby, 2001). Radium-226 (^{226}Ra) measurement is used as a proxy to determine the supported ^{210}Pb activity in the sediment (Appleby, 2001).

4.3.7.1 Sample preparation

Sub-samples were taken at the surface (0 cm), 2 cm, 3 cm, 5 cm, 7 cm, 8 cm, 10 cm, 15 cm, 20 cm, 30 cm and every 10 cm afterwards, for the length of the core. Each sample was extracted carefully to leave a 2 mm thick outer rim of sediment inside the core. Each sub-sample was placed in a weighed and labelled beaker. The beaker was reweighed with the sample and the wet weight of the sample recorded. The sub-samples were dried in the oven at 60 ° C for 48 hours. After 48 hours the samples were removed from the oven and reweighed to determine the dry weight of the sample. After reweighing, each sample was pulverised in a mortar and pestle to a fine homogeneous powder. The chemical procedures for alpha spectrometry of the fine homogeneous powdered samples were completed at ANSTO.

4.3.7.2 Chemical treatment

A sample weight of 0.2 – 2 g of sediment was accurately weighed into a 150 mL beaker. The ground samples were administered an additive by pipette of approximately 10 dpm of both the radioactive tracers Polonium-209 (^{209}Po) and Barium-133 (^{133}Ba) prior to analysis for Polonium-210 (^{210}Po) and Radium-226 (^{226}Ra). The radioactive tracers, ^{209}Po and ^{133}Ba, were added before processing to gauge the chemical recovery of ^{210}Po and ^{226}Ra post processing. There was the addition of a sample blank with each set of samples tested. After testing the sample reaction to 2M nitric acid (HNO_3), 25 mL of concentrated HNO_3 was added. The liquid was evaporated to dryness on a hot plate. Once the samples were dried and cooled, 5 – 10 mL of 10% H_2O_2 was added to cover the sediment in the bottom of the beaker. This step was repeated until 25 mL of 10% H_2O_2 was added. The samples were heated on a hot plate until the effervescence ceased and all organics were eliminated.

After cooling the beakers, reagent water was added to the beaker to bring the volume to 25 mL. A volume of 25 mL of concentrated HCl was added to each beaker. The addition of the HCl in the production of a constant boiling point acid composition dissolves all authigenic phases and leaches the surface of clays and primary minerals. The samples were left to reflux for four to six hours on a hot plate to dissolve all carbonates.

Once reflux of the samples was complete, the samples were removed from the hot plate and cooled. The material was rinsed three times in 50 mL of 6M HCl in the centrifuge at 4500 rpm for three minutes. An ether extraction was undertaken on the samples to extract any excess iron. On completion of the ether extraction the samples were left on a hot plate overnight to evaporate to dryness. Following the ether extraction, the sample was prepared for the autodeposition of ^{210}Po analysis with the addition of 50 mL of 0.1M HCl, 100 µL of 1.0M citric acid, 10 mg of Bismuth $(Bi)^{3+}$ holdback carrier and 1 g of hydroxyl-ammonium chloride. A silver disc was suspended in the solution for six hours. Each disc became the measurement source for ^{210}Po and the tracer ^{209}Po.

The isotopes of ^{226}Ra and the tracer ^{133}Ba remained in solution and collected by lead sulphate co-precipitation using 20 mL of sulfuric acid, 100 mL of 20% sodium sulfite and 10 mL of 10 mg mL^{-1} Pb^{2+} carrier in 0.1M HNO_3. The solution settled overnight and the supernatant was discarded. The pH was adjusted to > 9 and barium sulfate, and 1:1 acetic acid and water mixture were added to encourage precipitation of ^{226}Ra and the tracer ^{133}Ba. The precipitate was filtered onto a 0.1 µm membrane and used as the measurement source for ^{226}Ra and the tracer ^{133}Ba.

4.3.7.3 Sedimentation rates – ^{210}Pb

Profiles of $^{210}Pb_U$ versus depth (cm) are used to calculate sedimentation rates and profiles of $^{210}Pb_U$ versus mass depth (g/cm) are used to calculate sediment mass accumulation rates (Zaborska et al., 2007). The ^{210}Pb data was normalised against the sediment particle size, in particular the less than 2 µm fraction and the dry bulk density data. To extract a date using the unsupported $^{210}Pb_U$ the reference sites referred to in Ralph (2008) were used as a comparative site. The constant rate of supply (CRS) and the constant initial concentration (CIC) models were both used to determine a rate of sedimentation of the in-channel and floodplain zone of the Macquarie Marshes. The CIC and CRS models were used to compare the output, as neither model is totally suited to the marsh environment (Ralph, 2008).

4.4 Chapter Summary

The chapter outlined the methodology for surface samples collected along the lower Macquarie River and the key geochronology techniques used to establish sedimentation rates in the northern Macquarie Marshes, OSL and unsupported ^{210}Pb. It outlined the analysis undertaken for each sample collected and the data sources collected from external organisations. Additionally, it outlined the models used to determine the ages of sediments OSL and the sediment accretion models used for the unsupported ^{210}Pb data and data collection and laboratory techniques required to fulfil the needs of this project in the field, at Macquarie University and at ANSTO. Furthermore, the results of data collection and analysis are displayed and discussed with consideration of their implications on the lateral and longitudinal connectivity of the lower Macquarie River and the implications for channel breakdown.

Chapter 5: Results 1, Geomorphological and Hydrological Characteristics of the Lower Macquarie Marshes System

5.1 Introduction

Downstream patterns of geomorphic and hydrological characteristics are a key driver of longitudinal and lateral connectivity of water and sediment transfer within that system. (Dis)connectivity for the lower Macquarie River was assessed across several dimensions; reach-reach, trunk – tributary and channel – floodplain by examining the patterns of discharge and stream power, floodplain inundation through flood frequency magnitude assessment, and total suspended solids concentrations.

Patterns within the datasets assist in linking processes and forms within reaches and provide a rationale for further investigation into driving forces of channel behaviour. Patterns within the suspended solids data have been used to identify areas of sediment supply, transfer, deposition and competent discharge. Patterns of channel gradient and landscape setting assist in identifying the calibre and type of sediment generated and the potential energy of the reach. Patterns within the flow data and flood frequency/magnitude relationships identify lateral and longitudinal connectivity of sediment transfer and deposition. Patterns of geomorphic units in the channel zone can be used to identify points of erosion and deposition and indicate sediment movement within and between reaches. Vegetation blocking in reaches can imply sediment deposition and decreases in velocity.

Identification of lateral and longitudinal (dis)connectivity through an analysis of the mechanisms controlling the character and behaviour of the lower Macquarie River and, in particular, the northern Macquarie Marshes, identifies the processes that shape the contemporary wetland system. The resulting physical form of channel breakdown and the floodplain wetlands it supports greatly influences the ecosystem services provided by the Macquarie Marshes.

This chapter presents the geomorphological and hydrological results form fieldwork and lab analysis over a two-year period from 2008 to 2009 of the lower Macquarie River in central west NSW. The data highlights downstream patterns, trends and the mechanisms involved in determining river form. It describes the impacts of controls on water and sediment movement through the channel longitudinally and laterally from the channel to the floodplains. Ultimately, the patterns and trends displayed through the data determine the mechanisms that drive channel breakdown of the lower Macquarie River, forming the Macquarie Marshes and a unique suite of ecosystems services in semi-arid NSW.

5.2 Downstream Patterns of the lower Macquarie River

This section features the downstream patterns and trends in the physical form of the lower Macquarie River, with initial reach analysis beginning downstream of the Burrendong Dam wall and ending at the reach incorporating Bells Bridge Carinda, downstream of the Macquarie Marshes (Figure 5.1a).

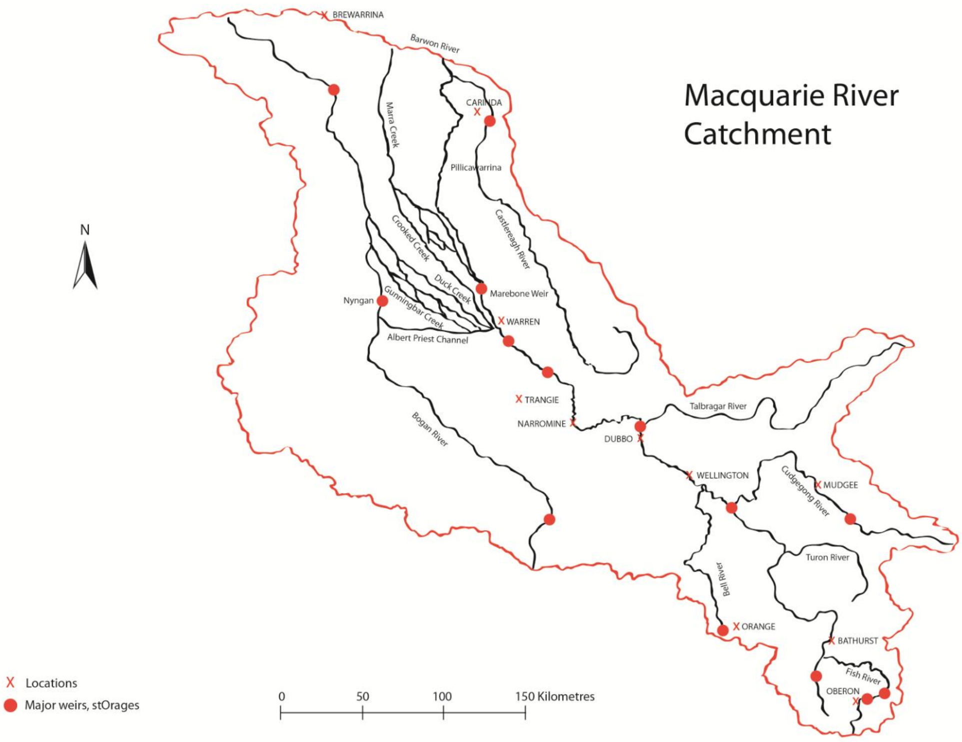


Figure 5.0.1a Macquarie River catchment showing the study reaches. Burrendong Dam is shown on the map as a major storage upstream of Wellington and Carinda.

5.2.1 Physical Controls on character and behaviour of the Macquarie River

This sub-section describes the reach styles, channel geometry, in-channel and floodplain geomorphic units, and reach behaviour at different flow stages. The valley setting and bed material texture substantially influence the types and forms of geomorphic units, channel gradients, floodplain formation and therefore flow characteristics (Brierley & Fryirs, 2005). Topography is a broad scale control on channel form and behaviour of the lower Macquarie River. There are four distinct valley settings downstream of Burrendong Dam. In this study, reaches have been broadly determined on the confinement of the valley and the ensuing character, behaviour and bed material texture (Brierley & Fryirs, 2005).

Four valley settings were identified of the lower Macquarie River and these are confined, partly-confined bedrock controlled, partly-confined planform controlled and laterally unconfined. The section of the lower Macquarie River being assessed presents six reach styles. One reach style is repeated and is the meandering fine-grained reach (reach) 5 upstream of the Macquarie Marshes (reach 6) and then repeated downstream of the Macquarie Marshes as reach 7. Each reach style has a particular morphology and assemblage of geomorphic units as detailed in the valley setting and reach style tree in Figure 3.6 and Table 5.1. The reach numbers refer to the reach styles from Burrendong Dam to Carinda, which are reach 3 to 7 in Figure 3.5. The Macquarie Marshes are reach 6 and have been divided into 6S for the southern Macquarie Marshes and reach 6N for the northern Macquarie Marshes to distinguish the marsh complexes.

Table 5.1 The reach styles and valley settings, and the associated river character and behaviour of the lower Macquarie River

Valley setting/ Reach Style	Landscape unit	River Character			River Behaviour
		Channel Planform	Geomorphic Units	Bed Material Texture	
Bedrock-confined valley Gorge (R1)	Escarpment	Single channel, highly stable, low sinuosity 1.0	Pools, glides, waterfalls, no floodplain	Bedrock – boulder – gravel – sand	Narrow valley. Vegetated islands and bank attached bars form on sand and gravel islands and bank-attached bars. The channel is heterogeneous.
Partly-confined Valley Bedrock Controlled Discontinuous Floodplain Pockets (R2)	Base of escarpment - rounded foothills.	Single channel, moderately stable, low sinuosity 1.1	Pockets of discontinuous floodplain, point bars, benches, pools, riffles/rapids, ledges	Gravel - sand	Progressively transfer sediment from point bar to point bar. Sediment accumulates on floodplain and inside of bends. Erosion of sediment from concave banks. Floodplains form behind bedrock spurs.
Partly-confined Valley Planform Controlled Discontinuous Floodplain Pockets (R3)	Alluvial valley in the rounded foothills	Single channel, some room for lateral migration, high sinuosity 1.2	Pockets of discontinuous floodplain, point bars, benches, pools, riffles/rapids, ledges	Smaller gravel - sand	Greater amount of deposition occurs in this reach due to the ability for migration across the narrow valley floor. Deposition on in-channel features and floodplain. Erosion along occurs along the concave bank of the reach leading to undercutting and ledge formation.
Laterally-unconfined valley Meandering Sand Bed (R4)	Flat alluvial valley plain	Single channel, lateral instability, high sinuosity 1.4	Continuous floodplain, in-channel sandy geomorphic units - mid channel sand sheet, point bars and ledges.	Sand	Accumulations of sediment occur along this reach, being deposited mid channel and at point bars. Room and evidence of lateral migration from ridge and swale type features. Suspended sediment vertically accretes on floodplain.
Laterally-unconfined valley Meandering Fine Grained (R5 &7)	Flat alluvial valley plain	Single channel, lateral stability cohesive sediment, high sinuosity 2.0	Continuous floodplain, ledges, long pools, runs, compound bank attached bar/island	Fine grained mud - clay, silt	Depositional environment. Avulsion occurs in this landscape interpreting channel infill over time. Reaches are very homogeneous. Deposition occurs on vertically accreted channel bed & floodplain.
Laterally-unconfined valley Fine grained Anabranch with Floodout Splays (R6)	Flat alluvial valley plain	Multi-channelled system, laterally stable, sinuosity range (1.6 – 1.0)	Continuous floodplain & Gilgai formations floodplain marsh channels. No in-channel geo-units.	Fine grained mud - clay, silt	Depositional environment. Avulsion occurs in this landscape interpreting channel infill over time. Reaches are very homogeneous. Deposition occurs on vertically accreted channel bed & floodplain. Floodout splays are intermediate.

The downstream pattern of channel gradient is an important intrinsic control on reach behaviour and character, and is related to downstream changes in sinuosity, bed material texture and valley setting. The gravel bed reaches downstream of Burrendong Dam have a slope ratio of 0.0009 m/m. At the representative sites Ponto Falls (R2) and Minore Falls (R3), the floodplain slope is greater in these reaches within the partly confined bedrock controlled channel setting at higher landscape elevations of rolling foothills. Slope ratios are 0.0006 m/m and 0.0005 m/m respectively. These reaches are confined within a narrow valley (Table 5.1). The valley width increases in a downstream direction from partly-confined to laterally-unconfined and the bed material texture transitions from gravel and sand to mud dominated. Floodplain and channel gradients decrease downstream from 0.0004 m/m at Turkey Farm Reserve near the township of Narromine (sand bed) to 0.0002 m/m at Marebone Weir downstream of the township of Warren (mud dominated) shown in Figure 5.1b. Sinuosity increases from values of 1.0 and 1.18 in reaches 1 and 2 before increasing to a more sinuous channel. As the river planform becomes a tighter meandering system in the low gradient unconfined reaches, the sinuosities increase from 1.4 to 2.0 in reaches 4 and 5. The increases in sinuosity around Warren (219 km) correspond with decreases in slope and increases in valley width. The sinuosity of reaches remains in the moderate to high sinuosity until the distributary and contributory channels of the Macquarie Marshes. Channels of the anabranching marsh system show local increases in minor steepening of the channel gradients, corresponding to increases in channel straightening. Re-channelisation of the Macquarie River trunk channel downstream of the Macquarie Marshes shows a decrease in channel gradient and a corresponding increase in sinuosity, Figure 5.1b.

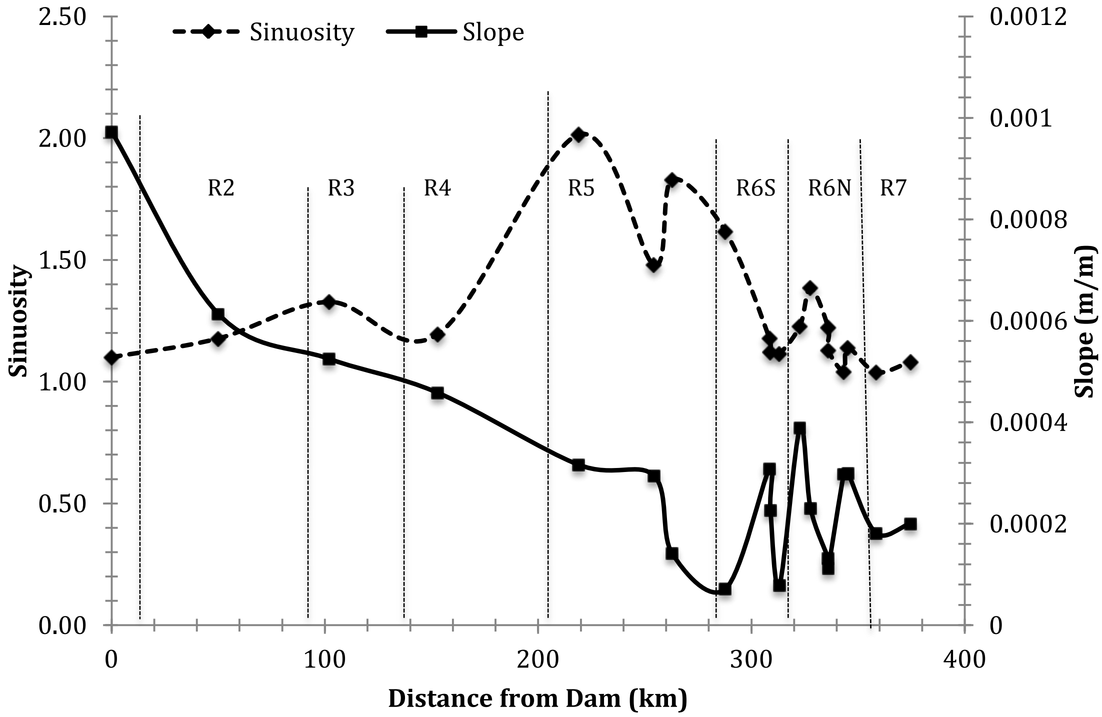


Figure 5.1b Floodplain (R1-5) and channel (R6-7) gradients and sinuosities of the lower Macquarie River. There is a general decrease in gradient and a general increase in sinuosity of the lower Macquarie River. However, there is evidence of channel gradient increases and sinuosity decreases within channels of the northern Macquarie Marshes.

Channel and floodplain elevation derived from LiDAR data of the Macquarie Marshes was field tested for precision by Hesse (2009) showed good vertical control to about two centimetres without obvious noise (point to point random variation). The LiDAR data was used to derive floodplain slope within the marshes and is reflected in the large scatter of channel slope values between the lowest slope ratio at Oxley of 0.00007 m/m and the last slope ratio at Miltara near Bells Bridge of 0.0001 m/m. There is a spike in channel gradient at the Breakaway in the south marsh 0.0003 m/m, Pillicawarrina 0.00038 m/m and the Bora Channel downstream of Bora Well 0.00029 m/m. The spikes are small changes in ratio from the lowest values of 0.00007 m/m at Willancorah and 0.0001 m/m at Longstowe, the start of the Bora Channel.

Floodplain and channel slope, and changes in valley width are shown in Figure 5.2. Elevation decreases downstream from 300 metres above sea level and valley width increases downstream from 250 kilometres from Burrendong Dam after confined, partly-confined bedrock controlled and partly-confined planform controlled valley settings. The elevation continues to decrease to 120 metres above sea level as slope decreases to an average of 0.0002 m/m in the Macquarie Marshes and valley width increases to approximately 200 kilometres.

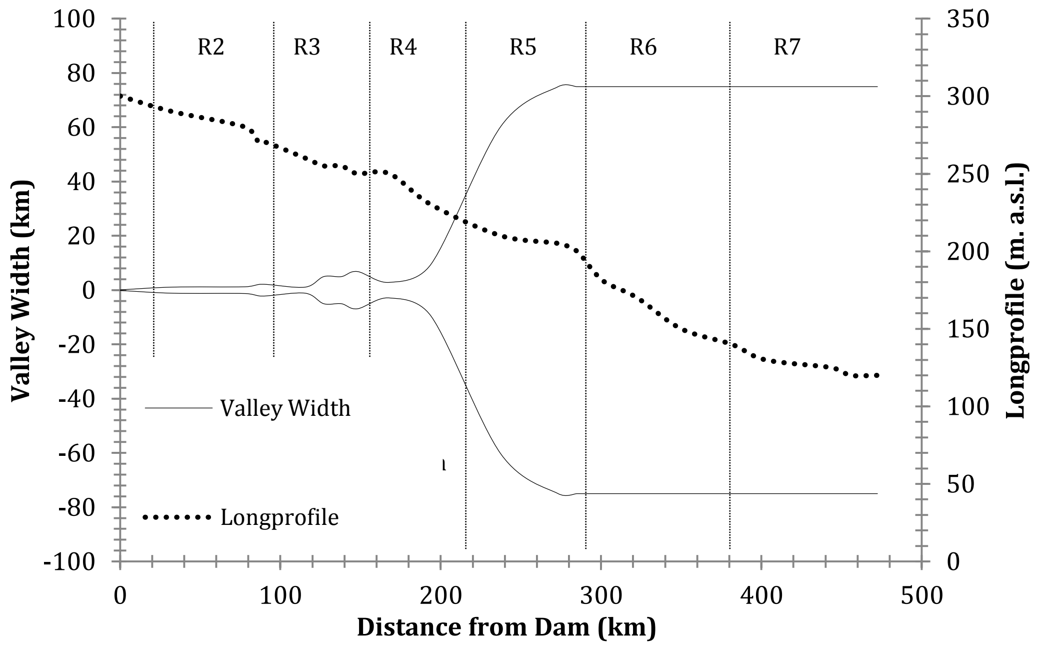


Figure 5.2 The valley width and floodplain elevation of the lower Macquarie River.

5.2.2 Channel morphology of the lower Macquarie River

Longitudinal patterns of channel morphology can be distinguished from the w/d ratio, channel cross-sectional area and cross sectional shape. Observed longitudinal patterns of channel shape from reach 1 to reach 7 include a general narrowing of the trunk channel and increases in the degree of homogeneity of the in-channel zone in the northern Macquarie Marshes. There are differences in the channel morphologies of the marsh channels between the southern and the northern Macquarie Marshes (Figure 5.3 a-c).

The in-channel and floodplain geomorphic units of the lower Macquarie River corridor change down catchment and are dependent on confinement, bed material texture and discharge. Reach 1 is bedrock confined with no floodplain units. In reach 1, there is bedrock and boulder steps, bedrock controlled pools, boulder bars and attached gravel bars and flood chutes. Reach 1 is typically a transfer reach.

Reach 2 is partly confined bedrock controlled with discontinuous floodplain pockets. In-channel geomorphic units present are point bars and compound point bars on the convex bends of gravel and sand coarsening upwards. There is a Bmax of 0.005 m to 0.15 m of the gravels. Bar length is up to 15 m with a width of 2 m. Benches are gravel at depth, fining upwards with a height of 1.5 m. Deep pools are approximately 100 m in length and up to 5 m in depth. Riffles are composed of gravel and are greater than 50 m in length and approximately 0.5 m in depth. Bank scour is visible in the form of erosional ledges. The floodplain geomorphic unit presents a defined floodrunner that is 30 m in length and 1 m wide. Scour holes are evident around floodplain vegetation. Terrace features have become rounded; evidence of age and the sedimentology of the floodplains is gravel at depth overlain by finer sand particles. Reach 2 is predominantly a transfer reach with deposition of bedload and reworking and erosion of banks and gravel bars.

Reach 3 is partly confined planform controlled by old terrace features with discontinuous floodplain pockets. Ridge and swale features are evidence of lateral migration and channel instability. Gravel bed pools are extensive in length up to 50 m and 1.5 – 2 m in depth. Riffles or rapids are shallow at 0.2 – 0.5 m in depth. Point bars are composed of medium to well sorted coarse gravels with a Bmax of up to 0.08 m down to coarse sand. Point benches are gravel at depth, fining upwards with waning flow and a height of 1.5 m. Erosional ledges present from periods of greater stream power and higher flow, possibly a result of human disturbance and recreation activities. Erosional ledges are has arisen as a result of scouring downstream of trees on the channel bank. They vary in height and width. The floodplain geomorphic unit presents cut-offs and floodrunners up to 70 m in length. The channel cross-sections are shown in Figure 5.3a. Typically a transfer zone in reach 3, however, erosion dominates over deposition.

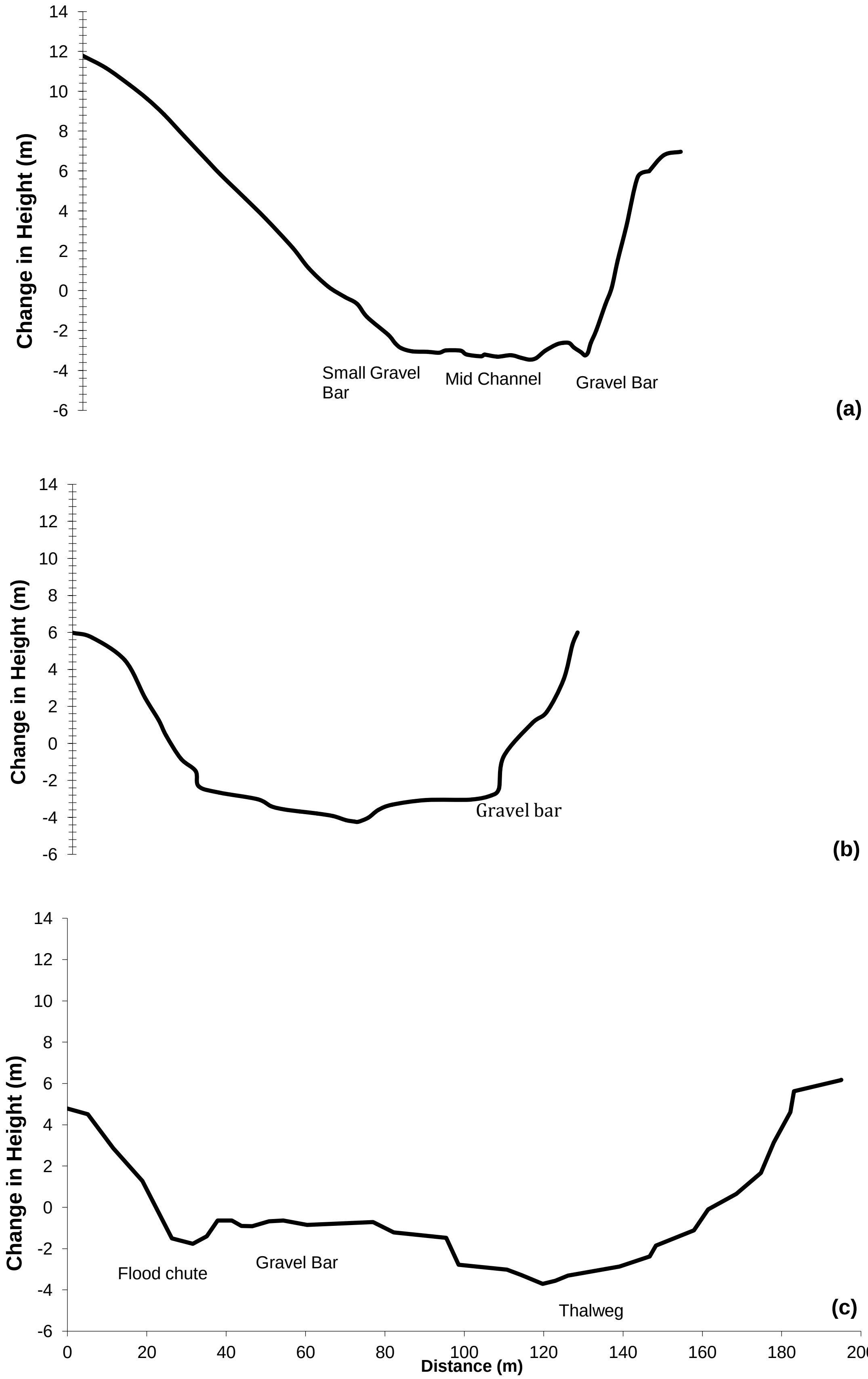


Figure 5.3a Channel cross sections: (a) R1 – D/S Burrendong Dam; (b) R2 – Ponto Falls; (c) R3 – Minore Falls. Left hand side – left bank and right hand side – right bank.

Reach 4 is laterally unconfined meandering sand bed channel and is depositional in periods of low stage flow and erosional in periods of high stage flow. In-channel geomorphic units present are a mid-channel sand sheet forming downstream of a vegetative barrier. The sheet was approximately 3 m in length and 1 m wide. Point bars are present on the convex meander bends, roughly at a height of 0.2 m and a width 2 m. Erosional ledges produced on the banks at high stage marks and range in height and width of up to a 1 m. Continuous floodplains present cut-offs where the flow has short circuited the original channel in overbank flows and a new channel section forms. Palaeochannels are also evident on the floodplain. Backswamps are present throughout the floodplains around the study reach. Levees are present along much of the reach, however, in many places it has been worn down by cattle, construction of weirs or human disturbance. Floodrunners are present on the floodplain, where overbank flows are funnelled through. Terraces confine the extent of floodplain and cause the floodplain to meander with the channel. Floodplain material is composed of sand in a semi cohesive nature mixed with clays.

Reach 5 and 7 are laterally unconfined meandering fine-grained channels with continuous floodplain. In-channel geomorphic units include ledges appearing low on channel banks due to incision by a constant low stage flow. Banks are at a low angle and long pools occur in the widened areas of the channel with small narrow runs between the next widened pools. Pool length is up to 25 m with a width of 10 m and a depth up to 0.5 m. There is a well-vegetated island at bankfull. At low flow, the island forms part of a compound bar with a flood chute. The compound bar is approximately 30 m in length and 8 m wide. Continuous floodplains contain palaeochannels in the landscape indicating the infilling of previous channels and avulsions. Also present are cut-offs and backswamps, and there are eroded incisions into the floodplain that have lead to incision of the left bank. Floodplains are composed of fine cohesive materials such as clays and silt, with a minor volume of sand. Channel more homogenous in form in reach 5 with more heterogeneity in reach 7. Reach 5 and 7 are deposition dominated with reworking of fine sediment during high stage flows.

Reach 6 is represented by sections of unconfined continuous meandering fine-grained trunk channel and fine-grained anabranching channels with floodout splays and continuous floodplain. Reach 6 has been divided into two because of quite distinct channel morphologies. Reach 6S (southern Macquarie Marshes) is characterised by primary distributaries, some that floodout removing streamflow from the system and some which re-route flow back to the trunk channel. Extreme channel incision of The Breakaway, the most recent channel formed by erosion, that major rock works have occurred to slow the flow of water and reduce further in-channel erosion. Rocks weirs create a pooling effect and most likely enhance sediment deposition and shallow channel gradients in pooled sections. It was observed in Bulgeraga Creek sandy deposits on the channel bed, likely to be reworked in-channel sediments and consistent bank erosion. Reach 6N (northern Macquarie Marshes) is characterised by mostly homogenous channels and floodout splays. The Gilgai floodplain units comprise of well-defined floodchannels present when overbank flows occur. Floodplains are composed of fine-grained clays and silt. These conhesive materials create a stabile floodplain environment, which can withstand scouring by the flow velocities in this environment. This is a dominantly depositional reach. Cross sections for reaches 4 to 7 are shown in Figures 5.3b and 5.3c. The trunk channel and initial anabranches at the beginning of the northern Macquarie Marshes show evidence of bank erosion and fin-grained bar deposition prior to the multi-channelled system.

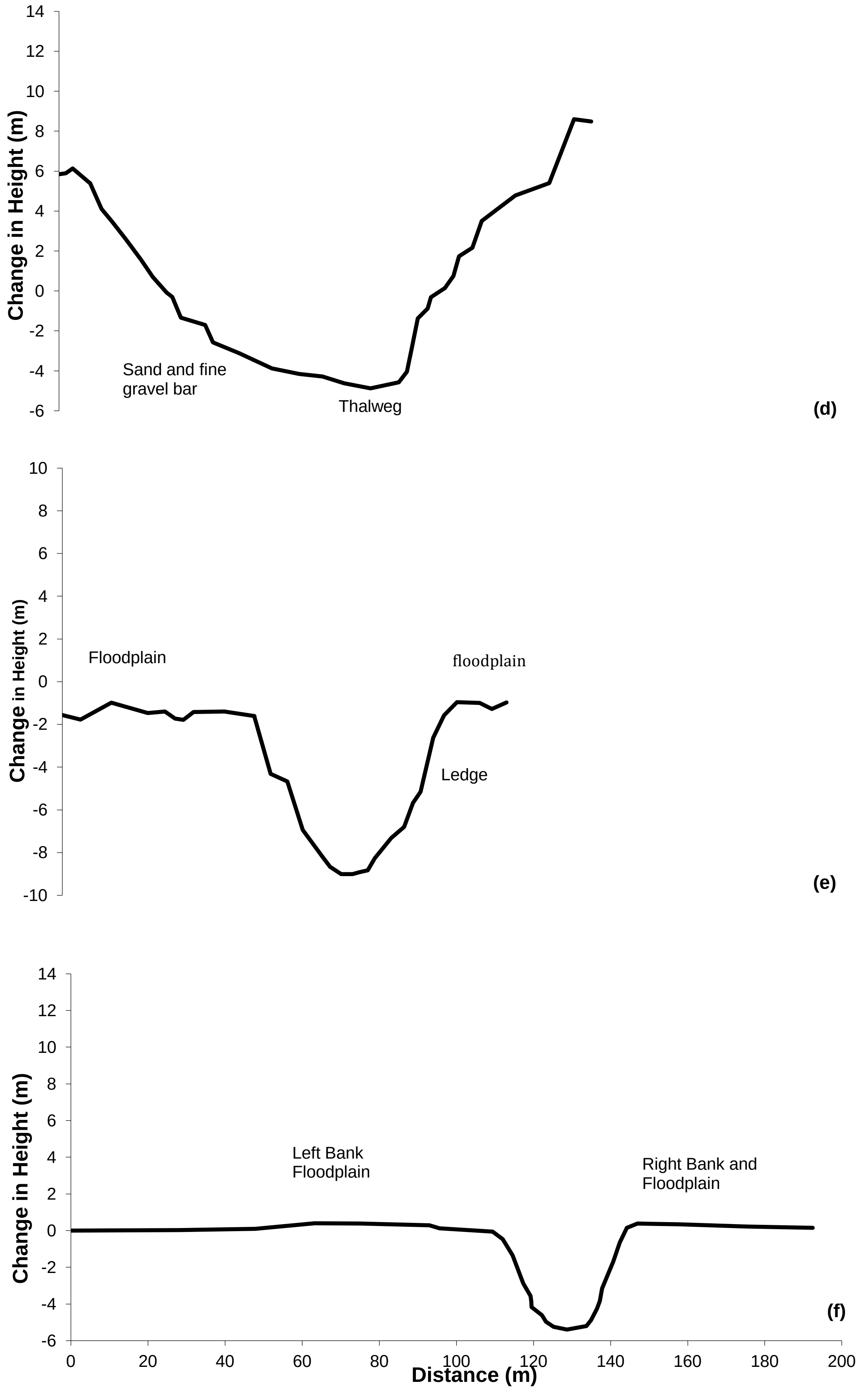


Figure 5.3b Channel cross sections: (d) R4 – Turkey Farm Reserve; (e) R5 – D/S Warren town; (f) R5 – Gradgery. Left hand side – left bank and right hand side – right bank.

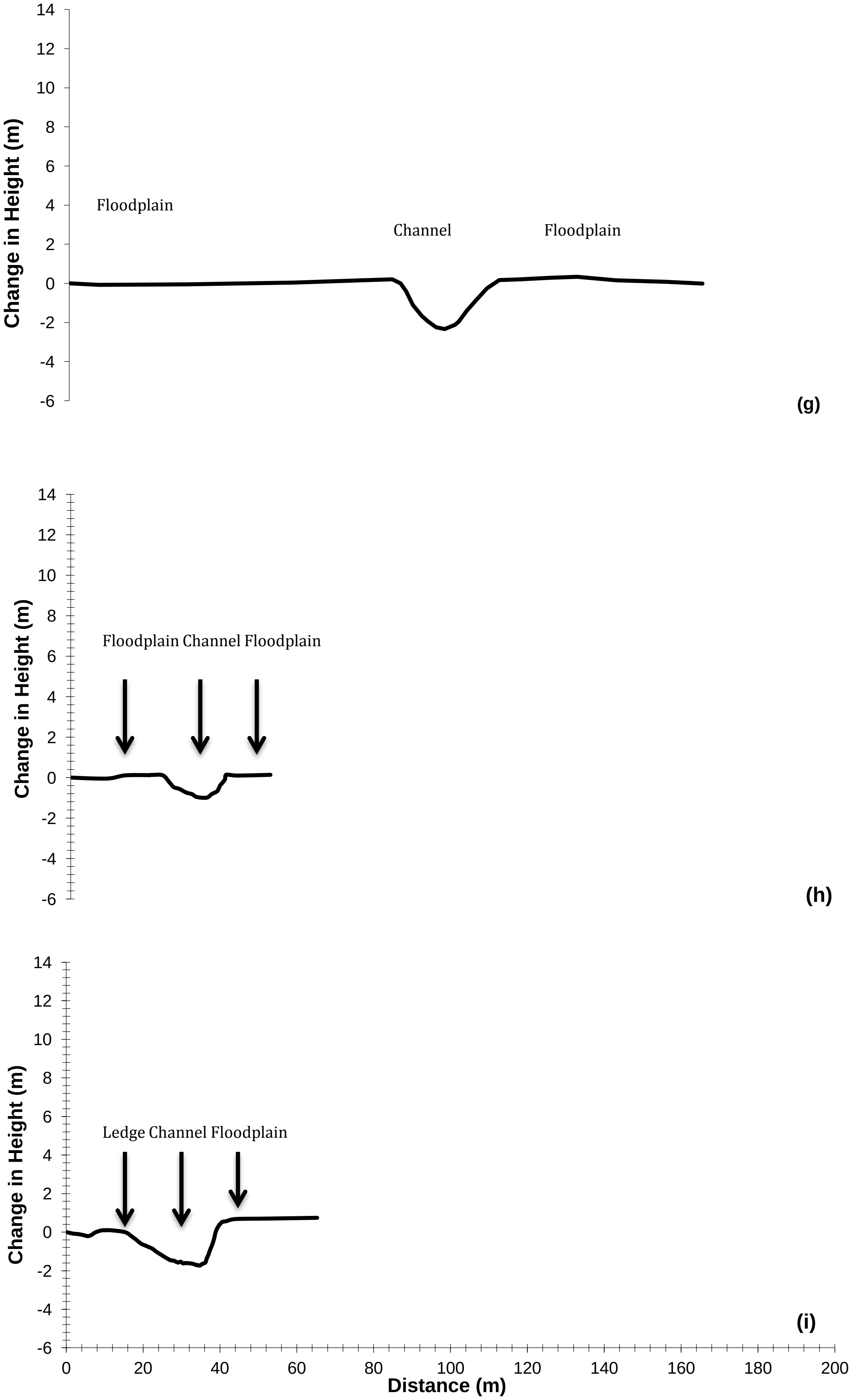


Figure 5.3c Channel cross sections: (g) R6S – Monkeygar Creek; (h) R6N – U/S Channel breakdown Bora Channel; (i) R7 – Bells Bridge. Left hand side – left bank and right hand side – right bank.

The reach-averaged width:depth (w/d) ratios of the channels within the southern Macquarie Marshes are greater than those of the northern Macquarie Marshes (ranging from 12 to 32), shown in Figure 5.4. Reach 6, the Macquarie Marshes, has been split into reach 6S and reach 6N to distinguish the different channel morphology between the two marsh complexes. The pattern evident in the reach averaged data for w/d ratios and channel area is a general increase in w/d ratio from reach 5 to reach 6N (ranging from 8 to 32) before decreasing at reach 7 (w/d of 15) and a general decrease in channel cross-sectional area from 58 m^2 at reach 5 to 6 m^2 at reach 6N and then increasing to 21 m^2 at reach 7. The channels in reach 6S are dimensionally different compared to channels in reach 6N. Reach 6N is characterised by channels with a range of width: depth ratios that are on average higher than other reaches and a small channel cross-sectional area with an average width: depth ratio of 32.4 and cross sectional area of 5.9 m^2. Reach 7 displays both moderate average width: depth ratio and channel cross-sectional area in comparison, similar to reach 6S and quite different to reach 5, which has been classed as the same reach type (Table 5.1).

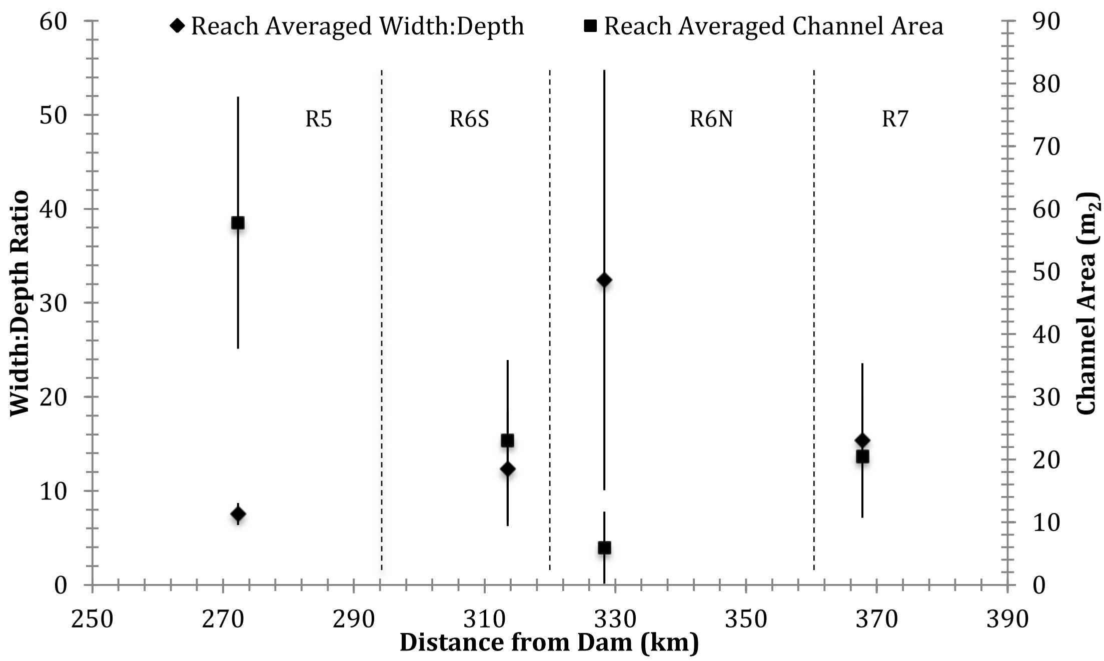


Figure 5.4 Reach averaged width: depth ratios and channel cross-sectional area from Marebone Weir to Bells Bridge Carinda.

The channel dimensions between reach 5 to reach 7 indicate spatial changes in the through-flow of suspended sediment and water, both longitudinally and laterally. It is likely there is a greater connection of the channel – floodplain of the reaches that have higher average w/d ratios and small average channel cross sectional areas such as reaches 6 and 7. Shrinking channel capacities are likely to be a result of reductions in streamflow, where water is lost the floodplain through primary and marsh distributary channels in the southern Macquarie Marshes and marsh distributary channels in the northern Macquarie Marshes. In addition, low channel gradients coupled with low w/d ratios and declining streamflow will affect specific stream powers and in-channel sedimentation.

5.3 Flow dynamics of the lower Macquarie River

This section deals with downstream patterns and trends in flow dynamics of the lower Macquarie River, the frequency and magnitude of flood return intervals and patterns in suspended sediment transport. These mechanisms of channel development and maintenance are analysed in regards to longitudinal and lateral connectedness of suspended sediment transport and water.

5.3.1 Velocity

Measurements of velocity were taken at sites along the lower Macquarie River between downstream Burrendong Dam and Bells Bridge. A particular focus was directed towards the northern Macquarie Marshes where samples were collected within a relatively close spatial range (Section 4; Figure 4.1). During the first sampling run in March 2008, it was interesting to observe the slow 'seeping' nature of flow in many of the marsh channels of the northern Macquarie Marshes. This was confirmed with a zero reading on the velocity-measuring device. The 'seeping' nature of flow was also observed on the Bora Channel behind the field house at Cresswell in September 2009.

Velocity measurements were taken within a few days of each other between 8 and 15 March 2008 during moderate stage flow, where discharge at Oxley (upstream southern Macquarie Marshes nature reserve) was 97 ML day^{-1} recorded at the NSW Office of Water gauge. Three measurements were taken and averaged for each site and then averaged over the reach, shown in Figure 5.5. The higher velocities of the gravel and sand bed reaches of the river are reflected in their location within partly confined valley settings and higher slope. Generally, velocity increases from reach 1 (0.56 ms^{-1}) to a peak of average velocity at reach 3 of 0.96 ms^{-1}, before the beginning of a general downstream decline to 0.05 ms^{-1}. There are slight increases in average velocity at reach 5 of 0.37 ms^{-1} and at reach 6N of 0.10 ms^{-1}. The differences between the southern and northern marshes are visible with an average velocity of 0.05 ms^{-1} in reach 6S to 0.10

ms^{-1} in reach 6N (channel velocities predominantly fed by the Bora Channel). The average velocity of flow in reach 7 as it exits the northern marshes through one defined trunk channel is 0.07 ms^{-1}.

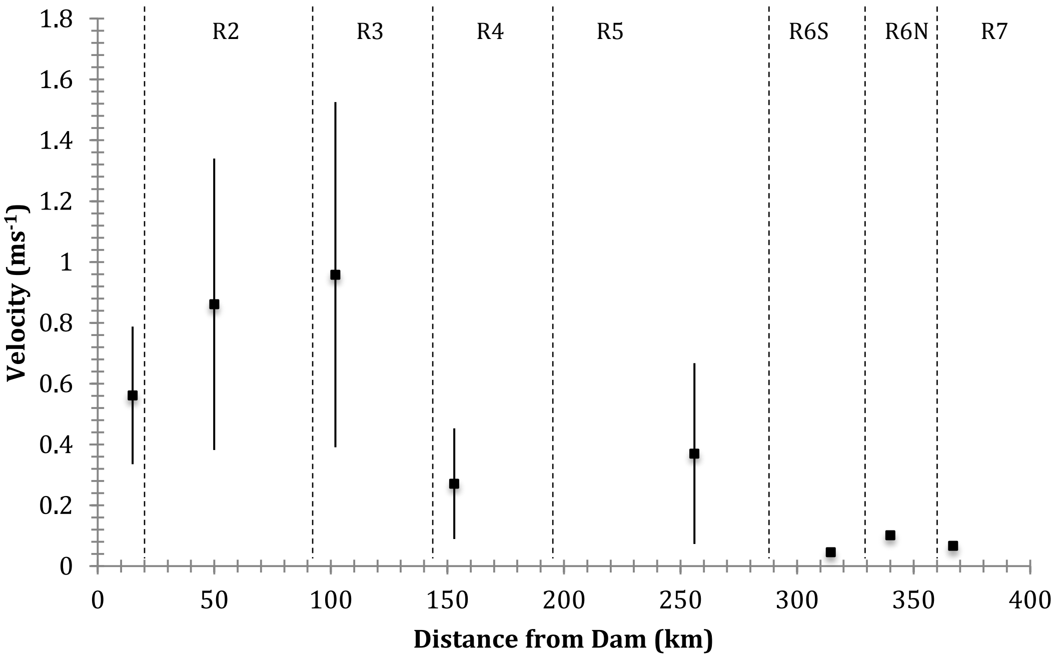
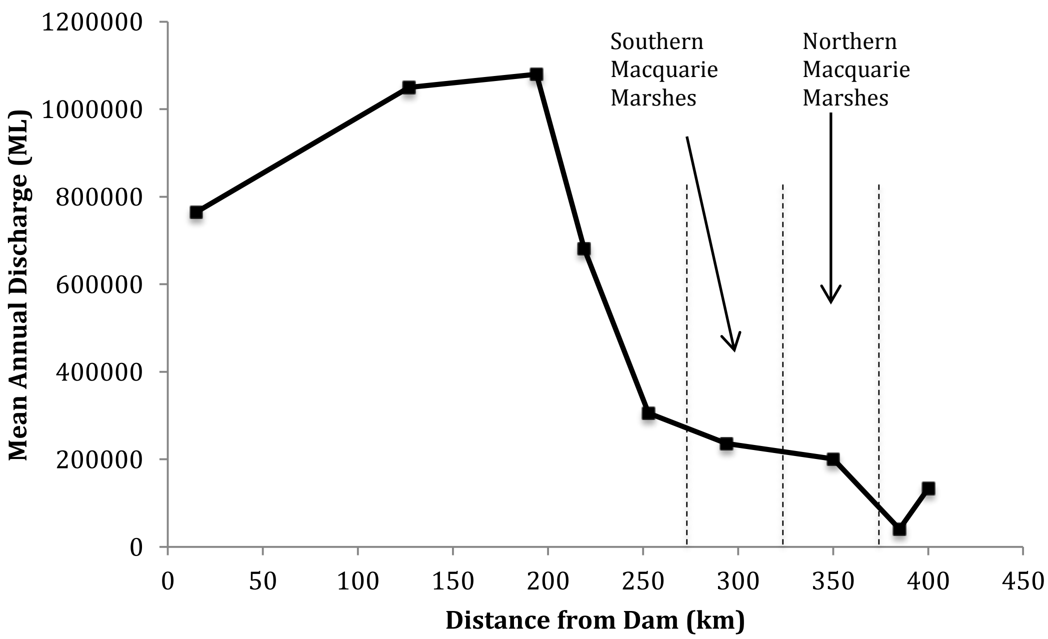


Figure 5.5 The reach averaged velocities with standard deviation of sites from downstream Burrendong Dam to Bells Bridge Carinda. The R^2 value of the linear trendline between velocity and distance downstream is 0.6986.

The reach-averaged velocity is reflective of where in the landscape the reach is positioned. The declining velocity towards the marshes, together with the decreasing slope, has implications for suspended sediment transport and the calibre of sediment transported. The calibre of sediment is reaches 1 to 3 are gravel dominated, reach 4 is sand dominated and reach 5 to 7 are mud dominated. The low channel velocities in reach 6 and 7 are conducive to suspended load dominated transport or in-channel aggradation. The increase of reach-averaged velocity in reach 6N is due to the small increases of channel gradient and channel straightening in the contributory marsh channels downstream of channel breakdown. Velocities decrease between reach 6N and reach 7 (single trunk channel) where the channel re-assumes a meander planform and channel gradients shallow.

5.3.2 Discharge, flood recurrence intervals and stream power

The mean annual discharge data was obtained from the NSW Office of Water gauge sites at downstream Burrendong Dam (reach 1), Dubbo (reach 2), Narromine (reach 3), Warren Weir (reach 5), Marebone Weir (reach 5), Oxley Station (reach 6 south), Pillicawarrina (reach 6 north), Miltara (reach 7) and Bells Bridge Carinda (reach 7) is shown in Figure 5.6. There is a significant pattern of mean annual discharge decreasing with distance down catchment from 1080072 ML at Narromine to 40891 ML at Carinda. Mean annual discharge peaks at Narromine after the tributary inputs of the Bell River upstream of Dubbo (at 127 km) and tributary inputs of the Talbragar River downstream of Dubbo and upstream of Narromine. The mean annual discharge input from the Bell River is 90933 ML and the Talbragar River is 60166 ML. Figure 5.6 shows the mean annual discharge against increasing catchment area. The catchment area for the lower reaches of the Macquarie River (reach 4 to reach 7) essentially ends at the input of the last perennial tributary, the Talbragar River between 127 km and 194 km downstream of Burrendong Dam. The last tributary input coupled with the semi-arid nature of the climate reduces the available runoff into the system. The patterns are the same within both figures, showing a decrease in discharge down catchment. A stand out discharge that is not on trend with the general decline in discharge is the inflexion in the graph between Miltara (at 385 km) and Bells Bridge Carinda (at 400 km). The increase in discharge between these two sites is likely to be a result of the northern bypass channel, running the length of the western flank of the northern Macquarie Marshes. This river regulation structure was excavated to divert flow away from the northern Macquarie Marshes straight to the single channel downstream of the Marshes, to reduce the loss of discharge to the floodplain.



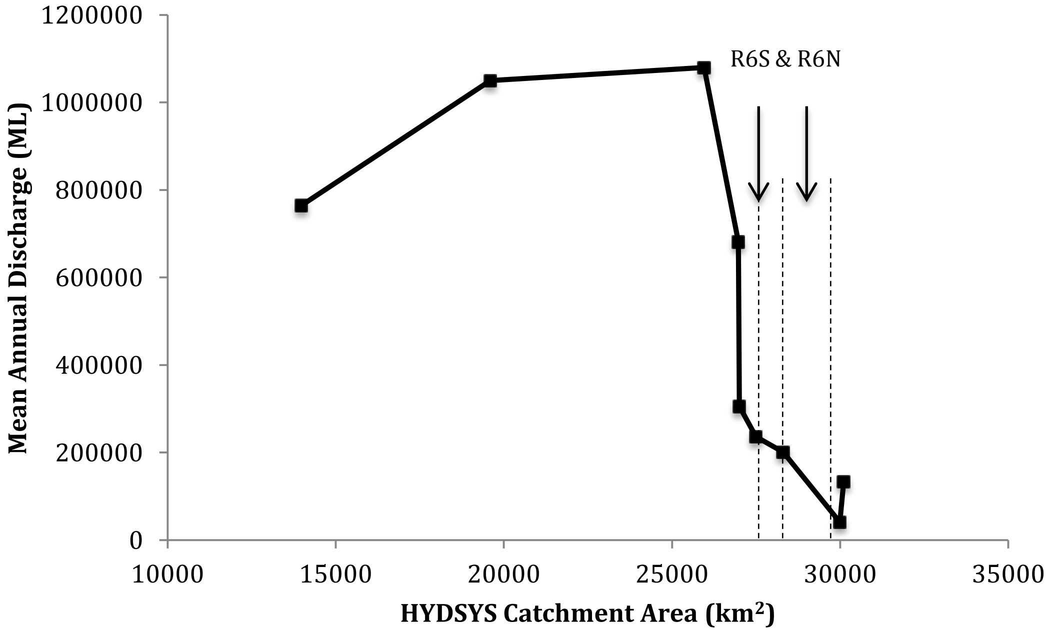


Figure 5.6 The top graph is showing the decline in discharge with distance down catchment. The bottom figure is showing the decline in discharge with catchment area. Both show a similar trend.

Figure 5.7 shows the bankfull discharge and specific stream power calculated for bankfull using the channel area and velocity measurements of sites downstream of Marebone (reach 5). Bankfull discharge and specific stream power decrease down catchment. Bankfull discharges and specific stream powers are lowest in some of the channels within the southern Macquarie Marshes (reach 6S) and the northern Macquarie Marshes (reach 6N). The increases in bankfull discharge and specific stream power in reach 6N corresponds to decreasing sinuosities, increasing channel gradients and the higher velocity measurements for those channels downstream of channel breakdown.

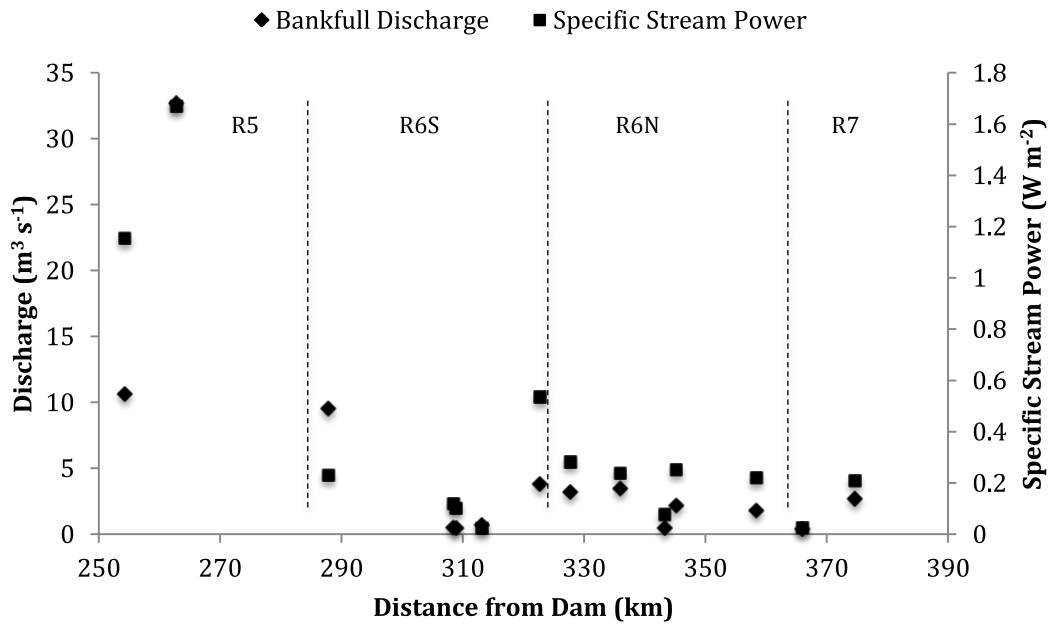


Figure 5.7 The calculated bankfull discharge and specific stream powers of the channels from reach 5 to reach 7 using channel morphometrics and velocity readings. The values for bankfull discharge and specific stream powers are similar to those derived from the gauge data using Geomorphic Assessor.

Flood return intervals for 18 sites along the lower Macquarie River were used to derive the frequency of overbank flow events. The stage heights associated with flood recurrence intervals are linked to explaining the temporal and spatial variability in suspended sediment transport through geomorphic work and laterally linking the transport of water and sediment laterally between the floodplain and channel. Stage heights and recurrence intervals also provide an indication of the physical connection between the channel and the floodplain. Flow is a key intrinsic mechanism of suspended sediment transport, and lateral and longitudinal connectivity of the lower Macquarie River, and is controlled by climate and runoff. The behaviour of each reach relies on the through-flow of sediment and water from upstream as well as processes within the reach.

The gross and unit stream power, and sediment transport capacity for selected sites along the lower Macquarie River were generated in Geomorphic Assessor using the discharge values derived from computed PINNEENA Log Pearson III flood frequency curves for gauges within the catchment. These closely correspond to the bankfull discharge and specific stream powers derived from channel morphometrics in Figure 5.7.

Table 5.2 presents the specific stream power related to the bankfull discharge and its frequency and specific stream powers for the bankfull recurrence interval. The channels with higher capacity in the partly-confined reaches are associated with generally higher specific stream powers (136.2 Wm^{-2}, 72$Wm^{-2}$and 49.4 Wm^{-2}) for a 1 in 100 year event than those of the laterally unconfined reaches with specific stream powers of 9.8 $Wm^{-2}$to 0.1 $Wm^{-2}$for bankfull discharges. This data can be compared to the geomorphic units within the channels and the floodplain features of the partly-confined reaches including erosion features (ledges, point bars and pools) and depositional features (floodplain pockets, benches and point bars) as described for these reaches in Table 5.1 and section 5.2.2. The specific stream power values correspond to those reported by Nanson and Croke (1992) for similar unconfined, lowland cohesive channels. Bankfull discharges decrease in a downstream direction, but increase slightly as flow rechannelises into a main trunk channel. This downstream decrease in bankfull discharge is an indication of changing channel volumes as indicated through changes in width: depth ratio and channel cross sectional area in Figure 5.4. .The sites from the Breakaway Channel in the southern Macquarie Marshes to Bells Bridge at Carinda, with the exception of the site at Pillicawarrina, reach bankfull before the calculated discharge for a 1 in 1 year flood event. These lower reaches are typically depositional or transitional in nature, indicated by the low specific stream powers and the relationship with suspended sediment transport mechanisms. Downstream of channel breakdown, where the channels display higher slopes and lower sinuosities of the northern Macquarie Marshes

Table 5.2 The bankfull discharge or the discharge of a 1 in 100 yr flood, for those that do not reach bankfull as derived from the gauge data. The specific stream powers associated with the bankfull discharge and the return interval.

Site	Bankfull Q (or >1 in 100 yr) (m3/s)	Specific Stream Power (W/m2)	RI
DS Burrendong	1480	136.2	1 in 100
Ponto Falls	1485	72	1 in 100
Minore Falls	1666.6	49.4	1 in 100
Turkey Farm Reserve	1043	39.1	< 1 in 50
DS Warren Town	214	9.8	< 1 in 2
DS Marebone Weir	83	8.1	< 1 in 2
Gradgery	90	3.4	< 1 in 2
Oxley	26	0.6	< 1 in 2
Breakaway DS Monkeygar	3	0.8	< 1 in 1
Monkeygar DS Breakaway	3	0.7	< 1 in 1
Monkeygar Willancorah	2	0.1	< 1 in 1
Pillicawarrina	18	1.3	< 1 in 2
Longstowe	2	0.2	< 1 in 1
Eastern NNR	1	0	< 1 in 1
Bora Well	1	0.2	< 1 in 1
Bora Cresswell	1	0.1	< 1 in 1
Miltara	7	0.2	< 1 in 1
Bells Bridge Carinda	11		

5.3.3 Daily mean discharge

The daily mean discharges at the five gauges within, above and below the Macquarie Marshes during the sampling time periods are shown in Figure 5.8. The discharge record provides an indication of the daily discharge experienced during suspended sample collection. The discharge graphs show a common pattern, the lag between discharge peaks at Marebone Weir (412090), where flow is regulated, and the Macquarie River at Oxley Station (421022), immediately upstream of the southern Macquarie Marshes nature reserve. A similar lag in the flood peak is visible in all four-discharge graphs. The Macquarie River at Pillicawarrina (421147) receives inflow from Bulgeraga Creek upstream of the gauge and provides an explanation for the increase in discharges at Pillicawarrina, a reach of the Macquarie River trunk channel between the southern and northern Macquarie Marshes. The gauges at Miltara (421135) and Bells Bridge (421012), downstream of the northern Macquarie Marshes, show marked decreases in discharge as diminishing flow is directed into floodplain wetlands in the northern Macquarie Marshes. There is considerably less discharge permeating through the northern Macquarie Marshes. This phenomenon provided the rationale behind the excavation of a northern bypass channel used to skirt flow around the northern Macquarie Marshes for landowners downstream of the marshes (Green et al., 2011). The peak in March 2008 was an environmental flow and in July 2008, water was released for stock and domestic supply. The daily mean discharge data supports the possibility of a disconnection within the Macquarie Marshes, preventing longitudinal and lateral connection of water and suspended sediment transport. The downstream reduction in discharge through the Macquarie Marshes is consistent with reduced velocities and carrying capacity of suspended load, indicating the potential for sediment deposition, which can be coupled with the suspended sediment data.

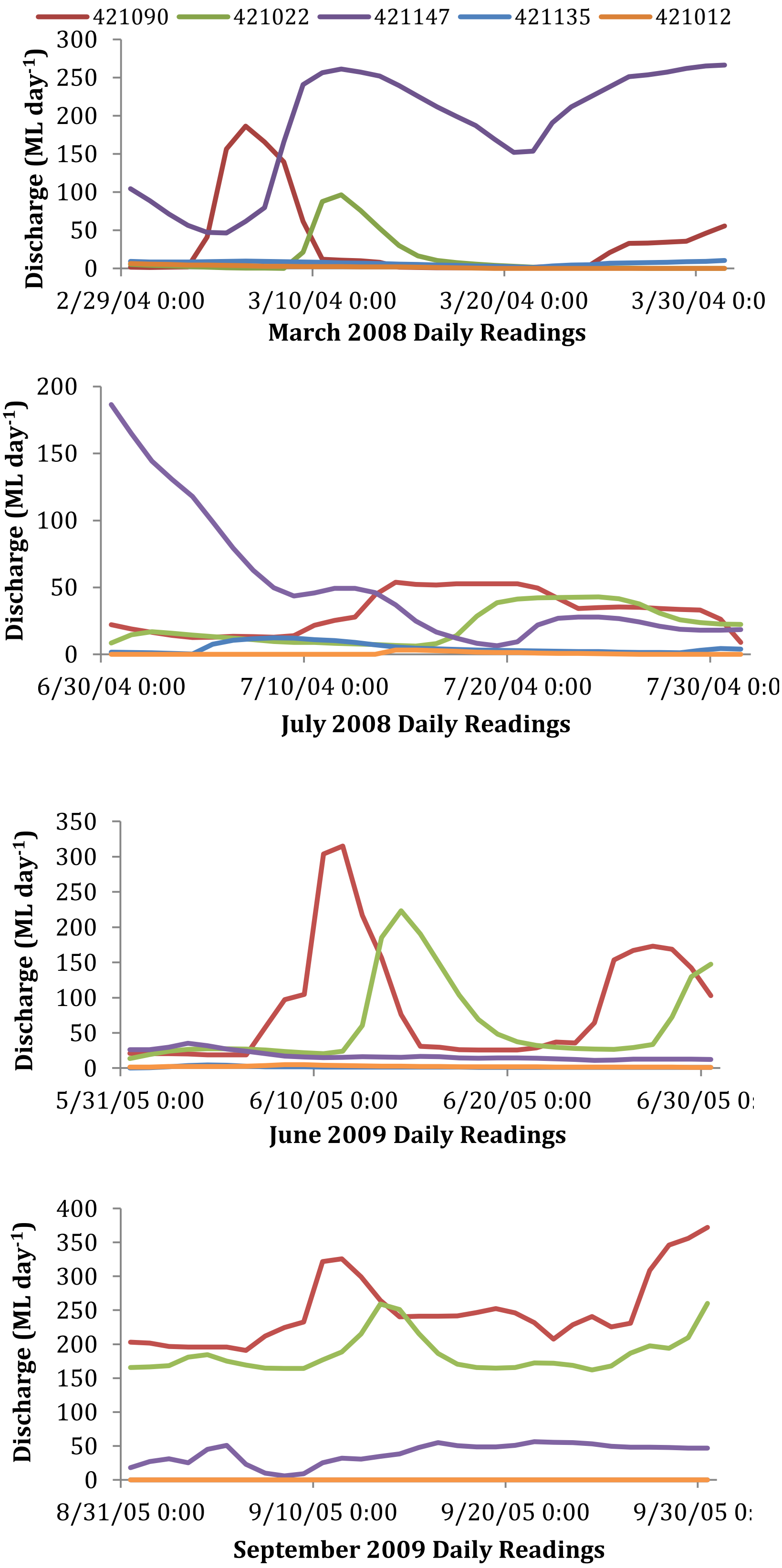


Figure 5.8 Daily mean discharges of the five gauges surrounding the Macquarie Marshes for the sampling periods. The gauge numbers represent: 421090 Marebone Weir (R5); 421022 Oxley Station (R6S); 421147 Pillicawarrina (R6N); 421135 Miltara (R7); and 421012 Bells Bridge Carinda (R7).

5.3.4 Suspended sediment samplers and stage height

The bottles in the stage samplers were filled in the period between July 2008 and September 2009. The mean monthly stage heights, at the gauge locations previously mentioned, for this period are shown in Figure 5.9b. The discharge data for the months suspended sampling was undertaken can be compared to the stage height data in Figure 5.9b of the same month. The stage height data can be used to determine flow height and the month the suspended sediment samplers filled. The data for each sampler location includes a channel cross-section pinpointing the exact location within the channel, the height of the sampler above the channel bed and the height of the inlet holes on the sampler. Through a comparison of stage height, the in-channel sampler location and the height of the water inlet holes, the month of filling can be determined. Patterns can be distinguished within the stage height data.

The stage height data at both Marebone Weir and Oxley stage mimic each other in shape where the same peaks and troughs are identified. There is reduction in stage height downstream through the gauge locations. Miltara gauge registers heights less than 10 cm and Bells Bridge, further downstream, registers no stage height during the months of January and February 2009. The samplers filled through different periods dependent on the route of flow from Marebone Break (Marebone Weir). The sampler in the Old Macquarie Channel on the property of Willancorah (between the gauges Oxley Station and Pillicawarrina) had filled in December 2008, whereas the sampler on the eastern edge of the northern Macquarie Marshes filled between June 2009 and September 2009. Suspended sediment and water transport through marsh channels that are elevated above the main flow routes remain longitudinally disconnected during periods of low flow (E.g. Bora Channel cross section Figure 5.9a).

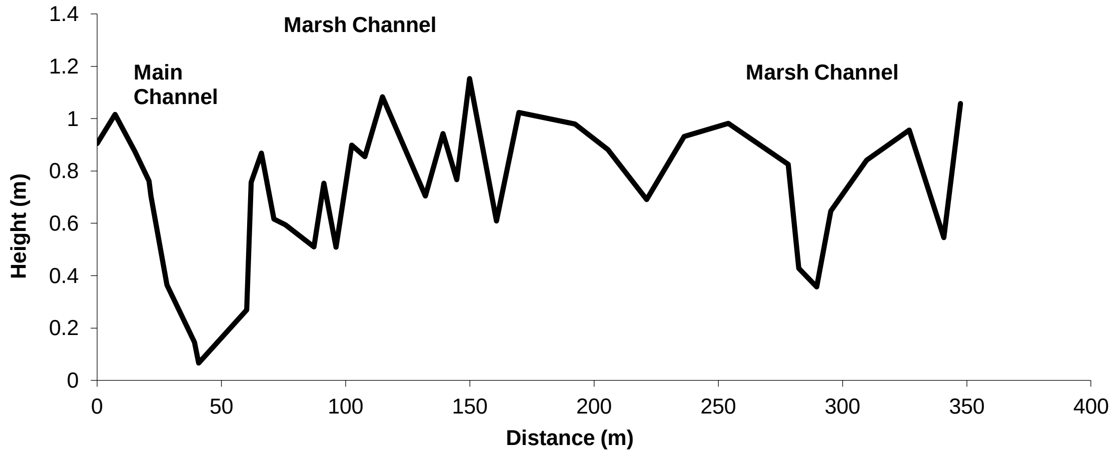


Figure 5.9a A cross section of the Bora Channel downstream of channel breakdown (or Bora Well).

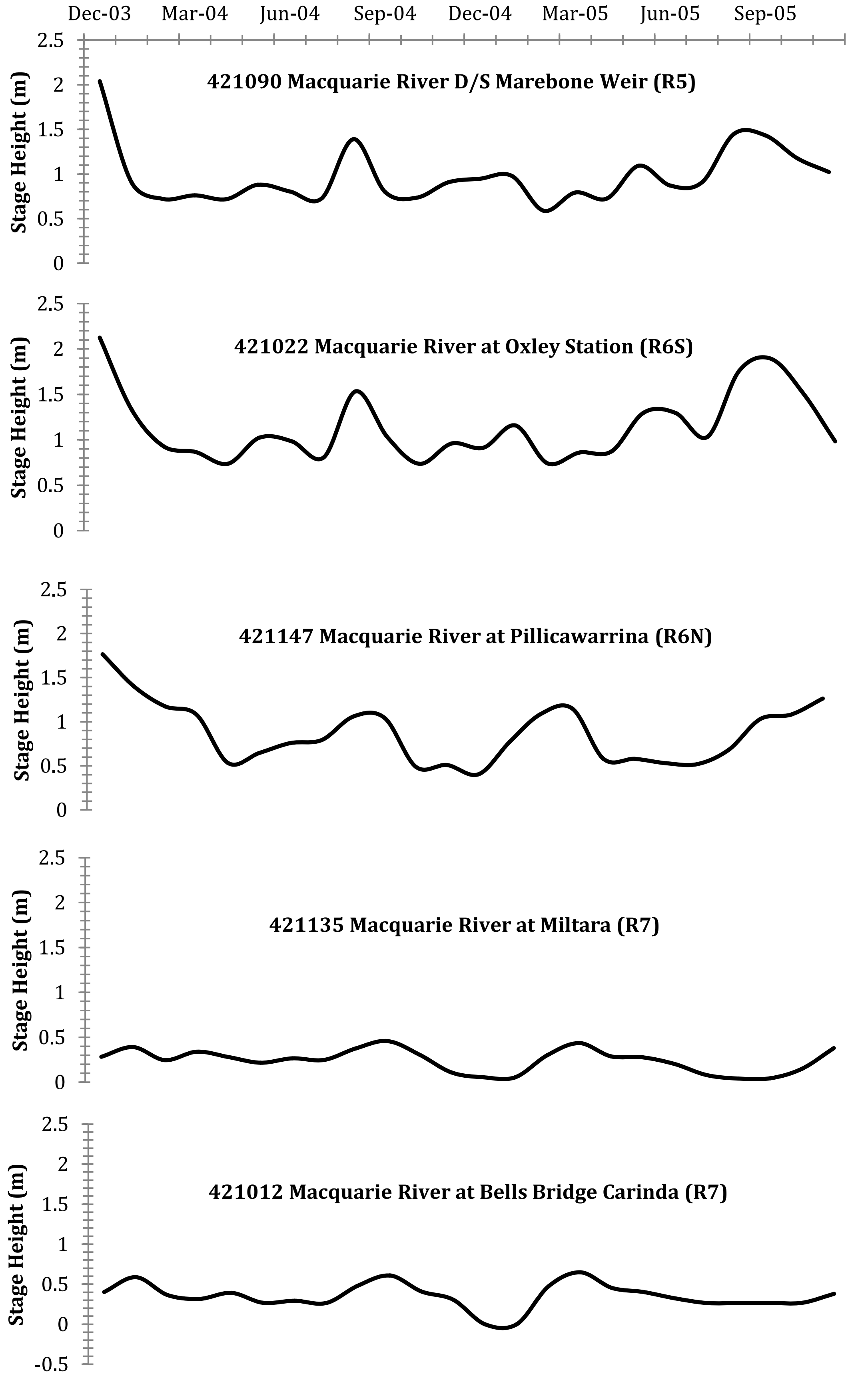


Figure 5.9b Stage heights recorded at the five gauges upstream, within and downstream of the Macquarie Marshes across the years 2008 and 2009.

The suspended sediment samplers could be a good method of sample collection at different stage heights, however there were some issues found with both styles of sampler. Neither design worked well in stocked paddocks. Cattle damaged all in-channel samplers on stocked land. The small channel samplers where the bottles are exposed to sunlight developed heavy algal growth. These samplers also continue to fill if the air exhausts are covered with water, which happened in a couple of cases, increasing sediment concentration. The closed sampler units performed well, although some were left for some time and developed small amounts of algae. The lab analysis to remove the algae before calculating the total suspended solids was time consuming. Figure 5.10 shows the results of the sample collection by the suspended sediment samplers. Although the concentrations are quite high, there is a pattern visible in the data that shows increasing suspended solids flowing into the southern Macquarie Marshes and the decrease in suspended solids through the Macquarie Marshes system before an increase in the re-channelised flow of the trunk channel at Miltara. A decrease is evident at Bells Bridge where two samplers were deployed.

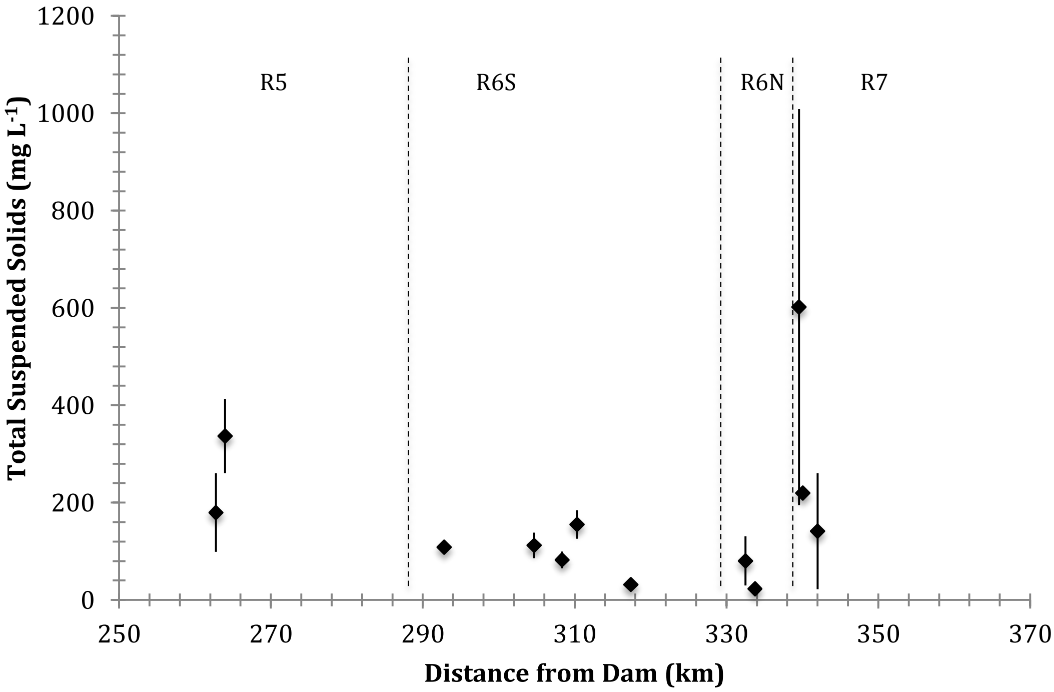


Figure 5.10 Mean total suspended solids and standard deviation calculated from the suspended sediment samplers that were deployed in July 2008 and collected in September 2009. Locations are marked on the figure and the reach number in brackets.

5.3.5 Gauge suspended sediment concentrations data

Patterns within the total suspended solids data of the lower Macquarie River can be linked to the physical characteristics of each reach, the landscape setting and the bed material texture in determining areas of sediment supply, transfer and deposition. The total suspended solids data from Office of Water gauges of the lower Macquarie River includes data from the two major tributaries entering the system, the Bell River at the township of Wellington and the Talbragar River, downstream of Dubbo (Section 3; Figure 3.1). The suspended solids entering the Macquarie River system from the Bell River, situated in a partly-confined bedrock controlled valley setting with gravel bed material texture, is minimal with baseline measurements around 10 mg L^{-1}. There are six peaks within the Bell River recorded data, associated with higher stage flows. A record taken in February 1983 of 1227 mg L^{-1} is the highest recording of the Bell River whereas other peaks show recorded values between 10 mg L^{-1} and 100 mg L^{-1}. The most recent peak in total suspended solids of the Bell River is from September 2010, a wet season as imposed by an El Nina cycle, with a cluster of total suspended solids values in the range of 250 mg L^{-1} to 700 mg L^{-1}. The total suspended solids entering the Macquarie River from the Talbragar River is higher than the recorded values of the Bell River. The general increase in total suspended solids of the Talbragar River tributary can be attributed to it's positioning within the catchment and the influence of the landscape setting on suspended sediment supply. The Talbragar River, in its lower reaches, has a partly confined planform with discontinuous floodplains and is sand-bed dominated. There is not a common baseline, but a spread of values between 5 mg L^{-1} and 100 mg L^{-1} with a higher degree of scatter around the 100 mg L^{-1} value. There are less defined peaks within the total suspended solids data of the Talbragar River, two values above 1000 mg L^{-1} and a strong cluster of values for late 2010 would represent one definable peak. The longitudinal through-flow of suspended sediment is well connected with the primary trunk channel.

The downstream pattern of mean total suspended solids of the lower Macquarie River is shown in Figure 5.11. The minor input of total suspended solids from the Bell River into the Macquarie River system is represented by a small increase in mean total suspended solids from 16 mg L^{-1}downstream of Burrendong Dam to 36 mg L^{-1}downstream of the Bell River tributary. There is a decrease in TSS between the Bell River and Dubbo. The Talbragar River discharges a substantial volume of mean total suspended solids, 87 mg L^{-1}, into the Macquarie River downstream of Dubbo. There is a 20 mg L^{-1} decrease in total suspended solids from the Talbragar River to Marebone Weir. The drop in TSS measurements at the main trunk gauges after tributary inputs could be the result of deposition, or dilution as it enters a primary channel. The highest mean value of total suspended solids has been recorded at Bells Bridge Carinda with a mean value of 116 mg L^{-1}. Mean total suspended solids gradually decrease from the gauge record at Marebone to the gauge record at the property "Miltara" before the spike at Bells Bridge Carinda. Low flow (and concentration), bank erosion and grazing agriculture are possible causes of increases in total suspended solids between the northern Macquarie Marshes and Bells Bridge. The southern Macquarie Marshes lie between the gauge at "Oxley" and the gauge at "Pillicawarrina" while the northern Macquarie Marshes lie between the gauge a "Pillicawarrina" and "Miltara". Mean daily discharge (ML/day) for the gauge data in Figure 5.11 show the decrease in discharge corresponding to the total suspended solids concentrations.

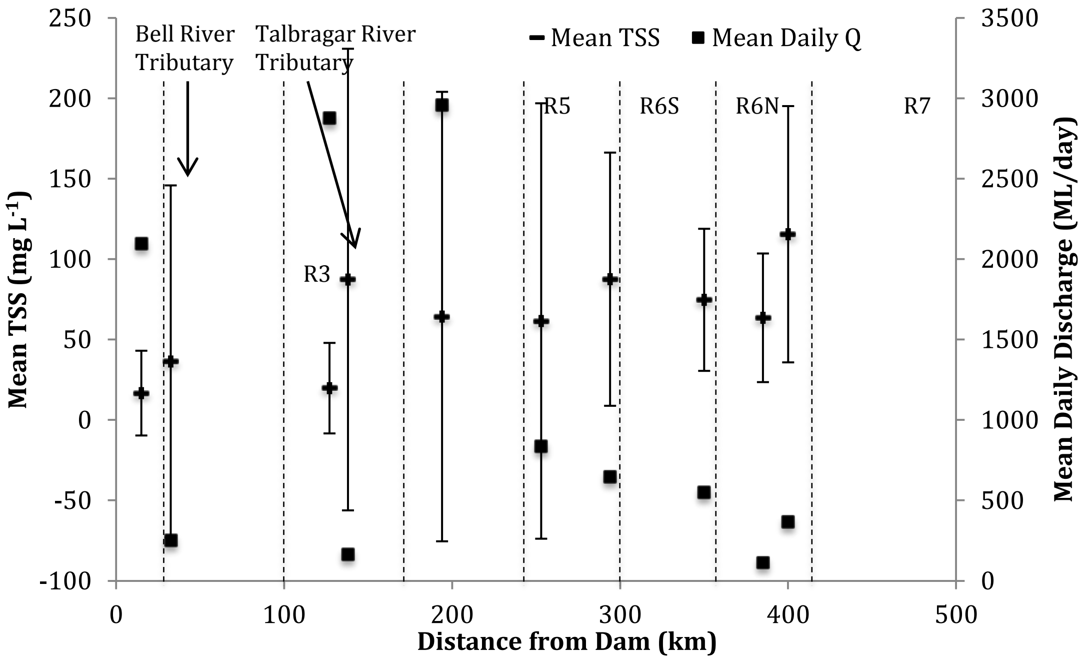


Figure 5.11 Average total suspended solids at the gauge locations along the lower Macquarie River. The R^2 value of the linear trendline for TSS against distance is 0.5684. Points from left to right are the gauge locations at: D/S Burrendong Dam; Bell River tributary; Dubbo; Talbragar River tributary; Narromine; Marebone Weir; Oxley Station; Pillicawarrina; Miltara and Bells Bridge Carinda.

5.3.6 In-situ suspended sediment concentration data

For this study, the total suspended solids samples for the lower Macquarie River were collected at four different time periods across two years. This sampling included sites within the Macquarie Marshes between NSW Office of Water gauging sites. The mean daily discharge through each collection is shown in Figure 5.8. The mean total suspended solids and standard deviation are shown in Figure 5.12a. Figure 5.12b focuses on the lower Macquarie River from Marebone Weir to Bells Bridge Carinda to provide a clearer picture of the pattern of suspended sediment transport through the southern and northern Macquarie Marshes.

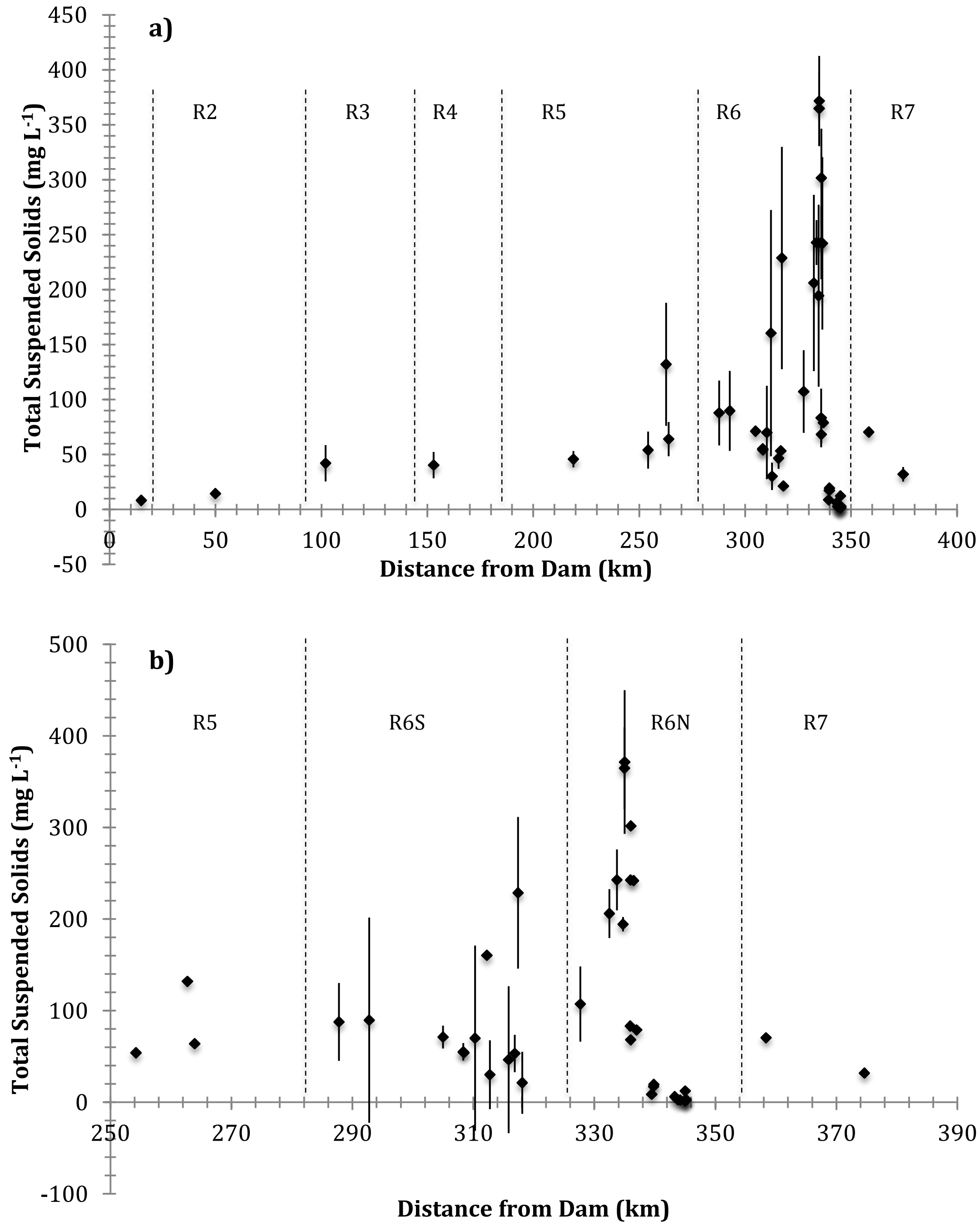


Figure 5.12 (a) Mean total suspended solids and standard deviation of samples collected in March 2008, July 2008, June 2009 and September 2009. (b) The mean total suspended solids and standard deviation between Marebone Weir and Bells Bridge Carinda. Locations and reach boundaries have been labelled on the figure.

The mean total suspended solids increase steadily from the transfer reaches of the partly confined gravel bed channel of reach 1 and 2 with total suspended solids less than 15 mg L^{-1}. Total suspended solids in reach 3, 4 and 5 increase further to 45.7 mg L^{-1}. As the channel transitions to a meandering fine grained reach, suspended sediments increase to approximately 100 mg L^{-1} downstream of Marebone Weir, at Gradgery and Oxley in reach 5.The southern Macquarie Marshes has a range of values from 21 mg $L^{-1}$to 228 mg L^{-1}. Pillicawarrina reach, with a single trunk channel, is the point (at a distance of 327 km) connecting the southern Macquarie Marshes and northern Macquarie Marshes. Total suspended solids increase sharply from 107 mg L^{-1} at Pillicawarrina to 242 mg L^{-1} at Longstowe. The variability in suspended solids concentrations over three sample runs of the site at Pillicawarrina 99 mg L^{-1} to 148 mg L^{-1}. Higher still were the samples collected downstream of Pillicawarrina between the gauge and Longstowe at The Mole with readings of 104 mg L^{-1} to 270 mg L^{-1}. The high suspended sediment concentrations correlates with the average increases in suspended sediment concentrations from the gauge readings between Oxley (southern Macquarie Marshes) of 87 mg L^{-1} and Pillicawarrina (upstream of the northern Macquarie Marshes) of 74 mg L^{-1}. Total suspended solids begin to decrease, again quite sharply, where channel breakdown and vegetation blocking increases at distances of 335 km from Burrendong Dam. At Bora Well, downstream of the extensive floodplain reed bed there is a small range of values of total suspended solids between 1.5 mg L^{-1} and 12 mg L^{-1}. The last two points correspond to Miltara and Bells Bridge where suspended solids increase to 70 mg L^{-1} at Miltara total and then decrease to 32 mg L^{-1}at Bells Bridge. Miltara is a property to the north of the Macquarie Marshes nature reserve. They stock cattle, which have been observed within the trunk channel, a possible mechanism of bank erosion, also observed to be quite common on the property.

The possible causes of the increase in total suspended solids leading into the northern Macquarie Marshes include erosion of the banks, trampling by cattle along the channel or decreasing discharge and ensuing concentration of the suspended load, although the length of this reach is quite short. Whichever the mechanism is that controls the localised higher total suspended solids between the southern and northern Macquarie Marshes, the general pattern of reductions in suspended sediment transport through the northern Macquarie Marshes is quite consistent with the reductions in discharge and the decreases in velocity demonstrated earlier in this chapter. Increases in total suspended sediment concentrations between the southern and northern Macquarie Marshes is likely to be a result of increased total suspended solids entering the trunk channel upstream of Pillicawarrina from the Bulgeraga Creek and potentially Mole

Marsh (upstream of Pillicawarrina). The Bulgeraga Creek recorded a mean total suspended solids concentration of 279.5 mg L^{-1} (combined into R6S) upstream of the road bridge for Gibson's Way. The high values of total suspended solids were recorded during the high stage event in March 2008. Subsequent measurements returned a mean measurement of 80 mg L^{-1}, recorded during low stage flows.

The channels of the northern Macquarie Marshes, devoid of geomorphic units and homogenous in character, provide evidence of the reduced total suspended solids flowing from the floodplain reed bed, making it a dominantly transfer reach. This is supported by the slight increases in velocity and decreases in sinuosity, measured for these channels. The pattern of suspended solids transport is quite different in the southern Macquarie Marshes when compared to the northern Macquarie Marshes. There are differences in the concentration and the deposition of suspended sediment. The rate of suspended sediment deposition is overshadowed by the relatively (to that of the northern Macquarie Marshes) high erosion rates within some of the channels of the southern Macquarie Marshes, increasing the suspended load into the northern Macquarie Marshes. This indicates the higher energy of parts of the system within the southern Macquarie Marshes compared with the northern Macquarie Marshes where there is only evidence of in-channel erosion initially as the Bora Channel bifurcates from the main trunk channel. The southern Macquarie Marshes thereby acts as both a sediment sink and a zone of sediment supply. The variability of erosional verse depositional dominant reaches within the southern Macquarie Marshes occurs over small spatial scales and different temporal scales (discharge dependent). The northern Macquarie Marshes acts predominantly as a sediment sink, removing suspended sediment from suspension and distributing discharge across the floodplain.

5.3.7 Suspended sediment yield of the Macquarie Marshes

The suspended sediment yield at points through the Macquarie Marshes was calculated using the mean gauge discharge and mean gauge suspended sediment data. The pattern of declining discharge is similar to the pattern of declining suspended solid yield. Figure 5.13 shows the decline in suspended sediment transport with declining discharge. Discharge plays a large role as a key control on suspended sediment transport through the Macquarie Marshes. There is a longitudinal discontinuity of suspended sediment transport through the marsh system. Discharge is predominantly lost through the northern Macquarie Marshes as distributary marsh channels redirect streamflow across the floodplain. Contributory marsh channels concentrated in the centre of the northern Macquarie Marshes re-direct a proportion of streamflow back into a single trunk channel. Mean suspended solid yield is similar entering the southern Macquarie Marshes and from the southern Macquarie Marshes entering the northern Macquarie Marshes.

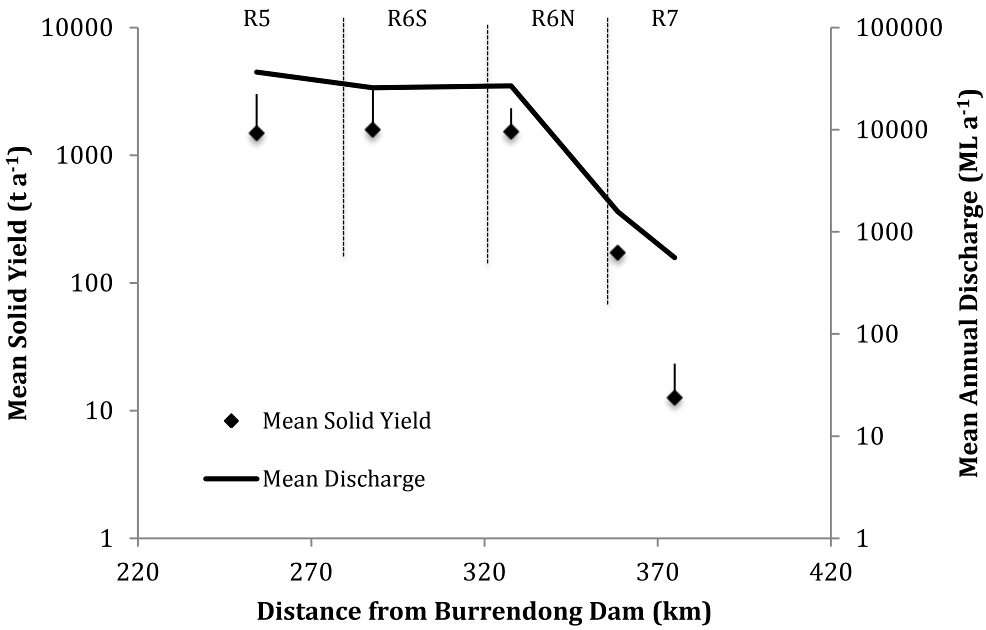


Figure 5.13 Annual suspended sediment yield for the Macquarie Marshes using the mean discharge and mean total suspended solids. Gauge data was used for the sites Marebone Weir, Oxley, Pillicawarrina, Miltara and Bells Bridge. Mean solid yield has positive error bars to show the range of values of the gauges with multiple readings.

5.4 In-channel Vegetation Blocking

Observations of in-channel vegetation at cross-sections sites along the lower Macquarie River indicate the trunk channel is characterised by predominantly vegetation-free in-channel zones. In-channel vegetation increases as channel gradients (Figure 5.1) and velocity (Figure 5.5) decrease, and overbank inundation increases over shorter time scales (section 5.3.2) towards the area of channel breakdown. Figure 5.14 characterises representative sites within the reach types of the lower Macquarie River by the percentage of in-channel vegetation across a cross-sectional profile. Vegetation within the channel increases channel roughness and has the ability to markedly decrease stream velocities and reduce geomorphic efficiency, corresponding well to the decreases in channel area, channel gradient and velocity.

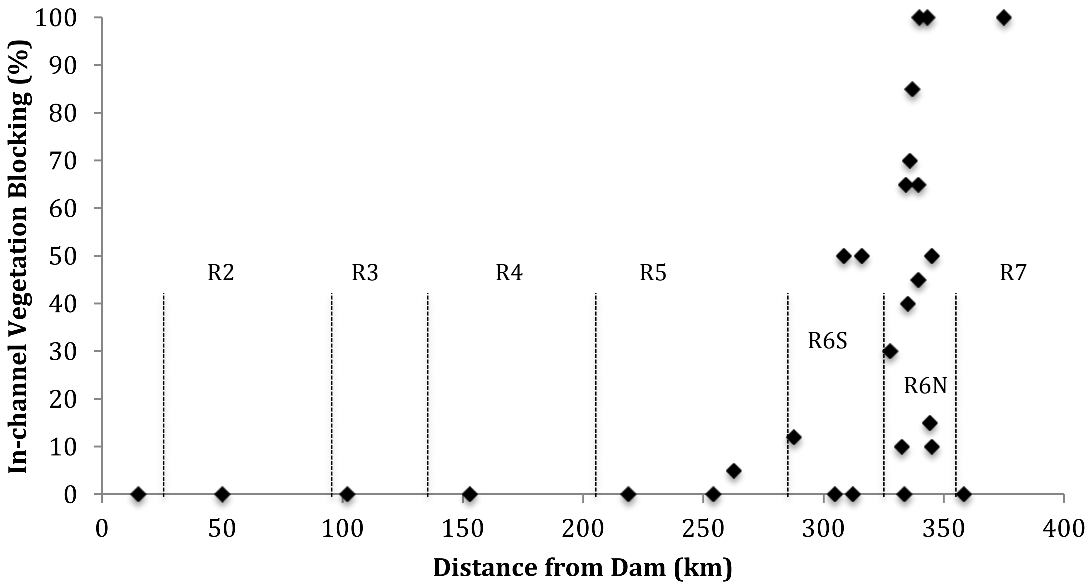


Figure 5.14 The percentage of vegetation blocking the in-channel zone of representative sites from downstream Burrendong Dam to Bells Bridge.

In-channel vegetation blocking correlates well with patterns in total suspended solids concentrations, particularly within the northern Macquarie Marshes (Figure 5.12b). In-channel vegetation blocking within the northern Macquarie Marshes at a number of sites is greater than 50% and many 100% blocked by vegetation. In-channel vegetation varies; however, the dominant species is common reed (*Phragmites australis*), with occasional stands of cumbungi (*Typha domingensis*), lignum (*Muehlenbeckia florulenta*), sedges, water couch (*Paspalum distichum*)and other weeds. Figure 5.15a are photographs taken of representative sites of reach 1, 4, 5, 6S and 7 (excluding 6N). Figure 5.15b are representative photos of the channel upstream of the reed bed and full-scale breakdown, within channel breakdown region and downstream of the reed bed of the northern Macquarie Marshes (6N). In-channel vegetation growth is observed to grow well in shallow channels with low streamflow velocities. The dense reed growth is common in wetted areas, particularly where there is maintenance of flow or pooling water (e.g. between dense in-channel reed sections).

Figure 5.15a In-channel vegetation growth from top left clockwise: R1 – D/S Burrendong Dam; R5 – D/S Warren Town; R5 – Gradgery; R6S – Breakaway Channel; R6S – Monkeygar Creek; and R7 – Macquarie River trunk channel at Miltara.

Figure 5.15b Comparably quite different in the amount of vegetation blocking of the channel within the northern Macquarie Marshes compared to the channels in Figure 5.14a. (left to right) Bora Channel on the property of Longstowe. The bifurcations have started; Representative of the channels downstream of Longstowe with almost 100% vegetation blocking; and the Bora Channel downstream of the reed bed where velocities increase and sinuosities decrease. Taken at a time when seeping flow was making its way down the channel in September 2009.

5.5 Connectivity

The data presented in this chapter has provided implications for both the suspended sediment transport and hydrological connectivity of landscape compartments within the lower Macquarie River corridor.

5.5.1 Longitudinal connection

No impediments of physical connection were observed between reaches of the lower Macquarie River between reach 1 and reach 5, or reach 7. The transfer of suspended sediment between reaches increases with distance following flow releases from Burrendong Dam (see Figure 5.12 a and b). The tributary-trunk connections of the Bell River and the Talbragar River with the Macquarie River are both physically connected with continuity of suspended sediment transfer as established through the gauge data (see Figure 5.11). Longitudinal continuity of streamflow has been measured by the continuous gauge discharge data (see Chapter 3 Table 3.1; Figure 5.8). Streamflow is continuous from Burrendong Dam to the Old Oxey Gauge, where streamflow is directed through anabranching streams. Dependent on stage height, not all channels are activated within the southern and northern Macquarie Marshes during the same time periods. The Macquarie River trunk channel at Bells Bridge often does not receive streamflow and is hydrologically disconnected unless the streamflow is at a sufficient discharge to make it through the two marsh complexes. The average annual gauge discharge is shown in Figure 5.16. The Bell River tributary meets the Macquarie River trunk channel at Wellington (25 km downstream Dam) to explain the increase in annual discharge.

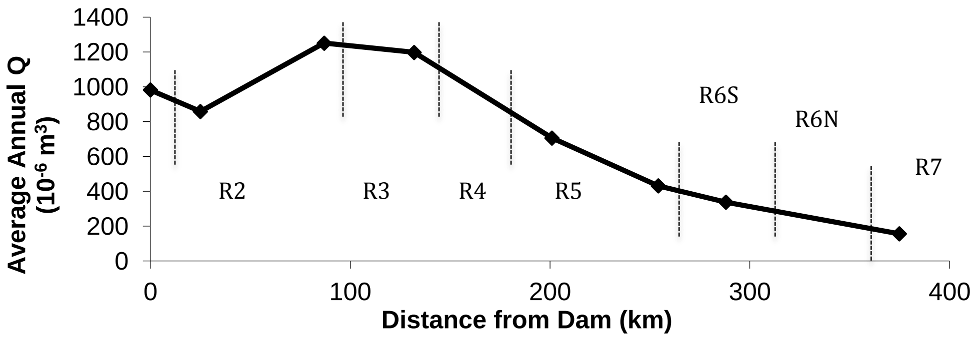


Figure 5.16 Average annual discharge data from the gauges along the lower Macquarie River. The gauges include from left to right: D/S Burrendong Dam, Wellington, Dubbo, Narromine, Warren, D/S Marebone Weir, Oxley and Carinda.

The reduction of streamflow between the gauges at Marebone Weir to Bells Bridge Carinda is shown Table 5.3. The gauge data for the period of 2008 and 2009 show the proportionate decrease in discharge from Marebone Weir to Bells Bridge Carinda. The increase in discharge between Oxley (southern Macquarie Marshes) and Pillicawarrina (northern Macquarie Marshes) is caused by the addition of streamflow of the Bulgeraga Creek, which re-joins the Macquarie Trunk channel upstream of the Pillicawarrina gauge. The extreme reduction of discharge leaving the northern Macquarie Marshes is a result of streamflow lost overbank to floodplains, distributary marsh channels and ponding within vegetation-blocked channels (Figure 5.14).

Table 5.3 Gauge data for 2008/2009 of the gauges upstream, downstream and within the Macquarie Marshes. It demonstrates the reductions in discharge down catchment and the discontinuity of streamflow between Pillicawarrina and Bells Bridge Carinda.

Gauge Station	Distance from Dam (km)	Gauge Discharge 2008/2009 (ML/a)	Proportional Decrease in Discharge from Marebone Weir (%)
D/S Marebone Weir (R5)	254.3	36598	
Oxley (R6S)	288.1	25687	30
Pillicawarrina (R6N)	327.7	26782	27
Miltara (R7)	359	1573	96
Bells Bridge Carinda (R7)	374.9	559	99

The in-channel geomorphic erosional and depositional features in each reach provide evidence of intercompartment and intracompartment active connection. Erosional ledges, depositional benches, point bars and pool-riffle sequences are evidence of sediment erosion, transfer and in-channel deposition through the lower reaches (Table 5.1). Although sediment is temporarily removed from the sediment cascade by storage in the point bar and bench features, the frequency of geomorphic effective flows show a pattern of recurrence at least on an interdecadal timescale of bankfull or near bankfull discharges and associated stream power, usually within a five year return period (Figure 5.6).

The fine-grained single meandering channels downstream of the Macquarie Marshes and linking the two marsh complexes, are connected physically but due to the ephemeral nature of discharge in the lower reaches of the river system on short temporal scales, are sediment-transfer inactive. The gauge stations at Miltara and Bells Bridge Carinda recorded zero discharge at periods within four months assessed for this study between 2008 and 2009 (Figure 5.8). During periods of zero discharge the physically connected system is inactive in suspended sediment transport. However, during periods of constant low flow and increasing stage these meandering single channels transfer suspended load into and between marsh complexes. The suspended sediment concentration transferred through the single meandering reaches of Reach 6 and 7 are between 148 mg L^{-1} at Pillicawarrina and 33 mg L^{-1} at Bells Bridge Carinda (Figure 5.12) a trend also shown by the sediment yield (Figure 5.13), which show active longitudinal connection during periods of flow.

The areas of channel breakdown in the northern and southern Macquarie Marshes are physically disconnected systems. The distributary marsh channels ultimately end in channel breakdown where flow velocities dissipate (Figure 5. 5). The marsh channels in the northern Macquarie Marshes are physically disconnected longitudinally by dense in-channel (Figure 5.15b) and floodplain vegetation. This promotes episodically active connection either through geomorphic agents such as flood discharge and stream power, heavy rainfall – runoff close to the channel or native animal tracks. The sediment yield (Figure 5.13) is an indicator of reduced sediment output from the northern Macquarie Marshes. However, it misrepresents the filtering processes of in-channel vegetation and deposition occurring within the northern Macquarie Marshes itself. When sediment yield is compared to patterns within the total suspended solids data (Figure 5.12 a and b), a more meaningful representation of the (dis)connectivity of suspended sediment transport is observed.

5.5.2 Lateral connection

The floodplain-channel physical connection in reaches 5, 6 and 7 are active in suspended load transfer. The flood recurrence intervals in Table 5.3 show the return interval overbank flows will be achieved under. In most cases for the lower reaches this interval is greater than a 1 in 1 or 1 in 2 year flood event. These reaches are actively connected on relatively short temporal scales, compared to reach 1 to 4, which are connected at greater than 1 in 100 year events (R1,2,3) or greater than a 1 in 50 year event (R4). Floodrunner features on the floodplain units in reaches 2 and 3 are evidence of floodplain scour during over bank flows. The floodplains reflect active connection with the channels of reach 6 in the northern marshes, where low magnitude events frequently inundate the floodplain where a greater than 1 in 1 year flow event will spill overbank in some of channel.

Overbank hydrological connection within the northern Macquarie Marshes is dependent on channel activation. Varying discharges determine the spatial and temporal variability of lateral connection through overbank flooding. This was observed through collection of suspended sediment samplers. The small variations in floodplain and height determine the primary distributary/contributory marsh channels, secondary and so forth. The lateral cross section of the Bora Channel (Figure 5.9a) shows the small height changes of the floodplain. Higher stage heights are required to activate channels offset higher than the banks of the primary distributary/contributory marsh channels.

5.6 Chapter Summary

This chapter analysed the physical properties of channel form and the surface variables that control channel morphology and suspended sediment transport. Discharge modelling provided key information about time and space scales of hydrological connection between the channel and floodplain units. Gauge data was used to determine the frequency – magnitude of bankfull flood recurrence and the recurrence of overbank flows. This data was modelled using Geomorphic Assessor. Vegetation blocking was assessed of the lower Macquarie River and correlated with key controls to assess the lateral and longitudinal linkages of streamflow and sediment transport.

Chapter 6: Results 2, Sedimentary Attributes & Results

6.1 Introduction

The sedimentary and geochronological results highlight the downstream patterns in a small geographical area, the northern Macquarie Marshes. Patterns of the in-channel and floodplain sedimentology, and the mass accretion rates of suspended sediment through geochronological dating techniques of optically stimulated luminescence (OSL) and ^{210}Pb radionuclide alpha-spectrometry dating are included for a section of the Bora Channel. The downstream trends detailed in this section include pH, Munsell colour, water content, particle size analysis, dry bulk density and loss on ignition for sedimentary organic and carbonate content.

A focus was taken on the northern Macquarie Marshes where sedimentation rates were measured at three in-channel locations and one floodplain location for comparison with the findings established for floodplain sedimentation rates by Freeman (2008) in the northern Macquarie Marshes and Ralph (2008) for channel and floodplain sedimentation rates in the southern Macquarie Marshes.

6.2 Bora Channel sedimentology

Cores were extracted from three in-channel sites and one floodplain site along the Bora Channel system, and the sedimentology derived. The style of coring device (hand corer and the nature of the heavy clay sediment, increased the variability in the length of cores extracted at each site (Appendix 6). The longitudinal profile between core sites and the core logs for each site are displayed in Figure 6.1. The change in floodplain elevation between core site 1 at Longstowe and core sites 2 and 3 in the northern nature reserve is a difference of -0.60 m. The change in floodplain elevation between core sites 2 and 3 and site 4 at Bora Well is a difference of -2.2 m and is likely to have influenced the slight increases in channel gradient downstream of channel breakdown. There are similarities in layer thickness and location of a dark grey clay layer at site 1 Longstowe and site 2 in-channel northern nature reserve. The layers are massive in structure, except for the sand layer in the upper profile of the core at site 4 Bora Well. Clay lenses were observed within the predominantly sandy layer.

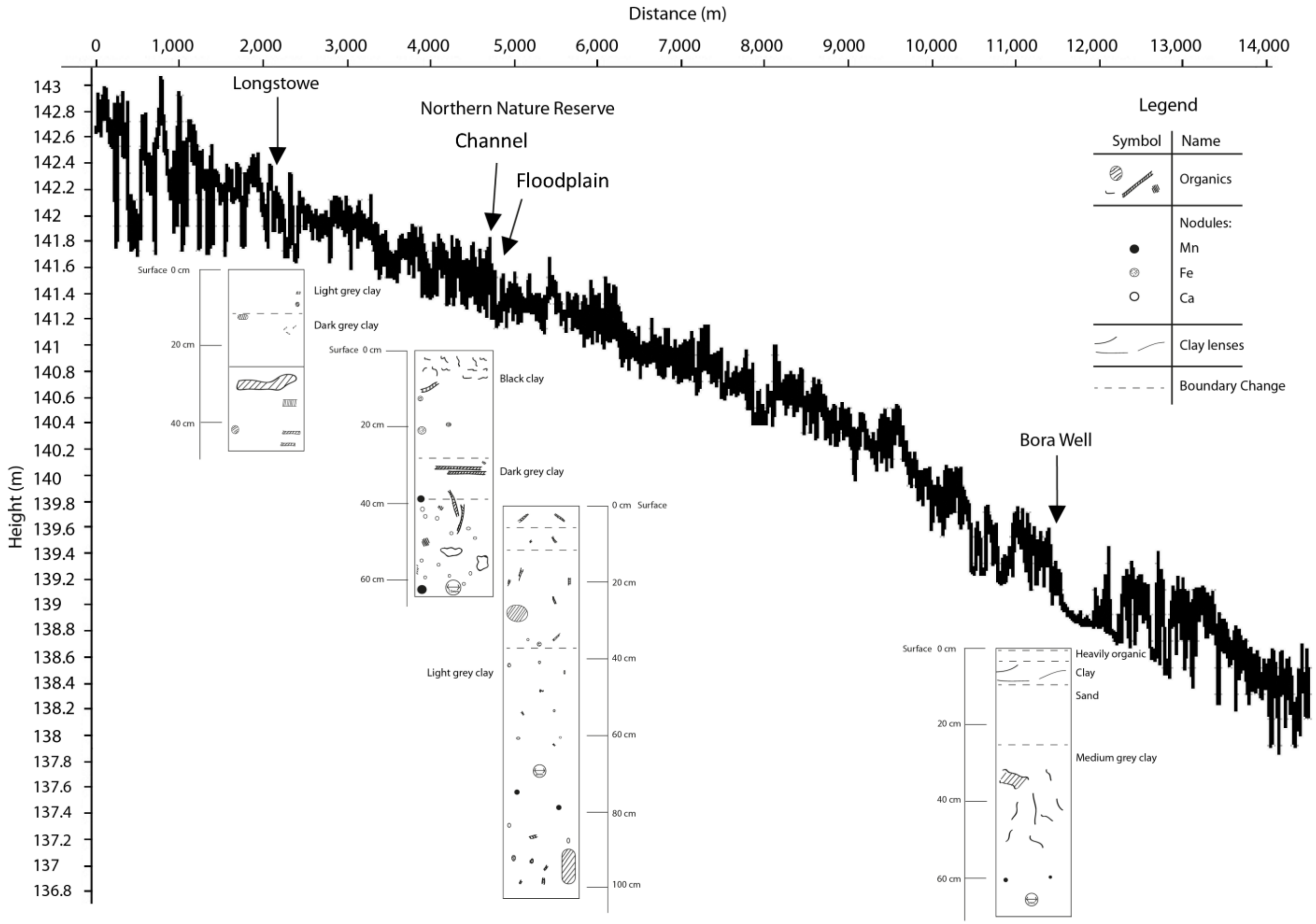


Figure 6.1 Longitudinal profile of the floodplain upstream – downstream with the core locations and core logs. Core profiles are all to the same scale.

6.2.1 Bora Channel – Longstowe

The results of core sedimentology for the furthest upstream core, LC, are shown in Figure 6.2. Key patterns are the dominance of clay sized particles in the top 20 cm of the core, the general increase in dry bulk density to a maximum of 1.7 g cm^{-3} and the general decrease in soil moisture. Fibrous organics were found throughout the core and no nodules were present. The soil moisture colour increased in lightness from very dark grey (2.5Y 3/1) surface layer and a black layer (2.5Y 2.5/1) was at a depth of 13 cm. The pH remains relatively constant at 6 to 7.

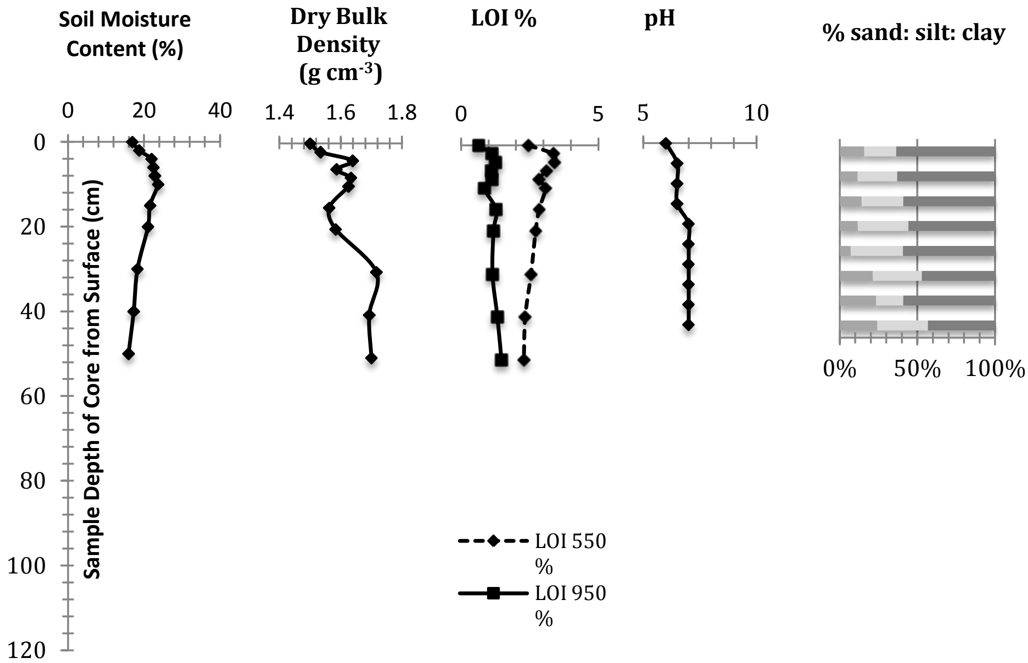


Figure 6.2 Sedimentary characteristics of the in-channel core at Longstowe (LC). The characteristics represented in this figure are soil moisture content, dry bulk density, loss on ignition for organics and carbonates, pH measurements and particle size for the top 20 cm.

6.2.2 Bora Channel – Northern Nature Reserve

The results of core sedimentology for the middle core, NNRC, are shown in Figure 6.3. Key patterns are the dominance of clay-sized particles in the top 20 cm of the core except for a sand-sized particle spike at 10 cm. There is general increase in dry bulk density to a maximum of 1.8 g cm^{-3} and the general decrease in soil moisture. Loss on ignition for carbonates at 10 cm was not determined as a result of sample loss within the kiln. The loss on ignition of organics peaks at a depth of four centimetres (3.7%) followed by a decrease in organics with depth. Assortments of organics were found throughout the entire core. An increase in the manganese and calcium carbonate nodules towards the base of the core correspond well with the increase in loss of ignition of carbonates at 950 °C and the increase in alkalinity of the sediment from a depth of 25 cm shown in Figure 6.3. The pH readings are constant at 7 except for an increase in pH to 8 between 30 cm and 45 cm. Two distinct layers were identified within the core, a transition layer between two distinct layers at a depth of 22 cm to 28 cm. The moist Munsell Colour (2000) at the surface was a very dark greyish brown (2.5Y 3/2) and darkened in with depth. The basal layer contained small dark lenses.

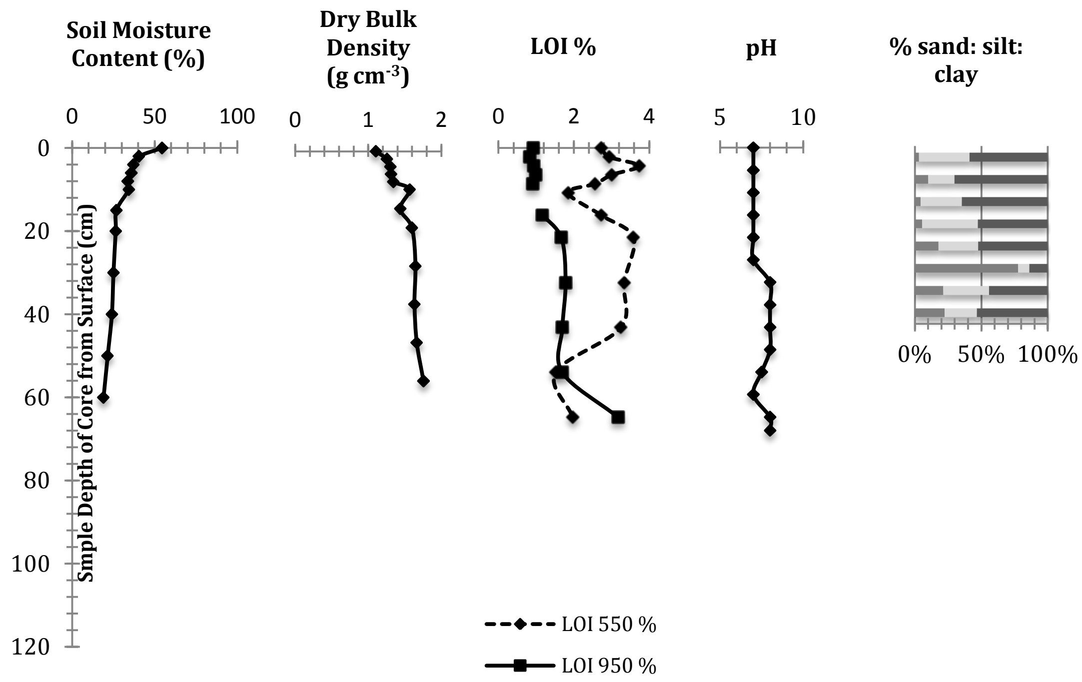


Figure 6.3 Sedimentary characteristics of the in-channel core on the northern Nature Reserve (NNRC). The characteristics provided in this figure from left to right are soil moisture content, dry bulk density, loss on ignition for organics and carbonates, pH and particle size of the top 20 cm.

6.2.3 Bora Channel Floodplain – Northern Nature Reserve

The deepest cores were extracted for this floodplain site, most likely due to the drier nature of the sediment (Appendix 7). The results of core sedimentology for the floodplain core NNRFL, adjacent to in-channel core NNRC, are shown in Figure 6.4. Key patterns are the dominance of clay sized particles in the top 20 cm of the core, the peak of dry bulk density at 15 cm of 1.7 g cm^{-3} and the general increase in soil moisture. Overall, organic content decreases with depth while carbonate content increases with depth, shown in Figure 6.4. The pH measurements increase from 6 at the surface to 8.5 at the maximum depth of 100 cm, increasing the likelihood of calcium carbonate, manganese and iron nodules to form. A distinct colour at 11 cm between the surface organic rich layer and the lower layer was followed by a slight colour change at a depth of 37 cm. The surface colour was black (2.5Y 2.5/1) and proceeded to very dark grey (2.5Y 3/1). Manganese nodules are present from a depth of 80 cm. The increases and decreases in the LOI of carbonates at 950 °C correspond to the frequency of calcium carbonate nodules appearing throughout the lower half of the core.

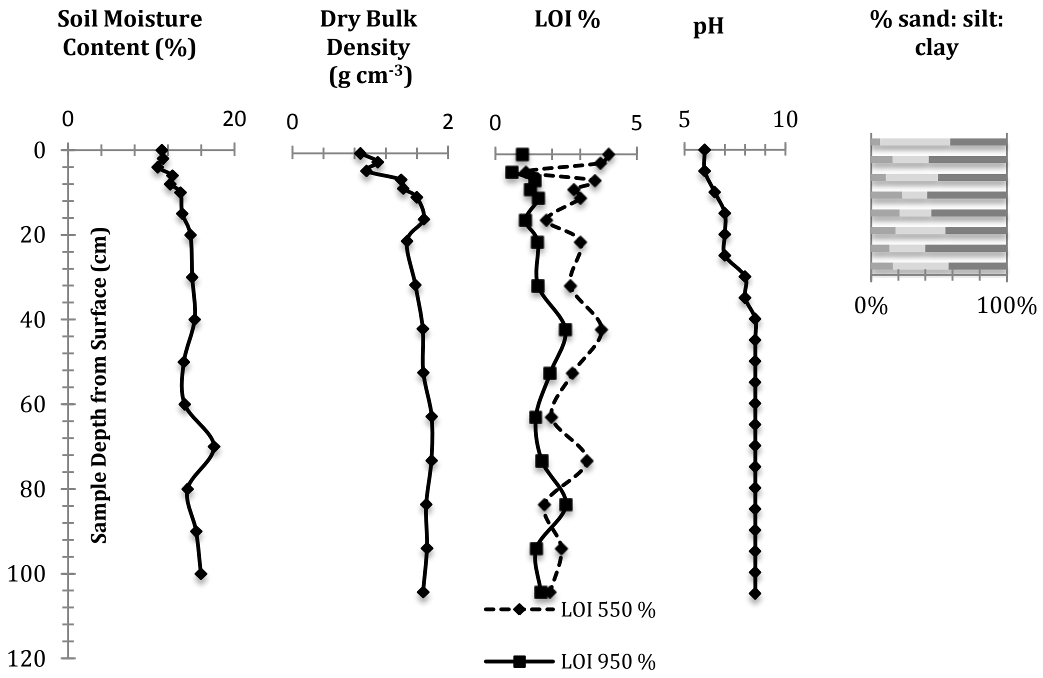


Figure 6.4 Sedimentary characteristics of the core extracted from the floodplain of the northern Macquarie Marsh nature reserve (NNRFL). The characteristics presented in this figure are of soil moisture content, dry bulk density, loss on ignition of organics and carbonates, pH and particle size for the upper 20 cm.

6.2.4 Bora Channel – Bora Well

The results of core sedimentology for the furthest downstream core that is downstream of the reed bed at Bora Well, BWC, are shown in Figure 6.5. Key patterns are the dominance of sand-sized particles at two and six centimetres. There is a general increase in dry bulk density with a maximum of 1.6 g cm^{-3} at 20 cm and the general decrease in soil moisture. The pH value is 5 at the surface with a steady increase in value to a pH of 7 with depth. Many distinct layer changes were visible in the BWC/03 core. The top 1 cm was an organic rich layer. Following the transition layer was a sandy clay layer between 3 cm to 9 cm depth. The sand layer contained long, sloping clay lenses throughout. The moist Munsell colour in the organic rich surface layer was a very dark greyish brown (2.5Y 3/2) followed by light olive brown (2.5Y 5/4) sediment to a depth of 9 cm, tying in with the change in sedimentary layers. Small manganese nodules were identified below a depth of 60 cm in the base of the core. The LOI_{950}% indicates minor reductions in carbonate through ignition.

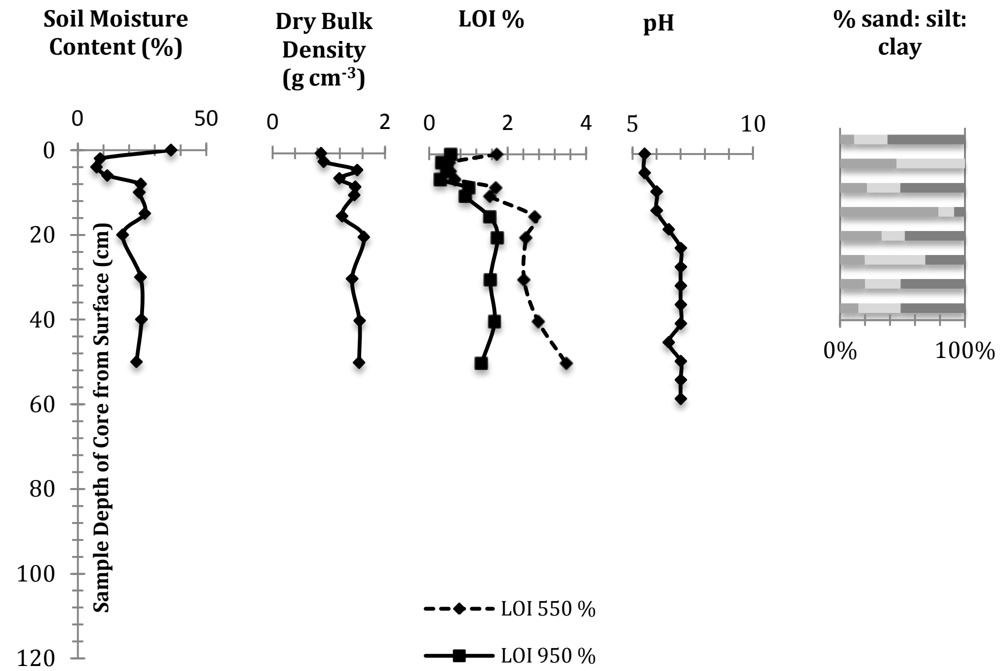


Figure 6.5 Sedimentary characteristics of the in-channel core at Bora Well (BWC) on the northern nature reserve. The characteristics provided in this figure are that of soil moisture content, dry bulk density, loss on ignition of organics and carbonates, pH and particle size of the upper 20 cm.

6.2.5 Comparative Sedimentology

There are no distinct patterns in the sedimentology of cores taken from different sites. However, a few general characteristics do occur. The carbonate content is generally lower than the organic content across all core sites. Most variability between sites is in the surface layers, such that the range in soil moisture is 16.92% to 54.56% and the range in organic content is 1.72% to 4.04%. Differences in sediment moisture are evident between the floodplain core and the in-channel cores and there are differences in moisture holding capacities of different sediments. Relatively low organics for a very organic rich system has been shown previously in the southern Macquarie Marshes (Ralph, 2008). Soil moisture tends to decrease with depth, likely due to depth and the cohesiveness of the material as a sealant to water movement with depth. Figure 6.6 shows a general trend in dry bulk density with increases from the surface to 10 or 20 cm before remaining steady to the maximum depth of the core. Low surface values of carbonate content correspond across sites and increase with depth, occurring with increases in alkalinity of the sediment. A higher percentage of carbonate was lost from the middle core site (NNRC) and adjacent floodplain core (NNRFL) ignition at 950 °C, of 3.17% and 2.49% respectively, corresponding to the higher content of calcium carbonate nodules within thecores at these sites. Whereas the site at Bora Well (BWC) contained fewer nodules at the base of the core and the LC core contained no identifies nodules. Reducing conditions for nodule formation were best at NNRC and NNRFL where pH conditions of 8 and 8.5 respectively, increased alkalinity with depth. Iron nodules were identified at the sites NNRC and NNRFL in the upper sedimentary layers of the cores. The manganese nodules were identified to be relatively small in size and located towards the base of the cores below depths 40 cm.

All sites contained assorted organics, in particular fine hair-like roots. All sites have a loss on ignition of organics less than 5% and only the site at Bora Well shows increases in organics and moisture with depth. A possible explanation of increases in moisture could be a result of the sandy layer in the top profile, enabling moisture to percolate further down through the profile. Moist colour units were similar between the in-channel sites and the floodplain site; LC, NNRC, BWC and NNRFL, where the basal sedimentary colour was dark grey with the preceding layer black in colour. The very dark grey sedimentary colour featured at all sites in the upper strata. The only location to present any sedimentary structure was the upper 10 cm strata at BWC. A shallow sandy layer with inclined clay lenses was not identified at any other site and is likely to be a result of local reworking of in-channel sediment.

The particle size fractions between sites were similarly split with the clay size fraction dominating most sites except for BWC. The in-channel sites at Bora Welland the northern nature reserve were the only sites to exhibit sand layers. The sand, silt and clay fractions were evenly split at Bora Well whereas the clay size fraction dominated NNRC, NNRFL and in particular LC. The in-channel site at Longstowe exhibited greater clay content and less silt content than the cores downstream. During the period of deposition, the particle sizes of the sedimentary layers can be related to the competence of discharge in moving the particles. The depth of the sand layer at NNRC is 10 cm whereas the depth of a similar proportion of sand is at 6 cm at BWC.

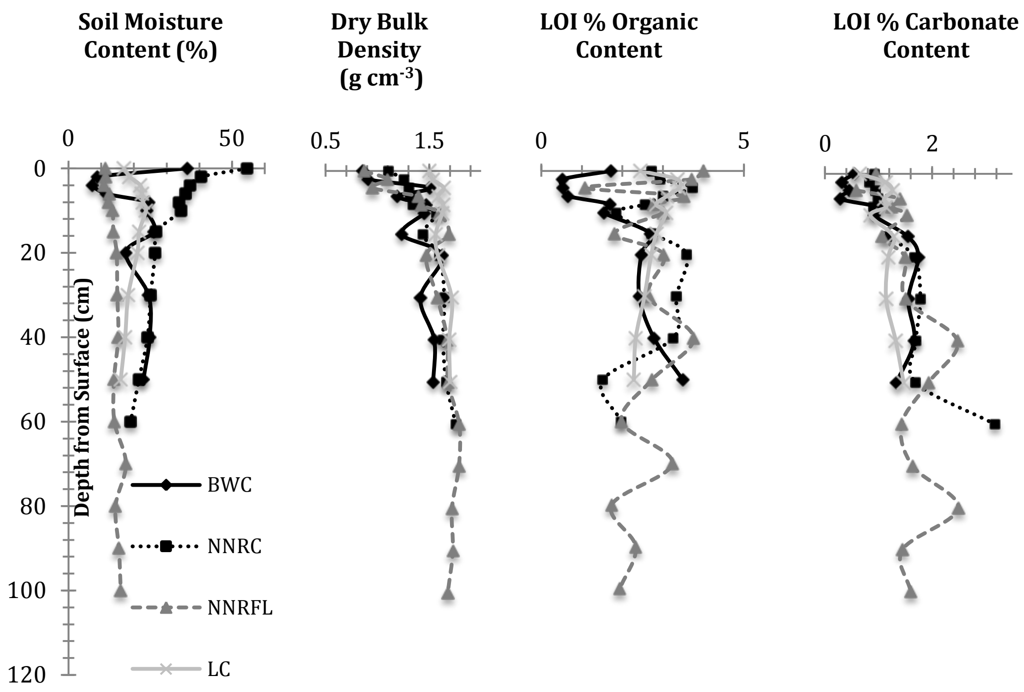


Figure 6.6 Soil moisture content, dry bulk density, and organic and carbonate content compared between the core sites of the northern Macquarie Marshes.

6.3 In-channel and floodplain sediment accumulation rates and storage times of the northern Macquarie Marshes

The results provided in this section include the sediment accumulation rates and sediment storage times of alluvial sediments of the northern Macquarie Marshes. The results obtained by optically stimulated luminescence (OSL) and ^{210}Pb alpha spectrometry dating techniques for sediment residence times are provided in the sections below and linked to the small-scale processes identified in Chapter 5. The implications for longitudinal and lateral connectivity in sediment transfer are examined.

Justifications for the sampling depths used for OSL and unsupported ^{210}Pb are a result of the findings of both Ralph (2008) and Freeman (2008). In both studies, $^{210}Pb_U$ was not found below 20 cm depth. The OSL samples were taken from the base of the core and at the level of the maximum $^{210}Pb_U$ profile. Figure 6.7 shows the location of cores and the geomorphic units on each channel cross-section and shows the differences in channel width, depth and shape.

6.3.1 Luminescence results

The dosimetry results for each site are provided in Table 6.1 and were used to calculate the final age estimate of the OSL samples in conjunction with the water content, cosmogenic value and the calculated minimum age value.

Table 6.1 Dosimetry results for the cores of the northern Macquarie Marshes.

Sample Code	Depth Range (cm)	U-238 (Bq/kg)	± 1 sd	Ra-226 (Bq/kg)	± 1 sd	Pb-210 (Bq/kg)	±1 sd	Th-228 (Bq/kg)	±1 sd	K-40 (Bq/kg)	±1 sd	Water Content (%)
NNRC/15	5 – 25	22.5	5.0	28.46	0.94	30.0	4.8	40.66	1.27	377.3	12.8	28.89
NNRC/65	40 – 65	22.5	3.8	18.25	0.72	24.4	3.9	34.41	1.06	320.4	10.8	20.46
NNRFL/08	4 – 15	25.1	4.9	26.5	0.93	13.2	4.5	43.48	1.30	388.6	12.1	16.77
NNRFL/90	80 – 100	25.6	5.0	24.97	0.83	26.0	4.3	38.43	1.19	391.6	13.2	16.93
BWC/08	4 – 20	16.8	4.2	18.36	0.74	28.6	3.9	29.31	0.96	328.2	11.2	18.61
BWC/65	45 – 65	18.1	5.5	26.96	0.96	24.1	4.5	44.91	1.37	477.1	14.1	23.37
LC/03	0 – 20	25.5	5.5	23.13	1.02	26.1	5.0	44.44	1.38	390.9	13.2	24.46
LC/55	25 – 55	28.1	4.8	17.17	0.78	24.8	4.0	38.81	1.17	378.1	12.4	19.90

Two twenty-four aliquot samples were analysed of each core. One sample was analysed at the depth at which excess unsupported ^{210}Pb showed no measurable quantity. The second sample was analysed towards the base of the core. An example of a dose response curve for the sample NNRC/65 is shown in Figure 6.8. The curve grows exponentially with the dose points. The natural luminescence is shown on the y-axis, and the intersection with the dose response curve is used to estimate the accumulated dose (x-intercept). Each aliquot was scrutinised against the rejection criteria detailed in

Jacobs et al. (2006). The rejection criteria used and the reasons for aliquot rejection of the Macquarie Marsh samples are listed in Table 6.2.

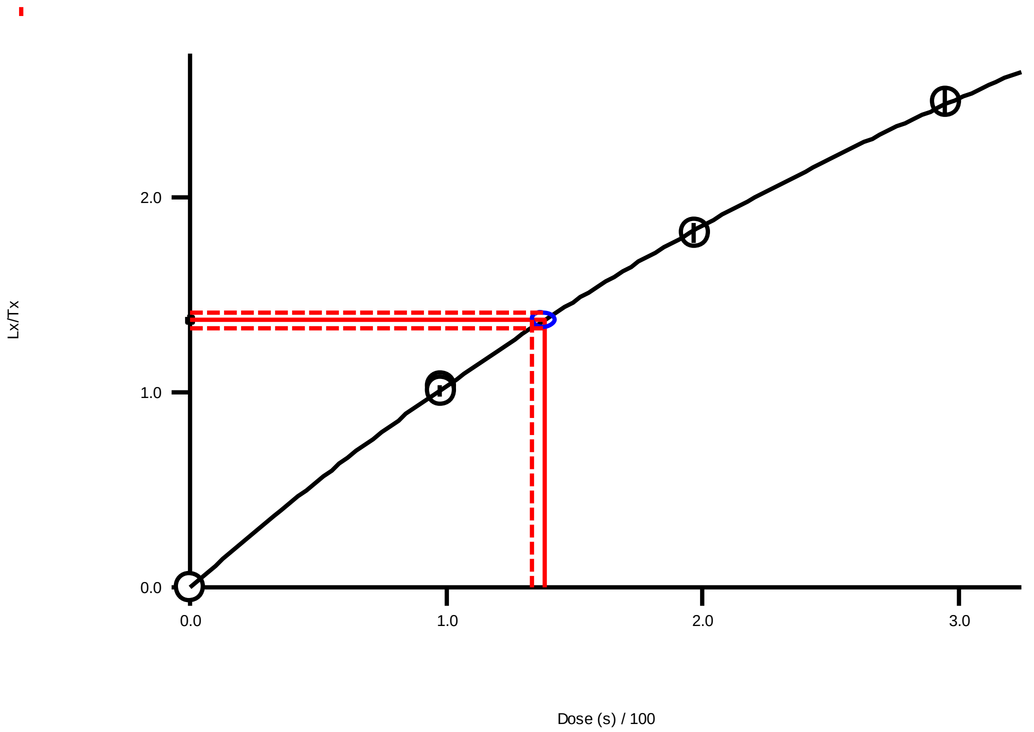


Figure 6.8 Example of a dose response curve for the core at the northern nature reserve site at a depth of 65 cm (NNRC/65). The perforated lines indicate a good regenerative dose calculation.

Table 6.2 The number and reason for aliquot rejection (Source: Jacobs et al., 2006)

Macquarie Marsh Sample	Number of Remaining Aliquots	Number of Aliquots Rejected	Rejection Criteria for Macquarie Marshes Samples
NNRC/15	15	1 aliquot was the natural; 8 aliquots were rejected.	Sensitivity correction – recycling ratios. All aliquots were dismissed due to the low dose recycling (RR1) exceeding 1.1 or less than 0.9.
NNRC/65	21	1 aliquot was the natural; 2 aliquots rejected.	Drastic changes in test dose sensitivity.
NNRFL/08	22	1 aliquot was the natural; 1 aliquot rejected.	Drastic changes in test dose sensitivity.
NNRFL/90	23	1 aliquot was the natural; No aliquots were rejected.	No rejections.
BWC/08	22	1 aliquot was the natural; 1 aliquot rejected.	Sensitivity correction – recycling ratios. All aliquots were dismissed due to the low dose recycling (RR1) exceeding 1.1 or less than 0.9. L_N/T_N did not intersect the growth curve. T_N< 3 x BG.
BWC/65	12	1 aliquot was the natural; 11 aliquots rejected.	L_N/T_N did not intersect the growth curve.
LC/03	22	1 aliquot was the natural; 1 aliquot rejected.	Sensitivity correction – recycling ratios. All aliquots were dismissed due to the low dose recycling (RR1) exceeding 1.1 or less than 0.9.
LC/55	21	1 aliquot was the natural; 2 aliquots rejected.	L_N/T_N did not intersect the growth curve.

The results using the retained aliquots and, initially, the central age model supported the generation of radial plots of each sample. The radial plots in Figure 6.9 show the aliquots of each sample, the associated error and scatter of the sample. The shaded zone on the radial plots indicates the 20% error allowance within the sample. There are no aliquots that fall within the standardised estimate at a depth of 15 cm for the core NNRC/03 although the aliquots have relatively low errors and high precision. There are seven aliquots located between the standardised estimates at a depth of 65 cm for the core NNRC/03. The radial plots show for: NNRC/65 is characterised by a high range of doses (Gy) with a high range of relative errors and precisions (b); NNRFL/03 is characterised by a high scatter of aliquots(c); show a high range of dose (Gy), relative errors and precision with few aliquots falling within the 20% standardised estimate. These results are also for the two depths of LC/03 (a). The core with the least scatter in the radial plots belong to the two samples taken from the Bora Well core, BWC at depths of eight centimetres and 65 cm (d). Sample BWC/08 presents the least scatter with the aliquots represented in a single bunch around and within the standardised estimate with low error and high precision. The BWC/08 sample at a depth of eight centimetres is the only radial plot that shows minimal scatter and one defined population. The OD recorded for each set of aliquots through the CAM is 69.8%. The likelihood of the small scatter in this sample is as a result of the high quartz layer, which would have represented a larger component of this same compared to the other cores sampled. This indicates the difficulty of using OSL in environments where inundation and duration of inundation is variable. Stream flow at this location is also the least turbid, promoting a greater chance for more complete bleaching than at the other locations within and upstream of the floodout.

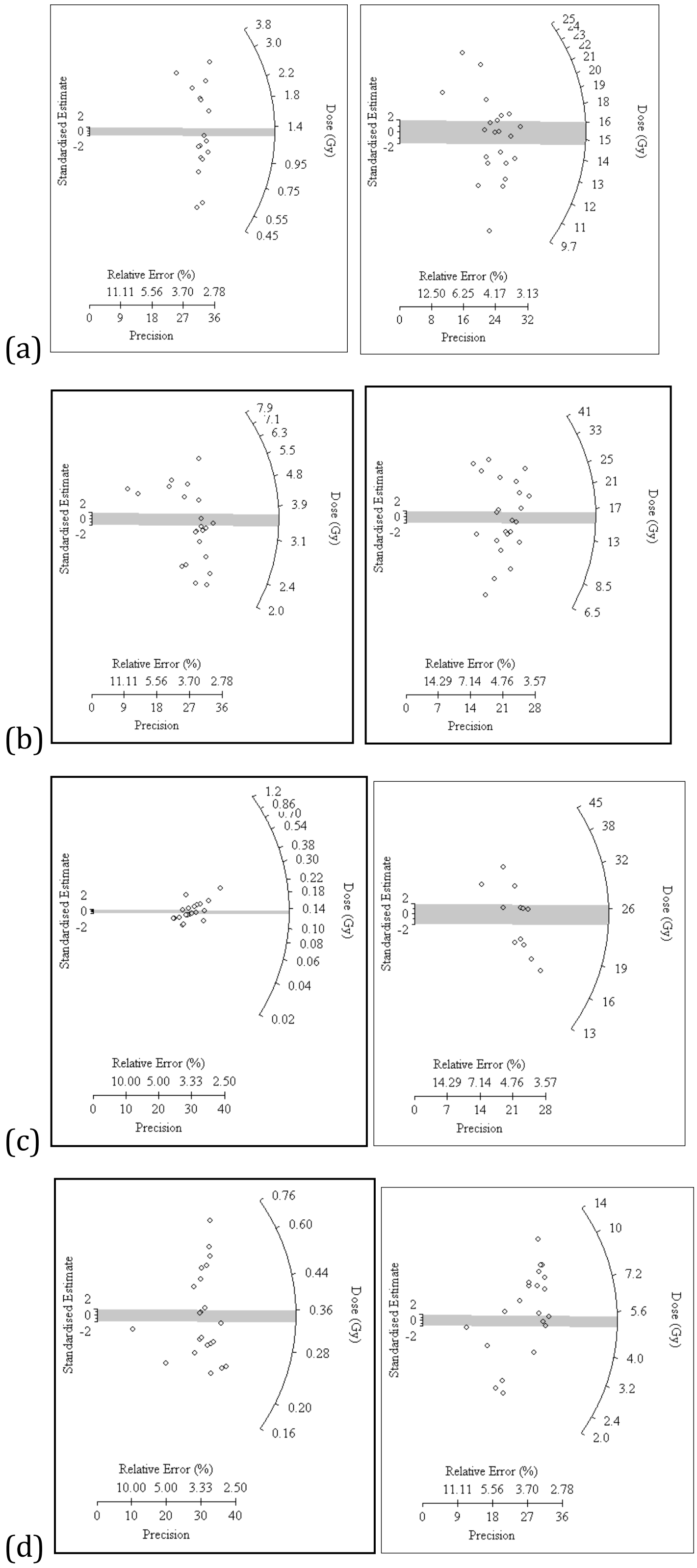


Figure 6.9 (a) the radial plots for NNRC/03 – Left plot at 15 cm and right plot at 65 cm depth. 15 aliquots after rejection at 15 cm with a central age of 1.481 Gy ± 0.267 Gy. 21 aliquots after rejection at 65 cm with a central age of 16.316 Gy ± 2.492 Gy (b) The radial plots of NNRFL/03 – Left plot at 8 cm and right plot at 90 cm. 22 aliquots after rejection at 8 cm with a central age of 3.619 Gy ± 0.540 Gy.23 aliquots after rejection at 90 cm with a central age of 15.335 Gy ± 2.238 Gy. (c) The radial plots of BWC/01 – Left plot at 8 cm and right plot at 65 cm. 22 aliquots after rejection at 8 cm with a central age of 0.133 Gy ± 0.020 Gy. 12 aliquots after rejection at 65 cm with a central age of 24.885 Gy ± 5.028 Gy. (d) The radial plots of LC/03 – Left plot at 3 cm and right plot at 55 cm. 22 aliquots after rejection at 3 cm with a central age of 0.348 Gy ± 0.052 Gy. 21 aliquots after rejection at 55 cm with a central age of 5.229 Gy ± 0.798 Gy. (a – d) The percentage of over dispersion (OD) for each set of aliquots through the CAM is 69.8 %.

Due to the high degree of scatter, and the high range of relative errors and precision within the majority of samples, the minimum age model (MAM) was then applied to calculate the deposition age of each sample. The age estimates and the associated error for each sample depth using OSL are shown in Table 6.3 in the final age column. The errors include both the random and systematic errors. The core with the greatest age estimation is at a depth of 65 cm from the Bora Well core (BWC/01), the site furthest downstream. An estimated age of 7291.2 ± 657.2 years B2K (before the year 2000) was obtained at this depth. The youngest recorded age of 43.8 ± 2.6 years B2K is also from the Bora Well core (BWC/01) at the shallow depth of eight cm. For the core taken furthest upstream (LC/03), the second youngest age was recorded at only 3cm depth, has of 75.2 ± 7.1 years B2K.

Table 6.3 can be used to distinguish between the values from the CAM and the MAM for each set of aliquots. The greatest difference between the D_e (Gy) values calculated using the CAM and MAM is 11.93 ± 2.03 Gy for NNRFL/03/90 with a reported D_e value of 15.33 ± 2.23 Gy using the CAM and a reported D_e value of 3.4 ± 0.2 Gy using the MAM. Another significantly large difference in the value of D_e was between the CAM and MAM of the NNRC/03/65 with a difference of 7.95 ± 1.95 Gy. This difference was closely followed by BWC/01/65 with a difference in D_e value of 7.885 ± 4.028 Gy between CAM and MAM. The sample with the smallest recorded difference between the D_e calculated using the CAM and the MAM is from BWC/01/08 with a difference of 0.05 ± 0.018 Gy. Sources of error that are difficult to avoid include the conversion from concentration data to dose rate, absolute calibration of concentration measurements, beta source calibration and beta attenuation factors. The systematic errors arise from water content and cosmic ray contribution. These sources of error contribute to the overall standard error of each sample.

Table 6.2 Age estimates and associated error for each sample depth using OSL dating technique in the final age column

Site	Sample	Depth Range (cm)	Central Value (Gy)	± se (Gy)	MAM	1 sig	Final Age	± se
Bora Well	BWC_01	8 – 13	0.133	0.02	0.083	0.002	43.82	2.62
In-channel		65 – 70			17	1	7291.177	657.2252
Longstowe	LC_03	3 – 8	0.348	0.052	0.16	0.01	75.15	7.08
In-channel		55 – 60			1.5	0.1	712.2761	71.99803
Northern Nature Reserve	NNRFL_03	8 – 13	3.619	0.54	1.8	0.1	852.57	87.97
Floodplain		90 – 95	15.33	2.23	3.4	0.2	1545.34	150.95
Northern Nature Reserve	NNRC_03	13 – 18	1.28	0.217	0.39	0.03	194.25	18.49
In-channel		70 – 75	15.75	2.35	7.8	0.4	4166.83	360.18

6.3.2 Dating sediments using $^{210}Pb_U(\propto)$ spectrometry

The results of the investigations into sediment accumulation rates using $^{210}Pb_U$ radionuclide-dating alpha spectrometry across the four sites in this study are presented in this section. The dataset is of α-spectrometry samples at depths between 0 – 20 cm and the justification for the chosed dating depths outlined in Section 6.3. This dataset will be correlated with the supplementary dataset from OSL in Section 6.3.2. Furthermore, the suitability of the CRS and CIC models for each site will be outlined and sediment Mass Accumulation Rates (MARs).

The original results of sediment MARs using CRS and CIC were recalculated with the dry bulk densities (Section 6.2.1 – 6.2.5). There was no improvement in the decay profile using the normalisation with the mud fraction (< 63 μm) and subsequently was not used. Below 10 cm at sites 1, 3 and 4, and below 15 cm at Site 2, $^{210}Pb_U$ activities are at background level and consequently cannot be dated by the $^{210}Pb_U$ method. $^{210}Pb_U$ (α) activity from four cores (Appendix 6) located along the channels of the Bora Channel complex at Longstowe, the northern nature reserve and Bora Well show mixed states of equilibrium between $^{210}Pb_T$ and $^{210}Pb_S$. Equilibrium is only reached in one core, Bora Well (BWC/C/02), at a ~ 5 cm below the surface or equivalent mass depth of 6.1 ± 0.6 g cm^{-2}. The remaining cores reveal no equilibrium with depth between $^{210}Pb_T$ and $^{210}Pb_S$

(Figures 6.10, 6.11, 6.12, 6.13). Background levels of $^{210}Pb_U$ were established at ANSTO after a review of samples originating from the Macquarie Marshes (Ralph, 2008; Freeman, 2008). The maximum mass depth of $^{210}Pb_U$ activity before all activity was lost below the background level was within the core from Site 2, northern nature reserve in-channel core, at a mass depth of 13.7 ± 0.7 g cm^{-2}. The in-channel core at Bora Well and the floodplain core at the northern nature reserve recorded no activity of $^{210}Pb_U$ after mass depths 10.1 ± 0.6 g $cm^{-2}$of 5.8 ± 0.5 g cm^{-2} respectively. The in-channel core at Longstowe showed no activity of $^{210}Pb_U$ after a mass depth of 3.8 ± 0.8 g cm^{-2}.

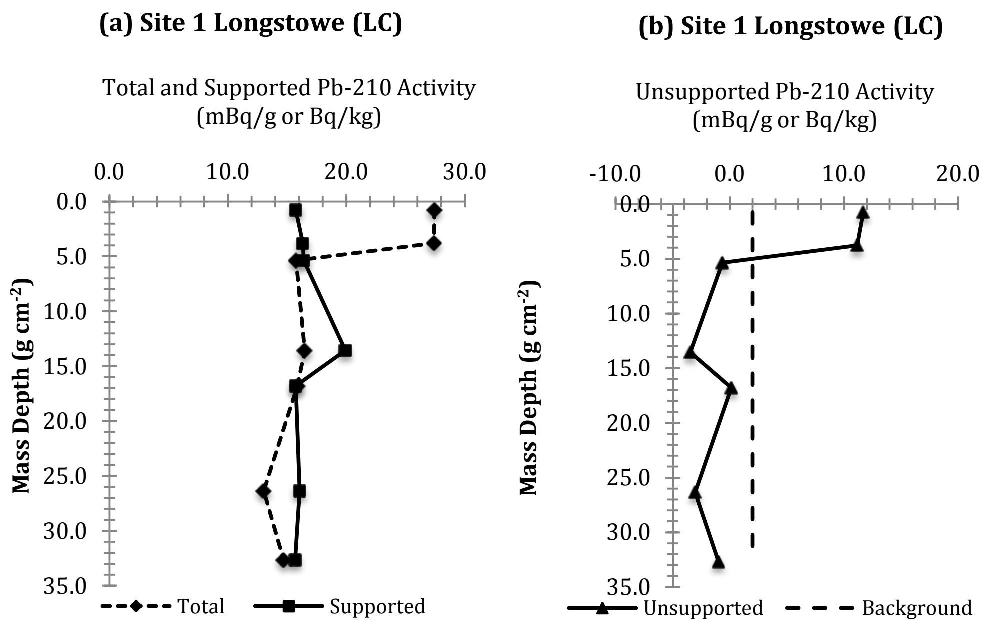


Figure 6.10 Decay profile by α - spectrometry for in-channel sediments of the Bora Channel at Site 1 Longstowe (LC/C/04). $^{210}Pb_T$ and $^{210}Pb_S$ attain equilibrium at a mass depth of 16 g cm^{-2}. However, it does not remain in equilibrium with depth and varies by three units at two points, mass depth 13.5 g cm^{-2} and 26.4 g cm^{-2}. All activity from 3.8 g cm^{-2} is below detection or less than typical background levels.

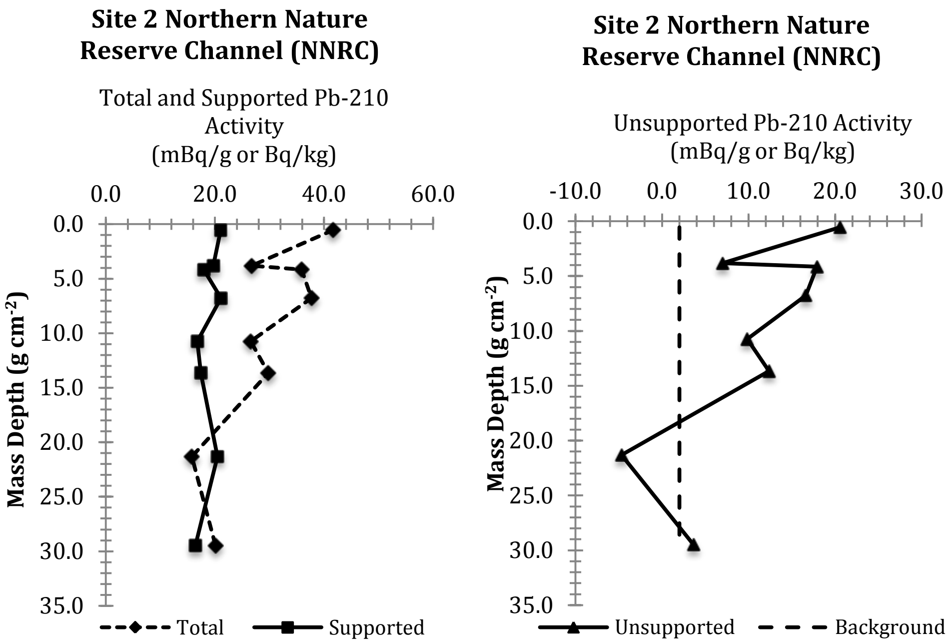


Figure 6.11 Decay profile by α - spectrometry for in-channel sediments of the Bora Channel at Site 2 Northern Nature Reserve (NNRC/C/02). $^{210}Pb_T$ and $^{210}Pb_S$ do not attain equilibrium. All activity from 13.7 g cm^{-2} is below detection or less than typical background levels with the acceptance of a reading at mass depth 29.5 g cm^{-2} with a detection just greater than background.

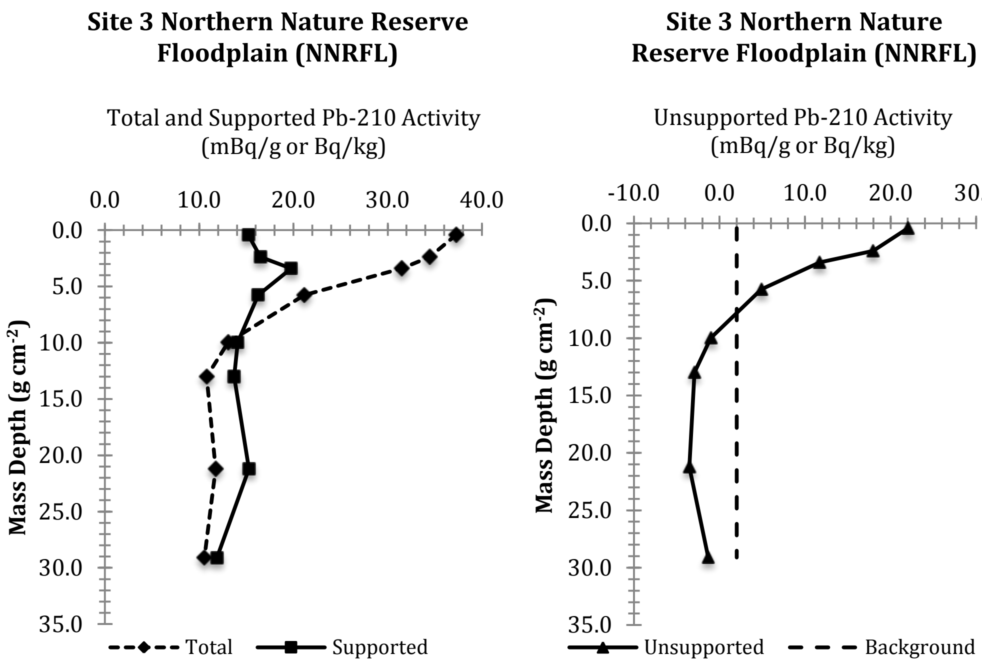


Figure 6.12 Decay profile by α - spectrometry for floodplain sediments at Site 3 Northern Nature Reserve (NNRFL/C/02). $^{210}Pb_T$ and $^{210}Pb_S$ do not attain equilibrium until the last measured point at mass depth 29.1 g cm^{-2}. All activity from 7 g cm^{-2} is below detection or less than typical background levels.

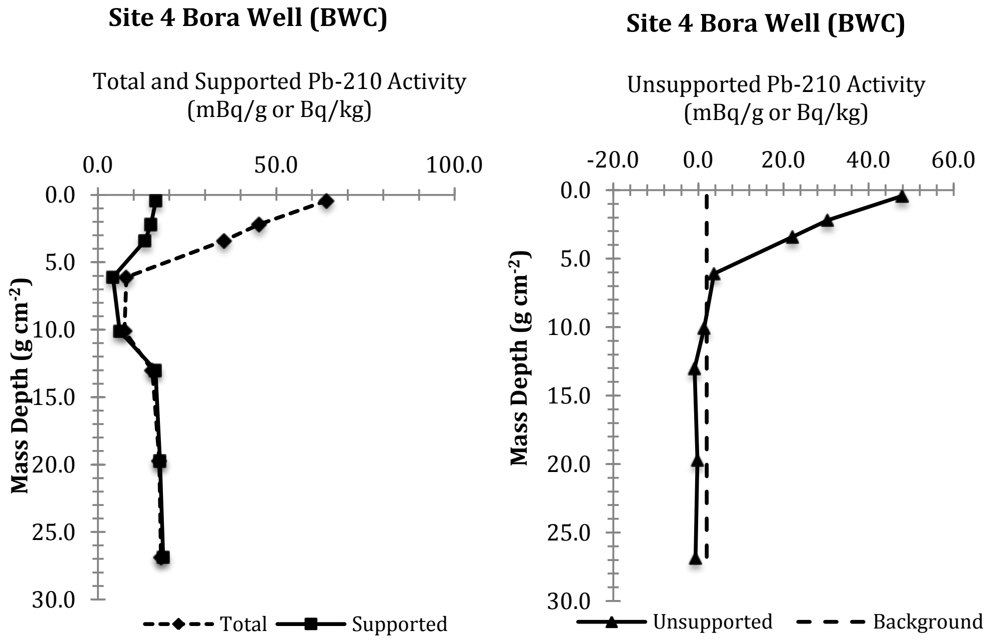


Figure 6.13 Decay profile by α - spectrometry for in-channel sediments of the Bora Channel at Site 4 Bora Well (BWC/C/02). $^{210}Pb_T$ and $^{210}Pb_S$ attain equilibrium at mass depth 6.1 g cm^{-2} and remain in equilibrium for the depth of the core. All activity from 7 g cm^{-2} is below detection or less than typical background levels.

The concentrations of $^{210}Pb_U$ (α) at the surface differed between sites. There was a general rapid decline in concentration of $^{210}Pb_U$ with depth within at least the top 5 cm (~ 5.8 ± 0.5 g cm^{-2} equivalent mass depth) of the core except for at site 2 core, NNRC/C/02, showed an inversion after a mass depth of 4.2 ± 0.6 g cm^{-2}. Site 4 at Bora Well maintains the highest surface concentration of $^{210}Pb_U$ (α) 47.9 ± 2.4 mBq/g, followed moderate surface concentrations at both site 2 (20.6 ± 1.8 mBq/g) and site 3 (22.0 ± 1.4 mBq/g).The lowest recorded surface concentration was revealed at site 1, Longstowe, with a $^{210}Pb_U$ (α) concentration considerably lower than any other site of 11.7 ± 1.3 mBq/g. The shape and depth of the decay profiles indicates that non-depositional diffusion of $^{210}Pb_U$ from the surface cannot be ruled out and the results of the CIC and CRS age-depth models could be deceptive. The CIC, CRS and mean MARs will be calculated for each site with that in mind, however, the use of the models with the decay points from site 1 (LC/C/02) will be unreliable due to the very low activities in the surface layers supporting only two data points.

6.3.3 Sedimentation rates and mass accumulation rates of the northern Macquarie Marshes using 210PbU(∝) and OSL

The mass accretion rates (MARs) were calculated using the derived ages of the CIC and CRS models and subsequent sedimentation rates. The overall investigations into sediment MARs using $^{210}Pb_U(\propto)$ radionuclide-dating technique all revealed relatively shallow depths of the extent of $^{210}Pb_U(\propto)$ activity. The resulting data obtained using OSL and unsupported ^{210}Pb, as techniques of dating recent sediments are estimations of sediment age and associated sedimentation rates or which MARs is derived using the dry bulk density data. Table 6.4 shows the calculated MARs for each depth interval for $^{210}Pb_U$ ($\propto$) ages of the sediment at the depth from which the sample was extracted.

The MAM was used to establish the minimum age of the sample due to the incomplete bleaching of the fluvial quartz. The conditions in the Macquarie Marshes, semi-permanent inundation and often turbid water prior to channel breakdown, is a suitable explanation for the discrepancy between sedimentation rates and the likelihood that the unsupported ^{210}Pb results are more reliable. There are errors associated with the shallow depths at which the upper section of the core was sampled, particularly at Site 1 Longstowe the core was sampled at the shallow depth of 3 cm.

The $^{210}Pb_U$ ($\propto$) CRS MARs results show a pattern that was expected between Site 1 and Site 4, which has the lower sediment accretion rates downstream of the unchannelised floodplain wetland with a surface MARs of 0.078 g cm^2 yr^{-1}. The largest accretion rates with the highest associated errors are from Site 1 at Longstowe in a more dynamic reach with a surface MARs of 2.430 g cm^2 yr^{-1}. The MARs from the in-channel Site 2 is substantially higher than the MARs surface sample at Bora Well with a surface MARs of 0.471 g cm^2 yr^{-1}. The floodplain MARs at Site 3, directly adjacent to Site 2, has a surface MARs of 0.091 g cm^2 yr^{-1}. The CRS MARs compare well with the CIC MARs, however there is quite a difference between the $^{210}Pb_U$ ($\propto$) MARs and the MARs calculated from the OSL ages. The OSL MARs are considerably lower than the $^{210}Pb_U$ ($\propto$) MARs, possibly expected because of the use of the conservative MAM when calculating OSL ages. MARs were derived from the OSL data using the bulk density data that was also used to derive MARs with the $^{210}Pb_U$ ($\propto$) data. The OSL MARs for Bora Well, which following the pattern of sediment deposition, has a higher mass accretion rate than any other core.

Table 6.4 Estimated MARs and equivalent sedimentation rates from the radinuclide cores LC/04, NNRC/02, NNRFL/02, BWC/02 and the derived sedimentation rates from OSL dating of the cores LC/03, NNRC/03, NNRFL/03 and BWC/01.

Site	Code	Suppliers Code	Depth (cm)	$^{210}Pb_U(\alpha)$ CRS MAR (g cm^2 yr^{-1})	$^{210}Pb_U(\alpha)$ CIC MAR (g cm^2 yr^{-1})	OSL MAR (g cm^2 yr^{-1})
Longstowe	LC/C/04	M459	0 – 2	2.430	2.022	
			0 – 3			0.053
			3-55			0.134
Northern Nature Reserve (Channel)	NNRC/C/02	M465	0 – 3	0.471	0.472	
		M466	3	0.155	0.512	
		M679	5	0.464	0.508	
		M467	8	0.498	0.474	
		M468	10	0.440	0.509	
			0 – 15			0.103
			15-65			0.023
Northern Nature Reserve (Floodplain)	NNRFL/C/02	M471	0 – 2	0.091	0.096	
		M472	3	0.091	0.116	
		M681	5	0.073	0.087	
			0 – 8			0.01
			8-90			0.197
Bora Well	BWC/C/02	M453	0 – 2	0.078	0.076	
		M454	3	0.046	0.059	
		M676	5	0.069	0.88	
			0 – 8			0.217
			8-65			0.012

6.5 Chapter Summary

The sedimentology of the Bora Channel system, where cores were extracted from three in-channel sites and one floodplain site, are telling of the dynamics of the lowland system. The massive structures of the layers within the cores are evidence of dynamics that are not high in energy. The only site that indicated higher energy dynamics was at Bora Well, downstream of the floodout.

The in-channel MARs derived from the unsupported lead-210 results and the OSL data shows a pattern consistent with the total suspended solids data in Chapter 5.4. The highest rates of in-channel sedimentation are consistent with high concentrations of the suspended load. The in-channel sedimentation rate decreases down the Bora Channel system and corresponds to decreases in the suspended load. The discontinuity of suspended sediment transport can be derived from these results and the relationship with in-channel vegetation and declining discharge.

Chapter 7: Discussion

7.1 Introduction

Three main findings have emerged from the data collected and presented in the preceding chapters:

1) The lower Macquarie River is characterised by varying degrees of longitudinal and lateral connectivity identified by contemporary suspended sediment transport, frequency-magnitude inundation relationships and physical connection over different temporal and spatial scales.

2) Sediment accumulation rates of the in-channel zone in the northern Macquarie Marshes are extremely slow in comparison to sedimentation rates identified in the southern Macquarie Marshes.

3) Low sedimentation rates of the northern Macquarie Marshes occur because of small-scale processes such that diminishing discharge, sediment deposition and in-channel vegetation growth promote river channel breakdown of the Macquarie River trunk channel.

This chapter initially explores the key findings described in chapter 5 and 6 that indicate the small sale processes controlling channel breakdown. Additionally, the analysis of the longitudinal and lateral connectivity of the lower Macquarie River established in chapter 5 and 6 will be discussed through its relationship with the small-scale processes controlling the movement of water and suspended sediment between landscape compartments of the channel corridor.

The key findings are compared to the findings of previous research of the Macquarie Marshes (i.e. Freeman, 2008; Ralph, 2008; Yonge and Hesse, 2009) and to similar systems globally. The chapter concludes by addressing the relevance of this research of the lower Macquarie River to the wider context of contemporary wetland ecosystem goods and services.

7.2 Dynamics of the Lower Macquarie River

The large-scale controls on the contemporary character and behaviour of reaches of lower Macquarie River are climate (i.e. hydrology) and landscape (i.e. landscape gradient, channel confinement, and bed material texture). The semi-arid climate controls the temporal and spatial variability of runoff and subsequent flow of the lower catchment, thereby controlling the hydrology. The landscape of the lower Macquarie River controls the channel gradient and the bed material texture. These two large-scale controls determine the volume, energy of flow and the suspended sediment transport capacity down catchment. Unlike river systems that increase in size and capacity with distance down catchment towards coastal regions, the Macquarie River flows inland where decreases in capacity and size reflect the semi-arid nature of the climate (Ferguson et al., 2006) and the lack of perennial tributaries (Kemp, 2010).

Suspended sediment concentrations increase down catchment (chapter 5.3) and bedload transport decreases as a result of reductions in specific stream power and fining of bed material texture down catchment (Bull, 1979). In a low gradient alluvial landscape river channels adjust their planform to achieve maximum suspended sediment transport capacity (Nanson and Huang, 1999). The lower Macquarie River develops a meandering planform as a result of shallowing channel gradients, diminishing landscape confinement and fining bed material texture down catchment (chapter 5.2). Figure 7.1 (a & b) defines the dynamics of the lower Macquarie River (reaches 4 to 7) and the behaviour of the reach (suspended sediment transport, declining discharge, lack of perennial tributary inputs, sediment supply and deposition). The key components of the lower Macquarie River system are identified and discussed below.

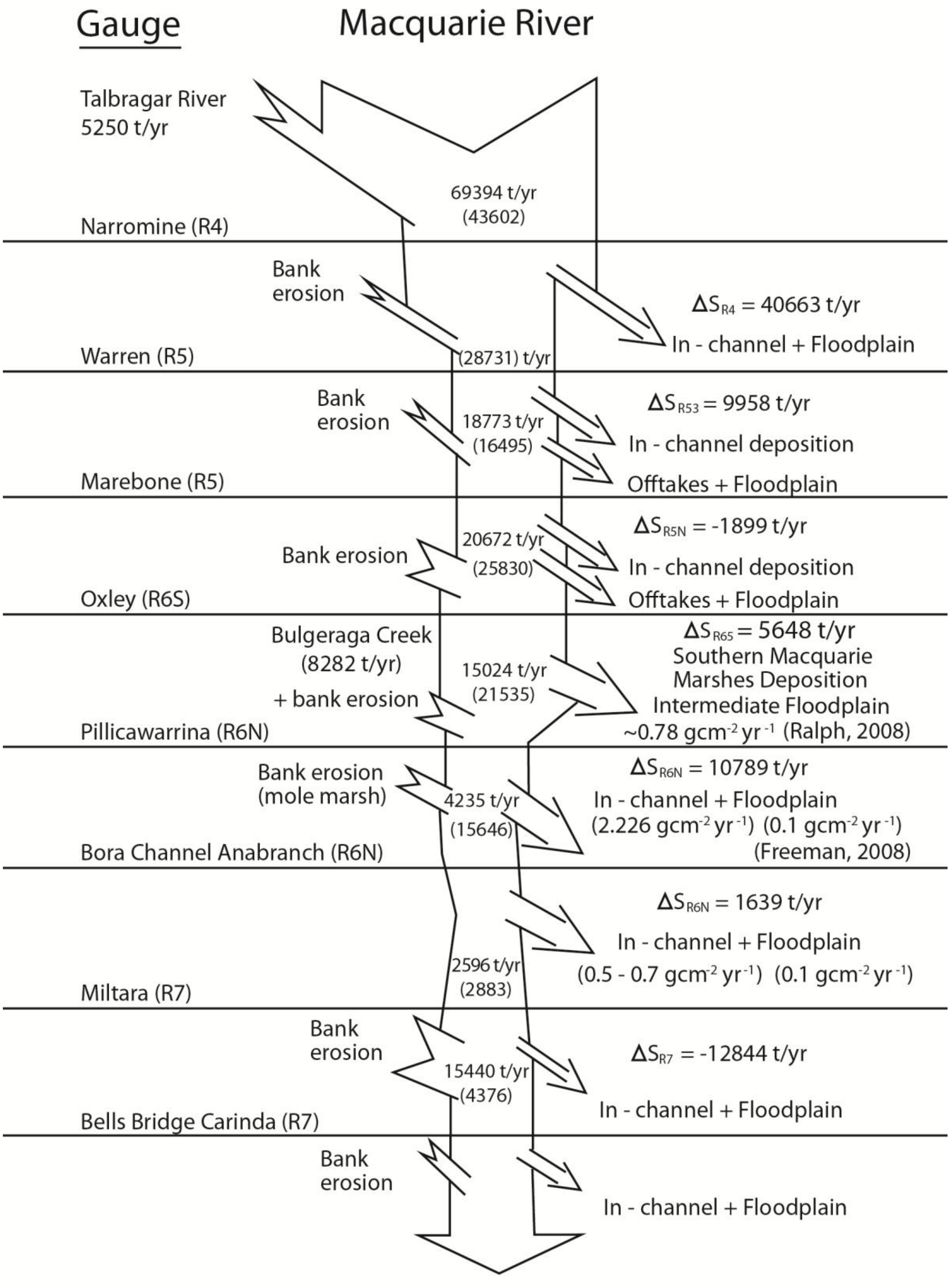


Figure 7.1a The change in net sediment retention or production through the lower Macquarie River System between Narromine and Bells Bridge Carinda. Gauge data has been used for the mean daily discharge and total suspended solids concentrations. The figure in brackets are the calculations using grab sample TSS concentrations.

Reach	Channel Characteristics	Vegetation Interactions	Longitudinal Connectivity Dynamics	Lateral Connectivity Dynamics
4 (Narromine)	Sinuosity: 1.19 Gradient: 0.0005 Number of Channels: 1 Bed material texture: Sand Geomorphic Units: Floodplains; point bars; sand sheet; erosional ledges along banks.	Thin riparian strip of River Red Gums. Bank vegetation includes River Red Gums and non-woody vegetation. 0% Vegetation blocking.	Daily discharge 3278 ML. Suspended sediment transport - Narromine 64 mg L^{-1} (gauge). RI Bankfull: < 1 in 50 yr (39.1 W m^{-2})	RI Overbank: > 1 in 50 yr
5 (Warren)	Sinuosity: 2.01 Gradient: 0.0003 Number of Channels: 1 Bed material texture: mud Geomorphic Units: Floodplains; pools; erosional ledges along banks; levees.	Sparse woody floodplain vegetation growth and aquatic in-channel vegetation. Vegetation blocking up to 5%.	Daily discharge 1873 ML. Suspended sediment transport - 61 mg L^{-1} (gauge). RI Bankfull: < 1 in 2 yr (9.8 W m^{-2})	RI Overbank: > 1 in 2 yr
5 (Marebone)	Sinuosity: 1.48 Gradient: 0.0003 Number of Channels: 1 Bed material texture: mud Geomorphic Units: Floodplains; pools erosional ledges along banks; levees.	In-channel (aquatic) and sparse floodplain (woody) vegetation growth. Vegetation blocking up to 50%.	Daily discharge 1181 ML. Suspended sediment transport - 62 mg L^{-1} (gauge). RI Bankfull: < 1 in 2 yr (8.1 W m^{-2})	RI Overbank: > 1 in 2 yr
6S (Oxley)	Sinuosity: 1.11 - 1.62 Gradient: 0.00007 – 0.0003 Number of Channels: multi-channeled Bed material texture: mud Geomorphic Units: Floodplains; floodout; erosional ledges along banks; levees.	In-channel (aquatic & semi-aquatic) and floodplain (semi-aquatic & woody) vegetation growth. Vegetation blocking up to 50%. In-channel woody debris.	Daily discharge 868 ML. Suspended sediment transport – 87 mg L^{-1} (gauge). In-channel sedimentation rates 0.6 to 1.0 g cm^{-2} yr^{-1} RI Bankfull: , 1 in 2 yr (0.6 W m^{-2})	RI Overbank: > 1 in 2 yr Overbank sedimentation rates of 0.78 g cm^{-2} yr^{-1} (levee) to 0.11 g cm^{-2} yr^{-1} (medial and distal floodplain (Ralph, 2008).
6N (Pillicawarrina)	Sinuosity: 1.39 Gradient: 0.0002 Number of Channels: multi- channeled Bed material texture: mud Geomorphic Units: Floodplains; floodout; erosional ledges along banks.	In-channel (aquatic & semi-aquatic) and floodplain (semi-aquatic & woody) vegetation growth. Vegetation blocking up to 50%. In-channel woody debris.	Daily discharge 833 ML. Suspended sediment transport – 74 mg L^{-1} (gauge). RI Bankfull: < 1 in 2 yr (1.3 W m^{-2})	RI Overbank: > 1 in 2 yr
6N (Bora Channel System)	Sinuosity: 1.04 – 1.22 Gradient: 0.0001 – 0.0003 Number of Channels: multi-channeled Bed material texture: mud Geomorphic Units: Floodplains; floodout.	In-channel (aquatic & semi-aquatic) and floodplain (semi-aquatic & woody) vegetation growth. Vegetation blocking up to 100%.	Daily discharge 177 ML. Suspended sediment transport – 242.9 mg L^{-1} (grab sample). Longitudinal disconnectivity: in-channel MARs 2.22 g cm^{-2} yr^{-1} upstream floodout and 0.08 g cm^{-2} yr^{-1} downstream of floodout. RI Bankfull: < 1 in 1 year (0.1 – 0.2 W m^{-2})	RI Overbank: > 1 in 1 yr Overbank sedimentation rates on the intermediate floodplain was 0.1 g cm^{-2} yr^{-1} and corresponds with MARs of Freeman (2008). MARs decrease with distance from channel from 0.1 g cm^{-2} yr^{-1} to 0.035 g cm^{-2} yr^{-1} (Freeman, 2008).
7 (Miltara)	Sinuosity: 1.04 Gradient: 0.0002 Number of Channels: 1 Bed material texture: mud Geomorphic Units: Floodplains; erosional ledges along banks.	In-channel (aquatic & semi-aquatic) and sparse floodplain (woody) vegetation growth. Vegetation blocking 0%. In-channel woody debris.	Daily discharge 177 ML. Suspended sediment transport – 40 mg L^{-1} (gauge). RI Bankfull: < 1 in 1 yr (0.2 W m^{-2})	RI Overbank: > 1 in 1 yr
7 (Carinda)	Sinuosity: 1.08 Gradient: 0.0002 Number of Channels: 1 Bed material texture: mud Geomorphic Units: Floodplains; erosional ledges along banks.	In-channel (aquatic & semi-aquatic) and sparse floodplain (woody) vegetation growth. Vegetation blocking up to 100%.	Daily discharge 388 ML. Suspended sediment transport – 115 mg L^{-1} (gauge). RI Bankfull: < 1 in 1 yr (0.6 W m^{-2})	RI Overbank: > 1 in 1 yr

Figure 7.1b Reach characteristics, vegetation associations and lateral and longitudinal connectivity

The erosion and deposition is not quantified in Figure 7.1 (a & b). However, it shows the net retention or production of the reach and the likely inputs and outputs between each gauge site. The range of in-channel and intermediate floodplain sedimentation rates are included on the figure. It is interesting to note the positive changes in sediment yield between most reaches, indicating net deposition. However, in reach 5 between Marebone and Oxley there is net production of the suspended load and likewise between Miltara and Carinda in reach 7. The production of suspended sediment in reach 7 is more than six times greater than the production in reach 5. This indicates the beginning of reach 7 as predominantly erosional.

The gauge total suspended solids data has been used in the change in yield calculations, with grab sample yields included in brackets. In the most cases, the yield figures are similar. However, the average concentrations of the samples collected in the field over the small time frame are not a true reflection of the long-term average. Declining discharge down catchment has removed the pattern of increasing suspended sediment concentrations between the southern and northern Macquarie Marshes. The table included in Figure 7.1 (a & b) brings together the relationships between channel characteristics, vegetation interactions and the longitudinal and lateral hydrologic connectivity and suspended sediment transport to the down catchment transfer of suspended sediment.

7.2.1 Declining discharge and contemporary suspended sediment transport

Declining discharge and suspended sediment transport control the hydraulic geometry of the lower Macquarie River and promote changes in channel gradient, width/depth (w/d) ratio and channel capacity with distance down catchment (chapter 5.2.2) (Leopold and Maddock, 1953; Schumm, 1969; Nanson and Huang, 1999; Jain and Sinha, 2004). Drivers of channel change are typically driven by the interrelation of sediment supply and discharge (Schumm, 1969; Gilvear, 1995), dictating the hydraulic geometry of the channel (Lane et al., 1996). Bedload transported by the lower Macquarie River ceases with declining discharges between reach 4 (meandering sand bed) to reach 5 (meandering fine grained) and reflected in the change of channel sinuosity (chapter 5.2.2; Figure 7.1). The meanders of the trunk channel increase in amplitude (Figure 7.2) with distance down catchment from reach 4 to support suspended sediment transport (Hudson et al., 2012). The morphodynamic response of the Macquarie River trunk channel to maintaining suspended sediment transport capacity in the low gradient landscape between reach 5 and reach 7 is through anabranching (Nanson and Huang, 1999).

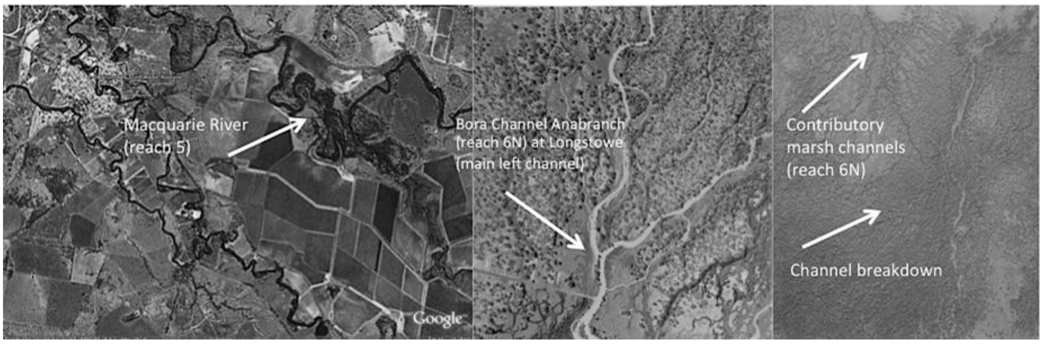


Figure 7.2 Channel planform changes as a response to declining discharge, low landscape gradients and increases in the suspended load. From left to right: high amplitude wavelengths of fine-grained meandering channel near Warren (R5); Bora Channel/Macquarie River trunk channel anabranch. The Bora Channel is the channel on the left showing reductions in sinuosity; floodout zone in the northern Macquarie Marshes and contributory marsh channels downstream floodout (top of image).

7.2.1.1 Suspended sediment supply

Suspended sediment supply within the lower Macquarie River is heavily driven by in-channel bank erosion (chapter 5.2.2). The suspended load increases down catchment (Figure 7.1) with total suspended solid concentrations entering the Macquarie Marshes with an average of 87.5 mg L^{-1}. Sediment inputs into the system from primary distributary channels and the main trunk channel increase the suspended load (concentration increases 74.7 mg L^{-1} (gauge) or 371 mg L^{-1} (in-situ)) between the southern and northern Macquarie Marshes (refer to Figure 7.1).

The increase in suspended sediment is unlikely to be related to evaporation. Minor reductions in the volume of streamflow were observed in the field, with the trunk channel sampled at bankfull flow periods (chapter 5.3). Within the 7 km between the most downstream sample point in the southern Macquarie Marshes and the sampling points at the start of the northern Macquarie Marshes, the threefold growth in suspended sediment concentration of the in situ samples is likely to be influenced by bank erosion, observed within the trunk channel and the primary distributaries. Bank erosion is visible on the concave banks of meander bends and is suspected to be a primary contributor of the suspended sediment load. However, cattle heavily graze the main trunk channel and the primary distributaries between the southern Macquarie Marshes nature reserve and the northern Macquarie Marshes nature reserve. Cattle also heavily graze the area where the main anabranch (Bora channel) diverges from the trunk channel prior to the northern Macquarie Marshes. Bed and bank trampling by cattle was commonly observed in the channels and evidenced by the destruction of suspended sediment samplers in channels of these areas and is likely to mechanically increase local suspended sediment concentrations (Trimble and Mendel, 1995; Smith and Dragovich, 2008). Figure 7.3 are photos taken within the Macquarie Marshes and show evidence of bank erosion and in-channel trampling by cattle.

Figure 7.3 Evidence of erosion of the channel zone entering the northern Macquarie Marshes. Photos from left to right: Bank erosion along Bulgeraga Creek, joining the trunk channel upstream of Pillicawarrina; in-channel bed trampling by cattle and evidence where a suspended sediment sampler was located; and bank erosion at Pillicawarrina.

It is likely that the primary driver of channel bank erosion is geomorphic effective flows (Wolman and Miller; 1960; Costa and O'Connor, 1995). However, the stream power associated with higher magnitude flows is not solely responsible for 'geomorphic work' (Costa and O'Connor, 1995). Flow duration floods of certain frequencies (Harvey, 1969), the calibre of sediment in transportation, the shear strength of banks, and the recuperative processes between different magnitude events determine the capacity of moderate to higher magnitude flows to rework in-channel sediments (Costa and O'Connor, 1995). The cohesive fine-grained nature of the bed and banks of the channel(s) in reaches 5, 6 and 7 are more resistant and less susceptible to hydraulic action through increases in velocity, further enhanced by the type and volume of in-channel vegetation and thereby enhancing resistance to shear strength (Bull, 1979; Lane & Richards, 1999). The resistant nature of bed and bank material and additional cohesiveness through in-channel and riparian vegetation are important factors when assessing the effectiveness of flood discharges (Costa & O'Connor, 1995; Lane &

Richards, 1999). If effective discharges occur during bankfull flows (Wolman and Leopold, 1957), the frequency of effective discharge occurs on return intervals between 136.2 W m^{-2} for a 1 in 100 year flood in reach 1, 72 W m^{-2} for a 1 in 100 year flood in reach 2, 49.4 W m^{-2} for a 1 in 100 flood year in reach 3, 39.1 W m^{-2} for a 1 in 50 year flood in reach 4, 9 W m^{-2} for a 1 in 2 year flood in reach 5, 0.1 – 0.8 W m^{-2} for a 1 in 1 / 1 in 2 year flood in reach 6, and 0.2 – 0.6 W m^{-2} for a 1 in 1 year reach 7. The specific stream powers correspond to those recorded for unconfined low gradient alluvial rivers by Nanson and Croke (1992). Leopold et al. (1964) described the geomorphic effectiveness of high magnitude events should be greater than 35 W m^{-2} to erode the channel and floodplain, corresponding to the predominantly aggradation nature of reaches 5 to 7 (Figure 7.1 a and b). Pickup and Warner (1976) found the most effective discharges to occur in a return period of 1.15 to 1.40 years, whereas bankfull discharges predominantly lie within a 4 – 10 year return period. Dury (1959) found on certain northern hemisphere rivers the return frequency of bankfull discharge to be every 1 – 2 years, as did Leopold et al. (1964). The product of competent discharges, where erosion is balanced with deposition, promotes channel change (Harvey, 1969). The commonly reported magnitude and frequency of bankfull discharge has also been reported for Australian rivers by Woodyer (1968) for inland rivers in NSW with a recurrence of 1.2 – 1.6 years. The lower anabranching reaches of the Namoi-Gwydir system challenged the reported recurrence interval with a return period of 3 years (Riley, 1973). However, the single channels of the upper system reached bankfull discharge on a 1.1 – 2 year recurrence (Kemp, 2010). Also comparable with the lower Macquarie River are the reported figures of bankfull discharge recurrence intervals for the single and anabranching reaches of the Murray River of between 1.5 and 2.5 years (Rutherford, 1994) and for the Murrumbidgee River after river regulation of 2.2 years (Page et al, (2005).

In the southern Macquarie Marshes there is evidence of channel incision of primary distributaries (Ralph and Hesse, 2010) and evidence of erosion of the banks of the meandering trunk stream (chapter 5.2.2). During higher magnitude events (Nanson and Huang, 1999) and backflooding (Yonge and Hesse, 2009), erosion of the floodplain and the formation of new channels occur. Within the northern Macquarie Marshes, channel incision and bank scour was identified along the meandering trunk channel and the Bora Channel immediately downstream of the bifurcation. No bank scour was identified downstream of the initial bifurcations where specific stream powers are heavily reduced from 0.5 W m^{-2} to 0.07 W m^{-2}, therefore reductions in shear stress decreases enough to cease sediment entrainment (Bull, 1979). Higher magnitude events coupled with longer flow durations, saturation of cohesive channel banks, or increases in stage height on very dry non-vegetated channel banks, are likely to be the cause of in-channel bank erosion of reach 5, channel within reach 6S and the trunk channel and start of the main anabranch in reach 6N, and in reach 7.

7.2.1.2 Sediment deposition

Coupled with sediment supply along the lower Macquarie River are areas of in-channel and overbank deposition. Overbank sediment deposition occurs at different spatial and temporal scales during periods of overbank flow in reaches with a widening valley that allows floodplain pockets. Discontinuous floodplain pockets in reaches 2 and 3 experiences overbank flooding and periods of sediment accretion over a frequency of a 1 in 100 year flood event. This figure does not compare to observed records, which show overbank flow periods have occurred over the last few wet (la Nina) years. As the valley widens (chapter 5.2) floodplains become continuous and wide and experience a more frequent recurrence of overbank flooding and ensuing scour and deposition cycles of the floodplain (chapter 5.2.2; Fryirs and Brierley, 2005). Channel cross sections were taken at representative sites for each reach to determine recurrence of overbank flooding through flood frequency analysis. The frequency of overbank flooding is unlikely to occur at the same time along the length of the channel, but at different times depending on bank height, the presence of levees and troughs (Hudson et al., 2013). It was observed along the lower Macquarie River that natural levees were commonly eroded in sections (chapter 5.2.2) and troughs in the channel banks were present near off-take channels (both regulated and natural).

Reaches 5, 6 and 7 are dominantly depositional (chapter 5.2.2). Declining discharge and low landscape gradients reduce the specific stream power required to transport bedload and increasingly down catchment, struggle to transport the suspended load (chapter 5.3), resulting in channel breakdown. Unable to be thoroughly detected through suspended sediment sample collections and gauge data in this study, Ralph (2008), Yonge and Hesse (2009) and Ralph and Hesse (2010) have documented sediment deposition within the southern Macquarie Marshes and the controls on channel bed aggradation. Data collected and analysed in this study show an almost equal suspended load being transported between the southern and the northern Macquarie Marshes in the gauge data and elevated concentrations in the suspended load in the in-situ data (chapter 5.3). However, Yonge and Hesse (2009) found the mechanisms of in-channel sediment deposition to be declining discharge and in-channel vegetation. The in-channel vegetation acts to further reduce velocities and increases backflooding and overbank flow (Yonge and Hesse, 2009). Channels within the southern Macquarie Marshes continue to aggrade until avulsion occurs on approximately 100-year time scales (Yonge and Hesse, 2009). Ralph (2008) found sediment accumulation rates of the immediate floodplain of Monkeygar Creek, in the southern Macquarie Marshes, to be ~0.78 g cm^{-2} yr^{-1}.

Suspended sediment data for the northern Macquarie Marshes shows a dramatic decrease from the elevated concentrations entering the northern Macquarie Marshes of 206 mg L^{-1} compared to concentrations sharply diminishing to 1 – 10 mg L^{-1} in the floodout zone and contributory marsh channels. Figure 7.1 shows the annual suspended sediment yield (section 7.2) with the load decreasing down catchment as the calculations take annual discharge into account. Unfortunately Figure 7.1 does not take into account the dramatic decrease in suspended sediment concentrations, it simply provides the input and output between gauge sites. These results combined with changes in suspended sediment concentrations and sediment accumulation rates coupled with an assessment of in-channel geomorphic units provides a more complete picture of the processes of sediment transport occurring in the northern Macquarie Marshes. Sediment accretion rates were determined for the in-channel zone and floodplain of the northern Macquarie Marshes to compliment earlier documented floodplain sedimentation rates by Freeman (2008). In-channel surface (0-2 cm) sedimentation rates using the average of the CRS and CIC MARs along the Bora Channel complex range from 2.226 g cm^{-2} yr^{-1} upstream of channel breakdown (Longstowe), 0.4715 g cm^{-2} yr^{-1} within the floodout and 0.077 g cm^{-2} yr^{-1} downstream of the floodout (Bora Well). The immediate surface floodplain sedimentation rates vary from 0.09 g cm^{-2} yr^{-1} within the floodout, to 0.12 g cm^{-2} yr^{-1} upstream at Longstowe (Freeman, 2008) and ~0.1 g cm^{-2} yr^{-1} downstream at Bora Well (Freeman, 2008). Sediment accretion rates in the northern Macquarie Marshes are slowest downstream of the area of channel breakdown as a result of diminishing discharge and enhanced sediment deposition (see Figure 7.1).

A loss of suspended sediment transport capacity leads to channel breakdown, promoting in-channel vegetation growth and increasing the filtering mechanisms that remove the majority of suspended sediment from the water column. The intermediate floodout characteristics of terminating distributary marsh channels of the northern Macquarie Marshes are characteristic of decreases in discharge and decreased fluvial efficiency by the small-scale processes caused by in-channel vegetation and subsequent slow rates of channel bed aggradation (Tooth 1999a).

7.2.1.3 In-channel and floodplain vegetation as a small-scale control

Declining bankfull discharges influence the capacity of the channels of the northern Macquarie Marshes to transport suspended sediment. Relationships between hydrology and channel cross sectional area influence the growth of in-channel vegetation (Tooth and Nanson, 1995; Jansen and Nanson, 2004; Pietsch and Nanson, 2011). In-channel vegetation is a key small-scale control on suspended sediment deposition within the Macquarie Marshes, particularly within the northern Macquarie Marshes where channel blocking by in-channel vegetation frequently reaches 80 – 100% (see Figure 7.3). In-channel vegetation continues to impede suspended sediment transport, supporting a positive feedback loop (Yonge and Hesse, 2009; Ralph et al., 2012), illustrated in Figure 7.4. The increases of in-channel vegetation and the presence of intact riparian vegetation increase the cohesiveness and resistance of the channels within the northern Macquarie Marshes to erosional processes during bankfull floods (Pietsch and Nanson, 2011). In the reaches with the highest w/d ratios in the northern Macquarie Marshes, up to 100% of the channel is blocked. This is a phenomenon also discussed by Yonge and Hesse (2009) in the southern Macquarie marshes, Zierholz et al. (2001) in a small upland wetland in Jugiong NSW, Gradzinski et al. (2003) in Poland and McCarthy et al. (1992) on the Okavango Fan in Botswana. Anabranching channel patterns that form the distributary and contributory marsh channels of the northern Macquarie Marshes have formed on low landscape gradients with low specific stream powers, in the range of 0.5 to 0.02 W m^{-2}, cohesive fine-grained banks and characteristic aggradational regimes (Knighton, 1998; Freeman, 2008; Ralph, 2008). These channels are characterised by significant areas of dense in-channel and floodplain reed beds.

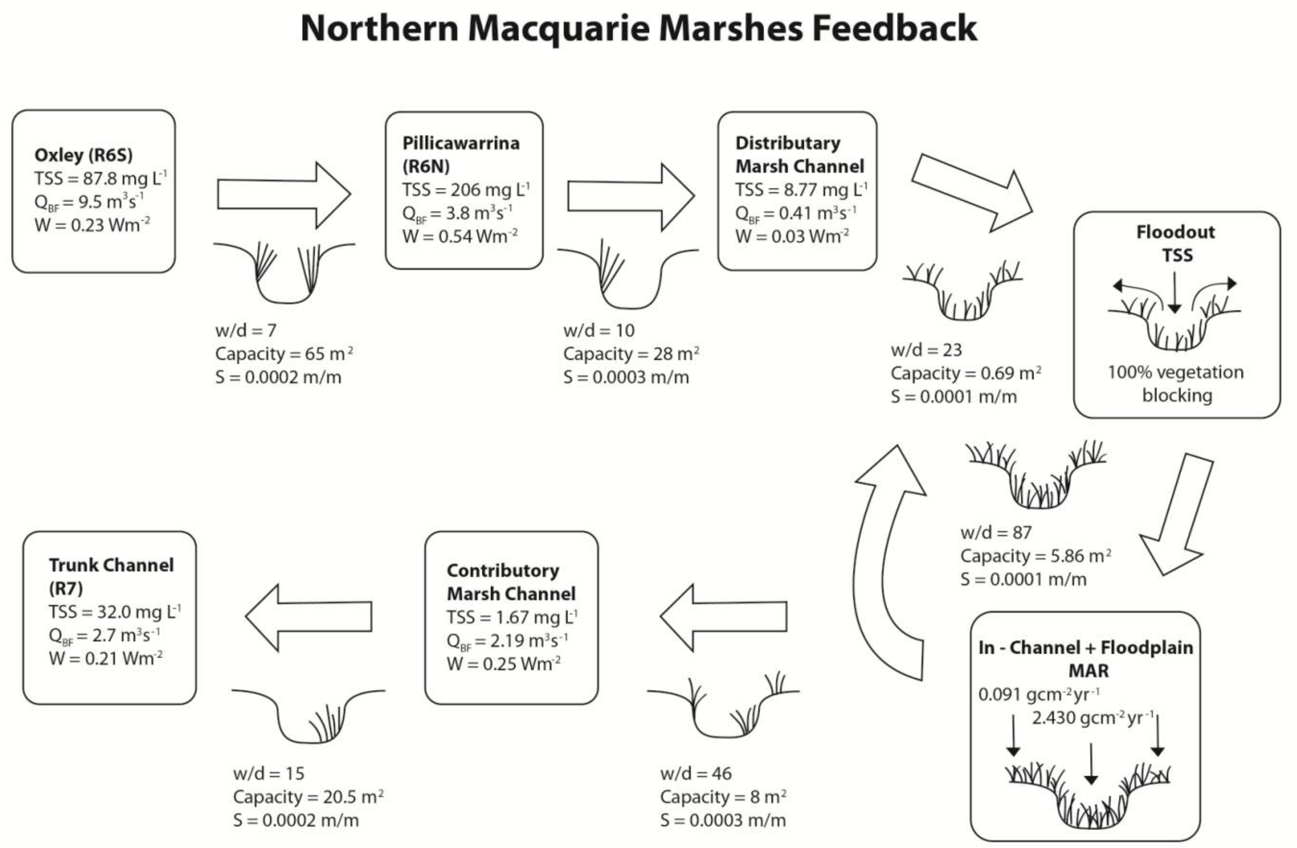


Figure 7.4 Positive feedback mechanisms of the northern Macquarie Marshes. TSS – total suspended solids; QBF – bankfull discharge; W – specific stream power; w/d – width/depth ratio; S – channel gradient; Capacity – channel area; MAR – mass accumulation rate.

The in-channel vegetation is not only important in deflecting energy from dryland channel banks, it also increases the shear strength of dryland channels (Tooth and Nanson, 2000a; 2004), it fuels a positive feedback, which further supports decreases in velocity and sediment aggradation, common in an anabranching system (Nanson and Knighton, 1996; Jain and Sinha, 2004). Root shear strength of the wetland sedges and reeds can govern channel morphology as the roots act to increase bed and bank stability (Grenfell et al., 2008) below the perimeter surface and reduce stream power above the surface, increasing inchannel sedimentation (Bull, 1979). The dense in-channel vegetation act as barriers (Fryirs et al., 2007a) to sediment transport down system, reducing fluvial efficiency and stream power, and thus are effective filters of the suspended load, evidenced through the immediate decrease of total suspended solids downstream of vegetation blocked area of channel breakdown. The common reed (*Phragmitesaustralis*) and narrow–leaved cumbungi (*Typhadomingensis*) are common wetland species growing in dense stands within the Macquarie Marshes. The vegetation growth of these two species is associated with the low energy environment of the Macquarie Marshes and act in reducing stream power and flow competence to move the suspended load, promoting sediment deposition (Bull, 1979). This correlates with the downstream changes in sediment accumulation rates of the Bora Channel of 2.430 g cm^2 yr^{-1}upstream of channel breakdown at Longstowe and 0.078 g cm^2 yr^{-1} downstream of the reed bed and the area of channel breakdown at Bora Well (chapter 5.3.6).

In comparison, the southern Macquarie Marshes in-channel vegetation associations of non-woody vegetation (Yonge and Hesse, 2010) promote deposition in a system with slightly higher stream power (Ralph and Hesse, 2010). Yonge and Hesse (2009) found the in-channel vegetation actively blocked material transfer through the channel initiating overbank flows. At Buckiinguy Break in the southern Macquarie Marshes, the dense in-channel vegetation growth dramatically reduces flow velocity and promotes sedimentation, effectively creating a positive feedback process (Bull, 1979; Ralph, 2008; Yonge and Hesse, 2009). The reduction in fluvial efficiency provides the optimal environment for avulsions, which have been identified as active in the southern Macquarie Marshes (Ralph, 2008; Yonge and Hesse, 2009). Similarly, in-channel reed growth leading to slow forming channel avulsions has been identified in the upper Narew River in north east Poland where low stream power and in-channel reed growth promote bedload sediment deposition in an anastomosing channel network (Gradzinski et al., 2003). Swamp sediment accumulation rates were calculated for the southern Macquarie Marshes by Ralph (2008) at 0.03 ± 0.003 cm yr^{-1}.

Wood in the floodplain marsh channels is common on the eastern and western flanks and the lower centre of the northern Macquarie Marshes as low open river red gum forest occupy the floodplain. Small river red gum saplings have been observed growing on the channel bed of some of the wide shallow channels downstream of Bora Well because of the greater availability of moisture in the semi-arid environment (Graeme and Dunkerley, 1993). The river red gums act to increase hydraulic roughness of the channel as both dead wood and live trees line the channel banks (Graeme and Dunkerley, 1993).

Quantification of the role of in-channel vegetation as a control on in-channel sedimentation within the northern Macquarie Marshes was achieved through in-channel sediment accumulation rates using OSL and ^{210}Pb geochronology techniques (chapter 6) and to further investigate the very slow sedimentation rates on the floodplain of the northern marshes (Freeman, 2008). The sediment accumulation rates within the channel zone were higher in some cases compared to those measured by Freeman (2008) on the floodplain. Low sediment accumulation on the floodplains was in the order of 0.12 g cm^{-2} yr^{-1} at Longstowe upstream of the floodout of the northern marshes and ~0.1 g cm^{-2} yr^{-1} at Bora Well downstream of the floodout (Freeman, 2008). Notably, areas of higher in-channel sedimentation rates occurred in the channel in the northern nature reserve (site 2) and the adjacent proximal floodplain (site 3). Overbank sedimentation at Longstowe, of 0.12 g cm^{-2} yr^{-1} (Freeman, 2008) is higher than the in-channel zone when compared to the conservative estimate of the OSL MAR of 0.053 g cm^2 yr^{-1}. However, the $^{210}Pb_{U(\alpha)}$ CRS MAR for the in-channel core at Longstowe was 2.430 g cm^2 yr^{-1}. The rate of in-channel sediment accumulation within the channel zone at Longstowe was the highest between the three channel cores. The lowest in-channel sedimentation rates were recorded at Bora Well (site 4) with a CIC/CRS averaged MAR of 0.077 g cm^2 yr^{-1}. The changes down catchment of in-channel sediment deposition correlates with the positive feedback loop as described in Figure 7.3.

7.2.2 Declining discharge, in-channel vegetation and suspended sediment transport as controls on channel morphology

The reduction in the frequency of competent discharges enhances channel breakdown of the lower Macquarie River (chapter 5.3). Discharge decreases down catchment, similar to studies reported of other inland draining fluvial systems in south-eastern Australia such as the Gwydir River (Pietsch and Nanson, 2011) and the Lachlan River (Kemp, 2010). Declining discharges with distance down catchment is a result of large scale controlling factors such as the semi-arid nature of the climate controlling catchment precipitation and runoff, catchment geology controls on topography and bed material texture, and lateral unconfinement and associated low channel gradients (Schumm, 1979). The lack of perennial tributary inputs downstream of the Talbragar River and the controlled discharge of the regulated lower Macquarie River decrease the effective catchment area and further reduce discharge.

Downstream trends of declining bankfull discharge and bankfull specific stream powers from 136.2 Wm^{-2} in reach 1 to 0.1 Wm^{-2} in reach 6N demonstrates the reductions in flow competence. This results in the inability of reach 6 (6S & 6N) to continue to transport suspended sediment, correlating well with the decrease in total suspended solids (see Figure 7.1; Figure 7.4). Morphological changes associated with reductions in flow competence were evident in changes to channel width, channel depth and cross sectional area. Downstream changes in channel morphology are the result of changes to discharge and suspended sediment transport coupled with increases of in-channel vegetation. Sediment transport is supported for reaches 1 to 5, sections of reach 6 and reach 7, evident through the changes in reach averaged velocities (chapter 5.3), and the variety of erosional and depositional geomorphic features (chapter 5.2.2) of the lower Macquarie River. These are influenced by the magnitude, duration and frequency of effective discharges and the ability to transport sediment within and between reaches to achieve down catchment morphological changes (Wolman and Leopold, 1957; Wolman and Miller, 1960; Costa and O'Connor, 1995; Benda et al., 2004).

Low average channel capacities in the northern Macquarie Marshes are close to five times less then the average channel capacity of 24 m^2 in the southern Macquarie Marshes. The trend in reductions in w/d ratios does not translate to the channels downstream of channel breakdown in the northern Macquarie Marshes. In the northern Macquarie Marshes the w/d ratio increases with further declines in discharge through the floodout and contributory marsh channels. Figure 7.5 shows the changes in w/d ratio with declining discharge from reach 5 to reach 6S. The initial channels upstream of the floodout in reach 6N show low discharge and low w/d ratios. The w/d ratios of the channels in the floodout and the contributory marsh channel downstream of the floodout show higher w/d ratios and low discharges.

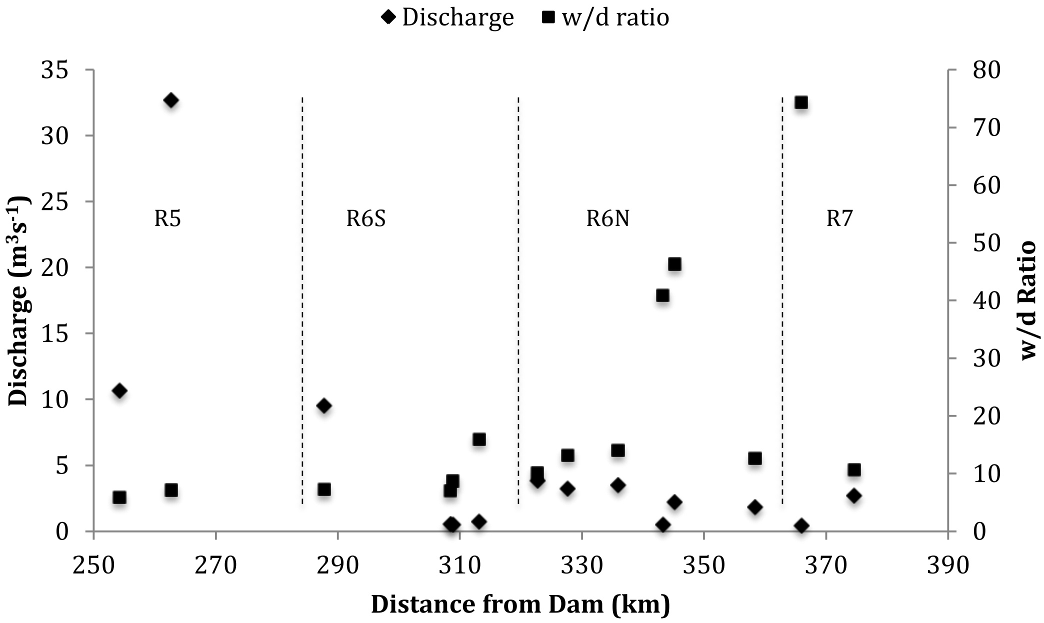


Figure 7.5 Corresponding discharge and w/d ratio down catchment from reach 5 (Marebone) to reach 7 (Carinda). The reaches are labelled on the figure.

Leopold and Maddock (1953), Schumm (1960 & 1979) and Church (1992) have previously documented that suspended load channels are likely to have a low w/d ratio. That assertion contradicts the results of this study. There is a wide range of w/d ratios within the northern Macquarie Marshes, from a ratio of 10 to a ratio of 90. However, a wide range of channel capacities does not parallel the wide range in w/d ratio. The small range of channel capacities extends from 1 m^2 (distributary marsh channel) to 24 m^2 (trunk channel into the northern Macquarie Marshes). The anabranching channels straighten, shallow and widen in a downstream direction. The contributory marsh channels downstream of channel breakdown in the northern Macquarie Marshes are the exception to the low w/d ratios documented elsewhere (Pietsch and Nanson, 2011) in suspended load systems. These channels exhibit higher w/d ratios of 40 to 90 with channel capacities ranging from 3 m^2 to 10 m^2. This is a difference between the northern and southern Macquarie Marshes where the highest documented w/d ratio is 27 and the channel capacities range from 11 m^2 to 45 m^2. Channels downstream of channel breakdown have the highest w/d ratios coupled with slight increases in channel gradient and increases in sinuosity in comparison to the meandering trunk channel in reach 5 and the channels in reach 6S. Comparably, Pietsch and Nanson (2011) have noted similar changes to the hydraulic geometry of the distributaries of the Gwydir anabranching-distributary fluvial system, which is also characterised by a semi-arid climate and as an inland flowing river draining the western flank of the Great Dividing Range in northern New South Wales. Pietsch and Nanson (2011) found that hydraulic geometry changes were a response to the relationship of several variables: declining discharge, shallow channel gradients, channel roughness, velocity and bed/bank shear strength as a result of in-channel and riparian vegetation. In south-eastern Australian inland flowing river systems, channel width was morphological response least reactive to bankfull discharges (Pietsch and Nanson, 2011).

These small-scale processes are two of the processes described by Tooth (1999a) as controls on floodout formation. In-channel vegetation acts as a biological barrier to flow and sediment transport, evidenced through the increases in vegetation blocking of the lower Macquarie River, increasing rates of overbank inundation through back-flooding (Yonge and Hesse, 2009) and further decreasing fluvial efficiency. The channels of the northern Macquarie Marshes are characterised by controls associated with intermediate floodouts (Tooth, 2000), such that in-channel vegetation, diminishing discharge and decreasing specific stream powers promote sedimentation (chapter 5.3.6), overbank flow and channel breakdown, supporting vegetated wetland floodplains (chapter 5.4). The riparian and in-channel vegetation of the channels entering the floodout are quite different to the channels exiting the floodout. The contributory channels exiting the intermediate floodout are characterised by a low proportion of in-channel vegetation (10% downstream compared to 100% upstream), and low open river red gum woodland in the riparian zone.

A distinguishing feature of intermediate floodouts are contributory marsh channels (Tooth, 1999a), such as those of the northern Macquarie Marshes, which re-form downstream of the unchannelised marsh floodplain. The concentration of flows into contributory marsh channels is the effect of local small-scale topographic highs. These areas of elevated alluvial floodplain occur where increased deposition has elevated the surface or as a response to organic matter and roots of reed bed or may be remnant palaeochannel levees or floodplain. Freeman (2008) demonstrated local topographic highs on the floodplain at Bora Well where the contributory channels transfer flow that has permeated through the floodplain wetland.

Attributes of the contributory marsh channels downstream of the intermediate floodout at Bora Well include slight increases in channel gradients, from 0.0001 m/m upstream to 0.0003 m/m downstream, and subsequent increases in velocity coupled with decreases in channel sinuosity downstream of 1.2 to 1.09. The channel morphologies of the contributory marsh channels are different to the distributary marsh channels characterised by low w/d ratios (range 10 to 20), low channel capacities (range 1 -7 m^2), low channel gradients and slightly higher sinuosities (1.2 – 1.3). The morphology of these initial channels in the northern Macquarie Marshes are typical of those documented for low gradient suspended load channels in Australia (Riley, 1977; Pietsch and Nanson, 2011). The velocities are significantly higher than those recorded upstream entering the floodout splay and were clearly observed in the field by a continuous break in the aquatic native plant *Azolla filiculoides* and the movement in the direction of channel flow of aquatic vegetation on the channel bed. For example, the measured velocity of 0 ms^{-1} upstream of the floodout compared to 0.49 ms^{-1} downstream of the floodout. Depth in flow increases from 1 m – 1.5 m upstream of channel breakdown in the Bora Channel and its initial anabranches in northern Macquarie Marshes. Depth of flow decreases to 0.3 m to 0.55 m in the distributary marsh channels. Increasing velocities downstream of the floodout (range 0.03 m s^{-1} – 0.5 m s^{-1}) are coupled with shallow depths of flow that range from 0.1 m to 0.45 m.

Though both marsh complexes behave in a similar way, the northern Macquarie Marshes contain a greater number of anabranching marsh channels that are characterised by a range of different hydraulic geometries and discharge characteristics. The characteristics of the channels within the northern Macquarie Marshes can be explained through the changes in suspended sediment transport dynamics, a response to the changes in discharges, sediment deposition and in-channel vegetation growth. The relationship of the small-scale processes of discharge and channel gradient, coupled with in-channel vegetation growth further reducing flow velocity, strongly promote the formation and maintenance of the multi-channelled northern Macquarie Marshes (see Figure 7.4).

7.3 Spatial and Temporal Variability in Longitudinal and Lateral Connectivity of the Lower Macquarie River

The mechanisms driving discharge and sediment transport of the lower Macquarie River vary down catchment, such that declining discharge and its relationship with suspended sediment transport decrease channel gradients and promote a multi-channelled system. Decreases in discharge and increasing suspended sediment concentrations in a low gradient unconfined landscape stimulate changes to channel morphology and capacity. As discussed within section 7.2 of this chapter, small-scale processes of declining discharge, shallowing channel gradients and in-channel vegetation promote decreases in specific stream powers, in-channel sediment deposition. The interactions of these small-scale processes culminate in an intermediate floodout (Tooth, 1999).

The spatial and temporal variability in suspended sediment transport of the lower Macquarie River is primarily governed by hydrologic connectivity both longitudinally and laterally coupled with suspended sediment transport through the system. Similar to the channels and the spatiotemporal variability in the activation of anabranching channels in the Fitzroy Basin Queensland (Thompson et al., 2011), the anabranching distributary and contributory marsh channels within the northern Macquarie Marshes are activated by streamflow at different temporal and spatial scales. Their activation is dependent on stage height and discharge volumes. Figure 7.1 illustrates the variability of in-channel changes in suspended sediment load between tributary-trunk and down catchment, and the mass accumulation rates of sediment within the southern (Ralph, 2008) and northern Macquarie Marshes. It also illustrates the variability of longitudinal and lateral hydrologic connectivity and suspended sediment transport to be discussed further in this section.

7.3.1 Longitudinal connectivity

The degree of hydrological longitudinal connectivity is governed by the key controls responsible for the dynamics of the lower Macquarie River as outlined in the section above. The large-scale controls of landscape confinement and climate (Montgomery, 1999) govern the small-scale processes (i.e. declining discharge, landscape gradient and in-channel vegetation growth), key controls of channel breakdown and variability in the spatiotemporal longitudinal connectivity of streamflow and suspended sediment transport.

The upstream boundary of the lower Macquarie River is downstream of Burrendong Dam wall, an effective sediment sink and a barrier to suspended sediment transport (Nilsson et al., 2005; Fryirs et al., 2007a) from the upper catchment. Various weirs and water storages along the lower Macquarie River (Kingsford, 2000) are likely to increase the numbers of barriers to suspended sediment transport and hydrological connectivity (Brierley et al., 2006; Fryirs et al., 2007a) down catchment. Using gauge data and return interval discharges (chapter 5.3) coupled with total suspended solids grab samples, there is evidence of the suspended sediment cascade continuing down catchment. Figure 7.1 represents the changes in suspended sediment load between reaches between reach 4 and reach 7. The suspended solid concentrations that increase down catchment (see Figure 7.4) from Narromine (reach 4) is not reflected in a negative (erosive) value in the annual load (t/yr) because of declining discharges between each reach. It indicates sediment deposition, except between Marebone (reach 5) and Oxley (reach 6) where sediment supply is markedly increased by a load of 17624 t/yr, indicating a more dominantly erosive reach, not evident at the representative field sites.

It is likely that the lowland alluvial system of the lower Macquarie River is an example where slope and the channel network is decoupled because of the tectonically stable system (Collins and Walling, 2004). Therefore, bank erosion (chapter 5.2.2) is likely to be the dominant source of this increase in suspended sediment load, in addition to the small associated specific stream powers associated with common overbank flows every 1 in 1 to 1 in 2 years.

Landscape compartments down catchment are physically connected between reach 1 to reach 6 (Jain and Tandon, 2010). Reach 1 acts as a booster (Brierley et al., 2006; Fryirs et al., 2007) to sediment transport because of its position within the landscape and associated discharge and channel gradient. It was identified as a transfer zone. Reach 6, the Macquarie Marshes, itself acts as a barrier (Brierley et al., 2006; Fryirs et al., 2007) to the through-flow of streamflow and sediment transport because of the high rates of in-channel vegetation growth acting as obstacles to the transfer of water and sediment (Brierley et al., 2006; Fryirs et al., 2007) coupled with low discharges and shallow channel gradients (see Figure 7.4).

The semi-arid nature of the climate and the often-ephemeral conditions of reach 6 and 7 (i.e. due to droughts and river regulation) reduces the longitudinal hydrologic connectivity between reaches, resulting in spatiotemporal variability of in-channel sediment deposition as a result of interrupted streamflow (Jaeger and Olden, 2012). The gauge readings for the site at Miltara and Bells Bridge Carinda (both downstream of channel breakdown) often record reading of zero discharge (chapter 5.3). It was also observed within the field the patchy nature of hydrological connectivity as a result of channel breakdown in the Macquarie Marshes, where hydrological activation was observed within some channels but not others. Degrees of hydrological connectivity does not always guarantee suspended sediment transport (Benda and Dunne, 1997). Such is the case in the northern Macquarie Marshes, where in-channel vegetation blocking allows for the continuity of streamflow, although at a very reduced velocity and volume, but impedes suspended sediment transport as it acts a barrier (Fryirs et al., 2007a) to transportation through decreasing already reduced velocities and further enhancing deposition. This disconnect was particularly obvious between upstream of the floodout where there was streamflow compared to downstream of the floodout where only the primary contributory channel and seeping flow. This is a key example of the physical disconnection within a landscape compartment (i.e. by vegetation and channel breakdown) (Jain and Tandon, 2010). This physically disconnected system is connected hydrologically and suspended sediment transport is disconnected (see Figure 7.4). Hydrologic connectivity is only temporarily impeded as in-channel vegetation filter and reduce the velocities of streamflow, increasing the length of time and volume of discharge in a downstream direction.

The decoupling of suspended sediment transport and hydrologic connectivity was measured and quantified for the in-channel zone of the northern Macquarie Marshes to determine the role of in-channel vegetation as an impediment to suspended sediment transport. Similar studies have shown in-channel vegetation to be an important buffer in low gradient fluvial systems (e.g. McCarthy et al., 1988; Zierholz et al., 2001; Gradziński et al., 2003; Ralph, 2008; Yonge and Hesse, 2009), resulting in channel bed aggradation. Woody debris, identified in the lower reaches of the Macquarie River (chapter 5.4), particularly in reach 5, 6 and 7, acts as barriers to suspended sediment transport. Although it can initiate channel bed and bank scour during moderate to high flows, it initiates sedimentation around the debris during low flows, by locally reducing flow velocity (Nanson and Knighton, 1996; Poole et al., 2002).

In-channel vegetation blocking correlates with the in-channel sedimentation rates of the Bora Channel system, the most active hydraulically multi-channelled zone of the northern Macquarie Marshes (as observed through various field trips and as a result of the northern by-pass channel on the eastern flank of the northern Macquarie Marshes (chapter 3)). The rates of channel bed aggradation decrease with distance through the channel breakdown, with the lowest rates of channel aggradation occurring downstream of channel breakdown in the contributory marsh channel (see section 7.2.1.2). The sandy layer in the upper profile of the core site at Bora Well (downstream of channel breakdown; see chapter 6.2) is evidence of localised reworking, likely to be of in-channel sediments. In periods of increased stream power during higher magnitude low frequency flows, the influence of the vegetation is reduced during long flow durations and increased sediment transport longitudinally is restored (Costa & O'Connor, 1995), which could explain the sandy deposits downstream of channel breakdown in a channel environment of low specific stream powers (see Figure 7.4).

Tributary – trunk interactions were assessed using the gauge measured total suspended solids and discharge data and the affect on sediment loads in a down catchment direction once the tributary meets the trunk channel. The tributaries are physically and actively connected (Jain and Tandon, 2010). It is likely that the total suspended solids entering the trunk channel are diluted (chapter 5.3). It is also likely that a degree of the change in sediment load is accountable to losses between active tributary – trunk connections. Off-takes activated through higher stages of flow in reach 5 distribute streamflow away from the main trunk channel and would also remove a proportion of the suspended load (see Figure 7.1).

7.3.2 Lateral connectivity

In this study, the frequency and magnitude of overbank flood events were used to indicate the temporal variability of the contemporary hydrologic lateral connectivity between the channel and the floodplain of the lower Macquarie River (Hudson et al., 2012; Hudson et al., 2013). Figure 7.1 (section 7.2) shows the differences in hydrologic connectivity between the channel – floodplain from reach 4 to reach 7. The landscape position of the reach within the catchment, the channel capacity and channel gradient were the determinants in the temporal variability of overbank flooding. For example, full confinement of reach 1 (gorge) is positioned within the landscape so that there is no lateral connectivity (section 5.2.2). Increasing frequency of overbank flows increases with distance down catchment as channel capacities decrease (chapter 5.2 and 5.3), so that the temporal variability of activation of floodplain geomorphic units, as both sources during high geomorphically effective discharges (Wolman & Miller, 1960; Harvey, 1969, Nash, 1994) and longer duration of flooding (Hudson et al., 2013) and sinks (Brierley and Fryirs, 2005; Thompson et al., 2011), for sediment reworking and entrainment occurs at different times throughout the catchment. The channel – floodplain connection in reach 2 and 3 are physically connected through hydrological connectivity during higher magnitude low frequency events (Phillips, 2011; see chapter 5.3).

Floodplains in lowland fluvial environments buffer energy through overbank flow (Gilvear, 1999; Grenfell et al., 2008) and support a heterogeneous mix of ecosystems (Arthington et al., 2006). Overbank inundation is likely to affect the spatiotemporal dynamics of floodplain building processes (Asselman and Middelkoop, 1995) on all parts of the wide alluvial floodplains of the lower Macquarie River. The variability in sediment deposition rates on the floodplain of the Macquarie Marshes is evident through the common decline in sediment accumulation rates with distance from the channel (Walling and He, 1998). The degree of lateral connectivity within the northern Macquarie Marshes was measured through floodplain sedimentation rates and compared to sedimentation rates of Freeman (2008). Spatial differences in sedimentation rates with distance from channel are evident in Figure 7.1. Typically considered depositional zones (Wolman and Leopold, 1957), floodplain sedimentation rates of the Macquarie Marshes are dependent on the spatial and temporal extent of inundation. Higher rates of sediment deposition occur close to the main channel and decrease at the outer extent of floodplain inundation (Asselman and Middelkoop, 1995; Walling and He, 1998), as was documented by Freeman (2008) for the northern Macquarie Marshes and Ralph (2008) for the southern Macquarie Marshes (Figure 7.1). This indicates the high degree of spatial and temporal variability channel - floodplain hydrologic connection and suspended sediment transport.

The frequency of overbank flows along alluvial river corridors has been discussed by a number of authors who have conducted inundation studies (Day et al., 2008; Phillips, 2011; Hudson et al., 2012) and have noted that hydrologic connectivity occurs at river stages below flood stage. Hudson et al. (2013) found that a considerable amount of the channel bank was overtopped of the lower Mississippi River at discharge magnitudes well below flood stage. The argument offered by Hudson et al. (2013) is that inundation studies to determine the temporal variability of hydrologic connectivity, does not take into account the spatial differences in channel bank height, levee development or troughs along a pre-determined reach. Troughs along the channel bank are often related to meander bend cutoffs and weak spots along the upper channel banks affected by erosive flood processes (Hudson et al., 2013). It is worth considering the potential of the lower Macquarie River system to be hydrologically connected laterally during 'non-flood' stages of flow as differences in channel bank heights within the same reach were measured of up to 0.8 m along the lower Mississippi River (Hudson et al., 2013). A more well rounded approach for understanding the spatial and temporal connectivity of channel - floodplain can be determined through increasing the number of channel cross sections and modelling the frequency and magnitude of overbank flows (Hudson et al., 2013).

Buffers and barriers (Brierley et al., 2006 and Fryirs et al., 2007a) along the lower reaches of the Macquarie River include both natural (chapter 5.2.2) and man-made levees (Steinfeld and Kingsford, 2013) and vegetation growth (Poole et al., 2002), both in-channel and one the floodplain. Heavily reduced channel capacities within the Macquarie Marshes correlates to decreasing discharge and increasing in-channel vegetation (see Figure 7.4). The interconnectedness of the channel, floodplain and in-channel vegetation of the Macquarie Marshes influence the geomorphic and hydrologic characteristics of the system (Lane & Richards, 1997; Poole et al., 2002) by driving increases in lateral connectivity through longitudinal (dis)connectivity. In-channel vegetation acts as a biological barrier to the through flow of streamflow and sediment transport. Channel constriction by vegetation of up to 100% within some channels of the southern Macquarie Marshes and nearly all of the floodout zone within the northern Macquarie Marshes, leads to backflooding (Yonge & Hesse, 2009) sending flow overbank and increasing the rate of deposition upstream of the channel constriction (Thompson et al., 2011) and affecting the distribution of suspended sediment supply to the floodplain surface. Natural and manmade levees of the channels of reach 5 and 6 also impact the temporal variability in overbank flooding of floodplains, through increasing channel bank height and restricting both the physical connection between channel and floodplain (Jain and Tandon, 2010) and the hydrological connection as they do along the Missouri River (Galat et al., 1998).

7.4 Implications for Ecosystem Services

The Macquarie River channel breakdown and the formation of wetlands is an environment that is dominantly depositional, similar to the wetland system documented by Grenfell et al. (2009), and hosts as range of ecosystem services and include recreation, assimilating with nature and scientific value (Kingsford, 1995; Costanza et al., 1997; de Groot et al. 2000).

Wetlands have been considered as water filters (Comin et al., 1996; Gell et al., 2009), an ecosystem service associated with these environments. Evident through the reductions in suspended sediment concentrations within the northern Macquarie Marshes, they act to buffer sediment transport by decoupling fluvial efficient flows and suspended sediment transport (Grenfell et al., 2009).

Understanding the spatial and temporal links between flow variability and hydrological connectivity in dryland river systems, such as the Macquarie Marshes, is essential to understanding the impact of changes of the flow regime on suspended sediment transport and the associated impacts on landform development and maintenance (Sheldon et al., 2002; Arthington et al., 2006). Knowledge of the links between the geomorphic landscape compartments and how these linkages influence ecology within the landscape are important in understanding the long-term history of the earth system (Viles et al., 2008; Rice and Macklin, 2008) and to promote sound catchment management strategies to conserve the value of the fluvial ecosystem services (Grenfell et al., 2008; Hudson et al., 2013).

7.5 Chapter Summary

This chapter addressed the small-scale processes driving channel breakdown of the lower Macquarie River through an analysis of down catchment relationships between discharge and sediment transport. The morphological changes of the channel zone with distance down catchment were described through the changes to w/d, channel capacities and channel shape. In-channel vegetation was highlighted as an important control on reducing flow velocities and enhancing in-channel sediment deposition within the northern Macquarie Marshes. Furthermore, the chapter addressed the longitudinal and lateral hydrologic connectivity and suspended sediment.

The interaction of short time-scale and small space-scale processes within the reaches of the lower Macquarie River creates temporary zones of both sediment storage and sediment erosion between and within reach compartments. This in turn determines future patterns of erosion and deposition.

The behaviour observed within each defined reach within the lower Macquarie River reflects its position within the catchment and the local interaction of externally imposed discharge fluctuations with internally driven controls of sediment supply (Lane & Richards, 1997). Spatiotemporal considerations were given to the lateral and longitudinal hydrologic connectivity and suspended sediment transport of the lower Macquarie River. The longitudinal disconnection and the enhanced lateral connection of suspended sediment transport supports the contemporary wetland ecosystem and the suite of ecosystem services it provides those living within the Macquarie River catchment.

Chapter 8: Synthesis and Conclusions

8.1 Synthesis

The aim of this study was to use geomorphic, hydrologic, sedimentary and geochronological techniques to develop a detailed understanding of suspended sediment transport of the lower Macquarie River with a focus on understanding the form and process dynamics in each reach with particular emphasis on channel breakdown of the northern Macquarie Marshes. Previous research in the southern Macquarie Marshes indicated a dynamic system where channel avulsions occurred on an approximate 100-year timescale and sediment accumulation in and around the channel was driving the channel avulsions. The channel avulsions were the determining factor in new wetland development across areas of the floodplain and the source of increased sediment load to the channels.

Patterns of sedimentation in the northern Macquarie Marshes were established in a subsequent project to determine if high sedimentation rates of the southern Macquarie Marshes propagated similar effects downstream to drive channel avulsion and wetland redistribution in the northern Macquarie Marshes. Processes of avulsion do not occur in the northern Macquarie Marshes and the sediment accretion rates of the floodplain at different distance intervals from the channel were found to be extremely low. The central objective of this study was to establish spatiotemporal nature of longitudinal and lateral hydrologic connectivity and suspended sediment transport and the implications for the ongoing support of wetland ecosystem services.

Four hypotheses were offered to test the contemporary connectivity of the lower Macquarie River as a control on channel breakdown and the residence times of sediment storage.

1. Suspended sediment transport increases from Burrendong Dam down catchment. Tributary inputs and bank erosion increase suspended sediment transport to the Macquarie River trunk channel. The suspended sediment transport greatly decreases through the northern Macquarie Marsh complex, because of ‘filtering’ by vegetation.

2. Sediment accretion rates of the in-channel zone and floodplain of the northern Macquarie Marshes are very slow in comparison to the sedimentation rates identified in the southern Macquarie Marshes. Sediment accretion rates are slowest downstream of the floodplain wetlands as a result of diminishing discharge and enhanced sediment deposition;
3. Processes controlling in-channel sediment deposition influence channel morphology and channel breakdown of the lower Macquarie River.
4. The area of channel breakdown enhances lateral connectivity and reduces longitudinal connectivity through changing channel morphologies and enhanced in-channel sediment deposition.

The six key research aims to test the hypotheses were:

1) Identify longitudinal changes in channel morphology and capacity and compare to investigations of longitudinal declines of discharge and stream power and thus decline in the carrying capacity of suspended load

2) Investigate the longitudinal changes in total suspended solid concentrations down catchment and the connectivity of the Bell and Talbragar River tributaries in terms of suspended sediment supply to the Macquarie River trunk channel. A focus is placed on the total suspended solids entering into the northern Macquarie Marshes and exiting downstream of the wetlands.

3) Identify the patterns within the down catchment suspended sediment transport and the determine the reasons of the patterns by referring to the down catchment geomorphology on a reach-by-reach basis with particular emphasis on in-channel erosional and depositional geomorphic units using aerial photographs, field observations and cross section surveys.

4) Characterise the character of sedimentation within the northern Macquarie Marshes and compare to the character of sedimentation of the floodplain of the northern Macquarie Marshes, and the in-channel and floodplain zones of the southern Macquarie Marshes.

5) Investigate the contemporary processes of in-channel sedimentation within three key areas of the Bora Channel in the northern Macquarie Marshes. Compare the contemporary in-channel rates of sediment accumulation with accumulation rates from adjacent floodplain sites of the northern Macquarie Marshes to establish whether bed aggradation is more dominant than floodplain accretion. Relate these findings to the in-channel sedimentation rates of the southern Macquarie Marshes.

6) Use flood return interval relationships to identify inundation of the floodplain and assess magnitude-frequency geomorphic effectiveness at selected sites within the reaches identified of the lower Macquarie River, which will add to the reasons behind the patterns within the suspended sediment transport.

The study documented the physical connection of compartments in the lateral and longitudinal dimensions, and explored the through-flow of suspended sediment between and within compartments. It explored the differences in the temporal and spatial scale of active hydrologic connectivity of the lower Macquarie River through modelling discharge and the magnitude – frequency of return intervals for a 1 in 1, 2, 5, 10, 25, 50 and 100 year flood event. Bankfull discharges were used to assess the effective discharge of a reach and changes in the controls that drive channel breakdown of the lower Macquarie River. Suspended sediment samples and discharge data was used to establish sediment yield relationships between Narromine (reach 4) and Bells Bridge Carinda (reach 7), and establish the geomorphic influence of in-channel and floodplain vegetation. The filtering capacity of dense in-channel and floodplain vegetation filters out the majority of suspended sediment in the northern Macquarie Marshes, confirming the second hypothesis.

Optically stimulated luminescence and unsupported lead-210 radionuclide techniques were used to establish sediment accretion rates and residence times of the in-channel zone with one floodplain core adjacent to Site 2 (in-channel). The cores retrieved from the channel zone upstream and downstream of channel breakdown were adjacent to floodplain cores of previous research (Freeman, 2008). Sediment accretion rates further explain the discontinuities of suspended sediment transport within the northern Macquarie Marshes. Issues relevant to the geochronological techniques used within the channel zone of the north marsh complex arose with both OSL and unsupported lead-210. Issues with OSL are well documented for fluvial environments, especially often waterlogged wetland environments. Water logging and fluvial environments impact natural radiation concentration, the volume of quartz grains available in the predominately mud-dominated system and particularly the incomplete bleaching of quartz grains before deposition. Unsupported lead-210 alpha spectrometry was used because of its successful use on marsh sediments in the southern Macquarie Marshes. There was one core that was deemed not suitable for radionuclide dating by ANSTO, which was from Site 1 at Longstowe. The ages established by the CIC and CRS models were comparatively similar. The MARs patterns between sites established by the CRS model ages confirmed the third hypothesis.

This study has confirmed the first hypotheses by identifying the different types of connections of compartments of the lower Macquarie River and suspended sediment transport between compartments. The lateral hydrologic connectivity increases down system. Longitudinal stream flow remains constant, although patchy in nature within the northern Macquarie Marshes, through losses to floodplain distributary marsh channels and channel breakdown. The discontinuities of suspended sediment transport in the northern Macquarie Marshes, combined with a reduction of geomorphic effective flows, are driven by declining discharge and in-channel vegetation.

8.2 Conclusion

Landscape setting influences the channel behaviour and suspended sediment load of the lower Macquarie River. Reaches 1, 2 and 3 are bedload dominated and are confined (R1), partly confined bedrock controlled (R2) and partly confined planform controlled (R3). The position of the reach within these areas of confinement plays a role in dictating the energy of the system and the ability of the reach to transport bedload materials. Lateral unconfinement downstream of reach 4 and increasing with distance down catchment promote decreasing channel gradients and decreasing channel capacities. The distal reaches of the lower Macquarie River are characterised by smaller channel capacities, narrower channels, cohesive channel sediments and suspended load dominant. Small-scale processes of declining discharge and stream power, and the reduction in fluvial efficiency to transport suspended sediment in conjunction with the influence of dense in-channel vegetation drives channel breakdown of the lower Macquarie River, resulting in the formation of the Macquarie Marshes.

In the northern Macquarie Marshes, suspended sediment transport is controlled by small-scale processes such as decreases in discharge and stream power and the enhancement of fluvial inefficiency through the constriction of dense in-channel vegetation, promoting sediment deposition. The controls on reach form identified in the Macquarie Marshes correlates with the general form of an anabranching network of channels (Nanson & Knighton, 1996; Brierley & Fryirs, 2005) displaying cohesive bed and banks in a dominantly depositional environment and exhibiting low width-to-depth ratios prior to channel breakdown. The anabranching nature of the northern Macquarie Marshes and its predisposition towards sediment accumulation promote reductions in the longitudinal connectivity and further force a reduction in sediment transport. The dense in-channel vegetation blocking and the channel morphologies that characterise the northern Macquarie Marshes contribute to enhanced lateral connection through frequent overbank flooding on 1 in 1 to 1 in 2 year time scales. The channels are dominantly aggradational, contributed to by the geomorphic work and filtering capacity of dense stands of in-channel reeds. The in-channel vegetation increases bed and back resistance. Floodplain vegetation, characterised by dense reed beds on unchannelised floodplain becoming woodier in variety with distance from the main distributary marsh channels, increase floodplain resistance to overbank flows by reducing flow velocities and increasing sediment deposition in and around areas of dense vegetation. Increases in velocities of the contributory marsh channels downstream of the unchannelised floodplain wetland are reflected in the lower recorded sinuosities of the channel and a great reduction in in-channel vegetation growth.

Three types of physical connectivity between compartments were established along the lower Macquarie Marshes. Active connected systems are associated longitudinally with reaches 2, 3, 4, 5 and 7 where there are no barriers affecting suspended sediment transport. Active connected systems are hydrologically connected through the lateral dimension on short time scales with reaches 5, 6 and 7, and on longer time scales with reaches 1, 2, 3 and 4. Inactive connected systems are associated longitudinally with the meandering single channel in reach 6 and 7 as these channels are physically connected longitudinally, however sediment transfer ceases in periods of zero stream flow. Inactive connected systems are associated laterally in reach 1, a deep gorge landscape setting. Partially active connected systems are associated with the distributary and contributory marsh channels in reach 6. The channels are longitudinally physically disconnected by dense vegetation blocking the in-channel environment. During low magnitude-high frequency events sediment transfer has been established through the extremely slow sediment accretion rates of the in-channel zone at Bora Well (Site 4).

Geomorphic effective flood discharges decrease with increasing distance down catchment. Stream powers dramatically decrease in response to diminishing discharge, decreasing channel capacities, the low channel gradients and the effect of in-channel vegetation at further shallowing channel gradients and reducing stream powers. Patterns within the suspended solids concentration data show the extreme nature of filtration processes occurring within the northern Macquarie Marshes by the intermediate floodout of distributary channels to unchannelised floodplain wetlands. However, this is not accurately reflected in the sediment yield data. The sediment yield provides a suitable pattern of decreases in suspended sediment although sediment load increase after the reformation of a single trunk channel, reflected in the suspended solids data, hides the nature of the in-channel reeds and floodplain wetland system that removes the majority of suspended sediment from stream flow.

Sedimentation rates were established for three sites in the channel zone and one adjacent floodplain site. Incomplete bleaching of fluvial quartz made OSL a difficult technique to use without the use of a secondary geochronological technique, due to the turbid waters reducing sunlight penetration to whole particles prior to deposition. The incomplete bleaching of northern Macquarie Marshes in-channel sediment predestined the use of the minimum age model to give the most conservative minimum age estimates. Unsupported lead-210 decay profiles indicate the rate of sediment transfer from the southern Macquarie Marshes to the northern Macquarie Marshes is very low. The in-channel rates of sediment accumulation in the northern Macquarie Marshes are far greater than the sediment accumulation rates on the adjacent floodplain. There is a pattern of increased deposition within heavily vegetated channels compared to the extremely low sediment accumulation rates downstream of the active wetland system. Down-profile distribution of sediment at each site is relatively homogenous, however there are subtle variations in the clay: silt: sand distributions. There are two distinguishable sand peaks in the sedimentary profiles within the top 10 cm at Bora Well (Site 4) and the other between 10 and 20 cm in the channel core of the northern nature reserve (Site 2). This alludes to increases in geomorphic effective flows throughout the contemporary system to entrain larger sand-sized particles and increasing the connectivity of suspended sediment transport. The cohesive nature of floodplain and channel sediments, the residence times of sediment storage and the type of in-channel and floodplain vegetation are likely to enhance the resistance of this landscape to geomorphological and hydrological controls on channel breakdown.

Channel breakdown and the (dis)connectivity of suspended sediment transport of the lower Macquarie River provide a suite of ecosystem services provided for those residing and working within the Macquarie River catchment. From this study, water filtration by the wetland system is a key service provided by the area of channel breakdown. The ecosystems that channel breakdown supports is world-wide provide a number of key goods and services including water filtration, recreation, tourism, agricultural support and changes to the microclimate. Through determining the controls on channel breakdown of the Macquarie Marshes or any wetland system, and the implications on geomorphological and hydrological connection, best management practices can be established to continue the longevity of such landscapes that may change as a result of anthropogenic land use and resource use.

8.3 Potential directions for future research

There are number of directions for further research of the lower Macquarie River system that have been recognised through this project. This section provides a number of avenues for future research that can be applied to the lower Macquarie River and Macquarie Marshes, and potentially similar systems.

Further investigations are required of the processes and functions maintaining the increases in channel gradients of the contributory channels in the vicinity of and downstream of Bora Well. A catchment inclusive sediment budget should be calculated for the Macquarie River catchment to truly identify the (dis)connectivity between the lateral, longitudinal and vertical linkages in the catchment to develop a greater understanding of the sensitivity of the system on a whole-catchment long-time scale. This could include investigations into the specific and favoured locations of sediment deposition within in different nodes of the active wetland system of the northern Macquarie Marshes to identify primary areas of deposition. Sediment tracing of suspended sediment to determine the origin of supply to the channel would be beneficial to further support the information around the respective energies and morphologies of the reaches of the lower Macquarie River.

Local increases in total suspended solids are likely to be a result of primarily in-channel bank erosion. However, cattle were observed to be heavily grazing the most active channels within the northern and southern Macquarie Marshes. A good follow up project would be to quantify production sources through the Macquarie Marhes. Total suspended solid concentrations were measured when the property 'Pillicawarrina' was still being grazed and was a location of sediment input. It has now been purchased by New South Wales National Parks Wildlife Service. It would be a worthwhile follow-up project to determine if injects of suspended sediment remain as high in this area.

Reference List

Abernethy, B., Rutherford, I.D., 1998. Where along a river's length will vegetation most effectively stabilise stream banks? *Geomorphology* 23, 55 – 75

Aitken, M.J., 1998. *An Introduction to Optical Dating*. Oxford University Press, Oxford.

Alam, M.M., Mustafa, M., 1986. Facies Model of Anastomosing-Fluvial Sedimentation in Semi-arid Eastern Australia: the Castlereagh River, New SouthWales, *Sediments Down Under, Abstracts of the 12th International Sedimentological Congress* 1986, 8

Allan, R.J., 1979. *Sediment-related Fluvial Transmissions of Contaminants: Some Advances by 1979*. Inland Waters Directorate, Environment Canada, Scientific Series 107, Ottawa, Canada.

Amos, K.J., Croke, J.C., Timmers, H., Owens, P.N., Thompson, C., 2009. The application of caesium-137 measurements to investigate floodplain deposition in a large semi-arid catchment in Queensland, Australia: a low-fallout environment. *Earth Surface Processes and Landforms* 34, 515 – 529

Appleby, P.G. 9. Chronostratigraphic techniques in recent sediments. In: W.M. Last and J.P. Smol (eds.), 2001. *Tracking Environmental Change Using Lake Sediments. Volume 1: Basin Analysis, Coring, and Chronological Techniques.* Kluwer Academic Publishers, Dordrecht, The Netherlands.

Arthington, A.H., Bunn, S.E., Poff, L., Naiman R.J. 2006. The challenge of providing environmental flow rules to sustain river ecosystems. *Ecological Applications* 16(4), 1311-1318

Asselman, N.E.M., Middelkoop, H., 1995. Floodplain sedimentation: quantities, patterns and processes. *Earth Surface Processes and Landforms* 20, 481 – 489

Assine, M.L., Soares, P.C., 2004. Quaternary of the Pantanal, west-central Brazil. *Quaternary International* 114, 23 – 34

Assine, M.L., 2005. River avulsions on the Taquari Megafan, Pantanal Wetland, Brazil. *Geomorphology* 70, 357 – 371

Bedford, B.L., 1996. The need to define hydrologic equivalence at the landscape scale for freshwater wetland mitigation. *Ecological Applications* 6(1), 57 – 68

Benda. L., Dunne, T. 1995. Stochastic forcing of sediment routing and storage in channel networks. *Water Resources Research* 33 (12), 2865 – 2880

Benda, L. Andras, K. Miller, D. Bigelow, P. 2004. Confluence effects in rivers: Interactions of basin scale, network geometry, and disturbance regimes. *Water Resources Research* 40, W05402

Bertoldi, W., Gurnell, A., Surian, N., Tockner, K., Zanoni, L., Ziliani, L., Zolezzi, G. 2009. Understanding reference processes: linkages between river flows, sediment dynamics and vegetated landforms along the Tagliamento River, Italy. *River Research and Applications* 25, 501 – 516

Bird, J.F. 1982. Channel incision at Eaglehawk Creek, Gippsland, Victoria, Australia. *Proceedings of the Royal Society of Victoria* 94(1), 11 – 22

Boulton A. J. & Lloyd L. N. (1992) Flooding frequency and invertebrate emergence from dry floodplain sediments of the River Murray, Australia. *Regulated Rivers* 7**,** 137–151.

Brenner, M., Peplow, A.J., Schelske, C.L. 1994. Disequlibrium between ^{226}Ra and supported ^{210}Pb in a sediment core from a shallow Florida lake. *Liminology and Oceanography* 39(5), 1222 – 1227
Brereton, G., 1993. *The history of investigations into the Macquarie Marshes,* NSW Department of Water Resources, Dubbo.

Brereton, G., Steenbecke, G., Witts, T., 2000. A Review of Recent Studies Investigating Biological and Physical Processes in the Macquarie Marshes. NSW Department of Land and Water Conservation, Central West Region, Orange, Australia.,

Brierley, G.J. Fryirs, K. 1999. Tributary – trunk stream relations in a cut-and-fill landscape: A case study from Wolumla catchment, New South Wales, Australia. *Geomorphology* 28, 61 – 73

Brierley, G.J., Fryirs, K.A., 2005. *Geomorphology and River Management: Applications of the River Styles Framework.* Blackwell Publishing, Victoria Australia.

Brierley, G., Fryirs, K., Jain, V., 2006. Landscape connectivity: the geographic basis of geomorphic applications. *Area* 38.2, 165 – 174

Brookes, A., 1987. River channel adjustments from channelization works in England and Wales. *Earth Surface Processes and Landforms* 12(4), 337 – 351

Brooks, A.P., Brierley, G.J., Millar, R.G., 2003. The long-term control of vegetation and woody debris on channel and flood-plain evolution: insights from a paired catchment study in southeastern Australia. *Geomorphology* 51, 7 – 29

Brock, P.M., 1998. The significance of the physical environment of the Macquarie Marshes. *Australian Geographer* 29 (1), 71 – 90

Brown, A.G., Carey, C., Erkens, G., Fuchs, M., Hoffmann, T., Macaire, J-J., Moldenhauer, K-M., Walling D.E., 2009. From sedimentary records to sedimentary budgets: Muliple approaches to catchment sediment flux. *Geomorphology* 108, 35 - 47

Brunsden, D., Thorne, J.B., 1979. Landscape sensitivity and change. *Transactions of the Institue of British Geographers* 4 (4), 463 – 484

Bull, W.B. 1979. Threshold of Critical Power in Streams. *Geological Society of America Bulletin Part I.* 90, 453 – 464

Bull, W.B., 1997. Discontinuous ephemeral streams. *Geomorphology* 19, 227 – 276

Australian Bureau of Meteorology, 2012. Climate Data Online. Accessed 12/03/2012 http://www.bom.gov.au/climate/data/

Chiverrell, R.C. Harvey, A.M. Hunter (nee Miller), S.Y. Millington, J. Richardson, N.J. 2008. Late Holocene environmental change in the Howgill Fells, Northwest England. *Geomorphology* 100, 41 – 69

Chiverrell, R.C. Foster, G.C. Thomas, G.S.P. Marshall, P. 2010. Sediment transmission and storage: the implications for reconstructing landform development. *Earth Surface Processes and Landforms* 35, 4 – 15

Chow, V.T. (ed), 1964. *Handbook of Applied Hydrology.* McGraw-Hill, New York.

Collins, A.L. Walling, D.E. 2004. Documenting catchment suspended sediment sources: problems, approaches and prospects. *Progress in Physical Geography* 28 (2), 159 – 196

Comin, F.A. Romero, J.A. Astorga, V. Garcia, C. 1996. Nitrogen removal and cycling in restored wetlands used as filters of nutrients for agricultural runoff. *Water Science and Technology* 35, 255 – 261

Costa, J.E., O'Connor, J.E., 1995. Geomorphically effective floods. Cost et al. (eds) In: *Natural and Anthropogenic Influences in Fluvial Geomorphology*. Geophysical Monograph 89. American Geophysical Union Books Board, Washington, DC USA.

Costanza, R., d'Arge, R., de Groot, R., Farber, S., Grasso, M., Hannon, B., Limburg, K., Naeem, S., O'Neill, R., Paruelo, J., Raskin, R., Sutton, P., and van den Belt, M. (1997) The Value of the World's Ecosystem Services and Natural Capital. *Nature*. 387: 253 - 260

Cote, D., Kehler, D.G., Bourne, C., Wiersma, Y. F., 2009. A new measure of longitudinal connectivity for stream networks. *Landscape Ecology*. 24, 101 – 113

CSIRO, 2013. Water availability in the Macquarie-Castlereagh. CSIRO Canberra, March 2008. Accessed online 22/09/2013, http://www.csiro.au/partnerships/MDBSYReports.html

de Groot, R.S., 1992. *Functions of nature: Evaluation of nature in environmental planning, management and decision making*. Wolters-Noordhoff, Groningen.

de Groot, R.S., van der Perk, J., Chiesura, A., Marguliew, S., 2000. Ecological functions and socio-economic values of critical natural capital as a measure for ecological integrity and environmental health. In: Crabbe, P., Holland, A., Ryszkowski, L., Westra, L. (Eds), *Implementing Ecological Integrity: Restoring Regional and Global Environmental and Human Health.* NATO-Science Series, IV. Earth and Environmental Sciences, vol 1. Kluwer Academic Publishers, Dordrecht/Boston/London, pp. 191 – 214

de Groot, R.S., Wilson, M.A., Boumans, R.M.J., 2002. A typology for the classification, description and valuation of ecosystem functions, goods and services. *Ecological Economics* 41, 393 – 408

Dean, W.E., 1974. Determination of carbonate and organic matter in calcareous sediments and sedimentary rocks by loss on ignition: Comparison with other methods. *Journal of Sedimentary Petrology* 44(1), 242 – 248

Dennison W.C., Orth, R.J., Moore, K.A., Stevenson, J.C., Carter, V., Kollar, S., Bergstrom, P.W., Batiuk, R.A., 1993. Assessing water quality with submerged aquatic vegetation. *BioScience* 43 (2), 86 – 94

Department of Environment, Water, Heritage and Arts, 2009. *The Macquarie Marshes*. Australian Wetland Database: Australian Ramsar Sites. Accessed online 7/10/2013, http://www.environment.gov.au/cgi-bin/wetlands/ramsardetails.pl?refcode=28

Desilets, S.L.E., Nijssen, B., Ekwurzel, B., Ferré, T.P.A., 2007. Post-wildfire changes in suspended sediment rating curves: Sabino Canyon, Arizona. *Hydrological Processes* 21, 1413 – 1423

Diehl TH. 2008. *A Modified Siphon Sampler for Shallow Water: U.S. Geological Survey Scientific investigation report 2007*-5282. USGS: Reston.

Dietrich, W.E., Dunne, T., Humphrey, N.F., Reid, L.M., 1982. Construction of sediment budgets for drainage basins. In: Swanson, F.J., Jan, R.J., Dunne, T., Swanston, D.N. (Eds), *Sediment Budgets in Forested Drainage Basins*. Technical Report PNW-141. United States Forest Service, Portland, Oregon.

Dollar, E.S.J., 2002. Fluvial Geomorphology. *Progress in Physical Geography* 26(1) 123 – 143

Droppo, I.G., 2001. Rethinking what constitutes suspended sediment. *Hydrological Processes* 15, 1551 – 1564

Duller, G.A.T., 2004. Luminescence dating of Quaternary sediments: recent advances. *Journal of Quaternary Science* 19(2), 183 – 192

Dury, G.H. 1959. Analysis of regional flood frequency on the Nene and the Great Ouse. *Journal of Geography* 125, 223 - 229

DWE, 2008. PINNEENA 9.2 – New South Wales Surface Water Data Archive (available on DVD). Department of Infrastructure, Planning and Natural Resources, New South Wales, Australia.

El-Daoushy, F. 1988. A summary on the lead-210 cycle in nature and related applications in Scandinavia. *Environment International* 14, 305 – 319

Ellery, W.N., Ellery, K., Rogers, K.H., McCarthy, T.S., Walker, B.H., 1990. Vegetation of Channels of the Northeastern Okavango Delta, Botswana. *African Journal of Ecology* 28, 276 – 290

Ellery, W.N., Ellery, K., Rogers, K.H., McCarthy, T.S., Walker, B.H., 1993. Vegetation, hydrology and sedimentation processes as determinants of channel form and dynamics in the Northeastern Okavango Delta, Botswana. *African Journal of Ecology* 31, 10 – 25

Eyles, R.J. 1977. Changes in drainage networks since 1820, Southern Tablelands, NSW. *Australian Geographer* 13:6, 377 – 286

Ferguson, R. I., Cudden, J. R., Hoey, T. B., Rice, S. P., 2006. River system discontinuities due to lateral inputs: generic styles and controls. *Earth Surface Processes and Landforms* 31, 1149 – 1166

Finlayson, M., 2005. Views from divergent stakeholders on the Macquarie – Cudgegong River Management Committee. *Ecological Management and Restoration* 2(**2**), 87 – 98

Fitzsimmons, K.E., Rhodes, E.J., Barrows, T.T., 2010. OSL dating of southeast Australian quartz: A preliminary assessment of luminescence characteristics and behaviour. *Quaternary Geochronology* 5(2/3), 91 – 95

Freeman, R., 2008. Sediment accumulation rates, geomorphic and ecological stability in the northern Macquarie Marshes, New South Wales, Macquarie University, Sydney, 103 pp.

Fryirs, K., Brierley, G.J. 1999. Slope-channel decoupling in Wolumla catchment, South Coast, New South Wales, Australia: the changing nature of sediment sources following European settlement. *Catena* 35, 271 – 287

Fryirs, K.A., Brierley, G.J., Preston, N.J., Kasai, M., 2007a. Buffers, barriers and blankets: The (dis)connectivity of catchment-scale sediment cascades. *Catena* 70, 49 – 67

Fryirs, K.A. 2013. (Dis)Connectivity in catchment sediment cascades: a fresh look at the sediment delivery problem. *Earth Surface Processes and Landforms* 38, 30 – 46

Fuchs, M., Lang, A., 2001. OSL dating of coarse-grain fluvial quartz using ingle-aliquot protocols on sediment from NE Peloponnese, Greece. *Quaternary Science Review* 20, 783 – 364

Galat, D.L., Fredrickson, L.H., Humburg, D.D., Bataille, K.J., Bodie, J.R., Dohrenwend, J., Gelwicks, G.T., Havel, J.E., Helmers, D.L., Hooker, J.B., Jones, J.R., Knowlton, M.F., Kubisiak, J., Mazourek, J., McColpin, A.C., Renken, R.B., Semlitsch, R.D., 1998. Flooding to restore connectivity of regulated large-river wetlands. *BioScience* 48, 721–733.

Galbraith, R.F., Roberts, R.G., Laslett, G.M., Yoshida, H., Olley, J.M., 1999. Optical dating of single and multiple grains of quartz from Jinmium rock shelter, northern Australia. Part I: experimental design and statistical models. *Archaeometry* 41, 339 – 364

Gell, P., Fluin, J., Tibby, J., Hancock, G., Harrison, J., Zawadzki, A., Haynes, D., Khanum, S., Little, F., Walsh, B., 2009. Anthropogenic acceleration of sediment accretion in lowland floodplain wetlands, Murray-Darling Basin, Australia. *Geomorphology* 108, 122 – 126

Gilvear, D.J., 1999. Fluvial geomorphology and river engineering: future roles utilising a fluvial hydrosystems framework. *Geomorphology* 31, 229 – 245

Gilvear, D.J., Heal, K.V., Stephen, A. 2002. Hydrology and the ecological quality of Scottish river ecosystems. *The Science of the Total Environment* 294, 131 – 159

Goldberg, E.D. 1963. Geochronology with ^{210}Pb in "Radioactive Dating". *International Atomic Energy Agency Symposium Proceedings*, Vienna 1962, 121 – 131

Goodbred Jr, S.L., Kuehl, S.A., 1998. Floodplain processes in the Bengal Basin and the storage of Ganges – Brahmaputra river sediment: an accretion study using ^{137}Cs and ^{210}Pb geochronology. *Sedimentary Geology* 121, 239 – 258

Graczyk DJ, Robertson DM, Rose WJ, Steuer JJ. 2000. *Comparison of Water Quality Samples Collected by Siphon Samplers and Automatic Samplers in Wisconsin: United States Geologic Survey, Fact Sheet—FS-067-00*. USGS: Reston.

Gradzinski, R., Baryla, J., Doktor, M., Gmur, D., Gradzinski, M., Ke˛dzior, A., Paszkowski, M., Soja, R., Zielinski, T., Zurek, S., 2003. Vegetation-controlled modern anastomosing system of the upper Narew River (NE Poland) and its sediments. *Sedimentary Geology* 157, 253 – 276

Graeme, D., Dunkerley, D.L., 1993. Hydraulic resistance by the River Red Gum, *Eucalyptus camaldulensis*, in ephemeral desert streams. *Australian Geographical Studies* 31 (2), 141 – 154

Green, D., Petrovic, J., Moss, P., Burrell, M., 2011. *Water resources and management overview: Macquarie-Bogan catchment*, NSW Office of Water, Sydney.

Grenfell, M.C. Ellery, W.N. Grenfell, S.E. 2008. Tributary valley impoundment by trunk river floodplain development: a case study from the KwaZulu-Natal Drakensberg foothills, eastern South Africa. *Earth Surface Processes and Landforms* 33, 2029 – 2044

Grenfell, M.C. Ellery, W.N., Grenfell, S.E. 2009. Valley morphology and sediment cascades within a wetland system in the KwaZulu-Natal Drakensberg Foothills, Eastern South Africa. Catena 78, 20 - 35

Gumbricht, T., McCarthy, J., McCarthy, T.S., 2004. Channels, wetlands and islands in the Okavango Delta, Botswana, and their relation to hydrological and sedimentological processes. *Earth Surface Processes and Landforms* 29, 15 – 29

Gurnell, A.M., Gregory, K.J., 1995. Interactions between semi-natural vegetation and hydrogeomorphological processes. *Geomorphology* 13, 49 – 69

Harvey, A.M., 1969. Channel capacity and the adjustment of streams to hydrologic regime. *Journal of Hydrology* 8, 82 – 98

Harvey, A.M., 2002. Effective timescales of coupling within fluvial systems. *Geomorphology* 44, 175 – 201

He, Q., Walling, D.E., 1996. Use of fallout Pb-210 measurements to investigate longer-term rates and patterns of overbank sediment deposition on the floodplains of lowland rivers. *Earth Surface Processes and Landforms* 21, 141 – 154

He, Q., Walling, D.E., 1996b. Interpreting particle size effects in the adsorption of ^{137}Cs and unsupported ^{210}Pb by mineral soils and sediments. *Journal of Environmental Radioactivity* 30, 17 – 137

Heiri, O., Lotter, A.F., Lemcke, G., 2001. Loss on ignition as a method for estimating organic and carbonate content in sediments: reproducibility and comparability of results. *Journal of Paleolimnology* 25, 101 – 110

Herron, N., Davis, R., Jones, R., 2002. The effects of large-scale afforestation and climate change on water allocation of the Macquarie River catchment, NSW, Australia. *Journal of Environmental Management* 65, 369 – 381

Hesse, P., 2009. *Geomorphic mapping for Pillicawarrina environmental water management*. Report prepared for the NSW department of environment, climate change and water. Access Macquarie Limited.

Hickin, E.J., 1984. Vegetation and river channel dynamics. *Canadian Geographer* 28:2, 111 – 125

Hooke, J. 2003. Coarse sediment connectivity in river channel systems: a conceptual framework and methodology. *Geomorphology* 56, 79 – 94

Hudson, P.F., Heitmuller, F.T., Leitch, M.B., 2012. Hydrologic connectivity of oxbow lakes along the lower Guadalupe River, Texas: The influence of geomorphic and climatic controls on the “flood pulse concept”. *Journal of Hydrology* 414 /415, 174 – 183

Hudson,P.F., Sounny-Slitine, M.A., LaFevor, M., 2013. A new longitudinal approach to assess hydrologic connectivity: Embanked floodplain inundation along the lower Mississippi River. *Hydrological Processes* 27, 2187 – 2196

Hughes, A.O., Croke, J.C., Pietsch, T.J., Olley, J.M., 2010. Changes in rates of floodplain and in-channel bench accretion in response to catchment disturbance, central Queensland, Australia. *Geomorphology* 114, 338 – 347

Jain, V., Sinha, R., 2004. Fluvial dynamics of an anabranching river system in Himalayan foreland basin, Baghmati River, north Bihar plains, India. *Geomorphology* 60, 147 – 170

Jain, V., Tandon, S.K., 2010. Conceptual assessment of (dis)connectivity and its application to the Ganga River dispersal system. *Geomorphology* 118, 349 – 358

Jacobs, Z., Duller, G.A.T., Wintle, A.G. 2006. Interpretation of single grain D_e distributions and calculation of D_e. *Radiation Measurements* 41, 264 – 277

Jansen, J.D., Nanson, G.C., 2004. Anabranching and maximum flow efficiency in Magela Creek, northern Australia. Water Resources Research 40, W045021 – W0450213

Jenkins, K.M., Boulton, A.J., Ryder, D.S., 2005. A common parched future? Research and management of Australian arid-zone floodplain wetlands. *Hydrobiologia* 552, 57 – 73

Kale, V.S., Singhvi, A.K., Mishra, P.K., Banerjee, D., 2000. Sedimentary records and luminescence chronology of Late Holocene palaeofloods in the Luni River, Thar Desert, northwest India. *Catena* 40, 337 – 358

Keith, D.A., 2004. *Ocean Shores to Desert Dunes: the Native Vegetation of New South Wales and the ACT.* Department of Environment and Conservation, Hurstville, NSW

Kelly, S.B., Olsen, H., 1993. Terminal fans – a review with reference to Devonian examples. *Sedimentary Geology* 85, 339 – 374

Kemp, J., 2010. Downstream channel changes on a contracting, anabranching river: The Lachlan, southeastern Australia. *Geomorphology* 121, 231 – 244

Kidson, R., Martin, W., Witts, T., 2000a. Historical Vegetation Mapping in the Macquarie Marshes 1949–1991. Central West Region. NSW Department of Land and Water Conservation, Orange, NSW, Australia.

Kidson, R., Martin, W., Witts, T., 2000b. Monitoring of River Red Gums (*Eucalyptus camaldulensis*) in the Macquarie Marshes. Central West Region. NSW Department of Land and Water Conservation, Dubbo, NSW 28 pp.

Kingsford, R.T., 1995. Ecological effects of river management in New South Wales. *Conserving Biology: Threats and Solutions* 144 – 161

Kingsford, R.T., Thomas, R.F., 1995. The Macquarie Marshes in arid Australia and their waterbirds: a 50-year history of decline. *Environmental Management* 19: 867–878.

Kingsford RT. 2000. Ecological impacts of dams, water diversions and river management on floodplain wetlands in Australia. *Austral Ecology* 25(2): 109–127

Kingsford, R.T., Auld, K.M., 2005. Waterbird breeding and environmental flow management in the Macquarie Marshes, Arid Australia. *River Research and Applications* 21, 187 – 200

Knight, M. J., 1980. Structural analysis and mechanical origins of Gilgai at Boorook, Victoria, Australia. *Geoderma* 28, 245–283.

Knighton, D., 1998. *Fluvial Forms and Processes: a new Perspective*. Arnold Publishers, London.

Knighton, D., 1999. Downstream variation in stream power. *Geomorphology* 29, 293 – 306

Krishnaswamy, S., Lal, D., Martin, J.M., Meybeck, M. 1971. Geochronology of lake sediments. *Earth Planet Science Letters* 11, 407 – 414

Lane, S.N., Chandler, J.H., Richards, K.S., 1994. Developments in monitoring and terrain modelling small-scale river-bed topography. *Earth Surface Processes and Landforms* 19, 349 – 368

Lane, S.N., Richards, K.S., Chandler, J.H., 1996. Discharge and sediment supply controls on erosion and deposition in a dynamic alluvial channel. *Geomorphology* 15, 1 – 15

Lane, S.N., Richards, K.S. 1997. Linking river channel form and process: Time, space and casualty revisited. *Earth Surface Processes and Landforms* 22, 249 – 260

Leopold, L.B., Maddock, T.J., 1953. The hydraulic geometry of stream channels and come physiographic implications. *U.S. Geological Survey Prof. Paper* 252

Leopold, L.B., Wolman, M.G., Miller, J.P., 1964. *Fluvial Processes in Geomorphology*. W.H. Freeman and Co., San Francisco, CA. 522 pp

Lepper, K., Larsen, N.A., McKeever, S.W.S., 2000. Equivalent dose distribution analysis of Holocene aeolian and fluvial quartz sands from Central Oklahoma. *Radiation Measurements* 32, 603 – 608

Lesschen, J.P., Schoorl, J.M., Cammeraat, L.H., 2009. Modelling runoff and erosion for a semi-arid catchment using multi-scale approach based on hydrological connectivity. *Geomorphology* 109, 174 – 183

Lexarta-Artza, I., Wainwright, J., 2009. Hydrological connectivity: Linking concepts with practical implications. *Catena* 79, 146 – 152

Mabbutt, J.A. 1977a. *Desert Landforms*. Australian National University Press, Canberra. pp 171 – 179

Mackay, A.K., Taylor, M.P., 2011. Event-based water quality sampling method for application in remote rivers. *River Research and Applications* (online publication)

McCarthy, T.S., Ellery, W.N., 1998. The Okavango Delta. *Transactions of the Royal Society of South Africa* 53, 157 – 182

McCarthy, T.S., Stanistreet, I.G., Cairncross, B., Ellery, W.N., Ellery, K., Oelofse, R., Grobicki, T.S.A., 1988. Incremental aggradation on the Okavango Delta-Fan, Botswana. *Geomorphology* 1, 267 – 278

McCarthy, T.S., Stanistreet, I.G., Cairncross, B., 1991. The sedimentary dynamics of active fluvial channels on the Okavango Fan, Botswana. *Sedimentology* 38, 471 – 487

Michaelides, K., Chappell, A., 2009. Connectivity as a concept for characterising hydrological behaviour. *Hydrological Processes* 23, 517 – 522

Molnar, P., Burlando, P., Ruf, W., 2002. Integrated catchment assessment of riverine landscape dynamics. *Aquatic Sciences* 64, 129 – 140

Montgomery, D. R. 1999. Process domains and the river continuum. *Journal of the American Water Resources Association* 35(2), 397 – 410

Morrison, M., 2002. Understanding local community preferences for wetland quality. *Ecological Management and Restoration* 3(**2**), 127 - 134

Munsell, 2000. *Munsell Soil Color Charts*, Year 2000 Revised Washable Edition. GretagMacbeth, New York.

Murray, A.S., Olley, J.M., Caitcheon, G.G., 1995. Measurement of equivalent doses in quartz from contemporary water-lain sediments using optically stimulated luminescence. *Quaternary Science Reviews (Quaternary Geochronology)* 14, 365 – 371

Murray, A.S., Wintle, A.G., 2000. Luminescence dating of quartz using an improved single-aliquot regenerative-dose protocol. *Radiation Measurements* 32, 57 – 73

Murray, A.S., Olley, J.M., 2002. Precision and accuracy in the optically stimulated luminescence dating of sedimentary quartz: a status review. *Geochronometria* 21, 1 – 16

Nanson, G.C., 1986. Episodes of vertical accretion and catastrophic stripping: a model of disequilibrium flood plain development. *Geological Society of America Bulletin* 97, 1467 – 1475

Nanson, G.C. Croke, J.C. 1992. A genetic classification of floodplains. *Geomorphology* 4, 459 – 486

Nanson, G.C., Huang, H.Q., 1999. Anabranching rivers: divided efficiency leading to fluvial diversity. In: Miller A.J. Gupta, A., (Eds), *Varieties of Fluvial Form*. Wiley, Chichester, pp. 477 – 494

Nanson, G.C., Knighton, A.D., 1996. Anabranching rivers: Their cause, character and classification*. Earth Surface Processes and Landforms* 21, 217 – 239

Nash, D.B., 1994. Effective sediment-transporting discharge from magnitude-frequency analysis. *Journal of Geology* 102, 79 – 95

Nilsson, C. Reidy, C.A. Dynesius, M. Revenga, C. 2005. Fragmentation and flow regulation of the world's large river systems. *Science* 308, 405 – 408

NSW NPWS, 1993. *Macquarie Marshes Nature Reserve Plan of Management*.

Noller, J.S., 2000. Lead-210 Geochronology. *Quaternary Geochronology: Methods and Applications*. AGU Reference Shelf 4.

Oldfield, P.G., Appleby, P.G., Thompson, R., 1980. Palaeoecological studies of lakes in the highlands of Papua New Guinea: I. The chronology of sedimentation. *Journal of Ecology* 68(2), 457 – 477

Olley, J.M., Caitcheon, G.G., Roberts, R.G., 1999. The origin of dose distributions in fluvial sediments, and the prospect of dating single grains from fluvial deposits using optically stimulated luminescence. *Radiation Measurements* 30, 207 – 217

Owens, P.N., Walling, D.E., Leeks, G.J.L., 1999. Deposition and storage of fine-grained sediment within the main channel of the river tweed, Scotland. *Earth Surface Processes and Landforms* 24, 1061 – 1076

Page, K., Nanson, G., 1996. Stratigraphic architecture resulting from Late Quaternary evolution of the Riverine Plain, south-eastern Australia. *Australian Geographical Studies* 36 (3), 289 – 311

Page, K., Nanson, G., Price, D., 1996. Chronology of Murrumbidgee River palaeochannels on the Riverine Plain, Southeastern Australia. *Journal of Quaternary Science* 11, 311 – 326

Page, K., Read, A., Frazier, P., Mount. N., 2005. The effect of altered flow regime on the frequency and duration of bankfull discharge: Murrumbidgee River, Australia. *River Research and Applications* 21, 567 – 578

Paijmans, K., 1981. *The Macquarie Marshes of inland northern New South Wales, Australia,* CSIRO Division of Land Use Research, Technical Paper 41.

Parfait, A., 1999, 'The Geomorphic Assessor', In: Proceedings of Second Australian Stream Management Conference, 8 – 11 February 1999, Adelaide, South Australia, p. 500.

Parkash, B., Awasthi, A.K., Gohain, K, 1983. Lithofacies of the Markanda Terminal Fan, Kurukshetra District, Haryana, India, in Collinson, J.D. and Lewin, J (eds) *Modern and Ancient Fluvial Systems, International Association of Sedimentologists Special Publication* 6, 337 – 344

Paton, T. R., 1974. Origin and terminology for Gilgai in Australia. *Geoderma* 11, 221–242.

Patton, P.C., Schumm, S.A., 1975. Gully erosion, Northwestern Colorado: A threshold phenomenon. *Geology* 3(2), 88 – 90

Pickup, G., 1976a. Adjustment of stream channel shape to hydrologic regime. *Journal of Hydrology* 30, 365 – 373

Pickup, G., Warner, R.F., 1976. The effects of hydrologic regime on magnitude and frequency of dominant discharge. *Journal of Hydrology* 29, 51 – 75

Pietsch, T.J., 2005. Fluvial geomorphology and late Quaternary geochronology of the Gwydir fan-plain. PhD Thesis, University of Wollongong.

Pietsch, T.J., Olley, J.M., Nanson, G.C., 2008. Fluvial transport as a natural luminescence sensitiser of quartz. *Quaternary Geochronology* 3, 365 – 376

Pietsch, T.J., Nanson, G.C., 2011. Bankfull hydraulic geometry; the role of in-channel vegetation and downstream declining discharges in the anabranching and distributary channels of the Gwydir distributive fluvial system, southeastern Australia. *Geomorphology* 129, 152 – 165

Poole, G.C., Stanford, J.A., Frissell, C.A., Runnin, S.W., 2002. Three-dimensional mapping of geomorphic controls on flood-plain hydrology and connectivity from aerial photos. *Geomorphology* 48, 329 – 347

Prosser, I.P., Slade, C.J., 1994. Gully formation and the role of valley-floor vegetation, Southeastern Australia. *Geology* 22, 1127 – 1130

Pye, K., Blott, S.J., 2004. Particle size analysis of sediments, soils and related particulate materials for forensic purposes using laser granulometry. *Forensic Science International* 144, 19 – 27

Ralph, T.J., 2008. Channel breakdown and floodplain wetland morphodynamics in the Macquarie Marshes, south-eastern Australia, Macquarie University, Sydney, 601 pp.

Ralph, T.J., Hesse, P.P., 2010. Downstream hydrogeomorphic changes along the Macquarie River, southeastern Australia, leading to channel breakdown and floodplain wetlands. *Geomorphology* 118, 48 – 64

Ralph, T.J., Hosking, T.N., Iles, J., Hesse, P.P., 2012. Sediment, organic matter and nutrient supply to an Australian floodplain wetland and implications for management. In: Grove, J.R. and Rutherfurd, I.D. (Eds). *Proceedings of the 6th Australian Stream Management Conference,* 1 *Managing for Extremes, 6-8 February 2012,* Canberra, ACT, published by the River Basin Management Society, pages 466-474.

Rendell, H.M., 1995. Luminescence dating of Quaternary sediments. In: Dunay, R.E., Hailwood, E.A. (eds). *Non-biostratigraphical Methods of Dating and Correlation Geological Society Special Publication* 89, 223 – 235

Rice, S.P. Church, M. 2001. Longitudinal profile in simple alluvial systems. *Water Resources Research* 37 (2), 417 – 426

Rice, S.P., Macklin, M.G., 2008. Geomorphology and Earth System Science: a reflection. *Earth Surface Processes and Landforms* 33, 2118 – 2120

Riley, S.J., 1973. *Development of Distributary Channels with Special Reference to Channel Morphology*. [PhD thesis], University of Sydney, Sydney.

Riley, S.J., 1977. Some downstream trends in the hydraulic, geometric, and sedimentary characteristics of an inland distributary system. In: Gregory, K.G. (Ed.), *River Channel Changes.* John Wiley and Sons, pp. 337 – 352

RPS, 2010. *The Benefits of Soil Conservation Works in the Moonie (Back Ck) and Upper Boogera Clusters of the Talwood Planning Group.* Queensland Murray-Darling Committee.

Rowell, D.L., 1994. *Soil Science: Methods and Applications*. Longman Group Ltd, London.

Rutherford, I.D., 1994. Inherited controls on the form of a large, low energy river: the Murray River, Australia. In: Schumm, S.A. (Ed), *The Variability of Large Alluvial Rivers.* American Society of Civil Engineers, New York, pp. 177 – 197

Schumm, S.A., 1969. River Metamorphosis. *Journal of Hydraulics Divison Proceedings of the American Society of Civil Engineers*. **HY1**, 255 - 273

Schumm, S.A., 1977. *The Fluvial System.* Wiley, New York.

Schumm, S.A., 1979. Geomorphic thresholds: The concept and its applications. *Transactions of the Institute of British Geographers* 4(4), 485 – 515

Schumm, S.A., Harvey, M.D., Watson, C.C., 1984. *Incised Cannels: Morphology, Dynamics and Control*. Water Resources Publication, Littleton, Colarado.

Sheldon, F., Thoms, M.C., Berry, O., Puckridge, J., 2000. Using disaster to prevent catastrophe: referencing the impacts of flow changes in large dryland rivers. *Regulated Rivers: Research & Management* 16, 403 – 420

Sheldon, F., Boulton, A.J., Puckridge, J.T. 2002. Conservation value of variable connectivity: aquatic invertebrate assemblages of channel and floodplain habitats of a central Australian arid-zone river, Cooper Creek. *Biological Conservation* 103, 13 – 31

Shi, C., Zhang, D.D., You, L., 2003. Sediment budget of the Yellow River Delta, China: the importance of dry bulk density and implications to understanding sediment dispersal. *Marine Geology* 199, 13 – 25

Singhvi, A.K., 1986. Thermoluminescence dating of Quaternary red-sand beds: A case study of coastal dunes in Sri Lanka. *Earth and Planetary Science* 80(1/2), 139 – 144

Smith, B.P.G., Naden, P.S., Leeks, G.J.L., Wass, P.D., 2003. Characterising the fine sediment budget of a reach of the River Swale, Yorkshire, U.K. during the 1994 to 1995 winter season. *Hydrobiologia* 494, 135 – 143

Smith, H.G., Dragovich, D., 2008. Sediment budget analysis of slope-channel coupling and in-channel sediment storage in an upland catchment, southeastern Australia. *Geomorphology* 101, 643 – 654

Smith, N.D., McCarthy, T.S., Ellery, W.N., Merry, C.L., Ruther, H., 1997. Avulsion and anastomosis in the Panhandle Region of the Okavango Fan, Botswana. *Geomorphology* 20, 49 – 65

Soster, F.M., Matisoff, G., Whiting, P.J., Fornes, W., Ketterer, M., 2007. Floodplain sedimentation rates in an alpine watershed by radionuclide techniques. *Earth Surface Processes and Landforms* 32, 2038 – 2051

Srivastava, P., Juyal, N., Singhvi, A.K., Wasson, R.J., Bateman, M.D., 2001. Luminescence chronology of river adjustment and incision of Quaternary sediments in alluvial plain of the Sabarmati River, north Gujarat, India. *Geomorphology* 36, 217 – 229

Stanistreet, I.G., McCarthy, T.S., 1993. The Okavango Fan and the classification of subaerial fan systems. *Sedimentary Geology* 85, 115 – 133

Stanford, J.A., Ward, J.V., 1993. An ecosystem perspective of alluvial rivers: connectivity and the hyporheic corridor. *Journal of the North American Benthological Society* 12(1), 48 – 60

Steinfeld, C.M.M. Kingsford, R.T. 2013. Disconnecting the floodplain: earthworks and their ecological effect on a dryland floodplain in the Murray-Darling Basin, Australia. *River Research and Applications* 29, 206 – 218

Stokes, S., Bray, H.E., Blum, M.D., 2001. Optical resetting in large drainage basins: tests of zeroing assumptions using single-aliquot procedures. *Quaternary Science Reviews* 20, 879 – 885

Stone, P.M., Walling, D.E., 1997. Particle size selectivity considerations in suspended sediment budget investigations. *Water, Air and Soil Pollution* 99, 63 – 70

Thompson, C.J., Croke, J.C., Purvis – Smith, D., 2011. Floodplain sediment disconnectivity at a tributary junction and valley constriction site in the Fitzroy Basin, Qld, Australia. *Geomorphology* 125, 293 – 304

Thomsen, K.J., Murray, A.S., Bøtter-Jensen, L., Kinahan, J., 2007. Determination of burial dose in incompletely bleached fluvial samples using single grains of quartz. *Radiation Measurements* 42, 370 – 379

Tomkins, K.M., Hesse, P.P., 2004. Evidence of Late Cenozoic uplift and climate change in the stratigraphy of the Macquarie River valley, New South Wales. Australian Journal of Earth Sciences 51, 273 – 290

Tooth, S., Nanson, G.C., 1995. The geomorphology of Australia's fluvial systems: retrospect, perspect and prospect. *Progress in Physical Geography* 19 (1), 35 – 60

Tooth, S. 1999a. Floodouts in Central Australia, in Miller, A.J. and Gupta, S (eds) *Varieties of Fluvial Form*, John Wiley and Sons, 219 – 248

Tooth, S. 1999b. Downstream changes in floodplain character on the Northern Plains of Arid Central Australia, in Smith, N.D. and Roges, J. (eds) *Fluvial Sedimentology VI*, *Special Publication of the International Association of Sedimentologists* 28, 93 – 112

Tooth, S. 2000. Downstream changes in dryland river channels: the Northern Plains of Arid Central Australia. *Geomorphology* 34, 33 – 54

Trimble, S.W., Mendel, A.C., 1995. The cow as a geomorphic agent – a critical review. *Geomorphology* 13, 233 – 253

Viles, H.A., Naylor, L.A., Carter N.E.A., Chaput, D., 2008. Biogeomorphological disturbance regimes: progress in linking ecological and geomorphological systems. *Earth Surface Processes and Landforms* 33, 1419 – 1435

Wakelin-King, G.A., Webb, J.A. 2007. Threshold-dominated fluvial styles in an arid-zone mud-aggregate river: The uplands of Fowlers Creek, Australia. *Geomorphology* 85, 114 – 127

Wainwright, J., Turnbull, L., Ibrahim, T.G., Lexarta-Artza, I., Thornton, S.F., Brazier, R.E. 2011. Linking environmental regimes, space and time: Interpretations of structural and functional connectivity. *Geomorphology* 126, 387 – 404

Walling, D. E., 1983. The sediment delivery problem. *Journal of Hydrology* 65, 209 – 237

Walling, D.E., He, Q., 1994. Rates of overbank sedimentation on the flood plains of several British rivers during the past 100 years. *Variability in Stream Erosion and Sediment Transport IAHS* 224, 203 – 210

Walling, D.E., He, Q., 1998. The spatial variability of overbank sedimentation on river floodplains. *Geomorphology* 24, 209 – 223

Walling, D.E., Owens, P.N., Leeks, G.J.L., 1998. The role of channel and floodplain storage in the suspended sediment budget of the River Ouse, Yorkshire, UK. *Geomorphology* 22, 225 – 242

Walling, D.E., 2005. Tracing suspended sediment sources in catchments and river systems. *Science of the Total Environment* 344, 159 – 184

Walling, D.E., Owens, P.N., 2003. The role of overbank floodplain sedimentation in catchment contaminant budgets. *Hydrobiologia* 494, 83 – 91

Wallinga, J., Murray, A.S., Duller, G.A.T., Törnqvist, T.E., 2001. Testing optically stimulated luminescence dating of sand-sized quartz and feldspar from fluvial sediments. *Earth and Planetary Science Letters* 193, 617 – 630

Wang, Z-Y., Li, Y., He., Y., 2007. Sediment budget of the Yangtze River. *Water Resources Research* 43, 1 – 14

Watkins, J.J., Meakin, N.S., 1996. *Explanatory Notes Nyngan and Walgett 1:250000 Geological Series Sheets*. Geological Survey of New South Wales, Sydney.

Watters, J.R., Stanley, E.H., 2007. Stream channels in peatlands: The role of biological processes in controlling channel form. *Geomorphology* 89(1/2), 97 – 110

Whiteoak, K., Binney, J., 2012. Literature review of the economic value of ecosystem services that wetlands provide. Final report prepared for the Department of Sustainability, Environment, Water, Population and Communities. Marsden Jacob Associates, Australia.

Wintle, A.G., 1997. Luminescence dating: Laboratory procedures and protocols. *Radiation Measurements* 27(5/6), 769 – 817

Wintle, A.G., Murray, A.S., 1999. Luminescence sensitivity changes in quartz. *Radiation Measurements* 30, 107 – 118

Wintle, A.G., Murray, A.S., 2000. Quartz OSL: Effects of thermal treatment and their relevance to laboratory dating procedures. Radiation Measurements 32, 387 – 400

Wolman, M.G., Leopold, L.B., 1957. River floodplains: some observations on their formation. *US Geological Survey Professional Paper*, 282-C

Wolman, M.G., Miller, J.P., 1960. Magnitude and frequency of forces in geomorphic processes. *Journal of Geology* 68, 54 – 74

Wolman, M.G., Gerson, R., 1978. Relative scales of time and effectiveness of climate in watershed geomorphology. *Earth Surface Processes* 3, 189 – 208

Woodyer, K.D., 1968. Bankfull frequency in rivers. *Journal of Hydrology* (New Zealand) 6, 114 – 142

Yonge, D. Hesse, P. 2009. Geomorphic environments, drainage breakdown and channel and floodplain evolution on the lower Macquarie River, central western New South Wales. *Australian Journal of Earth Sciences* 56, S35 – S53

Young, A.R.M. 1986. The geomorphic development of dells (upland swamps) on the Woronora Plateau, NSW, Australia. *Zeitschrift fur Geomorphologie* 30(3), 317 – 327

Young, R.W., Young, A.R.M., Price, D.M., Wray, R.A.L., 2002. Geomorphology of the Namoi alluvial plain, northwestern New South Wales. *Australian Journal of Earth Sciences* 49, 509 – 523

Zaborska, A., Carroll, J., Papucci, C., Pempkowiak, J., 2007. Intercomparison of alpha and gamma spectrometry techniques used in ^{210}Pb geochronology. *Journal of Environmental Radioactivity* 93, 38 – 50

Zierholz, C., Prosser, I.P., Fogarty, P.J., Rustomji, P., 2001. In-stream wetlands and their significance for channel filling and the catchment sediment budget, Jugiong Creek, New South Wales. *Geomorphology* 38, 221 – 235

Zimmerman, R.C., Goodlett, J.C., Comer, G.H., 1967. The influence of vegetation on channel form in small streams. *International Association of Hydrological Sciences Publication* 75, 225 – 275

Appendix 1

NSW OFFICE OF WATER.
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DATA ENQUIRY - WARNING TO USERS

Analyses plots and other data presentations make use of information on the NSW Office of Water (NOW) archive.

Because of the historic nature of the archive there may well be errors and omissions in the data, or the quality of the information may make it unsuitable for the intended purpose.

Data integrity may not be examined before they are used in analytical programs and the DWE makes no guarantee that they conform to guidelines set down by Australian Rainfall and Runoff.

This applies in particular to frequency analysis (HYPL3), flow duration analysis (HYFLOW and HYLOWFL) and to correlation programs (HYMASS, HYCATCH HYPLOTXY); outputs from these analyses should only be undertaken if definitive decisions are to be made.

Users of these and similar programs should be aware that:

- data extracted may not be homogeneous due to changes at the site, land use changes, storage construction, changes in rating tables etc,
- data may contain periods where only daily-read data are available and monthly or annual peak data stored are actually daily values,
- periods of missing data within the record may influence the result,
- data may be of variable quality and could include periods that have been estimated by a variety of methods,
- extraction of peak series data takes no account of independence criteria,
- all plotted data (eg from HYPLOT, HYMPLOT) contain no indication of data quality. If this is required, reference should be made to the included monthly tabulation,
- quality codes 130 (measured data not yet coded) and 131 (estimated data not yet quality coded) refer to data which has not been subjected to current quality assurance validation procedures. It is possible that these data may be improved using techniques developed after the data were archived, and
- all flow data may be subject to change at any future time due to the availability of more recent gauging's which better define the stage/discharge relationship.

Disclaimer

The State of New South Wales and the Office of Water and its employees, officers, agents or servants do not accept any responsibility for any inaccuracies or omissions contained in this data and for any actions taken on the basis of information supplied. The State of New South Wales and the Office of Water, and its employees, officers, agents and servants, expressly disclaim all and any liability and responsibility to any person in respect of anything and of the consequences of anything done or omitted to be done by any such person in reliance, whether wholly or partially upon the contents of this data.

Appendix 2

The site details of suspended sediment and velocity samples

Site Number	Sample	Waypoint	
1	CA08/0308/01	554583	6632797
2	CA08/0308/02	554558	6632861
3	MA/08/0308/03	565567	6630161
4	B/08/NS/water/	550803	6607942
5	B/08/NS/water/	551008	6607900
6	B/08/NS/water/	551073	6607892
7	B/08/NS/water/	550738	6607574
8	B/08/NS/water/	550802	6607488
9	B/08/NS/water/	550689	6607422
10	B/08/NS/water/	550709	6607391
11	B/08/NS/water/	550610	6607395
12	B/08/NS/water/	550620	6607391
13	B/08/NS/water/	550739	6607467
14	B/08/NS/water/	550826	6607831
15	B/08/NS/water/	550862	6607839
16	M/08/NS/water/	575311	6497239
17	M/08/NS/water/	563987	6528690
18	M/08/NS/water/	561260	6542267
19	M/08/NS/water/	553905	6556704
20	M/08/NS/water/	549194	6575366
21	UB/08/NS/water	549674	6602845
22	UB/08/NS/water	549541	6602871
23	UB/08/NS/water	549493	6602869
24	UB/08/NS/water	549442	6602897
25	UB/08/NS/water	549368	6602898
26	UB/08/NS/water	549280	6602930
27	UB/08/NS/water	549218	6602927
28	UB/08/NS/water	549157	6602949
29	UB/08/NS/water	548758	6602997
30	UB/08/NS/water	548655	6603050
31	UB/08/NS/water	548592	6603122
32	M/08/NS/water/	551942	6597345
33	M/08/NS/water/	552091	6597373
34	M/08/NS/water/	552251	6597298
35	M/08/NS/water/	554270	6598183
37	M/08/NS/water/	568547	6591023
38	M/08/NS/water/	554536	6582283
39	M/08/NS/water/	551384	6581446
40	M/08/NS/water/	548216	6581479
41	UB/08/NS/water	550901	6598386
42	UB/08/NS/water	550944	6598366
43	UB/08/NS/water	550825	6598144
44	UB/08/NS/water	550821	6597994
46	UB/08/NS/water	550748	6598008
47	UB/08/NS/water	550581	6598069
48	UB/08/NS/water	550447	6597989
49	UB/08/NS/water	550360	6597576
50	UB/08/NS/water	550462	6597468
51	UB/08/NS/water	550506	6597437
52	UB/08/NS/water	550348	6597379
53	UB/08/NS/water	550111	6596557
54	UB/08/NS/water	550002	6596508
56	UB/08/NS/water	550010	6596344
57	UB/08/NS/water	557089	6618573
58	UB/08/NS/water	557063	6618513
59	LB/08/NS/water	551175	6609637
60	LB/08/NS/water	550893	6608308
61	M/08/NS/water/	616329	6442945
62	M/08/NS/water/	631405	6436969
63	M/08/NS/water/	670915	6406252
64	M/08/NS/water/	697429	6383865

Appendix 3

Site	Location	GPS	Sampler Type	Notes
1	Bells Bridge Carinda - u/s bridge	55J 0554580 6632696	D	Against left bank. Free from vegetation or obstruction.
2	Bridge Carinda - d/s bridge	55J 0554576 6632861	S	In amidst the in-channel reed bed. Downstream end of reed bed.
3	Marebone Weir Gauge	55J 0565825 6527333	D	Free standing on left bank. No obstructions or vegetation nearby.
4	Bulgeraga Ck - Mt harris-Grad Rd	55J 0564763 6536863	D	Left bank upstream of bridge and small, short weir that acted as a car crossing.
5	Mac R Gradgery-Mt Harris Road	55J 0562230 6534800	D	Near right steep bank.
6	Bulgeraga Ck - Oxley Station	55J 0560135 6563665	D	Trampled banks by cattle. Placed near steep, eroded left bank.
7	Macquarie River - Oxley Station	55J 0554171 6557067	D	Just upstream of gauge on left bank.
8	Old Macquarie R - Sth N R	55J 0546017 6574139	S	Placed in a pool on a meander bend. Middle of channel bed.
9	Breakaway - downstream end	55J 0548564 6577385	D	Upstream end of an in-channel reed bed.
10	Monkeygar Ck - u/s Sth N R	55J 0549645 6570553	D	Upstream end southern Nature Reserve. Mid clear channel.
11	Monkeygar Ck - mid Sth N R	55J 0550137 6574154	D	Monkeygar Ck downstream of the start of the Breakaway. U/s and d/s reed beds.
12	Breakaway channel - Sth N R	55J 0550078 6574098	D	Beginning of the Breakaway Channel southern nature reserve.
13	Monkeygar Ck - Sth N R	55J 0551929 6578257	S & D	Monkeygar Ck at the northern end of the southern nature reserve. Mid channel.
14	Macquarie River - Miltara	55J 0557058 6618414	S	In-between right bank and star picket - protection from cattle damage.
15	Macquarie River - Roumani	55J 0557894 6622761	D	Sampler near right bank amongst in-channel reed bed. Thick reed bed.
16	Start Bypass/Mac R Split NNR	55J 0551853 6597336	S	Shallow water sampler. Right bank of shallow Macquarie River channel.

17	Macquarie River breakdown NNR	55J 552450 6597898	D	Shallow banks. Azola covered channel. Reed beds in clumps extending across channel. Sampler right bank in thin reed area.
18	Macquarie River breakdown NNR	55J 0552170 6598137	S	Very shallow channel. West of site 19. Sampler placed in mid channel.Clear from vegetation.
19	Macquarie River at Willancorah	55J 0548319 6581432	S	Shallow sampler placed mid channel of dry river bed. High channel banks although limited flow. No in-channel veg.
20	Monkeygar Creek Willancorah	55J 0551338 6580572	S	Placed mid channel on the border of SNR and Willancorah. Sampler installed should have been a D.
21	Monkeygar Creek Willancorah	55J 0550003 6585007	S	Installed mid channel upstream of rock weir. Smooth channel banks. Cattle present.
22	Bulgeraga Creek Willancorah	55J 0552994 6585100	D	Installed against the roots of a large tree on the left bank for protection against cattle. Very eroded banks. Right on fence boundary.
23	Macquarie River upper NNR	55J 0555839 6612061	S	Small, 'messy' channel. Installed mis channel. Lots of small vegetation surrounding channel. Macrophytes.
24	Bora Well NNR	55J 0550694 6606237	D	Installed on the edge of a primary contributory where two channels meet
25	Bora Well west of site 24	55J 0550538 6606072	D	Installed directly downstream from the large reed bed
26	Bora Well west of site 25	55J 0550453 6606128	D	Installed in an eastward flowing channel after the convergence of two contributory perpendicular channels.
27	Bora Well west of site 26	55J 0550245 6605807	D	Installed directly downstream from the large reed bed although installed upside down.
28	Halls Block	55J 0549354 6602777	D	Bottles filled to differing degrees.
29	Halls Block	55J 0540712 6602680	D	Samplers were placed amongst in-channel vegetation
30	Halls Block	55J 0550160 6602647	D	Channel constriction by vegetation evident in some places
31	Pillicawarrina	55J 0554912 6591470	D	Both bottles full however removed in June and tested for turbidity - too much algal growth.
32	Mole	55J 0554980 6596060	D	Both bottles full however removed in June and tested for turbidity - too much algal growth.
33 -37	Longstowe	55J 0550375 6597300	S, S, D, D	Deep channel sampler in the primary distributary was the only sampler to survive. The three samplers installed in the distributary marsh channels were trampled by cattle.

Appendix 4

The Manning's n coefficient at each site describing channel roughness and floodplain roughness. There is an explanation attached to each site for the reason for the coefficient value.

Site	Channel Roughness	Floodplain Roughness	Reason for Manning's n values
D/S Burrendong Dam	0.05	0.039	Steep confined stream with gravel, cobbles and boulders, < 30 m bankfull. The left bank had been cleared and leveled. B_{max} is 28 cm. The right bank has boulders and brush. The overbank flow on the left had been cleared for picnic area and on the right a road had been put in, although there is light brush.
Wellington	0.07	0.05	Small natural stream. Pool - riffle sequences. Fast flowing water indicative of steep slope. Weeds present along most of the channel bed. Gravels and cobbles present. Willows and other shrubs present within stream. B_{max} is 25 cm. Presence of ford creates a small waterfall. Both floodplains have been cleared for pasture grass.
Ponto Falls	0.08	0.04	Small natural stream. B_{max} of 14 cm. Minimal winding with pools and shoals. Gravels and cobbles. Willows along entire left bank. Phragmites along low flow channel and in thalweg. Gravel bar along right bank. River red gums on bank and in floodplain riparian strip along both banks.
Minore Falls	0.03	0.099	Small natural stream with gravel and cobbles. B_{max} of 3.9 cm. Straight uniform and clean reach. Willows and castor oil weed inhabiting floodplain.
Turkey Farm Reserve	0.061	0.08	Small natural stream. LWD, no boulders, although gravel and cobbles. Pools and shoals with weedy banks above low flow. Weed in thalweg. B_{max} of 1.1 cm. Willows and light brush with some trees along left floodplain with light trees and scrub along right floodplain.
U/S Warren Weir	0.075	0.05	Small natural stream. Very weedy along the channel banks with castor oil weed. Some macrophytes also inchannel. Winding with deep pools. Floodplain scattered with trees. Dense population of Castor Oil weed with 2 m of either bank.
Marebone Weir	0.045	0.042	Winding, reeds, macrophytes at edge of low flow channel, LWD, majorly human altered system, some pools and shoals. Left bank line of trees in a strip then cleared with grass. Right bank strips pf dense trees to a width of 3 m.
Gradgery	0.039	0.04	Small natural stream. Winding, macropytes colonising concave right bank, some LWD. Riparian medium or dense trees with scrub. Right

			bank not cleared, left bank cleared.
Oxley	0.04	0.042	Small natural stream. LWD, pools and shoals, different types of emergent macrophytes lining edge of right (convex) bank, winding. Right bank dense trees and light scrub beneath. Left bank cleared for pasture and stock access to water.
Bora Channel	0.033	0.05	Channel is straight and uniform. Bankfull < 10 m. There are inchannel phragmites along banks and in mid channel. Floodplains have medium density of vegetation and undulating plains formed by gilgai.
Bells Bridge Carinda	0.033	0.035	Channel clean and winding with very few macrophytes lining the low flow channel. Bankfull < 10 m. Floodplain contained few scattered trees and small amount of pasture grass.

Appendix 5

Raw ^{210}Pb data for Site 4 – Bora Well.

Client Name:	Nicola Smith
Client Institution:	Macquarie University
Project Title:	2010rc0055a
Core Description:	Bora Well

CIC model

Mass Accumulation Rate	0.078 ± 0.008		g/cm2/y
r2 =	0.967007222		

ANSTO ID	Depth (cm)			Dry Bulk Density (g/cm^3)	Cumulative Dry Mass (g/cm^2)			Mud < 63 µm Content (%)	Count Date	Total 210Pb (Bq/kg)			Supported 210Pb (Bq/kg)		
M453	0	-	1	0.86	0.4	±	0.4	86.6	04-Aug-10	64.1	±	2.1	16.2	±	1.2
M675	2	-	3	0.91	2.2	±	0.4	54.5	25-Nov-10	45.2	±	1.5	14.9	±	1.1
M454	3	-	4	1.50	3.4	±	0.5	77.7	04-Aug-10	35.3	±	1.3	13.2	±	1.0
M676	5	-	6	1.19	6.1	±	0.6	21.1	25-Nov-10	7.9	±	0.4	4.2	±	0.3
M455	8	-	9	1.47	10.1	±	0.6	64.8	04-Aug-10	7.4	±	0.3	6.0	±	0.4
M456	10	-	11	1.45	13.0	±	0.6	78.4	04-Aug-10	15.3	±	0.5	16.1	±	1.2
M457	15	-	16	1.24	19.7	±	0.6	76.6	04-Aug-10	17.2	±	0.6	17.4	±	1.2
M458	20	-	21	1.62	26.9	±	0.7	81.8	04-Aug-10	17.6	±	0.4	18.3	±	1.3

Uncorrected Unsupported 210Pb (mBq/g) or (Bq/kg)			Unsupported 210Pb Corrected to reference date 02-Aug-10 (Bq/kg)			Mud < 63 µm Content (%)	Calculated CIC Ages (years)			Calculated CRS Ages (years)			CRS model Mass Accumulation Rates g/cm2/y		
47.9	±	2.4	47.9	±	2.4	86.60	5	±	5	5.1	±	0.9	0.08	±	0.01
30.4	±	1.9	30.7	±	1.9	54.51	28	±	6	27.2	±	1.3	0.081	±	0.004
22.1	±	1.6	22.1	±	1.6	77.74	43	±	8	46.8	±	1.4	0.073	±	0.002
3.7	±	0.5	3.8	±	0.5	21.12	78	±	11	90.4	±	1.7	0.067	±	0.001
1.3	±	0.5	1.3	±	0.5	64.81	129	±	16						
-0.9	±	1.3		N/D		78.41									
-0.2	±	1.4		N/D		76.56									
-0.7	±	1.4		N/D		81.84									

Raw ^{210}Pb data for Site 3 – Northern Nature Reserve Floodplain

Client Name:	Nicola Smith
Client Institution:	Macquarie University
Project Title:	2010rc0058a
Core Description:	NNRFC/02

ANSTO ID	Depth (cm)			Dry Bulk Density (g/cm^3)	Cumulative Dry Mass (g/cm^2)			Mud < 63 µm Content (%)	Count Date	Total Pb-210 (mBq/g) or (Bq/kg)			Supported Pb-210 (mBq/g) or (Bq/kg)		
M471	0.0	-	1.0	0.87	0.4	±	0.4	88.8	05-Aug-10	37.3	±	0.9	15.2	±	1.1
M680	2.0	-	3.0	1.10	2.4	±	0.5	81.1	25-Nov-10	34.5	±	0.9	16.5	±	1.2
M472	3.0	-	4.0	0.95	3.4	±	0.5	87.5	05-Aug-10	31.5	±	0.8	19.8	±	1.5
M681	5.0	-	6.0	1.40	5.8	±	0.5	73.4	25-Nov-10	21.2	±	0.7	16.2	±	1.2
M473	8.0	-	9.0	1.42	10.0	±	0.6	75.7	05-Aug-10	13.1	±	0.4	14.1	±	1.0
M474	10.0	-	11.0	1.60	13.0	±	0.6	78.3	05-Aug-10	10.8	±	0.3	13.7	±	1.0
M475	15.0	-	16.0	1.69	21.2	±	0.7	84.0	05-Aug-10	11.7	±	0.4	15.3	±	1.1
M476	20.0	-	21.0	1.47	29.1	±	0.7	80.1	05-Aug-10	10.6	±	0.4	11.9	±	0.8

Unsupported 210Pb Corrected to reference date 02-Aug-10 (mBq/g) or (Bq/kg)			Calculated CIC Ages (years)			Calculated CRS Ages (years)			CRS model Mass Accumulation Rates g/cm2/y		
22.0	±	1.4	3.9	±	4.0	3.7	±	1.1	0.11	±	0.03
18.1	±	1.5	22.1	±	6.1	22.9	±	2.2	0.10	±	0.01
11.7	±	1.6	31.6	±	7.5	34.9	±	2.5	0.10	±	0.01
5.0	±	1.4	53.3	±	11.2	60.9	±	2.8	0.09	±	0.00
	N/D										
	N/D										
	N/D										
	N/D										

Raw ^{210}Pb data for Site 2 – Northern Nature Reserve Channel

Client Name:	Nicola Smith
Client Institution:	Macquarie University
Project Title:	2010rc0057a
Core Description:	NNRC/02

ANSTO ID	Depth (cm)			Dry Bulk Density (g/cm^3)	Cumulative Dry Mass (g/cm^2)			Mud < 63 µm Content (%)	Count Date	Total Pb-210 (mBq/g) or (Bq/kg)			Supported Pb-210 (mBq/g) or (Bq/kg)		
M465	0.0	-	1.0	1.11	0.5	±	0.5	93.20	05-Aug-10	41.6	±	0.9	21.1	±	1.6
M466	3.0	-	4.0	1.30	4.2	±	0.6	91.09	05-Aug-10	35.9	±	0.8	17.9	±	1.4
M679	5.0	-	6.0	1.31	6.8	±	0.6	90.58	25-Nov-10	37.7	±	0.9	21.1	±	1.5
M467	8.0	-	9.0	1.34	10.8	±	0.6	79.22	05-Aug-10	26.6	±	0.7	16.7	±	1.2
M468	10.0	-	11.0	1.57	13.7	±	0.7	21.79	05-Aug-10	29.8	±	0.8	17.4	±	1.3
M470	20.0	-	21.0	1.60	29.5	±	0.7	73.55	05-Aug-10	20.1	±	0.6	16.4	±	1.2
M678	2.0	-	3.0	1.26	3.8	±	0.8	86.34	25-Nov-10	26.7	±	0.9	19.7	±	1.5
M469	15.0	-	16.0	1.44	21.3	±	0.7	75.39	05-Aug-10	15.7	±	0.6	20.4	±	1.5

Unsupported 210Pb Corrected to reference date 02-Aug-10 (mBq/g) or (Bq/kg)			Calculated CIC Ages (years)			Calculated CRS Ages (years)			CRS model Mass Accumulation Rates g/cm2/y		
20.6	±	1.8	1.1	±	1.1	1.1	±	0.7	0.51	±	0.36
17.9	±	1.6	8.1	±	1.5	8.1	±	1.8	0.51	±	0.11
16.8	±	1.8	13.2	±	1.9	13.7	±	2.1	0.49	±	0.07
9.9	±	1.4	20.9	±	2.7	21.6	±	2.5	0.50	±	0.06
12.4	±	1.5	26.6	±	3.3	27.7	±	2.8	0.49	±	0.05
3.7	±	1.4	57.4	±	6.7	70.5	±	3.3	0.42	±	0.02
7.1	±	1.7									
	N/D										

Raw ^{210}Pb data for Site 1 – Longstowe

Client Name:	Nicola Smith
Client Institution:	Macquarie University
Project Title:	2010rc0056a
Core Description:	Longstowe

ANSTO ID	Depth (cm)			Dry Bulk Density (g/cm^3)	Cumulative Dry Mass (g/cm^2)			Mud < 63 µm Content (%)	Count Date	Total Pb-210 (mBq/g) or (Bq/kg)			Supported Pb-210 (mBq/g) or (Bq/kg)		
M459	0.0	-	1.0	1.50	0.7	±	0.7	81.6	04-Aug-10	27.4	±	0.8	15.7	±	1.0
M677	2.0	-	3.0	1.53	3.8	±	0.8	84.5	25-Nov-10	27.4	±	0.9	16.3	±	1.2
M460	3.0	-	4.0	1.64	5.4	±	0.8	82.0	04-Aug-10	15.8	±	0.4	16.4	±	1.1
M461	8.0	-	9.0	1.63	13.5	±	0.8	89.3	04-Aug-10	16.5	±	0.4	19.9	±	1.5
M462	10.0	-	11.0	1.63	16.8	±	0.8	75.7	04-Aug-10	15.9	±	0.4	15.7	±	1.1
M463	16.0	-	17.0	1.56	26.4	±	0.8	73.5	04-Aug-10	13.0	±	0.4	16.1	±	1.2
M464	20.0	-	21.0	1.58	32.7	±	0.8	73.0	04-Aug-10	14.7	±	0.4	15.7	±	1.1

Unsupported 210Pb Corrected to reference date 02-Aug-10 (mBq/g) or (Bq/kg)			Clay < 2 µm Content (%)	Mud < 63 µm Content (%)	Calculated CIC Ages (years)			Calculated CRS Ages (years)			CRS model Mass Accumulation Rates g/cm2/y		
11.7	±	1.3		81.58	0.4	±	0.4	0.3	±	0.6	2.45	±	4.50
11.2	±	1.5		84.54	1.8	±	0.4	1.5	±	1.2	2.46	±	1.92
-0.6	±	1.2		81.95									
-3.5	±	1.5		89.30									
0.1	±	1.2		75.71									
-3.0	±	1.2		73.50									
-1.0	±	1.2		72.97									

Appendix 6

Details for the three in-channel cores and one floodplain core of the northern Macquarie Marshes.

Date	Location	GPS	Landscape Location	Sample Code	Depth Hole (m)	Core Length (m)	Notes
SITE 1 19/09/2009	Bora Well ~ 293 m from RF PDC-01	55J 0550672 6606231	In-channel	0909/NS/BWC/C/01	1.5	0.7	Initial core was stuck and required a trench to remove it.
2/10/09	Bora Well ~ 293 m from RF PDC-01	55J 0550672 6606231	In-channel	0909/NS/BWC/C/02	0.8	0.7	plus bottom 2 cm bagged
2/10/09	Bora Well ~ 293 m from RF PDC-01	55J 0550672 6606231	In-channel	0909/NS/BWC/C/03	1.0	0.7	plus bottom 2 cm bagged
SITE 2 1/10/2009	Northern Nature Reserve ~ 500 m from Longstowe	55J 0550914 6599741	Floodplain	0909/NS/NNRFL/C/01	1.2	1.1	
1/10/09	Northern Nature Reserve ~ 500 m from Longstowe	55J 0550914 6599741	Floodplain	0909/NS/NNRFL/C/02	1.2	1.1	plus bottom 2 cm bagged
1/10/09	Northern Nature Reserve ~ 500 m from Longstowe	55J 0550914 6599741	Floodplain	0909/NS/NNRFL/C/03	1.2	1.2	plus bottom 2 cm bagged. OSL core.
SITE 3 30/09/2009	Northern Nature Reserve ~ 500 m from Longstowe	55J 0550921 6599733	In-channel	0909/NS/NNRC/C/01	1.0	0.7	
30/09/09	Northern Nature Reserve ~ 500 m from Longstowe	55J 0550921 6599733	In-channel	0909/NS/NNRC/C/02	1.0	0.7	
30/09/09	Northern Nature Reserve ~ 500 m from Longstowe	55J 0550921 6599733	In-channel	0909/NS/NNRC/C/03	1.0	0.9	
SITE 4 29/09/2009	Longstowe near RF LSB-01	55J 0550517 6597437	In-channel	0909/NS/LC/C/01A 0909/NS/LC/C/01B	0.27 0.32	0.27 0.32	~ 60 cm
29/09/09	Longstowe near RF LSB-01	55J 0550517 6597437	In-channel	0909/NS/LC/C/02A 0909/NS/LC/C/02B	0.31 0.33	0.31 0.33	~ 60 cm
29/09/09	Longstowe near RF LSB-01	55J 0550517 6597437	In-channel	0909/NS/LC/C/03	1.0	0.8	~ 12 cm at bottom exposed to daylight before being pushed back into the bottom of the core
29/09/09	Longstowe near RF LSB-01	55J 0550517 6597437	In-channel	0909/NS/LC/C/04	1.0	0.6	~ 10 cm slipped out of core barrel during removal. That remainder was left in the hole.