CHAPTER 1

Introduction

1.1 The Need for This Research

Since the early nineteenth century, there has been an increase worldwide in the adverse chemical and physical changes that have occurred to aquatic environments because of anthropogenic changes (Azrina et al. 2005; Kronimus et al. 2004; Lara 2001; Tejerina-Garro et al. 2005; Vorosmarty et al. 2003). The use of physical structures that fragment the flow regimes of riverine systems has become widespread for their agricultural benefits, water supply, power supply or regulation of the flow to mitigate flooding effects (Able et al. 1998; Cetra & Petrere 2006; Stein et al. 2002; Thoms et al. 2005; Usseglio-Polatera & Beisel 2002). Installation of these structures results in the alteration, sometimes severe, of the flow regime of the system, which in turn can cause alterations to the ecology, hydrolology, chemistry and geomorphology of the riverine environment (Thoms 2003; Williams 2001; Ye et al. 2003; Zhang et al. 2003).

Since early times, wetlands have been of particular significance to humankind because of their important role in the production of food supplies, and more recently, in their ability to be altered to assist agriculture and industry (Pfadenhauer & Grootjans 1999). The area of the world's wetlands has been recognised to be decreasing because of human effects for many years; a report to the Ramsar Convention in 1999 estimated that approximately half of the world's total area of wetlands has been lost since 1900 (Finlayson & Davidson 1999). Australia has also suffered from widespread loss and degradation of wetlands because of both ecological and non-ecological events, such as alteration or loss from urbanisation; alteration and loss for agriculture, horticulture and forestry; engineering structures for water resource management and flood mitigation; pollution; burning; translocation of natural and exotic flora and fauna species; poor bureaucratic and management decisions; and recreational activities (Davis & Froend 1999; Finlayson & Rea 1999; McComb & Lake 1990; Pressey & Adam 1995).

There has been global recognition of the need to reverse the process of wetland loss and degradation, and to undertake programs of wetland restoration. This has resulted in the implementation of one or more of a number of different restoration strategies to achieve the predicted goals (Bedford 1999; Erwin 2009; Goodwin et al. 2001; Nakamura et al. 2006; Pen et al. 2003; Pfadenhauer & Grootjans 1999; Zedler 2000).

Many coastal wetlands in eastern Australia have experienced anthropological changes introduced to mitigate the effects of flooding. The severe modifications to hydrological connectivity of these wetlands have resulted in adverse changes to their abiotic and biotic environments. The change in regional geological characteristics has also resulted in the formation of acid sulfate soils and their associated detrimental effects on the environment. There has been an increase in activity to rehabilitate these wetlands and reverse these negative environmental changes (Cook et al. 2000; Glamore & Indraratna 2001; Johnson et al. 2004; Nelson 2006; Middleton et el. 1985; Pollard & Hannan 1994; Pressey & Middleton 1982; Sammut et al. 1966).

This research focuses on the Yarrahapinni Wetland, on the Macleay River estuary in northern New South Wales (NSW). This wetland is typical of those on the NSW and Queensland coasts, which have been subject to extensive anthropological alterations by flood mitigation programs. The Yarrahapinni Wetland was excluded from tidal flow by a levee bank structure incorporating a one-way floodgate structure that only allowed rainfall outflow. These changes, supplemented by extensive drainage and excavations, resulted in the degradation of the biotic and abiotic environments, including the formation of acid sulfate soils. In 2007, the National Parks and Wildlife Service (NPWS) of NSW instigated a rehabilitative program of incrementally increasing the extent of tidal re-inundation (Cook et al. 2000; Johnston et al. 2003; Sammut et al. 1996; White et al. 1997; White & Melville 1993).

This research adopted an ecohydrological approach to monitoring and analysing the effects of these rehabilitative changes to the biotic and abiotic environments and the resulting interactions between them.

1.2 Aims and Objectives

The aim of this thesis is:

To investigate the changes to the hydrology and fish abundances of a coastal wetland undergoing tidal re-inundation, and to examine the degree of interaction between them to evaluate the outcomes of the rehabilitative program.

To achieve this aim the following objectives are addressed:

1. Quantify the magnitude of the tidal pulse and salinity of the water available externally for the tidal re-inundation of the Yarrahapinni Wetland.

2. Determine the effects of the incremental changes to hydrological connectivity of the wetland with the external estuary on the hydrology of the wetland.

3. Evaluate the changes to the fish and prawn assemblages before and after a small increase in the hydrological connectivity of the wetland.

4. Determine the changes to the spatial distribution within the wetland of the fish and prawn assemblages as the hydrological connectivity is incrementally increased.

5. Specify the role of *Phragmites australis* reeds in effecting the hydrology of the wetland throughout the alterations to its hydrological connectivity with the external estuary.

1.3 Precis

This thesis consists of eight chapters.

Chapter 2 presents a survey of the published literature available globally for knowledge to contribute to preparing this thesis. The published literature on ecohydrology is analysed to appraise the suitability of this method of investigation for this study. Literature pertaining to hydrological connectivity, wetlands, acid sulfate soils, wetland restoration, eastern Australian coastal wetlands and fisheries research techniques is also surveyed for information of relevance to this study.

Chapter 3 provides a description of the Macleay River in northern NSW, particularly describing the Yarrahapinni Wetland, the study area of this thesis. It includes descriptions of the climate, hydrology, geomorphology, topography and land use of the Macleay River catchment system. It also describes the history of the flooding on the Macleay River Valley, the anthropogenic changes made to mitigate this flooding and their adverse effects on the study area. The history of the role of *Phragmites australis* in changes to the Yarrahapinni Wetland is also described.

Chapter 4 quantifies the four stages of changes made to the hydrological connectivity of the wetland by incrementally opening sections of the floodgate structure. The changes to the wetland’s hydrology are described for the four stages of this opening program. The correlation between the water levels in the upper freshwater wetland section and the hydrological connectivity of freshwater outflow through the constraining stands of *Phragmites australis* is also established.

Chapter 5 examines the hydrology of Andersons Inlet, the estuary external to the Yarrahapinni Wetland, to determine the quality of the water available for tidal re-inundation. The correlation between the salinity of Andersons Inlet and rainfall events is established.

Chapter 6 investigates the effects of a small increase of hydrological connectivity to a “before and after” study of the fish assemblages to a region close to the internal side of the wetland floodgate system. These results are compared with those from two previous similar studies that were partially unsuccessful because of administrative difficulties in having the floodgates opened in coordination with these studies.

Chapter 7 describes the spatial distribution, within the Yarrahapinni Wetland, of the fish and prawn assemblages as the hydrological connectivity was increased. The available literature for habitat and spawning behaviour of individual species is appraised and compared with the habitation patterns in this wetland.

The major findings of this thesis are discussed in Chapter 8, which describes the implications of this research, its major achievements and makes recommendations for future analysis and research.

CHAPTER 2

Thesis Literature Survey

2.1 Ecohydrology

Ecohydrology is a relatively new science that studies the mutual interaction between the hydrological cycle and ecosystems (Porporato & Rodriguez-Iturbe 2002). It is an interdisciplinary science that integrates the physical processes of hydrology with the biological processes of ecology (Janauer 2000; Nuttle 2002). These processes combine within aquatic systems to maintain water quality and quantity within ranges to provide a suitable environment for native flora and fauna (McClain 2002; Zalewski 2002).

Beauregard et al. (2002) suggested that the first use of the term 'ecohydrology' in scientific literature was by Pedroli (1990), in an underground water study, and the term was later used at the International Conference of Water and the Environment in Dublin 1992 (Beauregard et al. 2002). The establishment of an ecohydrology subprogram of the fifth UNESCO International Hydrological Programme (1996–2001) led to a rapid increase in this field of research (Zalewski et al. 1997). However, many articles had been previously published that combined the disciplines of hydrology and ecology without using the term (see below); 'ecohydrology' has a diversity of definitions that have encompassed wider scopes as the science has developed (Bonell 2002; Kundzewicz 2002).

A literature search based on the research articles using the topic term 'ecohydrology', recorded on the Web of Science^{SM} database from January 1985 to December 2011 clarifies the development of this scientific discipline. Figure 2.1 shows the number of scientific articles published during five-year intervals within this period range, illustrating the rapid increase in recent years.

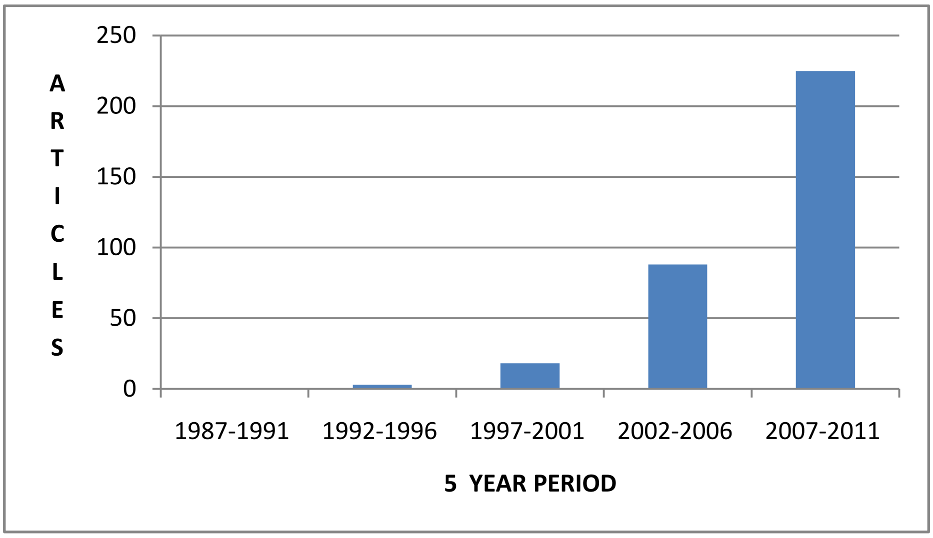

Figure 2.1: Number of scientific articles published on the subject of ecohydrology for five-year periods, from a Web of Science^{SM} survey

This search identified 341 journal articles published between 1985 and 2011: 240 (70%) for ecohydrology coupled with the topic terms 'plants' or 'vegetation', 84 (25%) for the topic pairing of ecohydrology and groundwater, and the same number (25%) for the pairing of ecohydrology and water management. Eight (2.3%) results were found for the topic combinations of ecohydrology and estuary, five (1.5%) for ecohydrology and tide or tidal, 21 (6.2%) for ecohydrology and fish. The results show that the science has been focused on freshwater–vegetation studies. The major countries of origin contributing to these articles were the United States (51%), Australia (8%) and China (7%). The results when 'ecology' and 'hydrology' were both used as topic terms in combination with a third topic, as those above, showed approximately twice the number of articles for each category, indicating that many studies have used the concept of ecohydrology without using the actual term.

A similar Web of Science survey was conducted by King and Caylor (2011), which examined the methodological approaches and the hydrological variables studied. This study found that 70% of the articles presented novel research and, of these, 64% contained observational studies, 39% entailed modelling and only 13% utilised manipulative experimentation. These results and the relative proportions of process and state variables used are shown in Figure 2.2 (Claret et al. 2001).

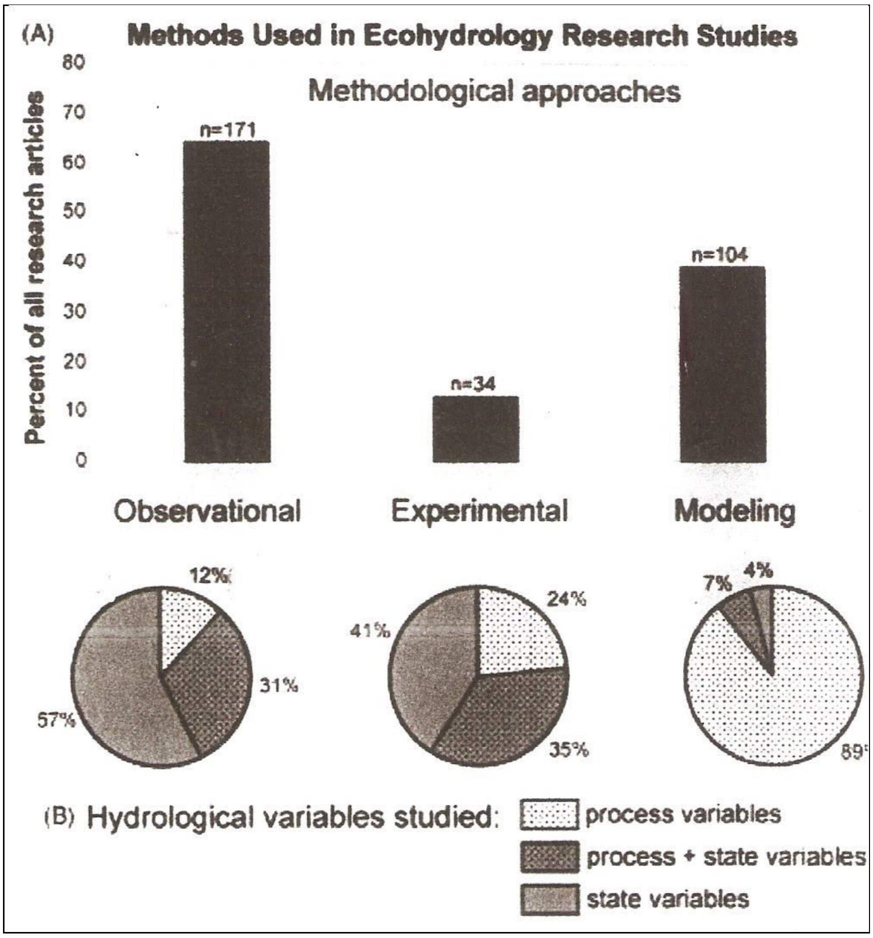

Figure 2.2: Methodological trends and hydrological variables used in journal articles titled ecohydrology (King & Caylor 2011)

An earlier survey of the topics ecohydrology, eco-hydrology, hydroecology and hydro-ecology, based on Web of Science^{SM} data for any type of publication, found that ecohydrology was used as a topic title in 60% of the publications (Hannah et al. 2004). This article also found that ecology–flora combinations accounted for 75% of the publications, ecology–fauna accounted for 21% and ecology–flora and fauna accounted for 4%.

Although the developing science of ecohydrology was initially dominated by flora ecology and freshwater hydrology studies, an increasing number of studies in other areas of this science have emerged. However, the field of fauna ecology and freshwater hydrology has produced many significant journal articles studying a variety of fauna groups. The groups involved include macroinvertebrates (Collins et al. 2007; Monk et al. 2008; Ogbeibu & Oribhabor 2002), waterbirds (Desgranges et al. 2006; Kingsford et al. 2004; Rayburg & Thoms 2009), amphibians (Babbitt et al. 2000; Kupferberg 1996; Leonardo et al. 2007) and fish (Bradford & Heinonen 2008; Chang et al. 2011; Pusey et al. 2010).

The Web of Science^{SM} survey of journal articles showed that only 7.4% of ecohydrological studies involved the hydrology of estuaries and oceans, which refers to aquatic environments involving waters of varying degrees of salinity. An ecohydrological approach has been applied to studies of lakes (Harper & Mavuti 2004), coral reefs (Wolanski 2005), estuaries (Chicharo et al. 2001) and bays (Huang 2010). The largest proportion (49%) of these salinity-orientated ecohydrological journal papers are devoted to coastal wetlands; 69% refer to wetlands in the United States and 15% concern those of both Australia and Canada.

This study concerns the tidal restoration of an NSW east coastal wetland that has suffered extensive acid sulfate formation because of flood mitigation drainage and tidal exclusion. A Web of Science^{SM} survey of journal articles that combine the topics acid sulfate (sulphate) and coastal wetland produced 38 articles—50% referring to Australian wetlands, 26% to the United States and 8% to Canada.

2.2 Hydrological Connectivity

The concept of connectivity was first implied in the first and second laws of motion by Isaac Newton (1687). These laws proposed that any physical entity would move from one state of motion to another state of motion if an unbalanced force were applied. These laws also state that the rate of change of state of motion is proportional to the relevant connectivity-restrictive property that exists between the two states, or more specifically, unbalanced force is proportional to acceleration.

Newton also applied this principle to heat transfer with his law of cooling (1701), which stated that the rate of heat transfer between two bodies is proportional to the temperature difference between the two bodies. The notion of connectivity is implied mathematically in these laws by the inclusion of a controlling constant in their mathematical forms. The principle involved in these laws is represented in Figure 2.3.

UNBALANCED DRIVING FORCE	→	CONTROLLING PROPERTY (CONNECTIVITY)	→	RATE OF CHANGE

Figure 2.3: The role of connectivity in some laws of physical change

These principles have been applied to many branches of science, as shown in Table 2.1.

Table 2.1: Examples of connectivity in the science laws

TYPE OF CONNECTIVITY	UNBALANCED DRIVING FORCE	CONTROLLING PROPERTY (CONNECTIVITY)	RATE OF CHANGE
Newton's physical motion laws	Unbalanced physical force	Resistance to motion (e.g. friction)	Acceleration (distance x time^{-2})
Newton's law of heat transfer	Temperature difference	Heat transfer coefficient	Heat transfer units (energy x time^{-1})
Electricity	Potential difference	Resistance	Electric current (ampere)
Biological inter-cell nutrient transfer (Osmosis)	Nutrient concentration difference	Permeability of cell membrane	Chemical concentration change per unit time
Fluid flow (Hydrological connectivity)	Hydraulic pressure difference	Flow constrictions	Flow rate (volume x time^{-1})

In all cases, the connectivity is treated as a specific physical vector quantity that is described qualitatively and quantitatively by both its magnitude and its direction of flow.

Connectivity is an important unifying theme in understanding hydrological processes and catchment scale ecological processes. Hydrolological connectivity controls the flux of matter and energy into a riverscape, such as a coastal estuarine wetland, which in turn controls the biological flux of organisms by internal and external migration (Pringle 2003; Tetzlaff et al. 2007).

A literature search based on the research articles using the topic term 'hydrological connectivity' recorded on the Web of Science[SM] database from January 1985 to June

2013 identified 558 journal articles. Of these, 332 were listed in the science categories of ecology, environmental science or marine and freshwater biology, and 89% of these had been published in the past 10 years. These statistics reveal the expanding recent interest in the importance of hydrological connectivity in understanding aquatic riverine environments.

Many of these studies relate to the effects of the loss of hydrological connectivity in riverine environments caused by anthropological changes and the need for restoration programs to reverse this process (Aarts et al. 2004; Bracken & Croke 2007; Heiler et al. 1995; Hein et al. 2003; Lee et al. 2006; Pringle 2001; Pringle 2003; Tetzlaff et al. 2007; Tockner et al. 1999).

The concept of hydrological connectivity is often used in journals in its qualitative sense, but it can also be quantified in terms of physical dimensions or classified by various criteria that identify its physical characteristics (Calabrese & Fagan 2004; Henein & Merriam 1990; Tischendorf & Fahrig 2000). Quantifying hydrological connectivity by a number of techniques allows the development of mathematical relationships with the riverine environment (Boys 2007; Bracken & Croke 2007; Karim et al. 2012; Michaelides & Chappell 2008; Van Nieuwenhuyse et al. 2011; Webb et al. 2011; Westgate et al. 2012).

2.3 Wetlands

The vital, fundamental ecological function of wetlands was recognised by the International Convention of Wetlands (the Ramsar Convention) in its formation and in the development of its treaty in 1971. The treaty also recognises the economic, scientific and cultural value of wetlands, and it was developed to stem the progressive encroachment on and loss of wetlands now and in the future (Ramsar 2009).The definition of a wetland accepted by the Ramsar Convention is:

> An area of marsh, fen, peatland or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or

salt, including areas of marine water the depth of which at low tide does not exceed six metres.

The Ramsar Convention has also expanded the wetland definition to include riparian and coastal zones adjacent to the wetlands, and islands or bodies of marine water deeper than 6 m at low tide lying within the wetlands.

Wetlands form at the interface of terrestrial and aquatic ecosystems, may have some of the features of both and perform unique, vital functions for the sustainability of both systems (Keddy 2010). Since early history, wetlands have also been of particular significance to humankind because of their important role in the production of food supplies and, more recently, in their ability to be altered to assist agriculture and industry (Pfadenhauer & Grootjans 1999). Figure 2.4 provides a diagrammatic summarisation of the interactions of these ecological functions and socioeconomic benefits.

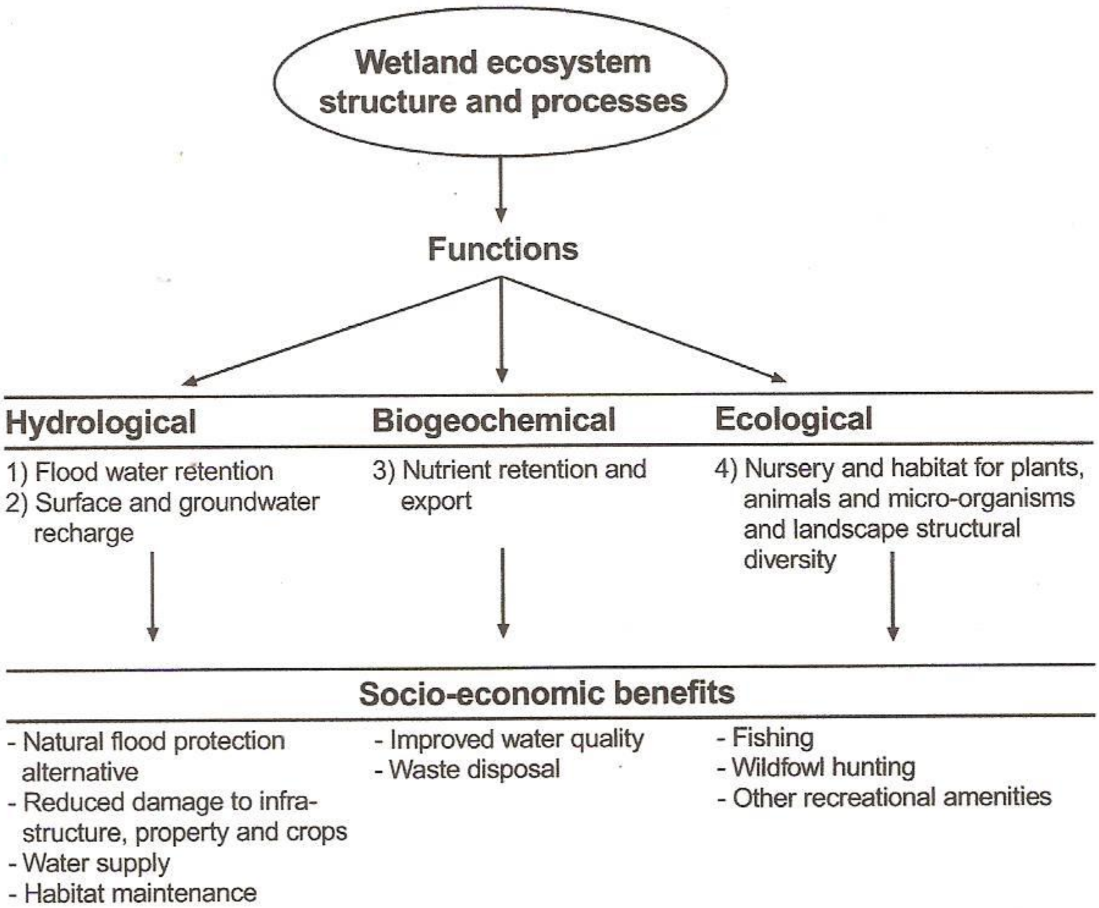

Figure 2.4: Ecological functions and socioeconomic benefits of a wetland (Turner et al. 2003)

The classification of wetlands involves a wide diversity of forms that usually express a unique hydrology and ecology requiring a specific approach to scientific investigation. The Ramsar classification of wetland types has three major categories—marine/coastal, inland and human-made—and 42 specific categories (Ramsar 2009). This study focuses on coastal wetlands and adopts the definition:

> A coastal wetland is a wetland associated with an estuary and includes coastal plain freshwater swamps and marshes, estuarine salt marshes, mangrove swamps, seagrass beds, intertidal mud, sand and salt flats, and intertidal forested wetlands. (Bildstein et al. 1991; Ramsar 2009)

The area of the world's wetlands has been recognised to be decreasing for many years because of human effects; a report to the Ramsar Convention in 1999 estimated that approximately half of the world's total area of wetlands has been lost since 1900 (Finlayson & Davidson 1999). Agriculture was considered the major cause of this loss, which was estimated as 60% in Europe and North America during this period (Czech and Parsons 2002; Gallant et al. 2007). Approximately 70% of the world's population live within the world's coastal zones (Bildstein et al. 1991), so coastal wetlands are particularly vulnerable to anthropogenic degradation (Britsch & Dunbar 1992; Lin et al. 2007; Turner 1997).

Australia has also suffered from widespread loss and degradation of wetlands from both ecological and non-ecological causes. These include alteration or loss from urbanisation; alteration and loss for agriculture, horticulture and forestry; engineering structures for water resource management and flood mitigation; pollution; burning; translocation of natural and exotic flora and fauna species; poor bureaucratic and management decisions; and recreational activities (Davis & Froend 1999; Finlayson & Rea 1999; McComb & Lake 1990; Pressey & Adam 1995). These losses and degradation have been the basis of Australian regional studies including investigations of south-western Australian coastal plains (Davis & Froend 1999; Halse et al. 2003), coastal and marine wetlands in St Vincent's Gulf, South Australia (Edyvane 1999), floodplain wetlands (Kingsford 2000), salt marshes in south-eastern Australia (Saintilan & Williams 1999), Murrumbidgee River region (Kingsford & Thomas 2002), Central Australia (Lehtinen et al. 1999), Murray–Darling Basin (Arthington & Pusey 2002), shallow wetlands on the New England Tablelands of NSW (Brock et al. 1999), Macquarie Marshes (Kingsford 1995) and coastal wetlands of NSW (Pressey & Middleton 1982).

Like many aquatic ecosystems, biological and hydrological processes are integrated within coastal wetlands. These processes can be integrated and quantified at multiple scales and then used as management tools to enhance the capacity of estuarine wetlands to absorb human effects (Acreman et al. 2009; Boruah & Biswas 2002; Jenson

2002; Joris & Feyen 2003; Larsen et al. 2007; Mtahiko et al. 2006; Rayburg & Thoms 2009; Trepel & Kluge 2002; Wassen & Grootjans 1996; Wolanski 2007).

The coastal wetlands on the east coast of Australia, and their associated estuaries, are usually associated with regions of high population and agricultural activity because of the fertile floodplain soils. These low-lying areas are regions with high coastal rainfall patterns, resulting in periodic flooding that can disrupt or damage the agricultural and non-agricultural activities and infrastructure of the regions (McInnes et al. 2002; Yeo 2002). This has led to these areas having a long history of structural flood mitigation works in the form of drains, levees and floodgate structures to minimise the damage of flooding, expedite the removal of floodwaters, control the tidal inflow of saline water and increase the area of agricultural land by draining low-lying areas. Many east coast estuaries have been subject to these alterations, including every major coastal river system in NSW (Haskins 2002; Middleton et al. 1985; Pollard & Hannan 1993; Pressey & Middleton 1982; Smith 2002; Williams & Watford 1997).

These alterations to wetlands and estuaries to mitigate the effects of flooding have often resulted in negative effects on these aquatic systems. They have contributed to the alteration of wetland functions and their loss and replacement by agricultural and urban development. The flood mitigation works often changed the hydrology, ecology, biology, chemistry and geology of these east coast wetlands. These changes include the loss or elimination of native fauna and flora species; their replacement by exotic species; alteration of the region’s aquatic and terrestrial ecologies; modification or elimination of tidal inflows; lowering of the water table by drainage; alteration to groundwaters and their associated aquifers; and formation of acid sulfate soils, resulting in the release of deoxygenated, acidic water that may also exhibit metal ion toxicity (Cook et al. 2000; Glamore & Indraratna 2001; Johnson et al. 2004; Nelson 2006; Middleton et al. 1985; Pollard & Hannan 1994; Pressey & Middleton 1982; Sammut et al. 1966).

The coastal wetlands in Northern America have also been subject to modification and loss by varying degrees through drainage and impoundment to facilitate their use for agricultural, urban and industrial uses. This has resulted in a range of negative effects similar to those experienced in Australia, including the formation of acid sulfate soils and their associated negative side effects (Hammersmark et al. 2005; Johnston 1994; McKee et al. 2004; Mitsch & Gosselink 1986; Turner & Lewis 1997; Zedler 1996).

2.3.1 Acid Sulfate Soils

Approximately 30% of the world's ice-free land area has developed acid soils, which occur in distinct northern and tropical global belts, usually as a result of drainage, forest clearing, or mining and agricultural practices (von Uexkull & Mutert 1995).

In NSW, the acid soils have usually formed from deposits of Holocene-age (< 10,000 years Before Present [BP]) iron pyrite (FeS_2), which formed in estuarine lowlands throughout the world as a result of the last major sea-level rise (Dent 1986; Sammut et al. 1996). While under anoxic conditions beneath the water table, these deposits are stable, but when drainage exposes the deposits to air, the damp deposits oxidise and become acidic (Melville et al. 1993; Stumm & Morgan 1981). This oxidation, resulting in acidity, occurs through a number of complicated chemical and biochemical pathways, but initially the FeS_2 is converted to ferrous iron ions (Fe^{2+}) and sulfate ions (SO_4^{2-}), which can be written as (Cook et al. 2000):

$$FeS_2 + 7/2\ O_2 + H_20 \text{ ----> } Fe^{2+} + 2H^+ + 2SO_4^+ \qquad \text{(Equation 2.1)}$$

Initially, this reaction is slow, but as the pH is lowered by the formation of the H^+, the ferrous ions produced are further oxidised to ferric ions and strongly catalysed by micro-organisms such as *Thiobacillus ferrooxidans* (White et al. 1997). The lowering of the pH also allows ferrous ions to remain soluble and become an oxidant to cause further conversion of the FeS_2, which produces more acid (Cook et al. 2000). The complete pyrite oxidation reaction can be summarised as (Sammut et al. 1996):

$$FeS_2 + 15/4O_2 + 7/2H_2O \text{ -----> } Fe(OH)_3 + 2H_2SO_4 \qquad \text{(Equation 2.2)}$$

A drained pyritic floodplain or coastal wetland can produce between 100 and 300 kg of sulfuric acid per hectare per year (White et al. 1997). This acidity destroys ambient vegetation and forms red (due to the presence of the Fe^{3+}) denuded open areas known as 'acid sulfate scalds' (Johnston et al. 2003; Rosicky et al. 1999; Tulau & Naylor 1999). It can also attack engineering structures such as concrete floodgate culverts, which has occurred on many east coast structures (White & Melville 1993).

The dissolved Fe^{2+} or the Fe^{3+} can be transported away from the original pyrite deposit in the surface water and, through dilution and reducing acidity, produce iron oxyhydroxide or iron hydroxide flocs, which can coat and destroy benthic communities and stream bank communities, obstruct the gill function of aquatic fauna, and consume oxygen (Fig. 2.5) (Cook et al. 2000; Sammut et al. 1996; Tulau 1999), as shown by:

$$Fe^{2+} + \tfrac{1}{4} O_2 + 3/2H_20 \text{ -----> } FeOOH_{(precipitate)} + 2H^+ \qquad \text{(Equation 2.3)}$$

Figure 2.5: Iron floc outbreak in the Yarrahapinni Wetland (Source: Author, February 2008)

The chemical reactions in acid sulfate soil that involve iron and sulfur result in the formation of iron monosulfides (FeS), which combine with organic oozes to form deposits known as monosulfidic black ooze (MBO). These fine black deposits can be found in most anthropogenically altered floodplain areas and wetlands in eastern Australia. The deposits have the ability to deoxygenate the water rapidly when submerged as well as the potential for oxidative release of metal ions (Bush et al. 2004; Johnson et al. 2003; Smith 2004; Tulau & Naylor 1999).

Metallic ions such as aluminium, iron, magnesium, manganese and heavy trace elements can also be released when the acid soil water solution reacts with clay minerals in the sediment (Bigham & Nordstrom 2000; Cook et al. 2000; Smith 2004; White et al. 1997).

The most serious consequences of the occurrence of acid sulfate soils in coastal floodplains have been found to occur if an extended dry period is followed by a period of heavy rainfall that produces flooding. During the dry period, the acidity increases near acid sulfate areas and the clay minerals are attacked, which produces metallic ions and FeS. When flooding occurs, the highly acidic, oxygen-depleted water, which often contains toxic levels of iron and aluminium, is flushed into the estuaries with devastating effects. Widespread mortalities of fish, crustaceans and molluscs occur, and the incidence of diseases such as epizootic ulcerative syndrome (red spot disease) occurs in fish populations.

2.4 Wetland Restoration

There has been global recognition of the need to reverse the process of wetland loss and degradation, and to undertake programs of wetland restoration. Worldwide, experience has shown that wetland restoration is not a simple process but requires a thorough understanding of the biotic and abiotic interactions occurring in the wetland involved. This enables an informed decision of the restoration procedures required and can result in implementing one or more of a number of different restoration strategies to achieve the predicted goals (Bedford 1999; Erwin 2009; Goodwin et al. 2001; Nakamura et al. 2006; Pen et al. 2003; Pfadenhauer & Grootjans 1999; Zedler 2000).

Restoration techniques and strategies involved in wetlands can be broadly categorised into three groups:

- those involving changes to the hydrology of the wetland,
- those involving changes to the flora of the wetland,
- those involving chemical and physical alterations to the wetland soils.

The types of hydrological changes utilised in wetland restoration vary considerably with the individual wetland. After extensive hydrological analysis, a program in the San Francisco Bay area in the United States predicted that a tidal range of 0.3 m, achieved by adjustable tide gates, was sufficient to achieve the wetlands restoration goals (Coats et al. 1989). Middleton (2002) described how the flood pulse concept, first developed for the restoration of Amazonian floodplains, has now been applied to riverine and tidal system restoration worldwide. In Europe, hydrological restoration techniques have varied from installing plastic membrane in the wetland embankments to assisting in water table control, penning boards, sluice gates and, in some cases, installing water pumps to transfer water to the wetland (Acreman et al. 2007).

Techniques of wetland restoration involving changes to the flora assemblages also vary considerably. In the US state of Delaware, samples of the salt marsh grass *Spartina alterniflora* were taken from estuarine creek banks, propagated by tissue culture and transplanted back to wetlands (Wang et al. 2003). Germination of seed banks in glasshouse experiments revealed 12 species suitable for restorative regeneration of ephemeral floodplain wetlands on the Nyl River, South Africa (Brock & Rogers 1998). A study on wetlands in the Yellow River Delta, China, explained strategies to improve the growth of *Phragmites australis,* to promote regeneration of the system (Tang et al. 2006). Another study of wetlands in the Yellow River Delta by Cui et al. (2009) proposed that propagation of *Phragmites australis* is detrimental to plant heterogeneity and plant diversity in the region's wetlands.

Forms of soil alterations such as channel formation, construction of embankments and wetland depth alterations are commonly used in conjunction with other restoration methods. Other techniques include transplanting soil into the wetland (Brown & Bedford 1997), complete and partial removal of disturbed soils where the wetland had been subjected to agricultural alteration (Dalrymple et al. 2003), marsh terracing (Rozas & Minello 2001) and treating wetlands with lime to control pH levels in acid sulfate soils (von Uexkull & Mutert 1995).

2.4.1 Australian East Coast Wetland Restoration

In Australia, there are an estimated 215,000 km^2 of acid sulfate soils, 41,000 km^2 of which are exposed to tidal influence (Fitzpatrick et al. 2008). A survey of 69 Australian wetland restoration projects found that 15 of these involved mangrove environments and 10 involved salt marsh environments, indicating a tidal regime (Streever 1997). All 25 wetlands listed changes to tidal hydrology as one of the methods involved in their restoration programs.

The benefits of tidal restoration of a wetland include:

- The regular flushing effect by tidal overtopping of acid sulfate areas removes the associated toxicity in small, regular, less harmful increments than the more disastrous effects often associated with flooding events.
- Returning to the original water table levels has associated advantages and stops further oxidation of acid sulfate soils.
- The chemical tidal buffering effect is a chemical reaction that relies on the bicarbonate anion content of seawater, which is part of the atmospheric calcium–carbon dioxide equilibrium reaction with the oceans. The bicarbonate ion reacts with the strong sulfuric acid in acid sulfate soils to form the much weaker carbonic acid and raise the pH to more acceptable values (Fig. 2.6) (Indraratna et al. 2002; Johnston et al. 2009; Pease et al. 1997; Sammut et al. 1994; Stumm & Morgan 1996).

$$Ca^{2+} + \underset{\substack{\uparrow \\ \text{seawater}}}{HCO_3^-} + \underset{\substack{\uparrow \qquad \uparrow \\ \text{ASS oxidation}}}{H^+ + SO_4^{2-}} \rightarrow \underset{\substack{\uparrow \\ \text{weak carbonic acid}}}{H_2CO_3} + Ca^{2+} + SO_4^{2-}$$

Figure 2.6: Tidal buffering chemical reaction (Indraratna et al. 2002)

In 2003, a conference was held in NSW to coordinate the managing of the changes to coastal floodplains by increasing the salinity through tidal re-inundation (Johnston et al. 2003). This conference was attended by representatives of Commonwealth, NSW State and Queensland State government departments, as well as various involved academics. One of the main conclusions from this conference was the recognition of the importance of salinity management from an agricultural perspective. The two recognised areas of risk were the effects of increasing salinity on agricultural land and forage crops and the effects on the increased salinity on groundwater and aquifers.

To overcome these risks, most wetland tidal restoration projects employ some sort of structure that can be controlled impede the some section of the normal tidal inflow from entering the wetland. The most common forms of such devices are drop boards and selective floodgates, often referred to as 'smartgates'. Drop boards have been used globally throughout history and are simple and economical to make and operate . Typically, they are wooden boards, approximately 50 x 10^{-3} m thick by 300 x 10^{-3} m wide, and long enough to reach the sides of the structure supporting the culvert, weir or floodgate to which they are applied. The appropriate number can be added (or removed) to provide the degree of flow control required by dropping them into the prepared grooves in the side of the structure (Fig. 2.7) (Leese 2000; NSW Fisheries 2002; Sammut et al. 1994; Tulau 1999; White 2009).

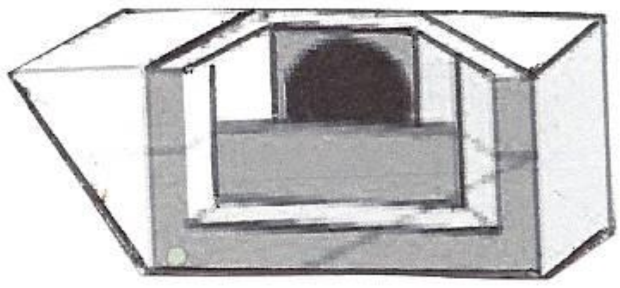

Figure 2.7: A schematic diagram of a precast concrete culvert fitted with one drop board (NSW Fisheries 2002)

The structure of floodgates selectively controlling tidal flow differs significantly with individual projects. In 2002, the NSW Department of Fisheries conducted a workshop on floodgate design and modification involving 17 papers describing modified floodgate design or varieties of commercially available floodgate designs (NSW Fisheries 2002). In 2009, a similar workshop based on designs of water control structures in coastal floodplains reviewed the use of 10 floodgate and 10 weir or culvert designs for tidally selectable structures (NSW Department of Industry and Investment [DI&I] 2009).

On the Shoalhaven floodplain in southern NSW, a network of five modified floodgates are designed to open and close at predetermined water levels. The entire water monitoring system equipment and the floodgate operating controls are networked to the local council premises by telemetry, enabling remote monitoring and floodgate control (University of New South Wales [UNSW], Water Research Laboratory 2013).

A tidal rehabilitation project on the East Trinity Wetland, near Cairns, in northern Queensland, incorporated automated opening floodgates, allowing lime-enriched tidal inflow onto acid sulfate affected areas (Powell & Martens 2005). A different use of lime was employed near Broughton Creek, a tributary of the Shoalhaven River in southern NSW. This project used the direct injection of a lime, fly ash and water slurry into boreholes in acid sulfate affected regions (Indraratna et al. 2006).

2.5 Fisheries Research

An integral part of this study is the changes in the behaviour of fish assemblages in the wetland as hydrological connectivity is reintroduced by tidal flushing and the aquatic environment improves. The quantitative and qualitative sampling of fish (and one prawn) species in a shallow tidal, coastal wetland with very restricted access and a fragile environment complicated the selection of sampling techniques (Jackson & Harvey 1997; Laegdsgaard & Johnson 1995; Rozas & Minello 1997).

2.5.1 Fish Sampling Methods

Some of the more commonly used methods to sample fish are:

1. Trawl nets, which are pulled through the water by one or more powered boats to engulf fish, are usually used for sampling performed on commercial operations (Merrett et al. 1991; Olin & Malinen 2003; Rozas & Minello 1997). This method is usually unsuitable for shallow wetlands because of access restrictions, the effects of the boat's propulsion system on the wetland environment, the nets' adverse effects on the substratum and benthic vegetation and risks of injury or mortality to the catch. Smaller sampling beam trawls (the net being held open by a small beam or frame) are used in shallow wetlands because they can be manually operated and their size has a much reduced effect on the environment (Sasekumar et al. 1992; Wennhage et al. 1997).

2. Seine nets, also referred to as beach seine nets, are commonly used for fish sampling. They are cheap, small engulfing nets, usually deployed from the shoreline in a U shape by two or more operators. They are best suited to a sloping, firm substratum and usually inflict little injury on the catch, which can be classified and released (Boys & Williams 2012; Clark et al. 1996; Gibbs et al.

1999; Gorman & Karr 1978; Guest et al. 2003; Kroon et al. 2004; Petrakis & Stergiou 1995; Pierce et al. 1989; Shepherd 1995).

3. Traps, which can mostly be grouped into three categories:

    a. Netting traps, which are large vertical fencing barriers, made from a variety of materials, designed to guide fish into a capture or holding region, are occasionally used for sampling (Butcher et al. 2005; Halliday & Young 1996; Shireman et al. 1981).

    b. Structural traps, which are smaller structured traps made from a large variety of materials, usually have one or more funnel entrances that discourage exit from the structure. Usually deployed vertically and anchored, they can be used in conjunction with baits, lights and refuge materials (Chick et al. 1992; Doherty 1987; He & Lodge 1990; Hickford & Scheil 1999; Jackson & Harvey 1997; Jacobsen & Kushlan 1987; Kushlan 1974; Meekan et al. 2001; Rozas & Minello 1997).

    c. Fyke nets are a small combination of traps (a) and (b) that usually have guiding fences leading to a long cylindrical capture region with metal or wooden hoops and multiple funnels. They are commonly used for wetland fish sampling (Arthington et al. 2005; Kuo et al. 1999; Mazumder 2004; Mazumder et al. 2005; Saintilan et al. 2008; Webb et al. 2011).

4. Gill nets are vertical entangling nets usually constructed from panels with a variety of mesh sizes to target different species. This technique is very species selective, and usually requires long periods of employment to achieve sufficient catch rates. This can lead to mortality or injury of the catch, which can include reptiles, birds or mammals (Jackson & Hardy 2011; Jensen 1990; Kurkilahti & Rask 1996; Moyle 1950; Regier & Robson 2011; Rudstam et al. 2011).

The techniques listed above for sampling are variations on traditional fishing techniques and are mostly economical and able to be performed by a single operator.

Many other fish sampling methods are available and some are technically sophisticated but require relatively more expensive equipment. Electrofishing is developing as an effective, non-fatal technique with low selectivity for species or size (Bain et al. 1985; Boys & Thoms 2006; Pajos & Weise 1994; Peterson et al. 2004; Rosenberger & Dunham 2005). High-frequency imaging sonars are also a relatively new technique, made possible by technological advancements, which can provide information on fish behaviour as well as sampling data (Moursund et al. 2003; Mueller et al. 2006; Rose et al. 2005). Baited Remote Underwater Video Stations (BRUVS), another recent technological development, are growing in popularity for gathering data for sampling and behaviour (Cappo et al. 2004; Stobart et al. 2007; Willis and Babcock 2000).

Many studies involving sampling to determine qualitative and quantitative abundances of fish assemblages employ more than one sampling method, which allows comparisons of sampling techniques. A study of sample shallow lake fish communities in New Zealand compared an aluminium mesh fencing trap net, small structural traps, gill nets, a beach seine net and a small purse seine net (Hayes 2013). Canadian studies compared a structural trap and a small sampling beam trawl net (Murkin et al. 1983), and seine nets, electrofishing and structural traps (Lapointe et al. 2006). Other sampling technique comparisons include night-time collecting with a lighted structural trap and daytime small beam trawl steered by a diver (Brogan 1994), fyke net and electrofishing (Ruetz et al. 2007), two types of structural traps and two types of fyke nets (Clavero et al. 2006) and beam trawls, fyke nets and fence trap nets (Butcher et al. 2005).

A comparison of the effects on fish and prawn communities of enclosing two mangrove swamp habitats was performed in 1991–1992. The two areas were the Hexham Swamp on the Hunter River, NSW, and the Yarrahapinni Wetland on the Macleay River, NSW—the focus area of this study. Fish and prawns were sampled by enclosing three regions near the shoreline with a 14-m net and poisoning these areas with rotenone, hauling a 10-m beach seine net from the shore and two 90-m gill nets, each with 9 x 10 m panels of different mesh size (Shepherd 1995).

The results of these studies clearly indicate that each sampling method has its specific advantages and disadvantages and they exhibit distinct selectivity of sampling technique and there are usually low correlations of sampling results between the varying techniques.

2.5.2 School Prawn (Metapenaeus Macleayi)

The school prawn, *Metapenaeus macleayi* (Haswell, 1879) (Crustacea: Penaeidae), is one of three species of penaeid prawns of recreational and commercial importance in NSW (Glaister 1978; Montgomery et al. 2010). School prawns spawn within inshore oceanic waters, move back into estuaries (particularly coastal wetlands) in the post-larval stage, mature for six to nine months and then migrate back to sea to spawn (Fig. 2.8) (Montgomery 2010*;* Ruello 1977).

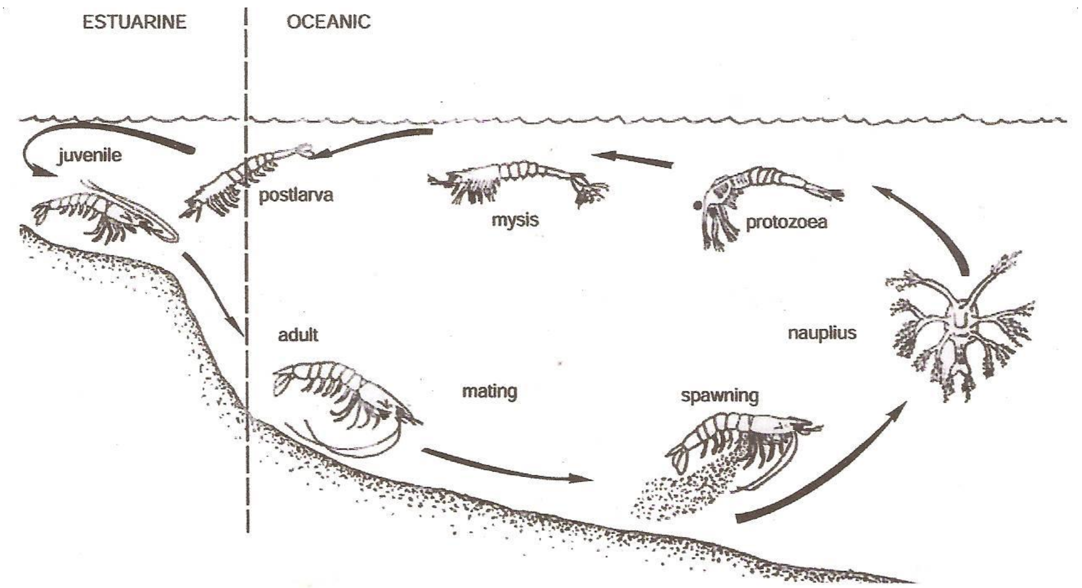

Figure 2.8: Life cycle of *Metapenaeus macleayi* (Montgomery 2010)

This migration cycle is dependent on the hydrological and geomorphological condition of the prawn target estuary, inshore ocean current patterns, diel period and moon phases. Post-larval school prawns rely on opportunistic ocean and tidal transport to enter the estuary to mature (Coles & Greenwood 1983; Glaister 1978). Adult prawns use the dark phase of the lunar cycle for protection from predators, during the ebb tide, to migrate back to sea (Coles 1979; Johnson 2008). When in the estuary, the school prawns bury in a suitable substratum until favourable tidal currents are present (Montgomery 2009; Ruello 1973).

This cycle is interrupted if heavy rainfall and flooding occurs in the estuary and the maturing prawns are flushed back to sea prematurely (Coles 1979; Glaister 1978).

The Yarrahapinni Wetland was a significant school prawn nursery area before being isolated from the Macleay River by flood mitigation structures in 1970 (Middleton et al. 1985), which eliminated this species from the area (Gibbs et al. 1999; Pressey & Middleton 1982). Monitoring of the reintroduction of tidal flow into the wetland has indicated that this wetland is returning to its prawn nursery status, which justifies a more extensive study of this resource (Boys et al. 2009; Kroon et al. 2004).

Previous studies of school prawns have used data derived from:

1. bycatch data of seine net sampling of fish assemblages (Boys et al. 2011; Gibbs et al. 1999; Kroon et al. 2004),
2. otto trawl nets operated from commercial or research vessels (Glaister 1978; Johnson 2008; Montgomery 2010*;* Ruello 1977),
3. small sampling beam trawl nets (Coles 1979; Coles & Greenwood 1983; McNeill & Bell 1992; Rotherham et al. 2008).

2.6 Conclusions

A review of the literature relevant to this study achieved the following conclusions:

1. Ecohydrology is a developing branch of scientific investigation that is ideally suited to comparing the effects of changes to the biotic and abiotic systems of aquatic environments.

2. Connectivity is the controlling theme in the understanding of the transfer of a physical entity from one state to a second by means of a controlling pathway.

3. Hydrological connectivity is the application of the general concept of connectivity to fluid systems and is a specific physical vector quantity able to be described quantitatively and qualitatively.

4. Anthropological changes to riverine systems have resulted in hydrological changes and fragmentation of many of these systems, frequently resulting in deterioration of the affected environments.

5. Wetlands form an interface between aquatic and terrestrial systems, and perform a unique function by contributing to the maintenance and health of both environments.

6. Approximately half of the total area of the world's wetlands has been lost in the past 100 years because of human effects.

7. Many of the coastal wetlands in eastern Australia have been severely degraded by hydrological modifications to mitigate the effects of coastal flooding. These changes have often resulted in the formation of acid sulfate soils and their detrimental consequences for that region's environment.

8. There has been a global increase in attempts to restore degraded wetlands, which employ varied combinations of remedial procedures, depending on local parameters.

9. The reintroduction of tidal flow, in various formats, has been found effective in the restoration of wetlands displaying acid sulfate soil degradation.

10. Studies of the literature on fish sampling methods indicated the most suitable techniques appropriate to the geomorphology and hydrology of the Yarrahapinni Wetland. Seine netting is most suitable for the downstream regions, which have firm, sandy, sloping foreshores, whereas fyke netting is more suitable for the upstream muddy, steep-banked, debris-covered creek regions. Sampling of the school prawn (*Metapenaeus macleayi*) was achieved from the bycatch of these two techniques.

CHAPTER 3

The Study Area and Its History

3.1 Introduction

This chapter describes the study area known as the Yarrahapinni Wetland, and its adjacent tributaries, situated on the Macleay River in northern NSW. A history of the flood mitigations on the Macleay River and their effects on the Yarrahapinni Wetland is also provided.

The changing administrative control of the wetland region is explained and the details of a tidal re-inundation program to achieve restoration of the environment are described.

3.2 Macleay Valley Catchment Area

The Macleay is a coastal river situated on the mid-north coast of NSW, Australia, in the vicinity of latitude 31 degrees south. Its catchment extends inland to the Great Dividing Range and includes the towns of Guyra and Walcha and the city of Armidale (Fig. 3.1). Its main tributaries are the Apsley, Chandler and Gara Rivers, which originate in the New England Tablelands.

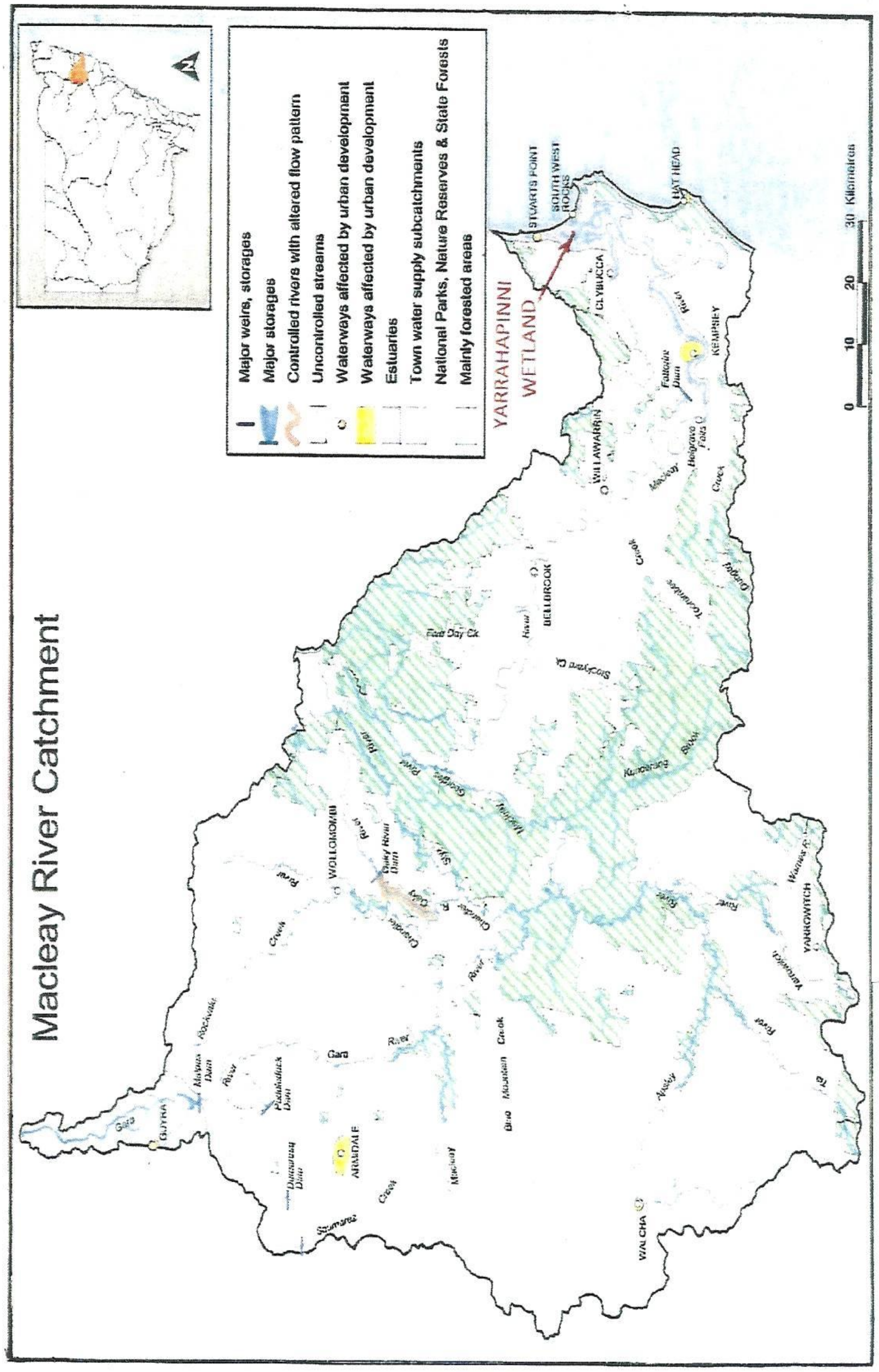

Figure 3.1: Macleay River catchment area (DECC 2009)

Figure 3.1: Macleay River catchment area (DECC 2009)

The topography of the river can be divided into three zones—upper valley, mid valley and lower region (Hurrell et al. 2009):

- The upper valley, part of the New England Tablelands, comprises approximately 40% of the total catchment area. Its elevation ranges from 900 m to 1200 m and is characterised by cleared grazing land.

- The mid valley region, 35% of the catchment area, descends through rugged gorge and steep hill terrain.

- The lower region, 25% of the catchment, comprises low hills and the coastal estuary floodplain. The majority of this region has been cleared for agriculture and grazing.

The climate within the catchment area varies between warm temperate to subtropical, and the coastal region is warmer and wetter than the tableland regions. A summary of annual rainfalls from the various regions, from the Australian Bureau of Meteorology (BOM) records, is:

- 820 mm per year in the upper valley,

- 1510 mm per year in the mid valley,

- 1260 mm per year in the lower valley.

The catchment mainly discharges through the river entrance, but varying small discharges occur through coastal creeks, depending on the rainfall distribution and tidal interaction. There is no predictable seasonable pattern for rainfall within the catchment, and the three regions have recorded highest monthly rainfall figures at different seasons (Hurrell et al. 2009).

3.3 Macleay Estuary—Geomorphology

The Macleay estuary extends approximately 54 km upstream from the ocean to the limit of tidal influence at Belgrave Falls, approximately 10 km upstream from Kempsey. The coastal floodplain has an area of approximately 400 km^2. Most of the river discharge occurs at a rock-walled river mouth, approximately 3 km northeast of South West Rocks (Fig. 3.2) (Tefler 2005).

Figure 3.2: Macleay River estuary (Kempsey Shire Council 2010)

Until 1893, the Macleay River entered the sea 3 km north of Stuarts Point. A major flood in that year breached the coastal sand barrier, thus forming a new entrance in its present position. The old estuary channel between South West Rocks and Stuarts Point is now referred to as the Macleay Arm and is now part of the extensive lower Macleay

River tributary network, which includes Clybucca Creek, Andersons Inlet and the Yarrahapinni Wetland—the focus of this study (Fig. 3.3) (Tefler 2005).

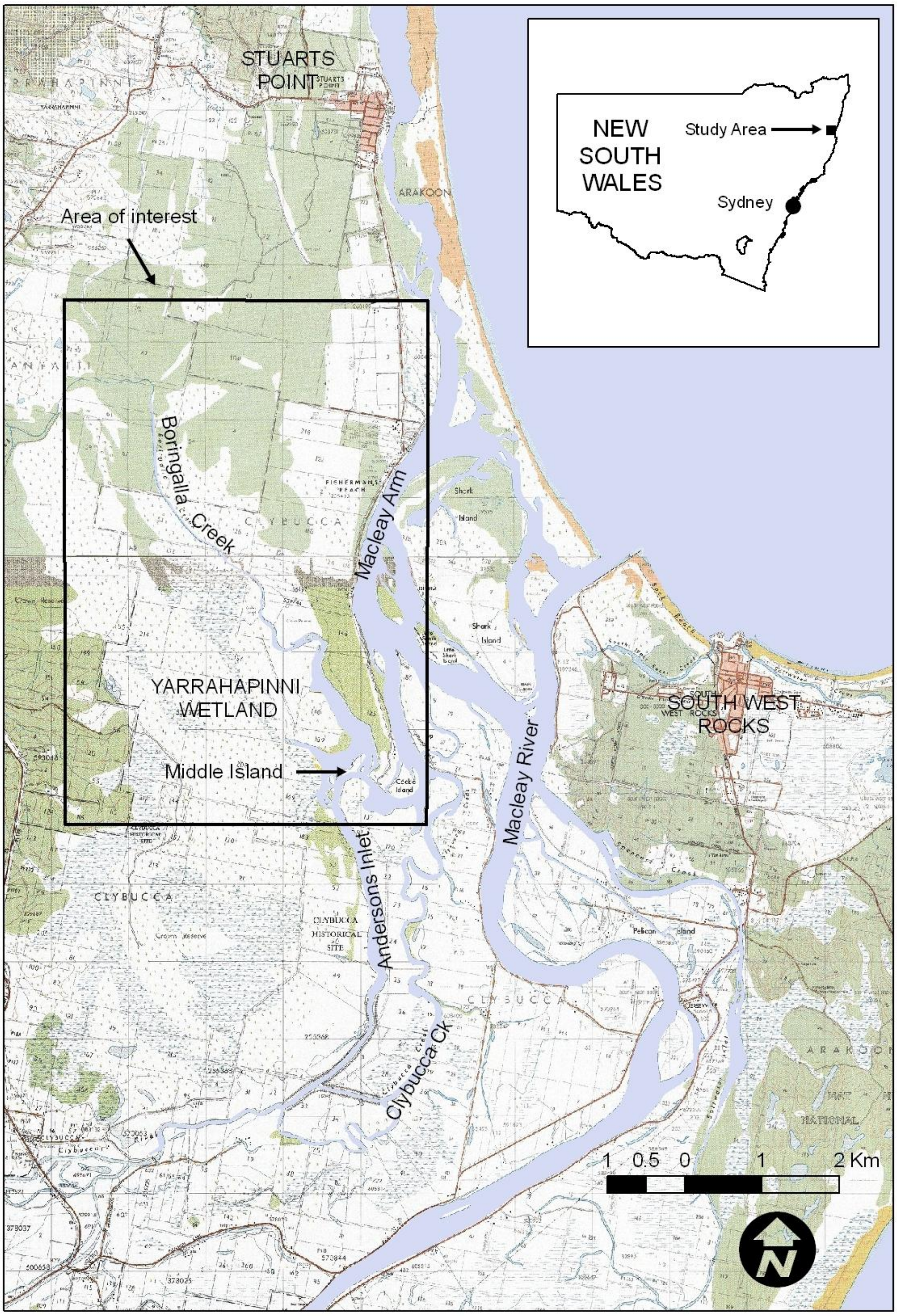

Figure 3.3: Lower Macleay River estuary network (NPWS,2011)

The alluvial morphology of NSW was significantly influenced by the rapid sea rise following the last glacial maximum, which occurred about 20,000 years ago. Sea levels rose from approximately 120 m below present levels, and 6500–7500 years ago, were about 1–2 m above them (Cohen 2005). These elevated levels inundated the pre-Holocene Macleay valley and caused the deposition of a transgressive sand sheet between the rocky headlands at Crescent Head, Hat Head and South West Rocks (Fig. 3.4). This sand sheet became the proto-barrier forming an open marine embayment. This barrier emerged to form a low-energy environment in the central mud basin, which allowed the deposition of estuarine muds and marine-influenced sediments, and eventually led to the formation of the deltaic plain, about 300 years ago (Cohen 2005).

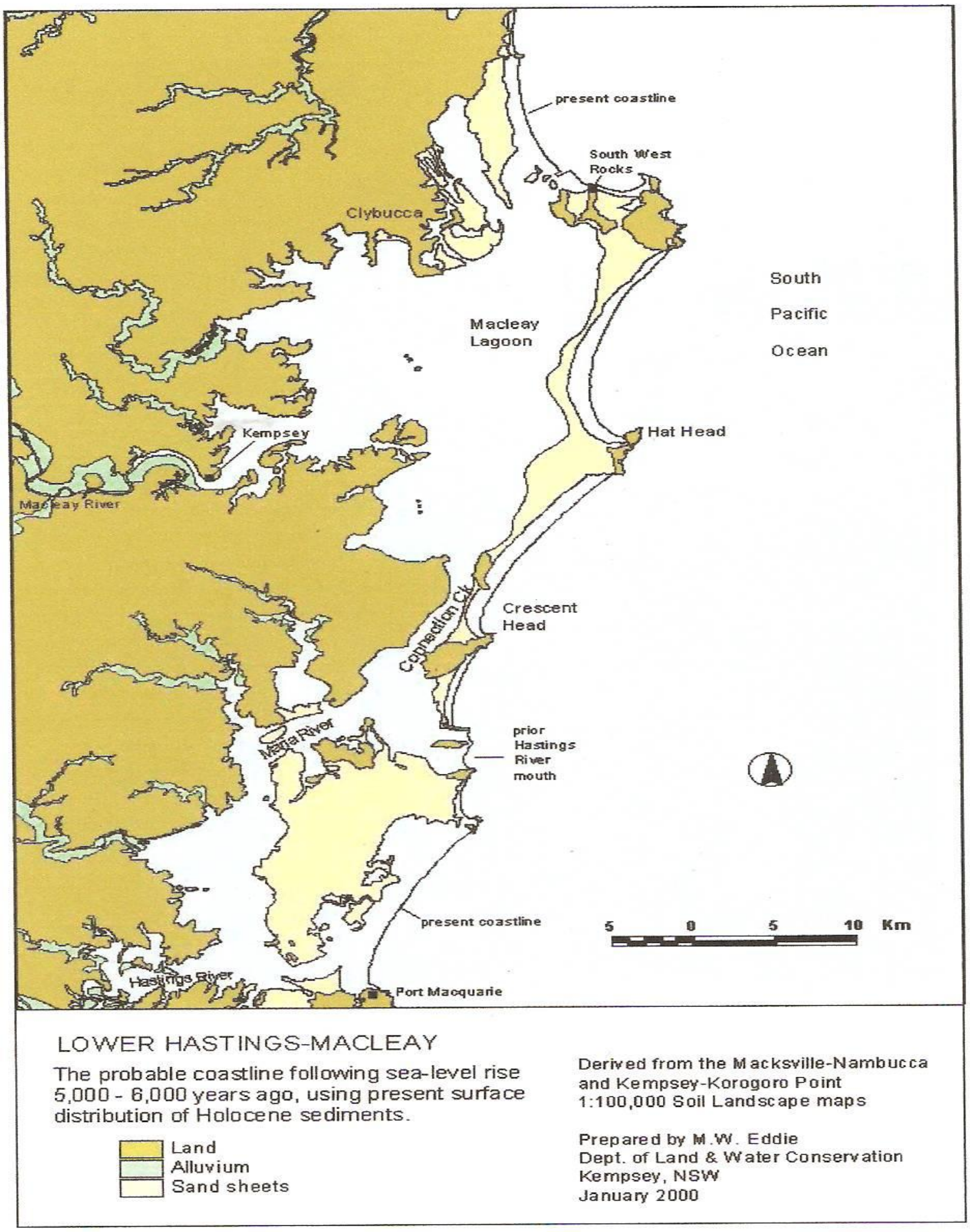

Figure 3.4: Schematic of the Macleay estuary in the mid-Holocene (from Cohen 2005)

This filled (delta) system can be divided into three broad process zones that reflect differing degrees of fluvial processes and tidal interactions (Hurrell et al. 2009):

- the fluvial process zone, extending from Belgrave Falls to approximately 19 km from the river mouth but also including upper Clybucca Creek (Fig. 3.3),
- the transition zone, between 19 and 8 km from the river mouth on the main river and most of Clybucca Creek (including Andersons Inlet, Fig. 3.3),
- the marine tidal zone, the remaining 8 km of the main river and the Macleay Arm.

The surface geology of the lower Macleay River region is shown in Figure 3.5.

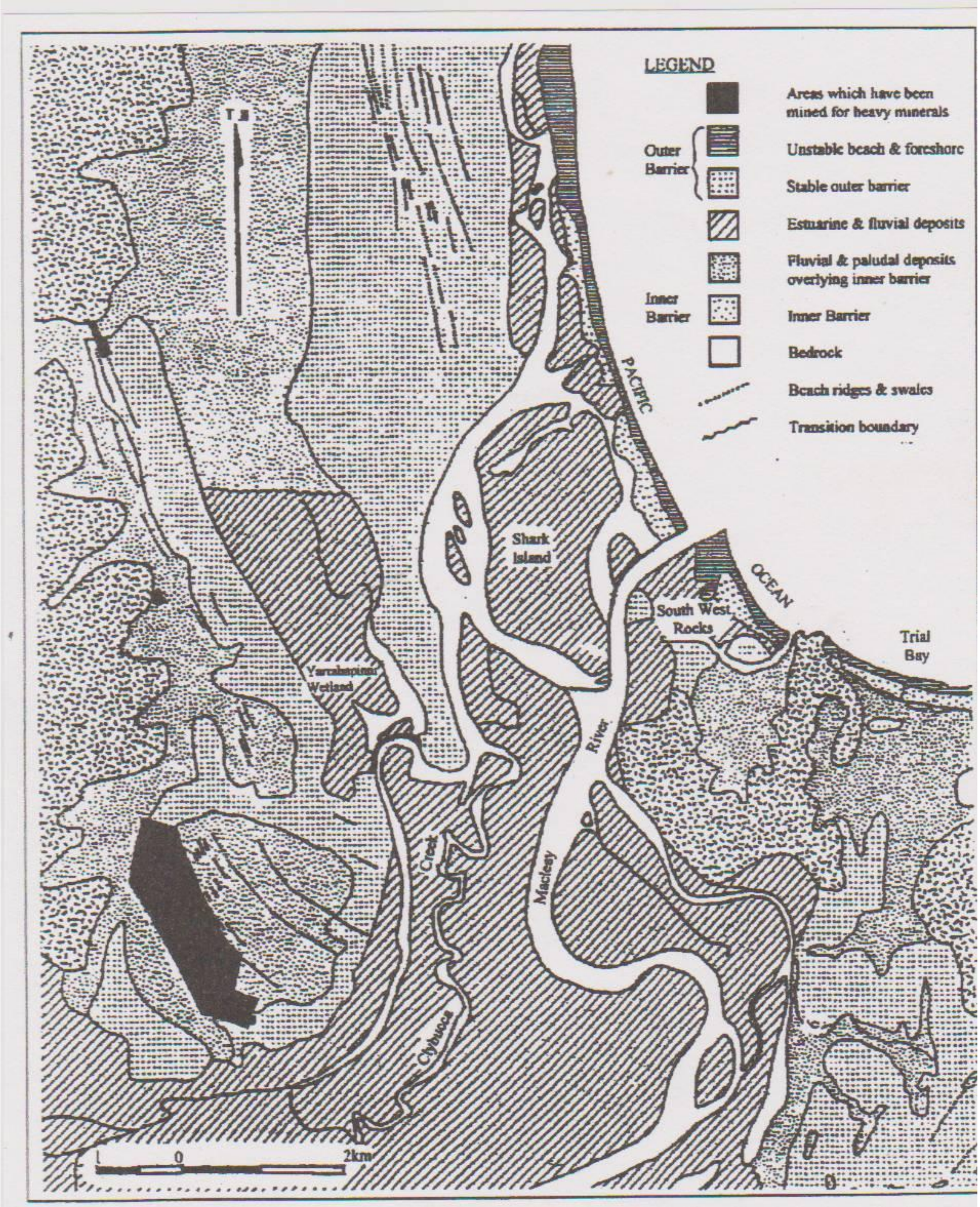

Figure 3.5: Surface geology of the lower Macleay River area (Shortland Wetlands Centre 1997 from Roy 1984)

3.4 Flood Mitigation on the Macleay River

The Macleay catchment mainly discharges through the river entrance, but varying small discharges occur through coastal creeks, depending on the rainfall distribution and tidal interaction. The size of the Macleay catchment area and the amount of annual rainfall mean that the river discharge readily exceeds the capacity of the relatively narrow river entrance, which leads to frequent flooding events in the lower estuary. The flood records for Kempsey (the largest town on the estuary) indicate the occurrence of 35 serious flood events that exceeded 5.5 m at the Kempsey Bridge recording station between 1833 and 1999. A flood exceeding this height causes significant losses to dwellings, infrastructure, agriculture and livestock, and sometimes loss of human life. The highest flood height recorded was 7.92 m in 1949, and the Kempsey Shire Council (KSC) estimates that annual exceedence probabilities for flood heights at Kempsey are:

- 1% for 8.2 m,
- 2% for 7.7 m,
- 5% for 7.5 m.

Serious floods can occur irregularly, and several severe floods can occur in a short period, such as occurred in 1863–1875, 1890–1893 and 1949–1950 (Webb et al. 1999).

Settlement on the Macleay floodplain commenced in 1835 and grew rapidly in spite of the threat of flooding and long-term inundation. With the enacting of the colonial Drainage Protection Act (1865), works commenced on the Macleay in 1870 to drain land adjacent to the river on the lower reaches. With government assistance, this drainage activity expanded rapidly across most of the Macleay floodplain for the next 80 years, usually under the control of local administrative bodies known as drainage unions. The primary aim of this activity was to drain wetlands to increase the area of agriculturally viable land (Tefler 2005).

In 1949, and again in 1950, the Macleay River suffered two of the largest floods on record, which caused significant damage across the whole floodplain and resulted in loss of lives. These two floods, and their consequences, triggered the formation of the Macleay Valley Flood Mitigation Committee (established by the NSW Government) whose aims were to conduct large-scale flood mitigation works to protect the township of Kempsey and the floodplain agricultural areas, and significantly expand drainage of the and erosion protection of the streams. A major program of this work commenced in 1954 and continued until the majority of the major construction projects were completed in 1976. There are now 181 floodgate structures, 352 floodgates, 34 km of levees, 147 km of major drains and 37 km of riverbank protection within the Macleay Shire. All of the major streams on the lower Macleay have had floodgates installed, including the Clybucca Creek–Andersons Inlet system and the Yarrahapinni Wetland (Webb et al. 1999).

3.5 Yarrahapinni Wetland

Prior to 1971, the Yarrahapinni Wetland was a 600-ha coastal wetland consisting of two parallel mangrove creeks (3 & 7 km long) and an open shallow area known as the 'Broadwater' that contained extensive salt marsh, seagrass beds and intertidal flats. The wetland connected to the Macleay estuary at a semi-circular bend in Andersons Inlet via four shallow channels between small mangrove islands, the largest of which is Middle Island (Fig. 3.3). This wetland was estimated to contain 20% of the area of mangroves of the Macleay estuary, and its plant community provided extensive habitat for numerous species of birds, fish and invertebrates. Evidence of the productivity of this wetland is that it is partially surrounded by some of the largest midden deposits in NSW (Nelson 2006; Shortland Wetlands Centre [SWC] 1999).

Between 1969 and 1971, significant flood mitigation works were carried out in the Yarrahapinni Wetland area. These works included closing the channels between the mangrove islands with approximately 800 m of earth and rock levee banks (Fig. 3.6). A small added channel was constructed east of Middle Island to accommodate a floodgate structure. This consisted of a 10-m long concrete culvert to which five steel, 2 x 1.5 m, top-hinged floodgates that allowed outflow but stopped inflow (Fig. 3.7 & 3.8). Extensive dredging was carried out in the upper reaches of the Yarrahapinni catchment to deepen and widen drains and form new channels, to improve the drainage of the area and increase the area of agricultural land available (Fig. 7) (SWC 2009; Tefler 2005). The exclusion of tidal inflow and the lowering of the water table by drainage resulted in severe deterioration of the wetland ecology, hydrology, geomorphology and chemistry (Pressey & Middleton 1982).

Figure 3.6: Levy bank in the vicinity of Middle Island (NPWS 2009)

Figure 3.7: Floodgate structure (NPWS 2009)

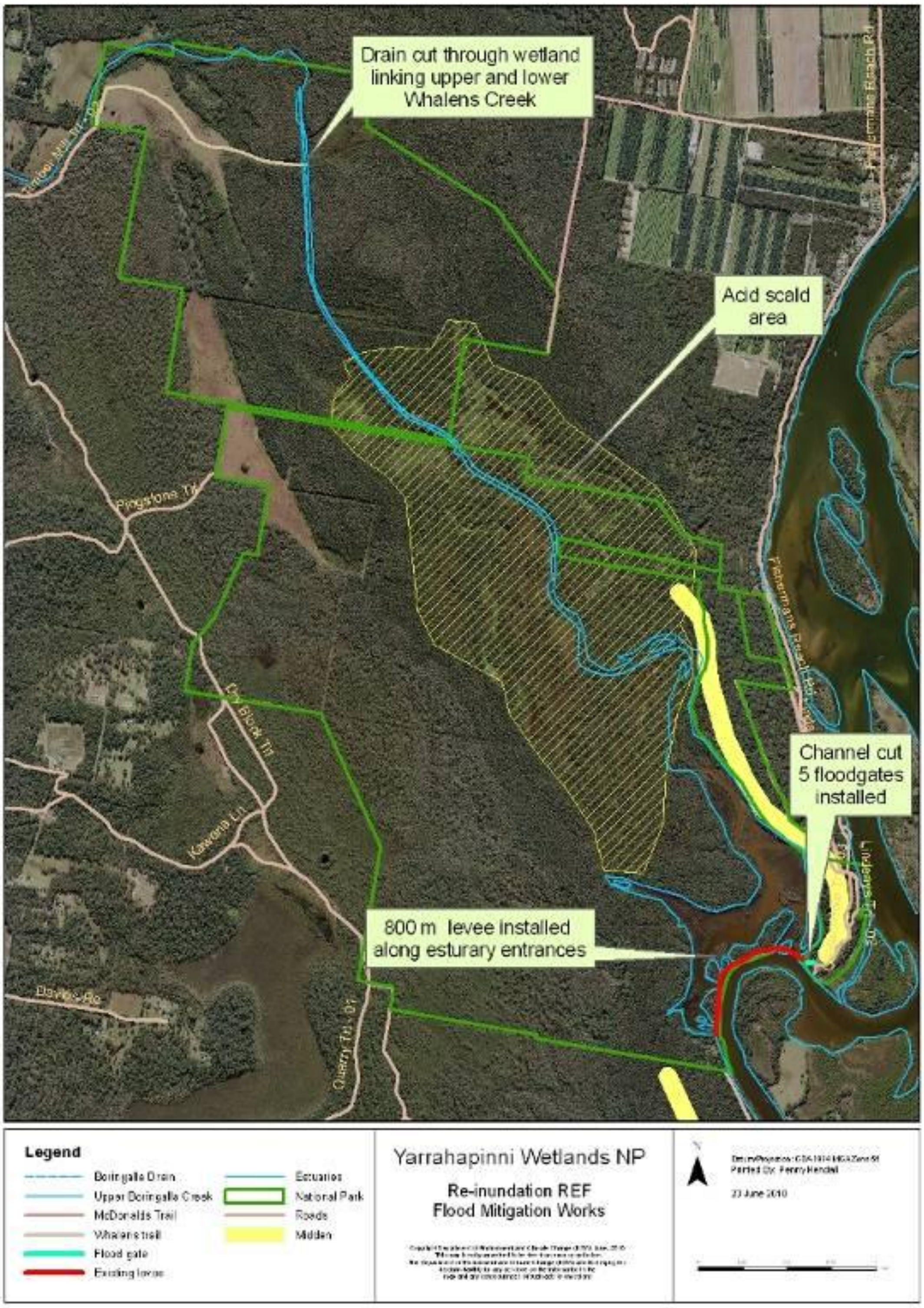

Figure 3.8: Major flood mitigation structures, Yarrahapinni Wetland (NPWS,2010)

Soils within the Yarrahapinni region consist mainly of marine quartzose sand sediments and fluvial sediments of immature lithic gravels, sand and mud. Within the wetland, there are extensive regions that were poorly drained hydric soils overlaying clayey sands, which sampling by the NSW Government Acid Sulfate Soil Risk Mapping Program found contained oxidised sediments within 10–40 cm of the soil surface, resulting in 714 ha being declared high risk (Schmidt 1992; Tulau & Naylor 1999). Formation of these acid sulfate soils resulted in acidic discharges during flooding, mortality of aquatic fauna, discharges containing high levels of aluminium and iron ions, and the formation of MBO sediments within the waterways. In addition, lowering of the water pH caused denuding of existing vegetation and thus formation of extensive areas of acid sulfate 'scalds' (Fig. 3.9 & 3.12) (Sammut et al. 1966).

Figure 3.9: Acid sulfate scald area in the Yarrahapinni Wetland (NPWS,2009)

Loss of tidal inflow and lowering of the water table by drainage also caused extensive siltation within the wetland and reduced the waterway area to less than 20% of its original area (Fig. 3.10). In addition, the vegetation within the wetland completely changed: the mangrove and salt marsh areas were drastically reduced and replaced by species such as *Casuarina glauca* (swamp oak) (Fig. 3.10, 3.11 & 3.12).

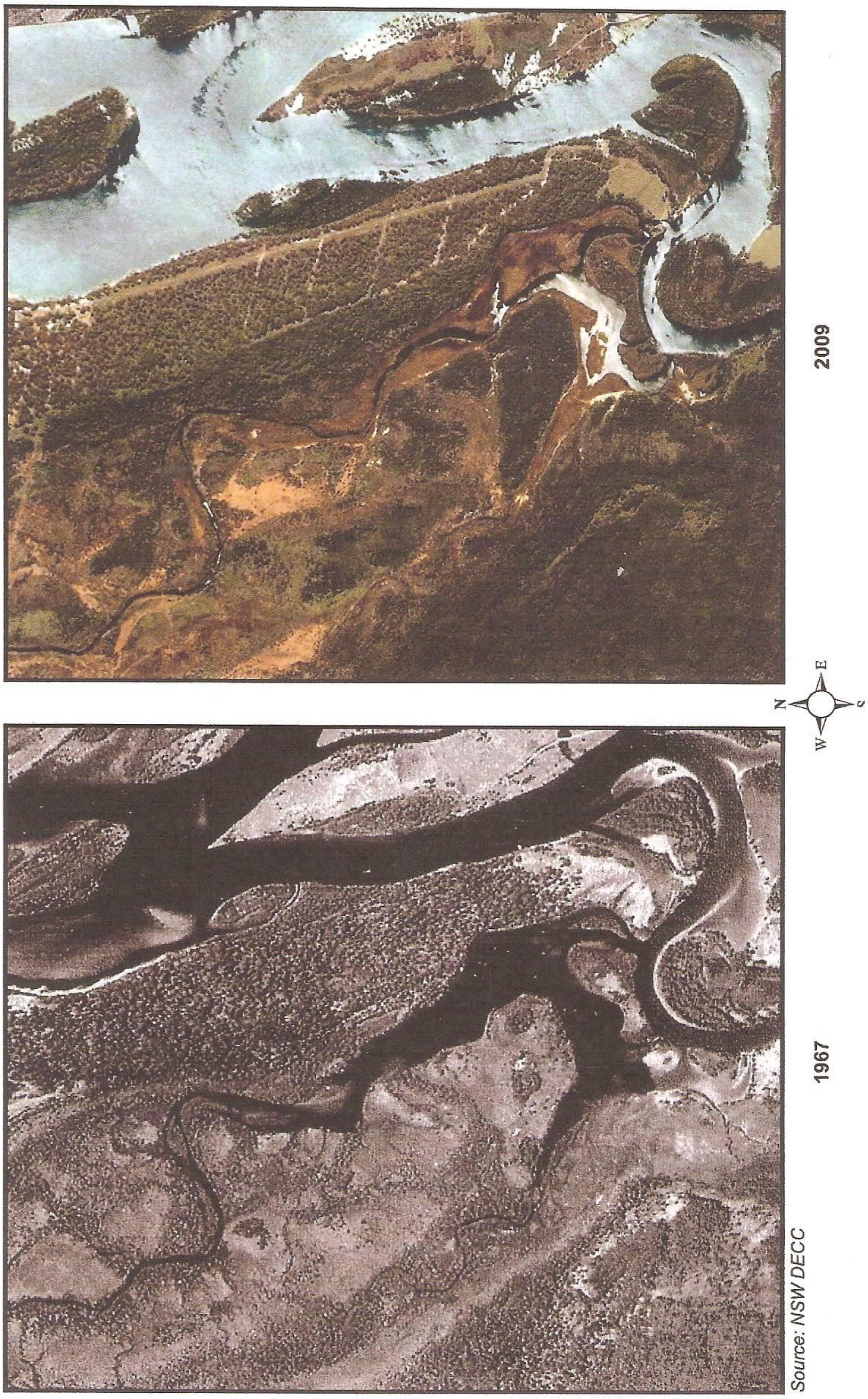

Figure 3.10: Aerial photographs of the wetland before and after enclosure

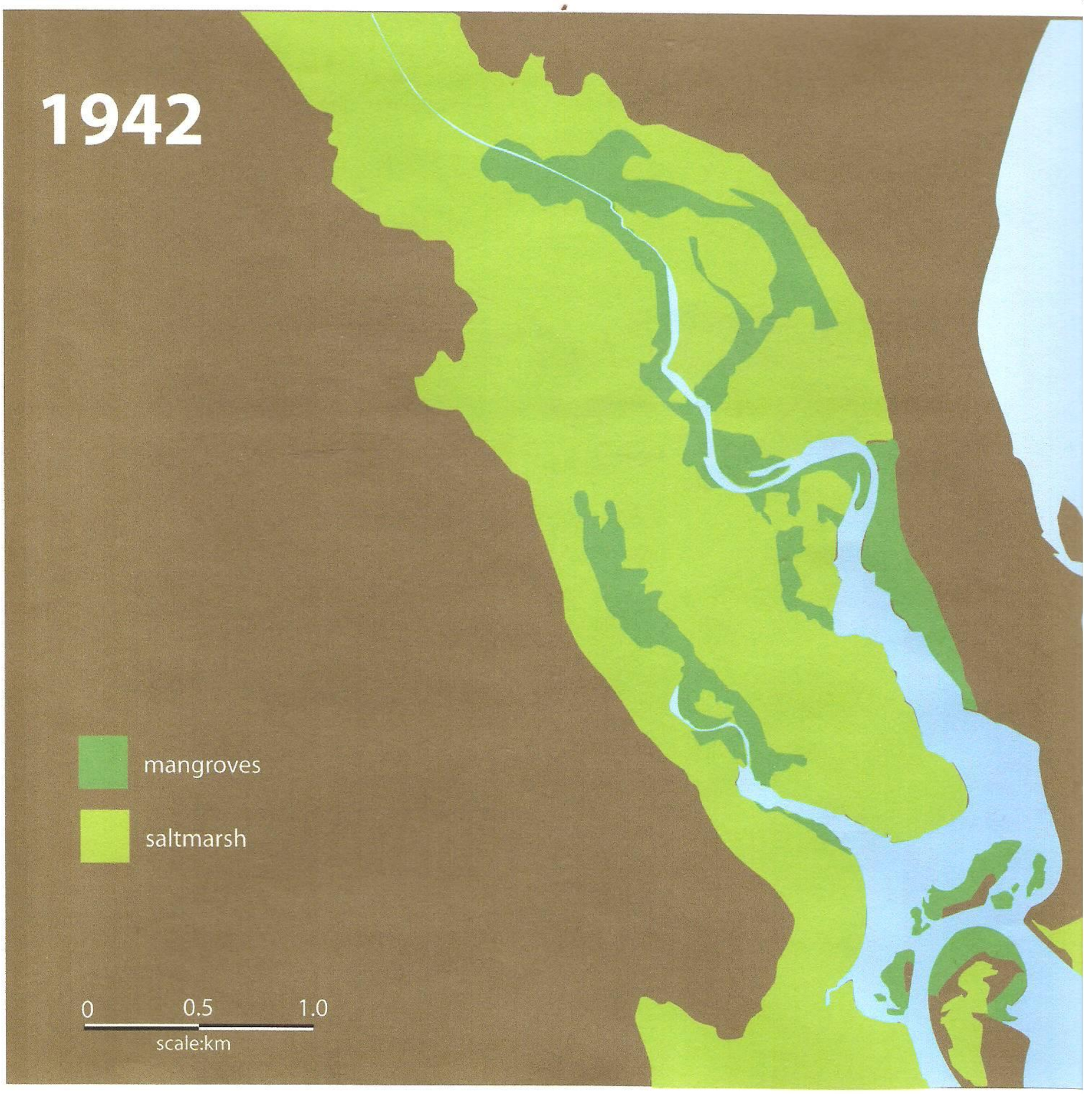

Figure 3.11: Vegetation and water area of Yarrahapinni Wetland prior to 1969 (NPWS 2009)

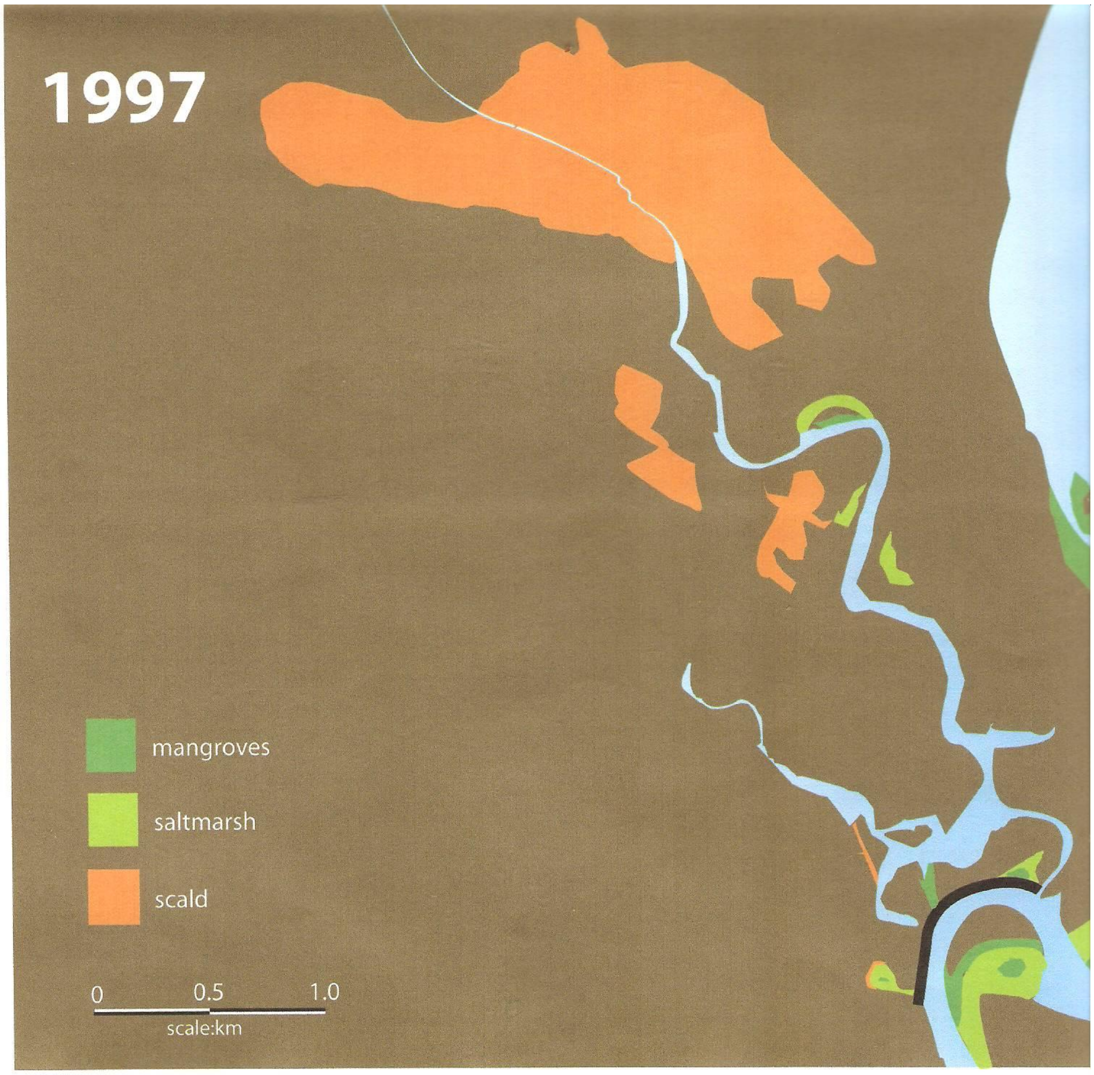

Figure 3.12: Altered Yarrahapinni Wetland (NPWS 2009)

Maintenance dredging of Borirgalla[1] Creek (Fig. 3.3) played a very significant role in the hydrological history of the wetland, so it is described in some detail as paraphrased interviews, conducted in 2010 and 2011, with the KSC staff who performed the dredging from 1983 to 1996.

> The Yarrahapinni Wetland was dredged every 12 to 18 months depending on the availability of machinery and requests from involved landowners. The excavator would enter the wetland from the north from the Pacific Highway or

[1] Also spelt Boringalla by some sources.

> from the south through private property. It would move along the western bank of Borirgalla Creek taking transverse 10-m scoops, with a 1-m wide bucket of vegetation and silt, which were placed in mounds along the bank. Sometimes the excavator had to work in very swampy conditions and used swamp mats made from pine logs and chains. Where possible the excavator could use the growing silt mounds as a firmer base. (pers. comm.)

The silt mounds are still evident as rows of yellow points on the western bank in a 2009 Light Detection and Ranging (LIDAR) image of the elevations and minor drainage (Fig. 3.13).

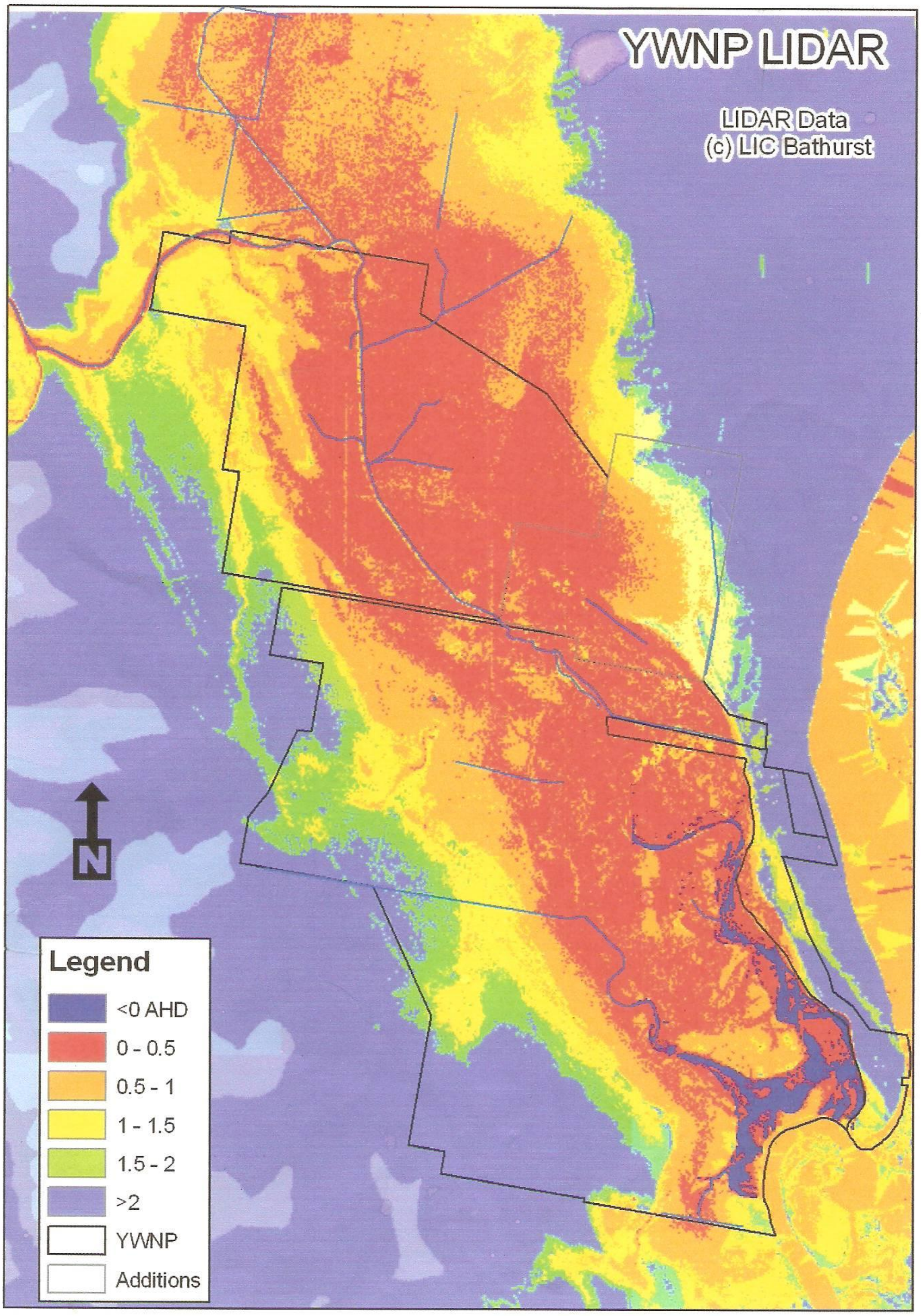

Figure 3.13: 2009 LIDAR image of elevations and minor drainage of the wetland (NPWS)

3.5.1 Phragmites australis

Once routine dredging ceased in Borirgalla Creek, the common reed *(Phragmites australis)* was able to propagate unchecked by first lining the bank regions and then spreading across the channel sections. By 2007, this creek was almost blocked at seven locations between 1 and 4 km from the floodgates (Fig. 3.14 & 3.15) to the beginning of a 500-m long total blockage (Fig. 3.15 & 3.16).

These reed beds fragmented the hydrology of the creek; the small amount of salinity entered the lower wetland by leakage of the floodgates and levees and levee overtopping during very high tides, but did not penetrate far beyond the first partial blockage. The total blockage completely isolates the upper region from any salinity inflow and the only hydrological connectivity is by floodwaters bypassing the reed bed and moving over the bank tops. Since the reintroduction of increasing amounts of tidal flow resulting from the tidal re-inundation program, the higher salinity has been progressively reducing and eliminating all of the partial reed beds by further reduction of the from the Borirgalla Creek channels restricting it to the bank regions.

Figure 3.14: Partial blockage by common reed *(Phragmites australis)*

Figure 3.15: Start of total blockage of *Phragmites australis*

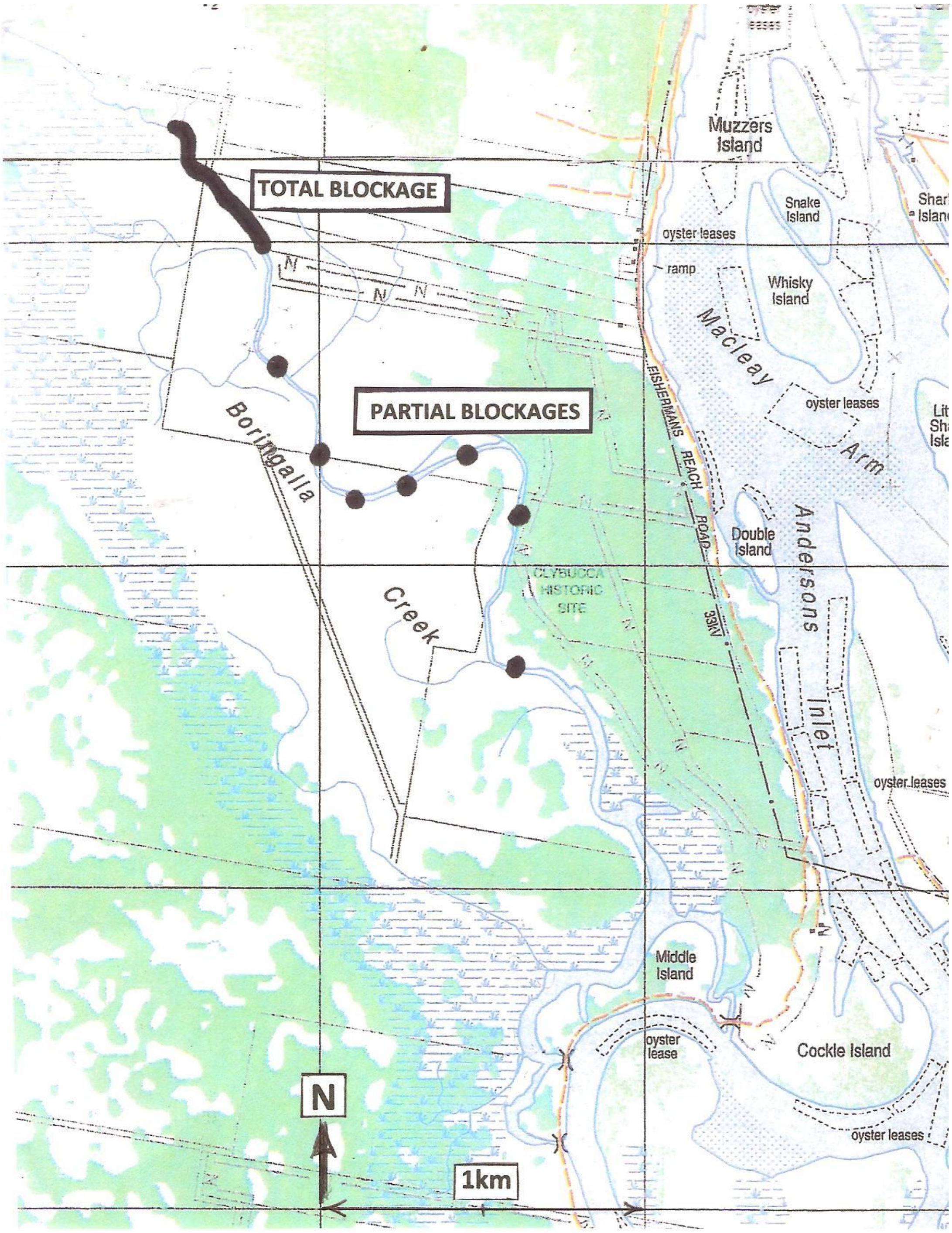

Figure 3.16: 2007 positions of *Phragmites australis* blockages (modified from LPI 2002)

3.5.2 Wetland Administration

Prior to 1991, all of the Yarrahapinni Wetland was crown land zoned Rural 1(a) under the Kempsey Local Environment Plan (1987), and much of the wetland was designated as Wetland No. 409 under the NSW State Environmental Planning Policy No. 14 (SEPP 14) to protect coastal wetlands. In response to public debate, the NSW Fisheries initiated a rehabilitation proposal to reintroduce tidal flow into this freshwater, degraded wetland, and in 1994, the Shortland Wetlands Centre (SWC) received funding to undertake a three-year research study to assess the effects of the rehabilitation. In 1996, the Yarrahapinni Wetlands Reserve Trust was formed to manage the proposed rehabilitation on behalf of the government (Nelson 2006, SWC 1999).

During this period, the NPWS of NSW expressed an interest in the rehabilitation of the Yarrahapinni Wetland and began purchasing agricultural land that would be affected by the reintroduction of rehabilitative salinity. In March 2007, the area was gazetted as the Yarrahapinni Wetlands National Park with the management of the park under the control of the NSW Department of Environment and Climate Change (DECC) with the assistance of the Yarrahapinni Wetlands Working Group. The NPWS initiated a program of incremental reintroduction of rehabilitative tidal flow by manipulation of the floodgate structure, which commenced in December 2007 and is still in progress.

Significant dates in this rehabilitation program are:

- 4 December 2007—Two of the five floodgates were replaced by gates fitted with an Armon float controlled gate that can be adjusted to close a 50 cm x 80 cm opening predetermined higher tide levels (Fig. 3.17).
- 1 July 2008—The Armon float apparatus was removed, leaving three gates fully closed and two closed with 50 cm x 80 cm openings.
- 5 February 2010—One floodgate with a small opening was totally opened.
- 9 August 2011—Two more full floodgates were opened.

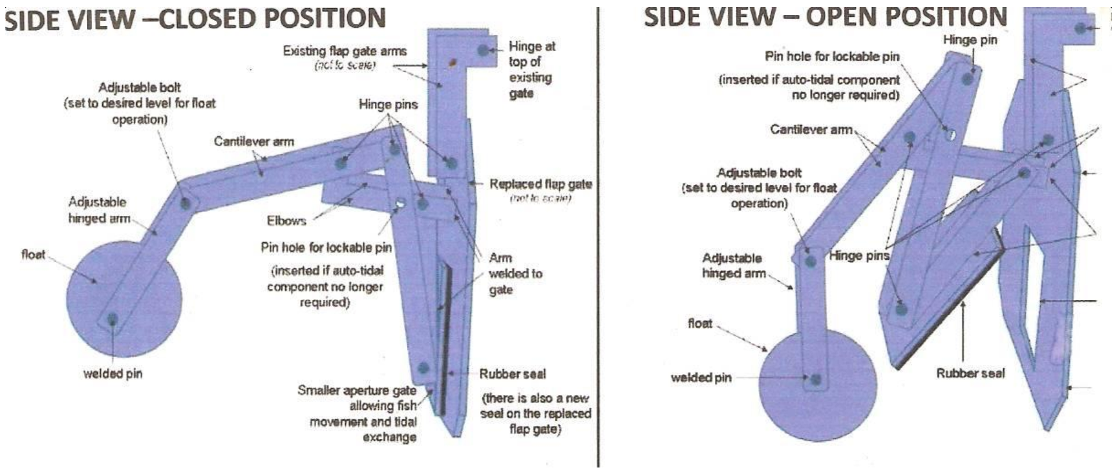

Figure 3.17: Schematic views of an Armon float controlled floodgate opening (NSW Department of Industry and Investment)

The rehabilitation plan proposed to eventually open all of the floodgates and remove an approximately 50-m section of the enclosing levee bank, probably towards the western end of the broad water area, where the major entrance was before flood mitigation.

3.6 Andersons Inlet

Andersons Inlet is the Macleay estuary tributary adjacent to the Yarrahapinni Wetland and the source of estuarine inflow to this wetland. Prior to 1966, it was a 4-km long terminating tributary of the Clybucca Creek system, a 16-km long estuary that discharged the catchment from the Clybucca wetland (also known as the Collombatti–Clybucca wetland) (Fig. 3.18). This system discharges flow into the Macleay Arm, which until 1893 was the original outflow for the Macleay River. The Macleay Arm now discharges into the Macleay River through an approximately 120-m wide channel, approximately 2 km from the new Macleay River entrance (Fig. 3.3) (Tulau & Naylor 1999).

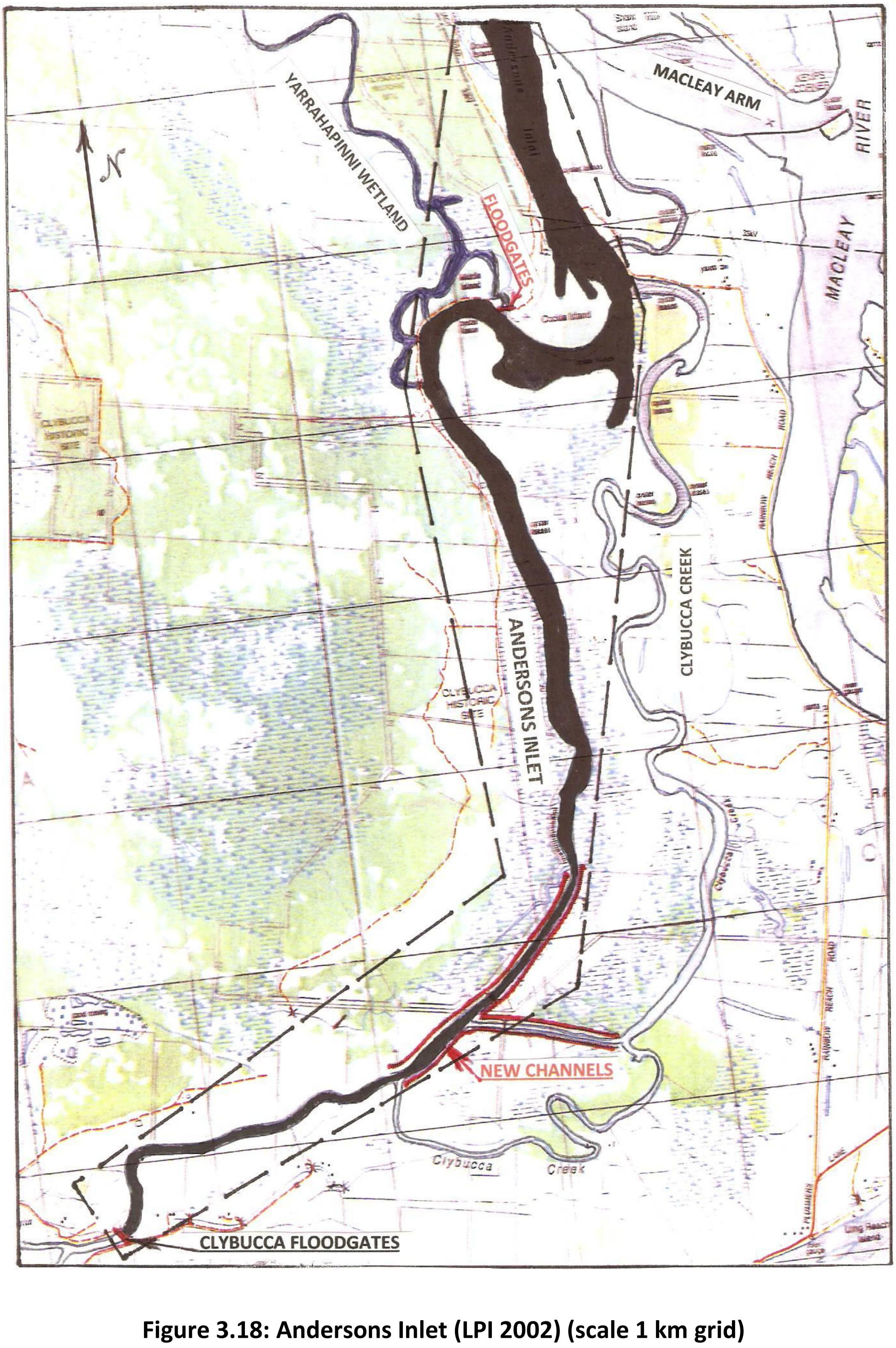

Figure 3.18: Andersons Inlet (LPI 2002) (scale 1 km grid)

Between 1966 and 1970, Andersons Inlet was modified by a series of flood mitigation works. These works included the construction of a floodgate culvert at Clybucca Creek and approximately 3 km of channel that extended it to rejoin Clybucca Creek at two new locations, thus providing a wider and more direct path for flood discharge from the above wetland so that Andersons Inlet has now become the main estuary (Tefler 2005). This study uses the naming system adopted by the NSW Department of Information Technology and Management (Land and Property Information [LPI] 2002), whereby Andersons Inlet is now the 10-km section extending from the Clybucca floodgates to the Macleay Arm and Clybucca Creek is the bifurcated sections to the east (Fig. 3.18).

In 2003, the Manly Hydraulics Laboratory (MHL) performed tidal data collection for the Macleay River. The data indicated that, for a typical flood tide, a total tidal prism for the Macleay River entrance was 16.65 $m^3 \times 10^6$. Approximately 43% of this entered the Macleay Arm, 14% entered the Andersons–Clybucca system and 11% reached the outside of the Yarrahapinni floodgates (MHL 2003). The tidal plane for Andersons Inlet outside the Yarrahapinni floodgates is shown in Figure 3.19, indicating a small tidal amplification between the South West Rocks site on the main river and the Yarrahapinni site.

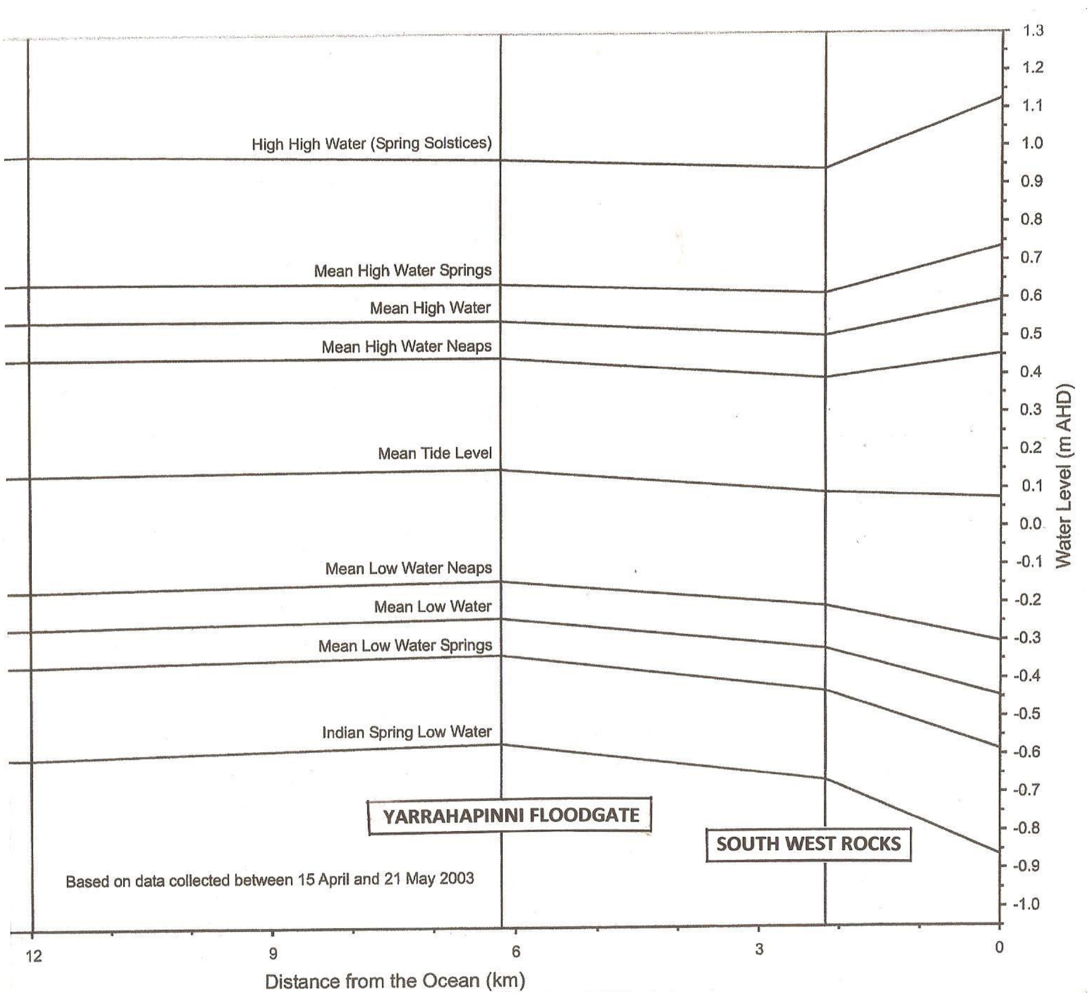

Figure 3.19: Tidal plane comparisons for the ocean, South West Rocks and outside the Yarrahapinni floodgates in Andersons Inlet (MHL 2004)

3.7 Rainfall

The rainfall runoff in the region affects both the internal hydrology of the Yarrahapinni and its external hydrology in Andersons Inlet, the source of its tidal flow. Being a fairly remote and low-population region, no single rainfall recording station is ideally positioned to monitor both systems. The catchment area for the Yarrahapinni Wetland is shown in Figure 3.20.

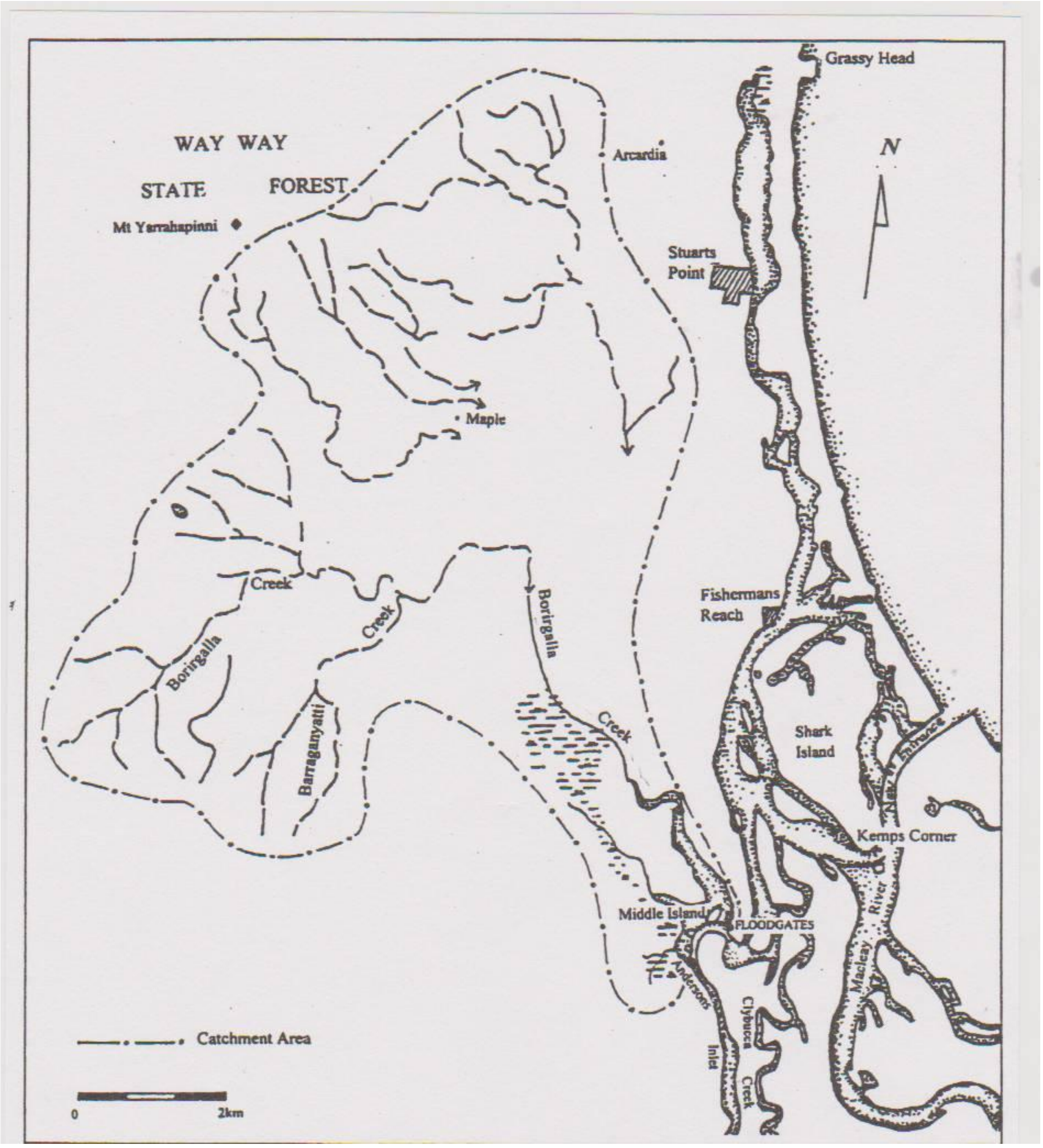

Figure 3.20: Map of the Yarrahapinni Wetland catchment (SWC, 1997)

Rainfall data for the study region are obtained from the three nearest BOM weather recording stations. Collombatti (Benbullen) station (No. 59068) is on the western edge of the Clybucca wetland catchment and is the best indicator for Andersons Inlet estuary (Fig. 3.20). Eungai Creek (Southbank Road) station (No 59075) is on the western edge of the Yarrahapinni Wetland catchment, and Fishermans Reach station (No 59143) is on the eastern edge.

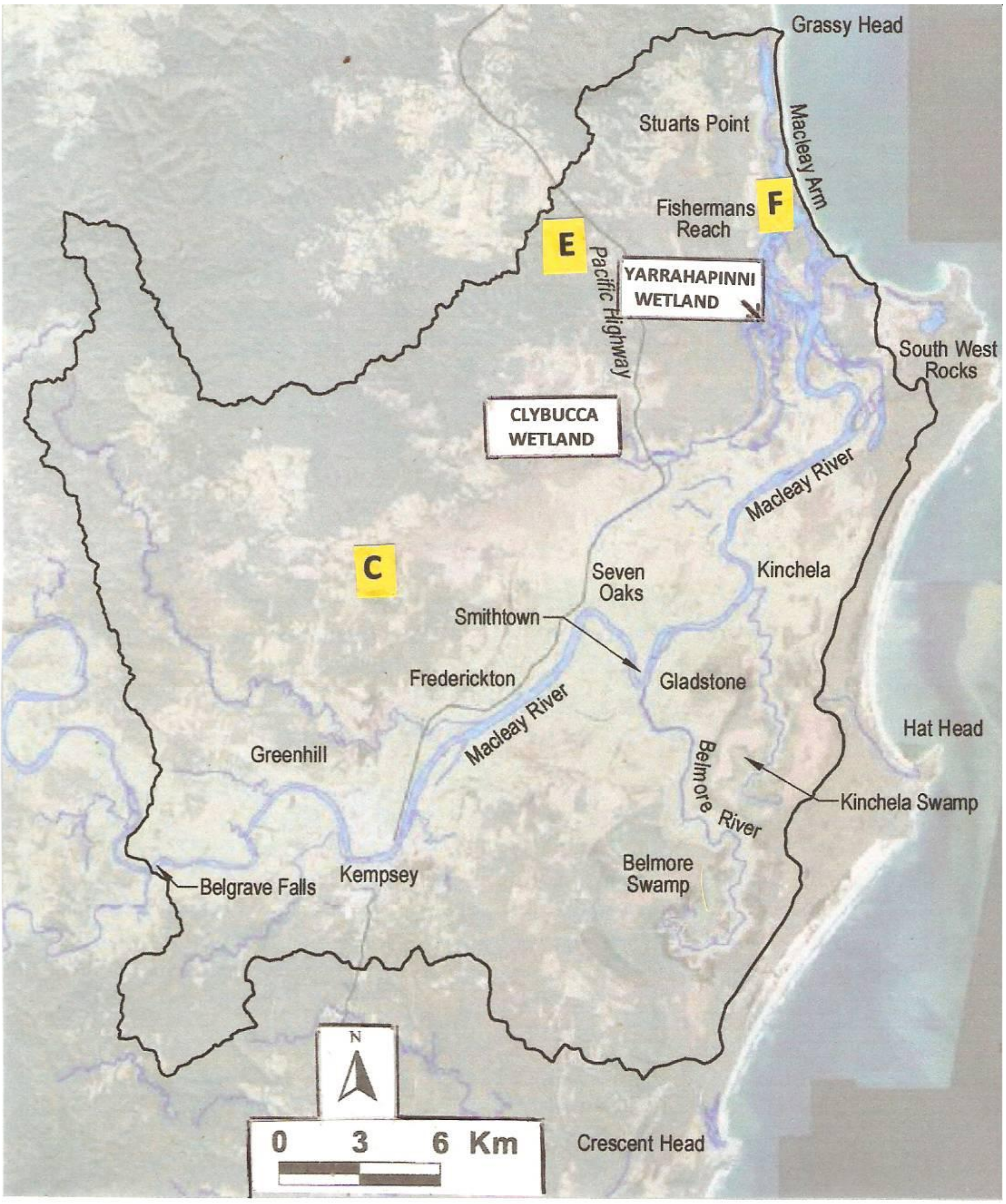

Figure 3.21: Locations of Bureau of Meteorology stations (KSC 2010) (C) Collombatti, (E) Eungai, (F) Fishermans Reach

The rainfall figures for all three stations for 2009 to 2011 are shown in Figure 3.22.

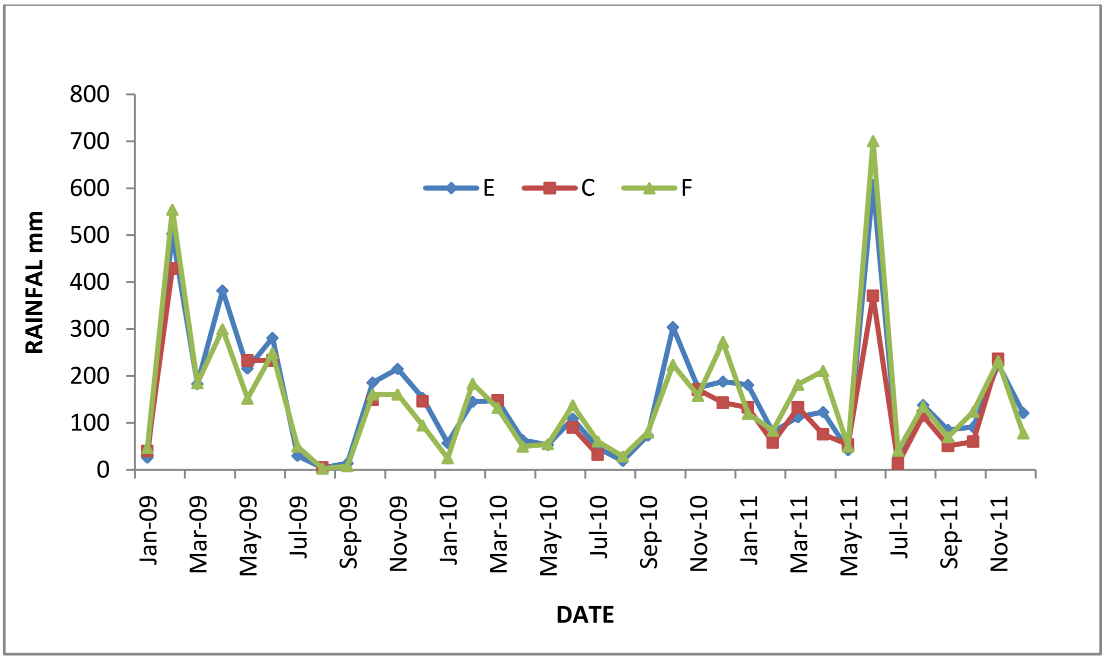

Figure 3.22: Rainfall figures for 2009–2011 for Collombatti (C), Eungai (E) and Fishermans Reach (F)

The recording station at Fishermans Reach was only in operation from January 2009 to December 2011 and, being adjacent to the ocean, was subject to coastal storms that did not affect most of the study region. The station at Eungai was considered a better indicator of consequences of rainfall on the Yarrahapinni Wetland system.

3.8 Summary

Yarrahapinni Wetland was a 600-ha, productive, mangrove–salt marsh coastal wetland, which adjoined Andersons Inlet, a tributary of the Macleay River on the north coast of NSW. In 1970, this wetland was severely altered, as part of the flood mitigation program, by enclosing it to stop tidal inflow, dredging to widen and deepen the main waterway, Borirgalla Creek, and the installation of a one-way floodgate structure. These changes resulted in the deterioration of the wetland by radically changing the hydrology, chemistry, geomorphology and ecology of the waterways and land areas.

The NSW NWPS commenced a wetland restoration program by purchasing many of the properties involved, having the region gazetted as a national park in 2007 and undertaking a trial to restore tidal flow by incremental changes to the opening of the floodgate structure.