"The Effects of Catchment Land Cover Change on Sedimentation in Back Lake, Merimbula, NSW."

Alison Borrell
University of Wollongong

Follow this and additional works at: https://ro.uow.edu.au/thsci

Recommended Citation
Borrell, Alison, "The Effects of Catchment Land Cover Change on Sedimentation in Back Lake, Merimbula, NSW.", Bachelor of Environmental Science (Honours), School of Earth & Environmental Science, University of Wollongong, 2013.
https://ro.uow.edu.au/thsci/71

Research Online is the open access institutional repository for the University of Wollongong. For further information contact the UOW Library: research-pubs@uow.edu.au
“The Effects of Catchment Land Cover Change on Sedimentation in Back Lake, Merimbula, NSW.”

Abstract

Mapping of the catchment was undertaken to determine the extent and distribution of land cover changes. It was found that expansion of the existing development on the floodplains of Merimbula Creek occurred in the 1970s. Further development requiring the clearance of vegetation on the northern margin of Back Lake has occurred from 1999 to present. A rapid decrease in vegetation occurred between 1972 and 1975, causing an 11% reduction in forested area. Mapping highlighted the widespread clearance that occurred as a result of development and the impacts of this were examined with cores extracted from Back Lake. The cores retrieved demonstrated that there has been a significant change in the sediment supplied to Berrambool Creek. Clay horizons in the most recent stratigraphic record were present throughout the creek in thicknesses varying from 14.5cm to 23cm. The clay layers were not identified elsewhere in the estuary, suggesting that the cause of the sedimentation occurred locally. It was concluded that the likely cause of the clay deposits was the removal of native vegetation from the adjacent land causing increased surface runoff and soil erosion enhanced by rainfall events.

Predictive modelling using a Coastal Eutrophication Risk Assessment Tool (CERAT) estimated that the loss of sediment into the lake through surface runoff and Total Dissolved Solids (TSS) is exacerbated through the clearance of vegetation. TSS volume increased by 282% using estimated future clearance conditions. Limited change was seen with the conversion of forest to urban area. This study concluded that there is a need for effective management of sediments within development sites. The monitoring of lake conditions can provide data that can be used to assess the effectiveness of sediment management practices. Additionally, monitoring data can provide a baseline to assess anthropogenic impacts, which may assist in effective ecological management of the estuary.

Degree Type
Thesis

Degree Name
Bachelor of Environmental Science (Honours)

Department
School of Earth & Environmental Science

Advisor(s)
Colin Woodroffe

Keywords
Estuary, sedimentation, estuary management

This thesis is available at Research Online: https://ro.uow.edu.au/thsci/71
“The Effects of Catchment Land Cover Change on Sedimentation in Back Lake, Merimbula, NSW.”

By
Alison Borrell

This thesis is presented as part of the requirements for the award of the Degree of Bachelors of Environmental Science (Honours) of the University of Wollongong.

October 2013
The information in this thesis is entirely the result of investigations conducted by the author, unless otherwise acknowledged, and has not been submitted in part, or otherwise for any other degree or qualification.

Alison Borrell

Cover photo supplied by Bega Valley Shire Council.
Abstract

Back Lake is a small estuary classed as an ICOLL (Intermittently Open and Closed Lake/Lagoon) on the south coast of NSW, Australia. Over the last 70 years, the continued expansion of the urban environment in Merimbula has occurred on the foreshores of Back Lake causing significant changes in land cover, and thus estuarine processes.

Mapping of the catchment was undertaken to determine the extent and distribution of land cover changes. It was found that expansion of the existing development on the floodplains of Merimbula Creek occurred in the 1970s. Further development requiring the clearance of vegetation on the northern margin of Back Lake has occurred from 1999 to present. A rapid decrease in vegetation occurred between 1972 and 1975, causing an 11% reduction in forested area. Mapping highlighted the widespread clearance that occurred as a result of development and the impacts of this were examined with cores extracted from Back Lake. The cores retrieved demonstrated that there has been a significant change in the sediment supplied to Berrambool Creek. Clay horizons in the most recent stratigraphic record were present throughout the creek in thicknesses varying from 14.5cm to 23cm. The clay layers were not identified elsewhere in the estuary, suggesting that the cause of the sedimentation occurred locally. It was concluded that the likely cause of the clay deposits was the removal of native vegetation from the adjacent land causing increased surface runoff and soil erosion enhanced by rainfall events.

Predictive modelling using a Coastal Eutrophication Risk Assessment Tool (CERAT) estimated that the loss of sediment into the lake through surface runoff and Total Dissolved Solids (TSS) is exacerbated through the clearance of vegetation. TSS volume increased by 282% using estimated future clearance conditions. Limited change was seen with the conversion of forest to urban area. This study concluded that there is a need for effective management of sediments within development sites. The monitoring of lake conditions can provide data that can be used to assess the effectiveness of sediment management practices. Additionally, monitoring data can provide a baseline to assess anthropogenic impacts, which may assist in effective ecological management of the estuary.
Acknowledgements

Firstly, I’d like to extend my thanks to my supervisors, Colin and Sam for all the assistance and time they provided me this year. You were both always quick to return anything back to me with valuable comments that I have learnt so much from. Thanks to Derek and Kyran from Bega Valley Shire Council, for your enthusiasm and help with the project. I really appreciated how much you went out of your way to provide me with data and answer all my questions.

Thanks to Brian Jones for your sediment expertise. Thank you to Chris and Heidi who were always happy to help with all my GIS issues, answering all my queries, and significantly improving my ArcGIS skills. A big thank you to Brent for your extensive field trip knowledge, teaching me all kinds of new things and keeping me thoroughly entertained with your excellent story telling.

Thanks to all my fellow science kids, you are all great. I don’t know where I’d be now without Friday cake days.

Thank you to my amazing family for just being themselves. And finally, a huge thank you to Lowana and Lachlan for their endless generosity and kindness. I am forever indebted to you both.
## Contents

Acknowledgements ........................................................................................................... iv

Contents .............................................................................................................................. v

Figures ............................................................................................................................... vii

**Chapter One: Introduction** .......................................................................................... 1

1.1 Study Context .............................................................................................................. 1

1.2 Aims and Objectives ................................................................................................ 3

1.3 Thesis Structure ....................................................................................................... 3

**Chapter Two: Literature Review** ................................................................................ 4

2.1 Introduction to Estuaries .......................................................................................... 4

2.2 Theory of Estuary Evolution .................................................................................... 5

2.3 Estuarine Classification ........................................................................................... 6

  2.3.1 Wave Dominated Barrier Estuaries ................................................................. 9

  2.3.2 Intermittently Closed and Open Lagoons (ICOLLS) ....................................... 10

  2.3.3 ICOLL Processes ............................................................................................... 11

2.4 Anthropogenic Impacts ............................................................................................ 13

  2.4.1 Increased Sediment Rates .............................................................................. 15

  2.4.2 Nutrients ........................................................................................................ 16

2.5 Approaches to Estuarine Management .................................................................. 18

  2.5.1 Management Strategies .................................................................................. 19

  2.5.2 Land Cover Assessment in Management ....................................................... 21

**Chapter Three: Back Lake** ....................................................................................... 23

3.1 Physical Setting ......................................................................................................... 23

  3.1.1 Regional Setting ............................................................................................. 23

  3.1.2 Catchment Characteristics ............................................................................ 25

  3.1.3 Human Environment ....................................................................................... 29

3.2. Current Approaches to Management .................................................................. 30

  3.2.1. Catchment Planning ..................................................................................... 30

  3.2.2 Entrance Management ................................................................................... 32

**Chapter Four: Methods** .............................................................................................. 34

4.3 Mapping of Catchment Area .................................................................................... 34

4.4 CERAT Modelling .................................................................................................... 37

4.5 Analysis of Short Cores ........................................................................................... 39

  4.5.1 Core Extraction ............................................................................................... 39

  4.5.2 Sediment Analysis ........................................................................................... 43

**Chapter Five: Results** ................................................................................................. 44

5.2 Aerial Photograph Analysis .................................................................................... 44

5.3 Land Cover Classification ........................................................................................ 47
Figures

Figure 1: Barrier estuarine evolutionary model after Roy (1984) (Hopley, 2013). .......... 6
Figure 2: Ternary process-based classification (Dalrymple et al. 1992) categorising estuaries based on the importance of wave, tide and river influence ........................................ 7
Figure 3: The four main estuary types in NSW. (Roy et al. 2001). ........................................ 9
Figure 4: Components within a typical ICOLL (Geoscience Australia, 2013) .................. 12
Figure 5: Schematic diagram of the effects of increased sediment loads on estuarine benthic organisms (Geoscience Australia 2013) .......................................................... 16
Figure 6: Back Lake in Merimbula; Inset: Merimbula is located on the south NSW Coast. ................................................................................................................................. 23
Figure 7: A comparison of water quality values between Back Lake and Merimbula Lake showing the Total Nitrogen load (TN), Sensitivity, Potential Eutrophication (PE) and the levels of chlorophyll (Geoscience Australia 2013) ................................................................. 24
Figure 8: Back Lake Catchment showing the South East Forests National Park and Bournda National Park (Haines & Rollason 2009) ........................................................................ 26
Figure 9: The elevation and drainage of the Back Lake Catchment ................................. 26
Figure 10: The units and lithology of the region and around Back Lake (Department of Primary Industries, 2004). ............................................................................................... 28
Figure 11: The locations of the housing estates north of Back Lake. ............................. 29
Figure 12: An aerial of the Berrambool and Sapphire Coast drives, with Mirador lots positioned on the hill north of the existing estates. (Photo provided by BVSC) .............. 30
Figure 13: The 2013 LEP zoning of the region, with Back Lake catchment highlighted. Inset: The increase in R2 (low density residential; pink area north of Back Lake (W1)) zoning, adding to the existing Mirador Estate R2 zone. Key for zones is R2 – Low Density Residential; R3 – Medium Density Residential; E1 – National Parks and Nature Reserves; E2 – Environmental Conservation; E3 – Environmental Management; E4 – Environmental Living; SP1 – Special Activities; SP2 – Infrastructure; SP3 – Tourist; RE1 – Public Recreation; RE2 – Private Recreation; W1 – Natural Waterways; W2 – Recreational waterways; B2 – Local Centre; B4 – Mixed Use. .................................................. 31
Figure 14: Back Lake during an artificial opening event, 26/6/13. Photo: Bega Valley Shire Council ............................................................................................................................... 32
Figure 15: A scatterplot of the values of three bands present in the aerial photography. The water (blue) and vegetation (green) show a large amount of overlap in all three bands. The scatterplots should not overlap if the training samples defined represent different classes .......................................................................................................................... 35
Figure 16: The catchment divided into three subcatchments, displaying the areas which exhibit contiguous outputs (OEH 2012).  

Figure 17: Core Locations across Back Lake. Inset: Sample A,B,C & D were grab samples extracted using a box sampler and cores 6 & 7 were taken to further clarify results found in core 5.  

Figure 18: Site locations in order from left to right, Core 5, Core 1, Core 4 and Core 3.  


Figure 20: Unsupervised land cover classification for 1972. Note the misclassification of forested areas as Class 2 (Grass).  

Figure 21: Areas in km² of developed land between 1948 and 1998. The excessive clearing that occurred in 1975 can be seen, with the most amount of cleared land present in 1975.  

Figure 22: Maximum Likelihood Supervised classification outputs from 1948, 1975 and 2010 imagery displaying the change in land cover. Factors affecting the classification include the varying colours across the years in each image producing different results. The spread of the urban area to the west of Back Lake and the revegetation of some corridors is evident.  

Figure 23: A broad land cover classification showing the increase of urban areas since 1948 to 2010. Land cover within the urban class in 1948 appears much more concentrated than 2010 where vegetation has been established.  

Figure 24: The current situation in the catchment with surface flow as the determinant (ML/km²/yr). The result of a 20% removal of forest from subcatchment 1 and with a land cover of either urban or cleared area is an increase in runoff from 139 ML/km²/yr to 159 ML/km²/yr.  

Figure 25: TSS increases from 10,399 kg/km²/yr to 39,999 kg/km²/yr if there is a 20% change of catchment cover from forest to cleared area. The figure on the bottom right shows the impact of a 20% removal of forest to urban area, producing no change in the amount of TSS from the current situation model.  

Figure 26: Subcatchment 2 has the highest TN of 299 kg/km²/yr. Subcatchment 1 has a slightly larger TN than subcatchment 3, of 199 kg/km²/yr. A land cover change scenario of a 20% decrease in forest area in subcatchment 1 to cleared area produces no change in TN. The same scenario was modelled with a change to cleared areas. This produced an substantial increase to 549 kg/km²/yr (bottom left).
A. Borrell (2013)

Figure 27: Current situation model of Back Lake taken from the CERAT tool. Data is for the whole catchment and shows that an increase in TN can lead to higher levels of Chlorophyll a, increasing the risk of eutrophication ................................................................. 57

Figure 28: The total phosphorus (TP) in the catchment .......................................................................................................................... 58

Figure 29: a) Sediment size distribution from Core 5  b) organic content of core 5.......................................................... 61

Figure 30: Grab Sample A is 53cm long with a change from silty mud to clay occurring at a depth of 30cm. Grab sample B was 48cm long, with the distinct change from clay to organic loamy sand occurring at a depth of 17cm................................................................. 62

Figure 31: A: Core 7 taken from the bank closest to Berrambool Housing Estate. B: Taken from the far bank, adjacent to the sporting oval................................................................. 63

Figure 32: Stratigraphic log of the 8 cores collected from Back Lake. Sandy mud was present in the cores from the central basin, and an organic coarse grained sandy mud was prevalent in the fluvial dominated regions. Please see page 66 for core legend................................................................. 64

Figure 33: Legend for stratigraphic log on page 65............................................................................................................................ 65

Figure 34: Lake Wollumboola and its size relative to the catchment area (Simms et al. 2003)........................................................................................................................................................................ 70

Figure 35: Three sedimentation rate scenarios for Back Lake according to the analysis of sediment cores and land cover trends from aerial photography................................................................. 72

Figure 36: Clearing adjacent to Berrambool Creek that occurred between the years of 1972 and 1975 for the development of Berrambool Housing Estate. This removed the top layer of grass exposing bare earth................................................................. 72

Figure 37: Gully erosion within Berrambool Estate and a storm water output................................................................. 73

Figure 38: Left: An example of the sediment fences present on the slopes leading down to north western margin of Back Lake aimed to slow sediment runoff into the lake, and a concrete storm water structure in Mirador Estate, installed in an attempt to hold and slow storm water before it is transported down the slope into the lake................................................................. 76
Chapter One: Introduction

1.1 Study Context

Estuaries can be found along much of the NSW coastline. Estuaries occur at the mouth of rivers, acting as a sediment sink between the catchment and the coast (Sloss et al. 2009). Estuarine form is influenced by many factors including geological setting, sea level and sediment deposition (Woodroffe 2002). The balance between fluvial, wave and tidal processes also influence estuarine form and as this balance varies between systems, distinct types of estuaries are produced giving rise to a multitude of classifications (Dalrymple et al. 1992; Kennish 2002; Roy et al. 2001).

Estuaries have always been important to humans, providing a transport link between rivers and the sea, and a valuable food source (Savenije 2006). Estuaries are generally bordered by fertile soils, flat land and provide a source of fresh water, leading to some of the most densely populated regions in the world existing in estuarine areas (Savenije 2006). Estuaries are now utilised by humans for a variety of purposes including urban centres, agriculture, ports, recreational facilities and tourism (Carvalho & Fidelis 2013).

Geologically estuaries are ephemeral features that exhibit various evolutionary states (Hodgkin & Heso 1998). Anthropogenic activities that occur in estuaries are often not compatible with natural estuarine functioning, leading to the development of highly altered and degraded features (Carvalho & Fidelis 2013). The rapid pace of development and growth that has continued to increase over time has introduced a range of stresses to estuaries (Kennish, 2002; Savenije 2006). Issues that face Australian estuaries include catchment and foreshore development, sedimentation, habitat loss, changes to flow and tidal flushing, eutrophication, excess pathogens and toxicants, introduced pests, resource exploitation and water extraction (Commonwealth of Australia 2002; Keneley et al. 2012; Kennish 2002). Estuary management should aim to enable the integration of developments in knowledge and governing agencies to attempt to control and curb the impact of societies on estuarine environments.

Evidence for the degradation of estuaries includes accelerated sedimentation rates, water and soil contamination and decreases in biodiversity that have been seen across a range of estuaries in catchments which have experienced high degrees of development (Kennish 2002; de Jonge et al 2002). In New South Wales, management is currently
focussed on preventing further damage and ensuring that estuaries that remain in good condition aren’t subject to activities that may compromise their health (HRC, 2002). Remediation efforts can be valuable, although mitigation of human impacts can be a long, difficult and costly task that in many cases is ineffective (HRC, 2002). Current management strategies need to be informed by research, and based on the short and long term functioning to ensure the health of estuaries in the future (Brooke, 2003).

Estuarine management is largely governed by policy and legislation. In Australia, both federal and state government initiatives have reported on the condition of estuaries. Local councils, guided by state government frameworks such as the NSW State Coastal Policy, oversee the management of coastal systems. In the past, the wide range of authorities overseeing management has led to a general lack of ‘guardianship’ placed over individual estuaries and lakes (CCA 2007; Keneley et al. 2012).

This study examines changes in an Intermittently Closed and Open Lagoon (ICOLL), Back Lake on the south coast of NSW in the local government area for Bega Shire Valley Council (BSVC). Previously, development has been restricted to the well-established town centre of Merimbula, with land clearing occurring on low lying areas and floodplains. This has meant that large proportions of the natural vegetation in the catchment have been retained. Back Lake supports a range of biological populations, such as important seagrass communities and the national parks in the catchment define the most southern extent for species such as the endangered long-footed potoroo and smoky mouse (NPWS, 2006). Development that occurred in the 1970s involved the clearing of both pasture land and forested areas adjacent to Berrambool Creek, exposing large sections of top soil. This provided an opportunity for excess sediment to enter the waterways, having a possible effect on the sediment deposited into both the creek and lake. The study examines sedimentation patterns within Back Lake. Predictions of future conditions arising from the modification of the catchment due to changes in land cover on the estuary foreshores are presented. In particular, the study examines whether there has been changes to the source of sediment deposited in the lake due to changing catchment conditions. Management of estuaries can only be effective with an understanding of the physical processes operating within an estuarine system (Williams 1981). Setting management targets for estuaries requires the identification of a baseline, which is best achieved in lakes that present low levels of human modification. Back Lake remains in a good condition, thus enabling near-natural states to be measured.
1.2 Aims and Objectives

The primary aims of this project are to investigate changes in catchment land cover from 1948 to present and determine if these changes have had an impact sedimentation processes in Back Lake, and thus affecting estuary health. The impacts of changes will be investigated in an attempt to quantify impacts and predict future implications arising from ongoing development with the catchment. To achieve this aim within the scope of the thesis the following objectives will be undertaken:

- Examine how the lake has changed in response to catchment land cover changes
- Quantify land cover change and model future scenarios to predict the impacts of land cover change.
- Identify the major anthropogenic influences on Back Lake and how they can be managed to retain and possibly improve overall health of the lake.
- Determine possible management strategies that may improve and maintain the natural qualities of Back Lake.

1.3 Thesis Structure

The introduction of this thesis is followed a literature review (Chapter Two) outlining current understandings of estuaries in the literature and definitions of estuaries, as well as proposed classification models. Estuary evolutionary processes and anthropogenic influences are described with an emphasis on ICOLLs. Chapter Three explains the physical settings of Back Lake and the Back Lake catchment.

Chapter Four outlines the methods used. This involved the mapping and analysis of catchment land cover, modelling with a predictive estuary health tool and the extraction of sediment cores. Chapter Five presents the results found from the methodology. The implications of the results are discussed in Chapter Six, and this information is synthesised and used to guide management based recommendations for Bega Valley Shire Council to achieve health targets for Back Lake.
Chapter Two: Literature Review

2.1 Introduction to Estuaries

Estuaries are dynamic coastal features that vary in geomorphology, salinity, biological activity and sedimentary deposition. Estuaries exist at the mouth of rivers, receiving sediment and water runoff from both catchment and marine sources. The supply of sediment and runoff to estuaries from rivers is dictated by catchment size, lithology and climate (Milliman 2001 in Woodroffe 2002). Anthropogenic activities within catchments can greatly alter processes occurring in estuaries. Classifications of estuaries have been based on unifying principles such as physical, geological and biological processes (Jay & Smith, 1988). The balance between fluvial, wave and tidal processes creates distinct systems and can be used to classify estuaries (Dalrymple et al. 1992; Kennish 2002; Roy et al. 2001).

To understand estuaries geomorphologists have attempted to define them on a number of levels. Definitions can be based on geomorphology (Boyd et al. 1992; Pritchard 1962; Roy 1984; Roy et al. 2001), evolutionary models (Dalrymple et al. 1972), entrance condition (Kjerfve & Magill 1989), tidal influence (Hayes 1975), salinity (Cameron & Pritchard 1963) and more recently according to a management context. A definition proposed by the American Society for the Advancement of Science (1967) has become one of the most widely adopted in the literature, stating that ‘an estuary is a semi-enclosed coastal body of water which has a free connection with the open sea and within which seawater is measurably diluted with freshwater derived from land drainage’ (Dalrymple et al. 1992; Potter et al. 2010; Pritchard 1967). Estuaries without a fully open inlet at all stages of the tide are defined as lagoons using this definition (Pritchard 1967). This definition is focused on temperate, northern hemisphere estuaries which typically don’t experience periodic closure of the connection with the ocean, or hypersalinity which are features typical of many Australian estuaries (Potter et al. 2010).

Potter et al. (2010) proposed a definition which aimed to include the main characteristics of all estuaries, including Australian estuaries, stating: ‘An estuary is a partially enclosed coastal body of water that is either permanently or periodically open to the sea and which receives at least periodic discharge from a river(s), and thus, while its salinity is typically less than that of natural sea water and varies temporally and along its
length, it can become hypersaline in regions when evaporative water loss is high and freshwater and tidal inputs are negligible.’ This broader definition incorporates intermittently open and closed lakes and lagoons (ICOLLs), and is more appropriate to the saline coastal lakes of south NSW including Back Lake.

2.2 Theory of Estuary Evolution

The morphological evolution of all estuaries is characterised by gradual infilling due to marine and fluvial sediment deposition. Differing local rates of infilling due to space availability and fluvial and marine sedimentation result in diversity of form in global estuaries (Roy et al. 2001). Infilling of estuaries is largely influenced by changes in sea level (Fujii & Raffaelli 2008). Holocene estuaries were formed during the post-glacial marine transgression (PMT) as sea levels rose, inundating low-lying coastal areas and river valleys (Thom & Short 1985; Nichols & Biggs 1985; Webster & Harris 2004). During periods of sea level rise, sediment is transported shoreward and reworked and then deposited along the coast creating coastal barriers (Dalrymple et al. 1992; Sloss et al. 2006; Thom & Roy 1985). Sea level began to slow approximately 6500 years ago, entering a ‘stillstand’ period (Thom & Roy 1985).

Sea level is a contributing factor in the rate of sediment supply to estuaries and as sea level slows, infilling will occur if the sediment accumulation rate is sufficient, exceeding submergence (Dalrymple et al. 1992; Nichols & Biggs 1985; Nichols & Boon 1994). Estuarine infill has been classed into four stages, as outlined by Roy (1984). These stages are based on the progression of estuaries through periods of gradual infilling due to marine and fluvial sediment deposition, as they ‘mature’ (Figure 1).

The four stages are:

1. Youthful: the estuary receives minimal sediment infill.
2. Immediate: partial infill of the basin occurs and delta progradation.
3. Semi Mature: extensive floodplains are formed due to delta progradation
4. Mature: Ongoing progradation causes the infilling of the basin and leaving cut off embayments.
Figure 1: Barrier estuarine evolutionary model after Roy (1984) (Hopley, 2013).

2.3 Estuarine Classification

The classification of Australian estuaries is a difficult task due to the broad diversity of morphologies and processes found across the continent. Various classification systems have been proposed over time and include classifications by Roy et al. (2001), Dalrymple et al. (1992) and Geoscience Australia (2013). Currently in Australia, there is no universal classification scheme for estuaries; however the classification system of Geoscience Australia has commonly been applied to Australian estuaries in a management context. This classification is based on a ternary diagram, modelled after classifications proposed by Dalrymple et al. (1992).
Dalrymple et al. (1992) classified estuaries according to the relative input of river, wave and tidal influence. Influence of these processes varies between estuaries. Lagoons are located on the bottom left of the diagram, wave action dominating morphology and estuarine processes (Figure 2).

Roy et al. (2001) categorised Australian estuaries based on the inheritance of coastal setting and differing rates of sediment infilling, as well as the relative influence of tide, wave and fluvially derived water and sediments (Roy et al. 2001). The classification includes a wider set of estuaries found on Australian coasts (Table 1). The subdivisions between types of estuaries within each group is based on the nature of present day entrance, as this determines the exchange of water between the estuary and the sea (Roy et al. 2001). Group 1 are considered transitional estuaries between open ocean and rivers with minimal fluvial input and wide entrances (Roy et al. 2001). Group 5 includes estuaries that are rarely brackish as a result of limited connections to the ocean. Groups 2-4 define estuaries that are generally considered to have ‘true’ estuarine environments (Roy et al. 2001). Group 4 classifies intermittent estuaries, including saline coastal lagoons.
Table 1: Classification of coastal water bodies in eastern Australia based on the level of marine influence (after Roy et al. 2001).

<table>
<thead>
<tr>
<th>Groups</th>
<th>Types</th>
<th>Mature Forms</th>
</tr>
</thead>
<tbody>
<tr>
<td>I. Bays</td>
<td>1. Ocean embayments</td>
<td></td>
</tr>
<tr>
<td>II. Tide-dominated estuaries</td>
<td>2. Funnel-shaped macrotidal estuary</td>
<td>Tidal Estuaries</td>
</tr>
<tr>
<td></td>
<td>3. Drowned valley estuary</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4. Tidal basin</td>
<td></td>
</tr>
<tr>
<td>III. Wave-dominated estuaries</td>
<td>5. Barrier estuary</td>
<td>Riverine Estuaries</td>
</tr>
<tr>
<td></td>
<td>6. Barrier lagoon</td>
<td></td>
</tr>
<tr>
<td></td>
<td>7. Interbarrier estuary</td>
<td></td>
</tr>
<tr>
<td>IV. Intermittent estuaries</td>
<td>8. Saline coastal lagoon</td>
<td>Saline Creeks</td>
</tr>
<tr>
<td></td>
<td>9. Small coastal creeks</td>
<td></td>
</tr>
<tr>
<td></td>
<td>10. Evaporative lagoons</td>
<td></td>
</tr>
<tr>
<td>V. Freshwater bodies</td>
<td>11. Brackish barrier lake</td>
<td>Terrestrial Swamps</td>
</tr>
<tr>
<td></td>
<td>12. Perched dune lake</td>
<td></td>
</tr>
<tr>
<td></td>
<td>13. Backswamp</td>
<td></td>
</tr>
</tbody>
</table>

In previous classifications in the literature, (Chapman et al. 1982; Roy et al. 1980; Roy 1984) coastal lagoons were classified as barrier estuaries which also included wave dominated estuaries. Barrier estuaries and saline coastal lakes present similar geomorphologic environments and have often been classed together. However, coastal lakes represent a less mature evolutionary state with less sediment infill and a sometimes intermittent connection with the ocean (Roy 1984). In the Roy et al. (2001) classification, a new class is suggested for intermittent estuaries. As can be seen in Figure 3, saline coastal lagoons remain as wave dominated with a closed inlet and no tide. Back Lake is defined under the intermittent class, as a saline coastal lagoon (Figure 4).
2.3.1 Wave Dominated Barrier Estuaries

Wave dominated estuaries are common along the south coast of NSW, developing in moderate to high wave energy conditions and where tidal influence is limited (Heap et al. 2001; Ryan et al. 2003). Wave dominated estuaries are partially infilled bedrock embayments, with sediment supplied from both terrestrial and marine sources (Ryan et al. 2003). They are characterised by a central basin separated from the ocean by a barrier. The barrier is an accumulation of marine sand transported by waves and wind, separating the central basin from the marine environment (Boyd et al. 1992; Chapman...
et al. 1982; Hanslow et al. 2000). The central basin is a low energy environment, generally in the seaward reaches of an estuary. The central basin is an effective sediment trap of terrestrial and marine sediment, with a relatively high inflow of water from river sources and high wave energy at the mouth of the estuary compared to tidal energy (Brooke 2003; Heap et al. 2001; Roy et al. 1980). As the estuary becomes mature the central basin infills and becomes shallower.

2.3.2 Intermittently Closed and Open Lagoons (ICOLLS)

Coastal lagoons and/or lakes are water bodies separated from the sea by a sand barrier (Woodroffe 2002). Generally, coastal lagoons exhibit a shallow basin bordered by tidal marshes or the original coast (Ryan et al. 2003). Coastal lagoons can have a permanent or intermittent connection to the ocean allowing the exchange of water, sediment and organisms (Bird 1994). If tidal action is too weak to remove sediment build up in the entrance, then the entrance channel is choked and closes. This gives rise to the important sub-category of ICOLLS,

The term ICOLL was initially applied only to Australian coastal lagoons however the term is gaining global recognition (Haines et al. 2006). ICOLLS have been classified as a subcategory of coastal lagoons as the limited connection to the ocean and a lack of significant catchment runoff produces distinct conditions (Gale et al. 2007). There are 70 coastal systems on the NSW coast that have been classified as ICOLLS and have a catchment less than 1 hectare (Dewarr & Hurrell 2010; Haines et al. 2006). ICOLLS typically have small catchment areas producing low runoff from rainfall and creating an inability to retain an open connection to the ocean. Rainfall events can create conditions which inducing water levels to become super elevated, causing the entrance to be opening to the ocean (Gale et al. 2007).

Due to the fragile nature of ICOLLS management of these systems has become crucial in NSW. Haines et al. (2005) devised an assessment of ICOLLS in NSW using morphometric parameters including waterway area, waterway volume, waterway shape and the proportion of time that the entrance is open or closed to the sea. These parameters are used to define three fundamental measures to determine estuary sensitivity (Haines et al. 2006).
Haines (2008) outlined six types representing geomorphic structure and behaviour of ICOLLs currently found in NSW. Table 2). These categories were created to allow ICOLLs in NSW to be grouped according to their entrance condition to assist in developing a consistent classification to allow a comprehensive management strategy to be developed. Back Lake is grouped as a regular intermittently open coastal lake.

Table 2: The six types of ICOLLs present in NSW as outlined by Haines (2008). Back Lake is classed as a regular intermittently open coastal lake.

<table>
<thead>
<tr>
<th>Type</th>
<th>Description</th>
<th>Examples from south eastern NSW</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Regular intermittently open coastal lake.</td>
<td>Back Lake, Wallaga Lake, Bega River, Merimbula Lake, Lake Wollumboola</td>
</tr>
<tr>
<td>2</td>
<td>Smaller intermittently open creeks (infilled paleo valleys)</td>
<td>Bournda lagoon, Nadgee River</td>
</tr>
<tr>
<td>3</td>
<td>Smaller intermittently open creeks (Interbarrier swales)</td>
<td>Brush lagoon, Kioloa lake</td>
</tr>
<tr>
<td>4</td>
<td>Open Creeks (riverine system) but may close under particular conditions.</td>
<td>St George’s Basin, Pambula Lake, Bondi Lagoon</td>
</tr>
<tr>
<td>5</td>
<td>Permanently open coastal lake/creek due to entrance training works. This type caters for estuaries which have been altered by management actions.</td>
<td>Lake Illawarra, Wagonga Inlet,</td>
</tr>
<tr>
<td>6</td>
<td>Perched Freshwater lagoons with no connection to the ocean (although potential for connection in future response to sea level rise and coastal erosion)</td>
<td>Barracoota Lake, (Gippsland)</td>
</tr>
</tbody>
</table>

2.3.3 ICOLL Processes

The complexity of estuaries is evident in the diverse range of processes that affect the physical and chemical characteristics within an estuary. Estuaries, as a transition between rivers and the sea, provide a unique set of hydraulic, morphologic and biologic characteristics which are very different to other water bodies (Savenije 2006). Estuary processes are controlled by geological setting, marine and fluvial influences and evolutionary history.

Estuaries are relatively unique systems in terms of hydrodynamics. This is due to the circulation of fresh and salt water which is the product of interactions of fluvial discharge, tides and existing estuarine water (Woodroffe 2002). The nature of water circulation and the extent and force of tide-action within estuaries is critical to ecological communities, groundwater and landscapes due to influences on
sedimentation and water quality gradients (Tagliapietra et al. 2009). The main elements controlling the hydrodynamic regime in estuaries on the south east Australian coast are storm and swell waves and oceanic currents (Roy et al. 2001).

Water levels in ICOLLs respond to catchment runoff, direct rainfall, evaporation and percolation through sand dunes (Figure 4, #2 & #4) (Haines 2008) and present two distinctly different hydrological regimes due to the presence of an intermittently closed and open entrance (Ranasinge & Pattiaratchi 2003). When the entrance is open, an ICOLL will exhibit regular tidal behaviour and water levels will respond to tidal regimes and wave action (Haines 2008). When ICOLLs are closed, they act as a reservoir, and are effective nutrient, sediment and contaminant traps (Roy et al. 2001), making them susceptible to anthropogenic inputs.

Figure 4: Components within a typical ICOLL. (Geoscience Australia, 2013).

Entrance closure also impacts the salinity of an ICOLL, causing a decrease in salinity as fluvial input becomes greater than input from marine sources. Salinity regimes will fluctuate in space and time as a response to a range of factors including rainfall and catchment runoff, temperature and surface evaporation. The morphology of entrance channels and the duration of entrance opening control the extent of marine influence (Pollard 1994). Freshwater input varies between estuaries depending on catchment size, rainfall and land cover (Woodroffe 2002). ICOLLs generally receive small freshwater input from fluvial sources as they possess small catchments with low yearly rainfall, which can create conditions of low water levels (Schallenberg et al. 2010).
The infilling of sediment is an important factor in determining processes. Depositional environments are determined by different substratum condition, hydrological regimes and nutrient cycling. This affects the habitats present within in ICOLL and influences species assemblages (Rainer 1981). Habitats typically supported by ICOLLs include macroalgae, salt marshes and seagrass beds (Figure 4, #6). Excess nutrients in the system such as nitrogen can lead to eutrophication (Figure 4, #9).

Sediment dispersal can best be viewed within three areas of the estuary; fluvial, estuarine and marine activity (Nichols & Biggs 1985). When the entrance to an ICOLL is closed, sediment dispersal from marine activity is limited to wind transport. Within the three zones, sedimentation transport and deposition is influenced by hydrodynamic circulation, tidal influence and the type of sediment present in the system (Figure 4, #5) (Woodroffe 2002). Waves provide the energy for littoral transport, building up sediments at the mouth of the estuary creating a sand barrier (Nichols & Biggs 1985). This process determines the extent of marine exchange that is able to occur, affecting a number of other processes within the estuary.

Fine sediment will be transported to the central basin which acts as a sediment trap (Figure 4, #8) whilst coarser sediment is deposited in salt marshes and low energy environments (Nichols & Biggs 1985). Marine sediment is transported by tidal currents into the central basin with wind providing another mechanism for marine sand transport (Brooke 2003). Rain and storm events provide peaks of sediment transport to estuaries from terrestrial sources, however large sediment loads will often be flushed straight out to sea (Nichols & Biggs 1985).

2.4 Anthropogenic Impacts

Estuaries are the result of the interaction between numerous processes and the geomorphology. Due to this complexity, estuaries can be vulnerable to impacts that may affect water and sediment quality, thereby affecting ecological functioning (Roy et al. 2001). Anthropogenic impacts on estuaries include degradation and eradication of biological communities, the alteration of sedimentary and hydrological processes and the contamination of water quality. The presence of human activities in estuarine
systems has led to the transformation of natural processes occurring in estuaries and in some cases degradation.

Development within catchments can induce drastic change to the behaviour of sediment and water in the estuary. This occurs due to the removal of native vegetation, the replacement of porous surfaces with non-porous surfaces (e.g. concrete) and the introduction of chemicals and pollutants to estuarine systems. In some cases, development within catchments has occurred on estuary foreshores involving the removal of riparian vegetation and establishment of urban and recreational areas on estuarine floodplains (Webster & Harris 2004). This has resulted in the need to alter estuaries to mitigate the impacts of natural processes such as flooding on infrastructure. The presence of algae can cause issues in regards to aesthetics and odour, with residents pressuring local government authorities to manage estuarine processes.

In wave dominated estuaries and ICOLLs, management of these issues is most commonly conducted through the manipulation of entrance condition with measures such as artificial entrance opening regimes, training walls and redirecting water flows (Geoscience Australia 2013). Artificial entrance opening regimes have become important in estuaries in order to protect material assets such as infrastructure and recreational areas which are situated on estuarine floodplains or in close proximity to waterways. Floodplains are flooded naturally during periods of high rainfall and storm events. If the entrance remains closed when water levels are elevated, properties and productive land in such settings may be subject to flooding (Keneley et al. 2012). Flood waters can be reduced by artificially cutting an entrance to allow water to dissipate to the ocean. Closed entrances can also contribute to low levels of water causing the exposure of mudbanks which create odour, water stagnation and turbidity (Williams 1981).

These management actions are often imposed without much concern for the associated impacts on ecological communities and natural processes (Keneley et al. 2012; Roy et al 2001). Reversing the effects of large-scale human modifications is a difficult task and the removal of artificially opening mechanisms is often unpopular with the public (Carvalho & Fidelis 2013).
2.4.1 Increased Sediment Rates

Evidence for increased rates of fluvial sedimentation since European settlement has been assessed using dating to determine the age of sediment in estuaries (Hollins et al. 2011; Hopley 2013; Sloss et al. 2011) with reductions in vegetation cover causing the onset of soil erosion within catchments (Bird 1994). Implications associated with an increase in sediment supply include rapid changes in estuary form and function affecting biological communities and water quality (Brooke 2003). As barrier estuaries are highly efficient at trapping terrestrial sediment, catchment use is the main driver for increases in sediment supply. Estuarine sediment is derived from both terrestrial and marine sources, with terrestrial sediment being transported by rivers.

To a degree, catchment land use controls the supply and distribution of sediment to the catchment waterways. This allows analysis of sediment deposition rates to provide indications of the condition of the surrounding catchment land (Sloss et al. 2011). Rates of sedimentation have drastically increased since European settlement, as catchments have been cleared for urbanisation, agriculture and farming and industry (Brooke 2003; Webster & Harris 2004). In areas where vegetation is removed and replaced with urban areas, agriculture or industrial zones it is likely that rates of soil loss will accelerate. Soil loss can be modelled by using parameters of erosivity of the soil, the force of rainfall, catchment slope and land cover characteristics'. The complexity of the factors required to accurately predict the soil loss that may occur in catchments highlights the difficulty in predicting and modelling future soil loss (Simms et al. 2003).

Increased sedimentation has a number of negative implications for estuaries including deleterious biological impacts, compromised water quality, reduced aesthetic value and the alteration of the natural processes that occur in an estuary. Water quality can be reduced as turbidity in the water column increases and this can lead to limitations in light availability, impacting on the productivity of organisms (Kennish 2002). Increased sedimentation can result in rapid and significant reductions in water depth, accelerating the evolution of an estuary (Haines 2008). Shallower water can lead to an increase in water temperatures, vary the amounts of sunlight able to reach the estuary floor and cause estuarine benthic organism to be damaged by wind. Organisms on the estuary floor are also at risk of being covered by settling sediment, impairing function (Figure 5) (Geoscience Australia 2013). The loss of seagrass communities can lead to phytoplankton blooms, which may be toxic (Webster & Harris, 2004).
Anthropogenic activities within the catchment can cause sediment to become polluted with contaminants. Sediment can be contaminated by organic matter as it adsorbs onto mineral surfaces and has a high affinity for fine grained sediments (Prandle 2009). Stormwater runoff can provide excess nutrients to estuaries that may also contaminate sediment (Birch & Hutson 2009) and this leads to increases in nutrients such as phosphate and nitrogen. High sedimentation rates can reduce the contact time between organic carbon and dissolved oxygen in the water column and produce increases in the concentration of carbon and nutrients in sediment (Geoscience Australia, 2013).

### 2.4.2 Nutrients

Increasing urban development and agricultural land use intensification have the potential to impact on water quality and ecological values of estuarine environments (Drewry et al. 2009). Pre-European estuaries were low nutrient systems, due to the eucalypt dominated vegetation, fire regime and infertile soils (Roy et al. 2001). Over the last 200 years in Australia, widespread clearing, the introduction of agricultural practices and urban development has increased nutrient loadings, creating enhanced primary productivity in some estuaries (Green 2013; Roy et al. 2001). Excessive inputs of nutrients such as nitrogen and sediment are expected to contribute to water quality problems such as eutrophication, algal blooms and turbidity, decreasing the habitat quality of estuarine water (Dettmann 2001; Drewry et al. 2009; Riedel & Sanders 2003).
A range of indicators can provide information on the health and sensitivity of estuaries. Surface runoff is the water from rainfall flowing over the ground towards waterways and is a medium for the transport of sediment and nutrients. Surface runoff can transport fine inorganic particles which are measured as Total Suspended Solids (TSS) (CSIRO 2003). TSS can be used as an indicator of increased sedimentation by urbanisation and agricultural land use (Geoscience Australia 2013).

Nitrogen is the limiting element for algal growth in estuaries and coastal waters and is required for growth by organisms (Kennish 1990). Total nitrogen includes all dissolved forms of inorganic (nitrates, nitrites and ammonia) and organic nitrogen. Organic nitrogen is produced by decomposition of aquatic life and sewage runoff inputs. Increased levels in inorganic nitrogen are the result of soil erosion and residential runoff (Spooner & Maher 2009). Increases in the presence of nitrogen can cause eutrophication, altering aquatic habitats. This is an effective way to measure estuary health as increases in TN can signify development, and mismanagement of surface runoff and/or groundwater management. Increases in TN can also be attributed to biological production. The implications associated with rises in TN means that it can be used as an indicator of estuary thresholds and health (Spooner & Maher 2009).

Another critical nutrient in estuarine systems is phosphorus. Total phosphorus (TP) is the measure of phosphate in a system and can also be used as an indicator of anthropogenic activities within the catchment as agricultural and urban runoff commonly contributes to increased phosphorus levels (Han et al. 2011; Huang et al. 2006).

Water quality in ICOLLS is highly dynamic, with near pristine systems displaying naturally high levels of nutrients such as nitrogen (Haines 2008). Water quality data should therefore be used with caution, particularly when employed to justify entrance management decisions (Haines 2008).
2.5 Approaches to Estuarine Management

Anthropogenic use of estuaries and estuary catchments has interfered with the natural functioning of estuaries, producing a range of effects. Due to the unique nature of estuaries, impacts of human induced change vary between systems making management difficult and often reactive. Since the 1990s, attempts to mitigate and prevent human induced impacts involved the incorporation of science into the planning and management of coastal systems (Thom & Short 2006). This has involved enquiries, reviews, policy initiatives, legislation, government outsourcing, administrative structuring and community engagement to enable the continual use of estuaries whilst avoiding further damage (Thom & Harvey, 2000).

The classification of estuaries has been important in regards to developing appropriate management strategies for individual estuaries as they are put under increasing pressure from anthropogenic change. With an increasing reliance on estuarine systems as economic, commercial and recreational resources it is important that successful and measureable management strategies are implemented. Early detection of human induced alteration to estuarine environments and rigorous, science-based data should be used to make informed decisions to minimise adverse impacts (Birch & Hutson 2009; Brooke 2003). It is critical that problems are addressed before damage becomes irreversible (Brooke 2003).

In addition to remediating sites of degradation, the importance of protecting sites that retain their natural values has been recognised (Haines et al 2008). This includes native bushland, rivers and their headwaters, and coastal environments. Evidence of degradation in estuaries can be seen in a number of estuaries on the NSW coast. Examples of cases where deleterious impacts have become critical to estuary health include the oyster contamination in Wallis Lake on the south coast in 1997 and the presence of blue green algal blooms in Lake Ainsworth and Myall Lake (HRC 2002). Damage caused to native ecosystems is often irreversible and the costs of rehabilitation can be large with few positive outcomes (HRC 2002). This further emphasises the importance of appropriate planning measures as the removal of native vegetation can cause irreversible damage and loss of critical habitats (Kennish 2002).

The management of estuarine systems to enable healthy functioning is crucial for allowing their continued status as valuable assets to society and as ecologically
productive ecosystems. Australia wide, estuary management has failed to implement an integrated approach in the past with fragmented and individualistic strategies proving to be ineffective in retaining estuarine values (Keneley et al. 2012). Estuaries that have been affected by inadequate protection include Burrill, Merimbula and Cudgen lakes on the south NSW coast, where existing assessments of activities impacting the lakes have been deemed insufficient (HRC 2002). This allowed for the ongoing development of the catchments to occur despite the fact that they have been classed as highly sensitive systems (HRC 2002).

Many indicators can provide information on the health of an estuary such as water quality, biological presence and activity, sedimentation rates and contaminants. Determining the health of an estuary requires addressing issues at both the catchment scale and within the lake. All factors contributing to the functioning of an estuary should be considered when determining the health status of an estuary. However, the collection of data in estuaries and approaches that involve a broad approach are time consuming and costly.

Valuable information on the history of sediment accumulation can be retrieved from the history of sediment deposition, the type and mineralogy of sediments enabling the construction of estuarine histories. To construct effective and informed management efforts, knowledge of past changes is critical to justify actions (Gwari & Ugoala 2009). Sediments can be an informative indicator of changes that have occurred in the estuary and they can be also used to determine the rate of change. The ability to determine the history and health of an estuary through sediment is one method that can be utilised to provide data on both estuary health and catchment use.

2.5.1 Management Strategies

A robust understanding of the factors which can control environmental processes is considered essential when planning for long-term management of natural resources. Knowledge of environmental indicators within different ecosystems can provide information on relevant trigger values (Ryan et al 2003). A vital component of achieving sustainable use of estuaries is community co-operation. Communities that participate in the formation of coastal management strategies and plans are more likely to support their implementation (Keneley et al 2012).
Management strategies can be implemented by governments through policy, legislation and frameworks. The Coastal Protection Act 1979 outlines provisions relating to the use and occupation of the coastal region and the NSW Coastal Panel is the statutory authority under the act. The NSW Coastal panel is comprised of local government and public authority nominees (OEH 2013).

There are a number of frameworks in place to provide support to councils that are lake managers. The NSW Coastal Zone Management aims reduce the impact of population growth on estuaries, and maintain the ecological health of estuaries. This program attempts to assist local governments through grants and technical assistance, with the preparation of coastal and estuarine studies, coastal zone management plans and assessing the health of estuaries (OEH 2013).

The Coastal Lakes Strategy was the result of an inquiry into coastal lakes by the Healthy Rivers Commission (HRC) in 2002. In 2004, the Natural Resources Commission (NRC) replaced the Healthy Rivers Commission (HRC). The Coastal Lake Strategy was an assessment and management framework that attempted to address the health of NSWs estuaries and provide overarching arrangements to achieve the long-term goal of healthier coastal lakes (HRC 2002). The framework was born out of the government decisions and proposals in its Action for the Environment statement and the Coastal Protection Package (Haines & Rollason 2009). It outlined a set of arrangements designed to improve management, allowing for progress to be made in a timely and cost effective manner (Haines & Rollason 2009). Drafted over 10 years ago, it used quantitative data to assess and classify coastal lakes using parameters such as natural sensitivity, current condition of the water body and catchment, recognised ecosystem and resource conservation values and other significant socio-economic factors. Estuaries were classified into four classes; comprehensive protection, significant protection, healthy modified conditions and targeted repair.

Other regional plans to identify action areas and provide frameworks for management of natural resources such as estuaries include the Southern Rivers Catchment Management Plan (CAP 2023). CAP is a ten year strategic plan identifying the priorities and actions for Natural Resources Management (NRM) in the region. It recognises that it is not possible to meet the full list of community and government aspirations within the existing time frames and resources. It provides an emphasis on prioritisation, which is
important in achieving critical management outcomes in an environment that encompasses such a wide range of complex interactions.

2.5.2 Land Cover Assessment in Management

Land cover is a fundamental variable, having an impact on and linking many parts of the human and physical environment (Foody 2007). Land cover is important in the management of estuaries as the type of land cover heavily influences the supply and delivery of sediment throughout the catchment and changes in land cover can be the primary cause of soil degradation (Lambin et al. 2001). Changes in land cover can also have an impact on the biodiversity and hydrology of regions (Sohl & Sleeter 2012, p226). Knowledge of the type and distribution of land cover can disclose important environmental information needed for scientific analyses, resource management and policy development (Foody 2007). In particular, the removal of natural vegetation cover has been seen to greatly accelerate processes such as gully erosion, riverbank erosion and surface runoff (Radke et al. 2004).

Land cover change is determined by using a range of modelling approaches requiring historical and current land-cover maps (Sohl & Sleeter 2012, p226). Land cover and land use are two terms widely used when assessing the state of the land and changes which have occurred. Land cover refers to the biophysical materials found on the land (Jensen & Cowen 1999). It can be derived from remote sensing data such as aerial photography. Land use cannot be calculated directly from remote sensing data as it requires a combination of remote-sensing observation and local and regional knowledge (Sohl & Sleeter 2012, p228). Land cover and land use are not interchangeable terms; however they are able to be linked if the correct information regarding the use of each land cover type is known (Comber 2008). The two possess differing functions with the main purpose of land cover being mapping for environmental purposes whilst land use mapping is utilised largely for policy making (Comber 2008).

Land cover classification can be achieved using a number of methods, with some methods better suited for certain applications, depending on the aims and the data sets available (Foody, 2007). The increase in the availability of satellite data and technological advances has improved classification techniques. Additional spectral bands that can enhance classification outputs include infrared and panchromatic bands.
The presence of an infrared band allows the differentiation of vegetated and non-vegetated regions using an NDVI index, and the spectral signatures can then be used to classify cover. Older imagery and aerial photographs do not have this capability.

Errors associated with creating thematic maps are large, as they are a simplified representation of reality (Foody 2007). Acknowledging inaccuracies and the extent of inaccuracy is important to establish the suitability of the map and take into account any flaws which may be present (Lillesand et al. 2004). Nonetheless, current techniques possess the ability to quantify changes in land cover and identify regions of land cover types to assist in the development of management plans and the achievement of outcomes.
Chapter Three: Back Lake

3.1 Physical Setting

3.1.1 Regional Setting

Back Lake is an ICOLL situated on the Northern fringe of Merimbula on the south coast of New South Wales (NSW) (Figure 6). Merimbula is approximately 470 km south of Sydney and 70 km north of the border between NSW and Victoria and (36°52'53.62"S, 149°55'38.36"E.) Back Lake has a waterway area of 0.3813 km² and a volume of 500 ML which makes Back Lake a relatively small estuary. Back Lake is fed by the freshwater Merimbula Creek that flows into the west of the lake, and drains most of the 31.03 km² catchment. Yellow Pinch Dam was built in 1997 in the upper reaches of the catchment to provide water to Merimbula. The dam does not release any water to the Back Lake catchment.

Figure 6: Back Lake in Merimbula; Inset: Merimbula is located on the south NSW Coast.
As an ICOLL, Back Lake is periodically connected or disconnected with the open ocean. The entrance of Back Lake is either artificially or naturally opened approximately every six months and is generally open for up to one week, depending on water levels (Haines & Rollason 2009). During the times when Back Lake is closed, tidal and wave action are unable to permeate the estuary, increasing the sensitivity of the lake to excessive nutrient and sediment inputs (Haines & Rollason 2009). When acting as a terminal lake, water levels respond to catchment runoff, direct rainfall, evaporation, leakage through the barrier beach and groundwater inflows and outflows (Robertson et al. 2011). During these conditions the water quality in Back Lake depends on the quantity and quality of water from the catchment, and the evaporation rate from the lake water body (WMA 1997).

Back Lake has been classed as having an ‘extreme’ natural sensitivity (HRC 2001). This classification refers to sensitivity as ‘the capability of the lake to tolerate modifications within their catchments or within their water bodies, without measurable degradation of their water ecosystems’ (HRC 2002). Geoscience Australia quantified sensitivity within the lake by creating a sensitivity index. This is determined by calculating the average of the ratio between change in potential eutrophication (PE) with land use and effective loading changes and how effective loading changes with land use (Geoscience Australia 2013). The small estuary area of Back Lake and the predominantly closed entrance produces a highly sensitive system to changes in the catchment. This can be seen by the comparison with Merimbula Lake in Figure 7, that has a much larger estuary size and a permanently open entrance, which allows the regular flushing of water, leading to higher water quality values as replacement of water within the system is frequent.

![Figure 7](image)

Figure 7: A comparison of water quality values between Back Lake and Merimbula Lake showing the Total Nitrogen load (TN), Sensitivity, Potential Eutrophication (PE) and the levels of chlorophyll (Geoscience Australia 2013).
3.1.2 Catchment Characteristics

On a catchment scale, the contributing drainage area to Back Lake has undergone a relatively small amount of anthropogenic change, with catchment condition classified as ‘largely unmodified’. The existing condition of Back Lake has been defined as moderately affected, indicating that whilst the catchment remains in good condition, the water area of Back Lake experiences some stress (HRC 2002).

Eight five percent of the Back Lake catchment is vegetated by open forest, shrub and patches of littoral forest (Haines & Rollason 2009; OEH 2011). The open forest is dominated by yellow and white stringy-bark and silver top ash and shrub species present include black she-oak and hickory wattle. Two national parks Bournda National Park and South East Forests National Park occupy a combined area of fifty percent of the catchment area (Haines & Rollason 2009). In addition to the area occupied by the two National Parks, Bournda Nature Reserve also plays an important role in protecting a variety of habitats and species (Haines & Rollason 2009), signifying the most Southern extent in distribution for several species such as the native grape and the hairy psychotria (NPWS 2000). The South East Forest National Park is part of an important continuous chain of reserves that span from the escarpment at Illawarra to south of the Victorian border (NPWS 2006). It is part of a system adjoining with Egan Peaks Nature Reserve, covering an area of 117.644ha in total. The chain of reserves provides habitat for four endangered plant species listed under the Threatened Species Conservation Act (TSC Act) and seven vulnerable plant species with two plant species endemic to the park (NPWS 2006).

The foreshore of Back Lake has been cleared extensively, with primary use as pastures prior to 1948 until 1972. Urban developments such as Berrambool Creek and Mirador Estate have extended into bushland on the northern side of Back Lake, fragmenting forest area. Ecology within the lake includes highly variable populations of seagrass, supporting populations of silky weed (Zosteraca) and sea tassels (Ruppiaspp.). Coverage of each species varies, with Zostera more prevalent during periods of entrance opening creating preferential tidal conditions, and Ruppiapreferring brackish conditions (WMA 1995). Distribution of the seagrass beds can decrease rapidly with opening events that drain the lake (WMA 1995).
Back Lake is bordered by steep sandstone slopes on either side of Back Lake that signify the northern and southern extents of the catchment (Figure 9). The Back Lake catchment is hilly with moderate to steep slopes of 10% to 30% throughout the catchment (WMA 1995). The northern side of Back Lake is a steeply sloping hill, on which Mirador Estate is situated. The southern side has low lying salt marsh before rising into a small ridge line between Merimbula Lake and Back Lake.
The geology of the region consists of sandstone, conglomerate with undifferentiated bedrock units, forming the Merimbula group (Figure 10). The coastal fringes of Back Lake and the estuary reaches are Quaternary alluvium consisting of fluvial sands, silts and clays (DPI 2004). Creeks within the Back Lake catchment contain valley fill units which are thin units of poorly sorted clay, silt and sand overlying bedrock (DPI 2004). The soil landscape of the catchment is mainly comprised of Yellow Pinch soils, which cover 97% of the catchment (WMA 1995). A summary of the soils in the catchment can be seen below,

Table 3: The major soil landscapes present in the Back Lake catchment.

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
<th>Location</th>
<th>Catchment %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yellow Pinch</td>
<td>Yellow Podzol</td>
<td>Rolling to steep hills, open forest and some closed forest.</td>
<td>97</td>
</tr>
<tr>
<td>Jellat Jellat</td>
<td>Alluvial Soils</td>
<td>Cleared food plains</td>
<td>1</td>
</tr>
<tr>
<td>Bemboka</td>
<td>Red and Yellow Podzols</td>
<td>Undulating low hills, cleared open forest</td>
<td>1</td>
</tr>
<tr>
<td>Wapengo Lake</td>
<td>Lacustrine Sands</td>
<td>Estuarine sand flats, mangrove and saltmarsh</td>
<td>0.5</td>
</tr>
<tr>
<td>Wallagoot Foredune</td>
<td>Siliceous sands</td>
<td>High beach foredunes and health</td>
<td>0.5</td>
</tr>
</tbody>
</table>

Yellow Pinch Soils have been classed as highly erodibility and acidic, with low permeability and fertility properties (WMA 1995). Yellow Pinch soils are a Yellow Podzolic soils, containing a dominant iron oxide of goethite, which contains aluminium oxide, providing the yellow colour (Davey et al. 1975). The principle clay minerals of these soils found in the NSW region is kaolinite and illite-smectite. Illite-smectite is more abundant in finer clay particles (Davey et al. 1975). The erosive properties of Yellow Pinch soils can be seen around Back Lake where development has occurred, and within creeks lines and gullies throughout the catchment that are very prone to erosion (Haines & Rollason 2009; WMA 1995).

Valley fill units are present on both the west and east end of Berrambool creek (Figure 9 and Figure 10) and are a probable source of sediment that is washed into Berrambool Creek during rain events.
Figure 10: The units and lithology of the region and around Back Lake (Department of Primary Industries, 2004).
3.1.3 Human Environment

The population of the Merimbula – Tura Beach region is estimated to be 10,088 (ABS 2011). Taking into account past population growth and current trends, it has been recommended that Merimbula region plan for an increase of 5000 extra residents by 2026 (BVSC 2008). Within the Back Lake catchment, current urban developments include the Berrambool and Sapphire Coast Drive subdivisions (Figure 11), as well as parts of Merimbula Township on the northern and southern foreshores of the lake. The most recent urban development within the catchment is Mirador Housing Estate, the construction of which is still underway. This is set to provide an additional 500 dwellings on the land to the north of the lake (BVSC 2008). Much of the native vegetation was initially cleared when development of Mirador estates begun and a number of lots remained undeveloped as can be seen in Figure 12.

Figure 11: The locations of the housing estates north of Back Lake.
3.2. Current Approaches to Management

3.2.1. Catchment Planning

Planning in the catchment is governed by Bega Valley Shire Council (BVSC) Local Environment Plans (LEPs) which dictate zoning and development approvals. The BVSC LEP for 2013 has been zoned to include additional R2 (Low Density Residential) zoning in the Mirador Estate area (Figure 13). Low Density residential zoning is generally used for land comprising existing or proposed low density residential development (BVSC, 2010). Berrambool Estate is zoned as Medium Density Housing (R3). The additional R2 zoning has avoided steep slopes that may be more susceptible to sediment loss and has been zoned as R2 in an attempt to limit potential runoff from the site (Haines & Rollason 2009).
Figure 13: The 2013 LEP zoning of the region, with Back Lake catchment highlighted. Inset: The increase in R2 (low density residential; pink area north of Back Lake (W1)) zoning, adding to the existing Mirador Estate R2 zone. Key for zones is R2 – Low Density Residential; R3 – Medium Density Residential; E1 – National Parks and Nature Reserves; E2 – Environmental Conservation; E3 – Environmental Management; E4 – Environmental Living; SP1 – Special Activities; SP2 – Infrastructure; SP3 – Tourist; RE1 – Public Recreation; RE2 – Private Recreation; W1 – Natural Waterways; W2 – Recreational waterways; B2 – Local Centre; B4 – Mixed Use.

There has been a range of conditions placed on the development occurring in Mirador Estate by the council. These include the implementation of buffer zones, the treatment of stormwater onsite and the retention of existing vegetation within allotments as much as possible (Haines & Rollason 2009).
3.2.2 Entrance Management

Clearing of native vegetation has altered the natural cycle of estuary openings (Keneley et al. 2012). Estuary entrance management is the manipulation and monitoring of entrance conditions in an attempt to tailor estuary processes to better suit anthropogenic requirements. The need for entrance management in south NSW has largely arisen due to impacts of high water levels on infrastructure and human assets. This affects local residents, and demand arises to mitigate undesirable conditions created by variable rainfall. Variable rainfall in south NSW creates long periods where the entrance is closed (Stephens & Murtagh 2000). Conditions that arise from long periods of entrance closure include the production of algae reducing visual amenity, an increase in odour and reduced water quality due to the lack of flushing ability (Hanslow et al. 2001; Roy et al. 2001). Entrance condition also affects the water levels throughout the estuary. Heavy rainfall may lead to an increase in the water level of the estuary that may not overtop the berm or scour an entrance to the ocean (Hanslow et al. 2001). This could cause the water level in the estuary to become elevated, posing a risk to housing, backyards and sports fields that exist in close proximity to waterways. Over three quarters of ICOLLS in NSW are artificially opened, namely for flood mitigation or due to poor water quality (Hanslow et al. 2001).

Figure 14: Back Lake during an artificial opening event, 26/6/13. Photo: Bega Valley Shire Council

Heavy rain events can cause an increase in the supply of water to the Back Lake catchment. If the water levels rise to above 1.4m, flooding is experienced at the Berrambool Sporting Complex and other low lying assets such as urban backyards (BVSC 2013). The current Review of Environmental Factors (REF) procedure for artificial opening of the entrance is to cut a channel when the water level reaches 1.4m or greater (as outlined in the Back Lake Management Policy) in order to re-establish a temporary tidal connection between the lake and the ocean. This is to allow
accumulated water to flush to the ocean and thereby lower water levels. The REF which was compiled by BVSC notes that there are no viable alternatives to the artificial opening of Back Lake. Future changes that have been suggested in the REF for Back Lake's entrance could be to implement a variable level. A variable level would mean that the entrance is opened at a variety of different water levels in an attempt to emulate natural water level fluctuations, providing ecological processes with variation in water heights. Some variation is already implemented with the entrance opened at slightly lower levels, provided certain conditions are met (BVSC 2013).
Chapter Four: Methods

4.3 Mapping of Catchment Area

A time series of aerial photographs ranging from 1948 to 2011, supplied by the Office of Environment and Heritage, was obtained for analysis. The images were supplied as scanned aerial photographs and consist of three spectral bands (blue, green and red). Each separate image had varying spatial resolutions and coverage of the catchment region. Not all images provided were incorporated into the analysis due to inadequate coverage of the study area. Aerial photographs were visually assessed to examine changing land cover on the foreshores of Back Lake as a result of development and any visible changes of the lake morphology.

Image classification was conducted to establish land cover using the mapping software, ArcGIS and ENVI to determine the spatial extent of land cover changes. Supervised and unsupervised approaches to classification were conducted. Two supervised methods were tested, a maximum likelihood approach and minimum distance-to-means. The maximum likelihood approach yielded the highest accuracy and was used for the final classification of the images. A Maximum Likelihood Classifier determines what class a pixel lies by computing the statistical probability of a pixel belonging to a class by assuming that pixels are normally distributed (Lillesand et al. 2004). This method takes into account the covariance and variance of the category spectral response patterns. Minimum distance-to-means creates a mean vector for each category, and a pixel is classified by determining the distance between the value of the unknown pixel and of the category means (Lillesand et al. 2004). The limitations associated with this method are its insensitivity to variance in the spectral response data (Lillesand et al. 2004). Therefore, this method is not widely used in cases where the spectral classes are close to another with a high degree of variance.

Before commencing the classification, the images needed to be interpreted and the key points extrapolated to enable the selection of the most appropriate classification method (Moran, 2010). The steps required in the classification process are training, classification, output and validation (Gambaraova et al. 2010). ArcGIS was used to prepare the aerial photography for analysis, and ENVI was used for image processing.

The images were geo-referenced using roads in the region as ground control points, with the most recent photos geo-referenced first. This was done as the roads present in
the recent images were able to be closely matched to the road layer that represented the present situation. Older images were georeferenced chronologically, working from the most recent to the oldest as this allowed the identification of consistent ground points.

Water was eliminated from the classification by digitising the lake borders and using the erase tool on ArcMap to remove them from the images. This was done to increase accuracy of the classification as the water and vegetation in the images shared similar covariance and variance in all three bands causing an overlap of pixels (Figure 15).

![Figure 15: A scatterplot of the values of three bands present in the aerial photography. The water (blue) and vegetation (green) show a large amount of overlap in all three bands. The scatterplots should not overlap if the training samples defined represent different classes.](image)

This contributed to an increase in classification error as the water class was largely incorporated into the forest class. Water was not required as part of the land cover classification as land cover was being determined within the catchment and the presence of visible water in the upper catchment is negligible. Only visible regions of Merimbula Creek were removed, as parts of the creek that were located in densely vegetated areas were unable to be differentiated. The Yellow Pinch Dam was also removed from images in which it was present. A mask was produced of the Back Lake Catchment Region to eliminate areas in the imagery that were not required for the classification.

The selection of training data is an important step in the classification process as training data provides a sample area which enables the categorisation of pixels into classes. The land cover classes established were forest, urban, bare earth and grass. The
grass and bare earth classes were defined as two classes to enable increased accuracy in classification however the black and white aerial photographs (1948, 1972, and 1975) proved difficult in visually discerning between urban, bare earth and grass. Due to this, only two classes were used for these years, cleared area and forest. Training data was selected with an aim to represent the full variability present in each class. Classes such as urban area encompass a high degree of spectral variation within the same land-cover class. This means that pixels are more likely to cross over with other classes, decreasing the accuracy of the classification.

Table 4: The definitions used for the supervised and unsupervised classification of images.

<table>
<thead>
<tr>
<th>Class</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Urban</strong></td>
<td>Included roads, houses, shops, waste treatment plant, car parks.</td>
</tr>
<tr>
<td><strong>Grass</strong></td>
<td>Included ovals, backyards and areas that have been cleared for development</td>
</tr>
<tr>
<td><strong>Bare Earth</strong></td>
<td>Bare earth with no vegetation present.</td>
</tr>
<tr>
<td><strong>Forest</strong></td>
<td>All areas that were vegetated by trees.</td>
</tr>
</tbody>
</table>

Each classifications was assessed for accuracy using a set of 100 random points to review the classes that the pixels were placed across each image and it was visually determined whether they had been correctly identified. Pixels that were misclassified were tallied and entered into an error matrix. An error matrix is a square table of numbers set out in rows and columns in which the number of pixels assigned to a particular class are entered. An error matrix is seen as an effective way to display accuracy as pixels that are assigned correctly are plainly displayed, along with pixels which were misclassified (Congalton, 1991). An estimated percentage of the agreement between the classification cover and image ground cover was then calculated using the error matrix. This method used a direct comparison between the aerial photography and the classified images. The use of ground truth points collected in the field is a more reliable method of accuracy assessment; however this was not available for the study.

To provide a clear visual representation of the changing land cover over time and for further comparison with results achieved from the supervised classification, classes were also digitised with a user defined method. Polygons were created for each of the classes by tracing over classes in images. This produced an indication of the areas of land cover types. The definitions of classes changed with this method of classification as
it is not possible to exclude trees and backyards in urban areas. The forest class was defined as one class and bare earth between the trees was not classified. The definition for the urban class included any land associated with housing including backyards, ovals and trees. Forest was classified as a large area dense growth of trees. The 1948 image did not allow for delineation between finer classes such as grass, bare ground and urban areas.

4.4 CERAT Modelling

The Coastal Eutrophication Risk Assessment Tool (CERAT) was developed by the Office of Environment and Heritage (OEH) and was launched in 2011. CERAT is a tool for predicting the likely direction and extent of change occurring under different environmental scenarios (Geoscience Australia 2013). The tool defines lakes and lagoons as estuaries that close and open intermittently, producing ephemeral connections to the ocean. CERAT contains data for lakes, lagoons and riverine estuaries along the NSW Coast, with data present for a total of 184 catchments (OEH 2012). The data included in the tool is collected from the NSW Natural Resource Commission condition indicators and relates to the Natural Resources Monitoring, Evaluation and Reporting Strategy 2010-2015 (Geoscience Australia). The NRMERS is a report compiled by the Office of Environment and Heritage (OEH) that aims to use scientific data to enhance the success of natural resource management (NRM) in NSW. The report aims to guide the monitoring, evaluation and reporting efforts of natural resources (OEH 2012).

Inputs available for use in CERAT include nitrogen loads, total suspended solids, total, chlorophyll and total phosphorus, and surface and base flows. The tool consists of four modules; a risk assessment, sustainable load assessment tool, a catchment model and an estuary model. The estuary model allows evaluation of the potential effects of management actions on the health of the estuary, and the impact on different determinants. It takes into account the vulnerability of an estuary to changes in inputs and planning decisions (OEH 2012).

CERAT is relevant in a management context, as limitations in the presence and availability of field data has led to a gap in current data for use in the assessment of estuarine health. CERAT has the ability to be used as an indicator of the trends occurring in estuaries. It is not recommended to be used as a precise tool due to assumptions that
are made in the interpretation of data which enables the tool to be applied to a wide set of estuaries. Limitations include the use of data with a broad spatial scale of 250m resolution. Local factors affecting flows of nutrients are not taken into account such as sediment management practices (Geoscience 2013).

The CERAT Catchment Model was used to model the impacts that proposed zoning of the land adjacent to Back Lake may have on future water quality. The area of forest present in the R2 zoning plan was calculated. The percentage change of land being converted from forested to both cleared land and urban land was determined. It is assumed that the vast majority of this vegetation will be removed within the zoning. This provided patterns of TN, TP, TSS and surface flow levels. These indicators all have an impact on the sediment supply and water quality of Back Lake.

The determinants used for the models were surface flow (a product of lateral flow and surface flow) and TSS. Outputs were produced displaying the impacts of converting forest to urban and cleared land on total suspended solids and surface flow. The resolution of data for Back Lake is divided into three subcatchments (Figure 16). Subcatchments have been determined based on flow catchments and the development of areas (WMA 1995).

Figure 16: The catchment divided into three subcatchments, displaying the areas which exhibit contiguous outputs (OEH 2012).
4.5 Analysis of Short Cores

The sedimentary history of an estuary may be determined by extracting sediment cores. This able to provide information on changes in the catchment and the follow-on effects that catchment use has on sediment distribution and deposition. Due to these capabilities, a series of short cores were taken in the study area of Back Lake (Figure 17). This was undertaken to determine the impacts of change in the catchment that was investigated with aerial photography of the Back Lake catchment and mapping of the change in land cover in the catchment.

4.5.1 Core Extraction

Six push cores were taken on 3rd July 2013 from Back Lake, from six different depositional environments present in the estuary (Figure 18). A metal pipe with a 250 mm diameter was inserted into the chosen site using a wooden block and hammer. The pipe was inserted until there was too much resistance to continue. Measurements were taken for the calculation of compaction, including the depth from the top of the water to the sediment, both inside and outside of the pipe. Water depth was also measured. The top of the pipe was then sealed with a rubber cap. The pipe was extracted using a clamp and two poles to lever the core from the sediment. The bottom of the pipe was sealed using a second rubber cap which was attached as the core was removed from the sediment. The amount of sediment lost from the bottom of the pipe was negligible, as the sealing effect provided by the use of the cap placed on the top end of the pipe enabled sediment to remain in the pipe. This method was conducted for all cores, except for core 6. Due to the loosely packed, coarse river gravel found in core 6, a slit was cut in the bottom cap to allow water to drain without disturbing the core sediment. The top of each core was marked to ensure that they remained the right way up and the top of the core was known.
Cores were transported back to the laboratory whilst remaining upright in the vehicle for the duration of the trip. Compaction was accounted for by measuring the depth to the soil outside of the pipe and the depth of the soil inside the pipe before the core was extracted. The difference between the two measurements provided the amount of...

Figure 17: Core Locations across Back Lake. Inset: Sample A, B, C & D were grab samples extracted using a box sampler and cores 6 & 7 were taken to further clarify results found in core 5.
A. Borrell (2013)

compaction which occurred when the pipe was inserted into the sediment. The amount of compaction was then spread over the core to obtain the true core length.

The six sites were chosen to provide information on the sediment present in the range of environments present in Back Lake (Table 5; Figure 18). Cores 1, 2 and 4 were retrieved from the central basin.

Table 5: Outlines the conditions present in the six depositional environments that were chosen for cores retrieval from within Back Lake.

<table>
<thead>
<tr>
<th>Environment</th>
<th>Cores</th>
<th>Description of site</th>
</tr>
</thead>
<tbody>
<tr>
<td>Central Basin</td>
<td>Core 1</td>
<td>The central basin of an ICOLL generally exhibits lower rates of sediment accretion. The central basin can provide a good account of sedimentation rates closer to that of natural conditions and can be used for comparison with cores that are likely to have been affected by increased sedimentation.</td>
</tr>
<tr>
<td></td>
<td>Core 2</td>
<td>Core 3 was extracted from the mouth of Paige’s Creek which adjoins the central basin as this creek is likely to deposit sediment runoff from Mirador Estate and then new zoned development. A core was retrieved from here to investigate current sediment deposition and identify any recent change in sediment type.</td>
</tr>
<tr>
<td></td>
<td>Core 3</td>
<td>Core 3 was extracted from the mouth of Paige’s Creek which adjoins the central basin as this creek is likely to deposit sediment runoff from Mirador Estate and then new zoned development. A core was retrieved from here to investigate current sediment deposition and identify any recent change in sediment type.</td>
</tr>
<tr>
<td>Salt Marsh</td>
<td>Core 4</td>
<td>The site of Core 4 was salt marsh, a significantly different environment from the other core locations. Housing was established adjacent to the salt marsh prior to 1948 (as determined from aerial photographs), and could display anomalies in sediment that may have been a result of clearing early on.</td>
</tr>
<tr>
<td>Berrambool Creek</td>
<td>Core 5</td>
<td>It is likely that excess sediment was deposited in Berrambool Creek as a result of the removal of clearing of the top soil for development in the 1970s. The cores extracted from the creek may provide an indication on the extent of disturbance that clearing had on the sediment supplied to the creek.</td>
</tr>
<tr>
<td></td>
<td>Core 6</td>
<td>Core 6</td>
</tr>
<tr>
<td></td>
<td>Core 7</td>
<td>Core 7</td>
</tr>
<tr>
<td></td>
<td>Core 8</td>
<td>Core 8</td>
</tr>
<tr>
<td>Merimbula Creek</td>
<td>Core 6</td>
<td>Taken from downstream of the junction of Berrambool Creek and Merimbula Creek, this is a higher energy environment receiving high velocity flows and transporting sediment to the central basin. Rain events would supply this part of the creek with runoff from Berrambool Creek, and may exhibit sediment similar to that of Berrambool Creek.</td>
</tr>
</tbody>
</table>
The cores extracted from the six locations ranged between 45cm to 100cm in length. The cores were taken back to the laboratory and opened longitudinally using a circular saw, and the core sediment was sliced in half using a pull wire. All the cores were photographed and visually logged following standard procedures outlined by the Australia Soils and Land Survey Field Handbook, 2nd edition (McDonalds et al. 1998). Two additional short cores (Cores 7 & 8) and four grab samples using a wedge shaped box sampler were extracted from Berrambool Creek to further examine the extent and pattern of deposition of the units identified within Core 5. Grab samples were extracted using a wedge shaped box with handles on the top. This was inserted into the soil, and a ‘lid’ slid over the open wedge face. The box was then removed with the sediment sample inside. The locations of the cores and grab samples were recorded using a GPS.
4.5.2 Sediment Analysis

Samples were taken from each core for sediment analyses. Sediment colour was determined using a Munsell soil colour chart. These colours were recorded at the time of splitting the cores to ensure colour wasn’t altered as a result of oxidisation. Grain size and associated sedimentological characteristics such as sorting, skewness, kurtosis, the number of modes per sample and the corresponding grain size for the modes was analysed using a Malvern Mastersizer 2000 laser particle size analyser. This technique measures the size of particles using laser diffraction. The dispersed particulate sample is drawn past a laser beam suspended in water, with the intensity of the light scattered proportional to the size of the particles (Malvern Instruments Ltd, 2012).

X-Ray Differentiation (XRD) analysis establishes mineral composition by measuring the angles of diffraction when lasers are passed through the sample. XRD analysis was used to identify the primary mineral composition within samples taken from cores 1, 3, 4 and 5. In order to undertake this analysis, samples were dried for a period of 24 hours at 50 °C. Samples were taken where major facies changes were identified, and where the presence of obvious changes was not apparent, a sample was taken every 2.5cm. Once dried, samples were crushed using a mortar and pestle. Traces and Siroquant software were used to aid the identification of the minerals present in the sediment samples.

Organic matter content was estimated by Loss on Ignition (LOI). LOI is an inexpensive and fast method, requiring minimal labour compared to traditional acid digestion methods (Wright et al. 2008). LOI assumes that the mass loss that occurs under high temperatures is proportional to the organic-content of the soil (Bhaiit & Bauer 2007; Wright et al. 2008). This was conducted to further contrast changes in sediment down core. The samples from Core 5 were taken from where major facies changes could be seen and dried in an oven overnight to remove all the moisture. Samples were then weighed and incinerated at 400°C for approximately 20 hours. The samples were weighed again and the difference in weight represented lost organic matter, providing the organic matter of samples.
Chapter Five: Results

5.2 Aerial Photograph Analysis

Back Lake and the surrounding foreshores were visually assessed and changes noted, on aerial images from 1948 to 2011 (Figure 19).

The analysis of aerial photos clearly displayed the conversion of pastoral land to urban areas since 1948. Forest area has decreased within the catchment with majority of the clearing occurring on the area north of Back Lake, for the establishment of Mirador Estate. Land use to the south and the west of the lake intensified to include a greater number of urban dwellings and also as a commercial centre. Riparian vegetation along Merimbula Creek has been regenerating since 1948.

The observable changes in Back Lake catchment by year are summarised below;

a. In 1948, Merimbula Creek was a small meandering creek that ran through the densely vegetated catchment until it reached the cleared area on the foreshores of Back Lake. Clearing had removed much of the riparian vegetation around the creek, presumably for grazing. Berrambool Creek is fed from a creek line adjacent to the creek and joins with Merimbula Creek. The creek became slightly wider with possible remnant meanders that formed small oxbow like lakes. A fluvial delta restricted the creek width as it approached the central basin. The lake was shallow with a narrow outlet towards the ocean. No vegetation is present on the sand barrier. Merimbula town can be seen to the South of the lake. There is no clearing evident north of Berrambool Creek and gravel roads are evident in Merimbula Township.

b. By 1972, clearing had removed vegetation on the top of the hill north of Back Lake and areas adjacent to Berrambool Creek. Between 1972 and 1975 construction began on Berrambool Estate. Notable clearing has occurred on previously grassed areas. There has been increased development on the South side of the Lake, and the development of a road that runs along the Northern side of the lake. Sediment can be seen in Berrambool Creek, with it appearing much lighter in colour than areas further downstream. Riparian vegetation has increased along Merimbula Creek and the sand bars in the central basin have become more stable, and vegetation has become established. Sediment can be seen building up on the bend leading toward Back Lake. Sediment is building up at the entrance as the berm increases in size. Channels within the central basin can be seen.

c. The 1989 image shows that the construction of Berrambool Estate has been completed. A large area on the hill cleared before 1975 is now revegetated. Berrambool creek continues to be cut off from the creek and vegetation is now evident at the Western end of the creek. The sand barrier continues to become
more vegetated. The building of the flood/ebb tidal delta can be seen as Merimbula Creek meets with the central basin. Berrambool sports complex has been constructed on the floodplain (former farm flats) adjacent to Merimbula Creek and Berrambool Creek.

d. In 1998, the site for Mirador on the top of the hill north of Back Lake has been extensively cleared leaving exposed bare earth. Berrambool Estate appears to have increased in density. Roads have become more prominent in the north west from the Mirador and Berrambool developments. The morphology of Back Lake shows little change. By 1999, the newly cleared area has been colonised by grass and housing development.

e. The 2005 photo shows a further increase in the area covered by clearance for Mirador Estate in a north westerly direction, with some new housing constructed. The point located north west of the central basin has been cleared of vegetation.

f. In 2011 the Berrambool Estate has remained stable in area and density. Development seems to have been completed in the Estate. The clearing of vegetation for Mirador Estate has continued and spread further north. There does not appear to be a significant amount of housing established in the areas that have been cleared. The area that was cleared adjacent to the central basin is still undeveloped, with the area cleared slightly larger than in 2005. Riparian vegetation re-establishment along Merimbula Creek has slowed, and little changes have occurred in the low lying coastal area.
5.3 Land Cover Classification

Analysis of land cover present from 1948 to 2010 in the Back Lake catchment showed an increase in both urban and cleared areas. The amount of forested area in the catchment has remained stable over this time, with most of the change occurring between the cleared, grass and urban classes. The initial clearing present in the 1948 image has remained the central area for development throughout all images.

The three methods of classification produced relatively similar results. The unsupervised classification did not use training samples and produced four classes, with the grass and bare earth classes unable to be visually separated. As the training regions were not defined by the user, allocation of the classes was determined by automatic grouping of pixels conducted using an algorithm. However it can be assumed that Class 1 is forest, Class 2 are grassed areas and Class 3 represents developed areas. Due to this constraint, bare earth, grass and urban statistics were combined to form a total ‘cleared’ class. As such, the unsupervised results therefore do not record an accurate representation of total catchment land cover, although they do provide a fair representation of the cleared areas present within the catchment (Figure 20).

Figure 20: Unsupervised land cover classification for 1972. Note the misclassification of forested areas as Class 2 (Grass).
The classification results for 1948, 1972, 1975 and 1998 from a supervised maximum likelihood classification can be seen in Figure 22. These years were all directly compared as they all conveyed the same coverage of the catchment. The spatial coverage of the photos covered approximately a third of the catchment area. Vegetation in the catchment in 1948, covered between 90% and 94% of total land area as shown by the results from the two supervised classifications. An accuracy assessment of the maximum likelihood classification found that this classification was 78% accurate (Table 7). The unsupervised classification yielded a result that predicted significantly less forested area than the supervised methods. Areas that were not vegetated in the 1948 photograph were obvious due to high reflectance in the image, appearing as bright white patches. This occurred between trees and was classified as developed area, however such areas in reality are bare ground. Apart from this, the image was classified accurately and provided a good indication of the vegetation cover of the catchment in 1948.

The minimum-to-distance and maximum likelihood classifications (supervised classifications) both showed a decrease in the vegetation class between 1972 and 1975, highlighting the removal of covered ground to form cleared areas. The unsupervised method did not differentiate between changes in land cover between these years and the classification remained similar. The area of land that was developed increased from 1.7km² to 3.0km² within the three years (Figure 21). This occurred primarily through the widening of vegetation corridors to Mirador Estate on the hill and the removal of grassed areas.

Table 6: The percentage of land cover types in years 1948, 1972, 1975 and 1998, gained from three different methods of classification. These four years are directly compared here as they all had the same catchment size present in the images classified.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Vegetated (%)</td>
<td>Developed (%)</td>
<td>Vegetated (%)</td>
<td>Developed (%)</td>
</tr>
<tr>
<td><strong>Maximum Likelihood</strong></td>
<td>94.0</td>
<td>6.0</td>
<td>84.2</td>
<td>15.8</td>
</tr>
<tr>
<td><strong>Minimum to distance</strong></td>
<td>90.0</td>
<td>10.0</td>
<td>84.6</td>
<td>15.4</td>
</tr>
<tr>
<td><strong>Unsupervised</strong></td>
<td>78.4</td>
<td>21.5</td>
<td>85.9</td>
<td>14.0</td>
</tr>
</tbody>
</table>
The 1999 and 2010 images had coverage of the entire catchment, providing a classification of the land cover of the whole catchment, unlike other years. The images consisted of three colour bands, so more classes could be delineated than the black and white images providing a more detailed classification. Current land cover appears to be similar to that of 1948, however it was found that vegetation had increased to reach 90% coverage of the catchment in 2010. The high representation of vegetation could be attributed to changes in grass colour causing pixels to be classified as different classes between years. This is shown by the 66% decrease in grass between 1999 and 2010. The condition of the grass in 1999 was very different to 2010, appearing brown in the image. This would cause the grass to be classified as bare earth or urban. However this indicates that clearance of forest areas hasn't been as widespread as between 1948 and 1972. The increase of vegetation in previously cleared areas would also add to these values, such as the increase in vegetation in riparian zones along Merimbula Creek since 1948. The accuracy assessment carried out indicated that 79% of pixels classified in 2010 were classified correctly (Table 7).

Table 7: Results from accuracy assessments of classifications conducted for 1948, 1972 and 1975.

<table>
<thead>
<tr>
<th></th>
<th>1948</th>
<th>1972</th>
<th>1975</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vegetated</td>
<td>Cleared</td>
<td>Accuracy of Class</td>
<td>Vegetated</td>
</tr>
<tr>
<td>Class 1</td>
<td>70</td>
<td>76%</td>
<td>Class 1</td>
</tr>
<tr>
<td>Class 2</td>
<td>22</td>
<td>100%</td>
<td>Class 2</td>
</tr>
<tr>
<td>Overall Accuracy</td>
<td>78%</td>
<td>Overall Accuracy</td>
<td>83%</td>
</tr>
</tbody>
</table>

Figure 21: Areas in km² of developed land between 1948 and 1998. The excessive clearing that occurred in 1975 can be seen, with the most amount of cleared land present in 1975.
Table 8: displays the percentage of the prevalence of each land cover class in 1999 and 2010 as determined by the three methods of classification. The area of the photographs was larger than the previous years as the whole of Back Lake catchment is captured.

<table>
<thead>
<tr>
<th></th>
<th>1999</th>
<th>2010</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forest</td>
<td>86.5%</td>
<td>90.6%</td>
</tr>
<tr>
<td>Urban</td>
<td>3.9%</td>
<td>5.9%</td>
</tr>
<tr>
<td>Bare</td>
<td>0.7%</td>
<td>0.2%</td>
</tr>
<tr>
<td>Earth</td>
<td>9.0%</td>
<td>3.3%</td>
</tr>
<tr>
<td>Grass</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Method</th>
<th>1999</th>
<th>2010</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Likelihood</td>
<td>86.5%</td>
<td>90.6%</td>
</tr>
<tr>
<td>Minimum to distance</td>
<td>88.5%</td>
<td>75.1%</td>
</tr>
<tr>
<td>Unsupervised</td>
<td>91.4%</td>
<td>89.7%</td>
</tr>
</tbody>
</table>

Table 9: The confusion matrix produced from a maximum likelihood classification of 1999 and 2010 images.

<table>
<thead>
<tr>
<th></th>
<th>Grass</th>
<th>Forest</th>
<th>Bare Earth</th>
<th>Urban</th>
<th>Overall % Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>1999</td>
<td>4</td>
<td>8</td>
<td>1</td>
<td>-</td>
<td>62%</td>
</tr>
<tr>
<td>Grass</td>
<td>-</td>
<td>63</td>
<td>-</td>
<td>-</td>
<td>82%</td>
</tr>
<tr>
<td>Forest</td>
<td>-</td>
<td>0</td>
<td>4</td>
<td>1</td>
<td>50%</td>
</tr>
<tr>
<td>Cleared</td>
<td>-</td>
<td>6</td>
<td>3</td>
<td>12</td>
<td>71%</td>
</tr>
<tr>
<td>Urban</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Grass</th>
<th>Forest</th>
<th>Bare Earth</th>
<th>Urban</th>
<th>Overall % Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010</td>
<td>3</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>100%</td>
</tr>
<tr>
<td>Grass</td>
<td>-</td>
<td>72</td>
<td>-</td>
<td>-</td>
<td>89%</td>
</tr>
<tr>
<td>Forest</td>
<td>-</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>67%</td>
</tr>
<tr>
<td>Cleared</td>
<td>-</td>
<td>6</td>
<td>1</td>
<td>10</td>
<td>59%</td>
</tr>
<tr>
<td>Urban</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>

Overall % Accuracy 87%
For the purposes of the supervised classifications, the forest class was defined to include any tree or shrub present in the image, including the riparian zones along Merimbula Creek and trees in backyards. OEH (2013) defines forest as a ‘dense growth of trees, plants and underbrush that covers a large area’. This would not include remnant vegetation which was defined as ‘forest’ for this project, creating a different classification outcome, as seen in comparisons of Figure 22 and Figure 23. Urban areas were defined by OEH as ‘areas in which people live characterised by dwellings with gardens/grey water/sewage and roads’ (OEH, 2012). The definition used for the supervised image classification included housing, roads and paved surfaces in an urban definition. Backyards were classified as grass or bare earth areas.

The maps produced from classifications, showed a general increase in developed areas between the years of 1948 to 2010 represented in both methods of classification (Figure 22 Figure 23). Development has increased significantly on the northern side of Back Lake, with roads fragmenting large areas of the forest. Figure 23 is the result of a land cover classification conducted according to user defined boundaries. It displays an increase in development around Back Lake’s foreshores, and the development as part of the Tura Beach estate in the northern extent of the catchment. The trend in development which the mapping has highlighted is expansion of urban centres around the town the floodplains of Merimbula Creek and on the hill north of Back Lake and Berrambool Creek. Further development could be assumed to be allocated in these zones. All of the classifications conducted of land cover in Back Lake catchment showed an increase through time in the amount of urban, cleared and grass land covers, with the most amount of change occurring in subcatchment 1 of the catchment.
Figure 22: Maximum Likelihood Supervised classification outputs from 1948, 1975 and 2010 imagery displaying the change in land cover. Factors affecting the classification include the varying colours across the years in each image producing different results. The spread of the urban area to the west of Back Lake and the revegetation of some corridors is evident.
Figure 23: A broad land cover classification showing the increase of urban areas since 1948 to 2010. Land cover within the urban class in 1948 appears much more concentrated than 2010 where vegetation has been established.
5.4 CERAT Modelling

The percentage reduction in forested areas in subcatchment 1 was calculated (Table 1). The 21.35% reduction (rounded to 20%) was applied to catchment models generated in CERAT. This percentage was applied to all subcatchments to enable the comparison of the effects of clearance of vegetation between the three subcatchments, which all retain different proportions of forest. The calculation used to model change in the subcatchment assumes that most of the vegetation will be cleared under a low density residential zoning (R2). It can be seen in the existing R2 zoned areas that limited vegetation remains within the zoned area, indicating that large scale removal of vegetation is the most likely scenario to occur with further development. Changes due to removal of forested area were modelled using the catchment model tool in CERAT under two scenarios, the first modelling the effect of a change from forest to cleared area and the second, a change from forest to urban area.

Table 10: The area (km²) of R2 zoning and the forested area currently present in subcatchment 1.

<table>
<thead>
<tr>
<th>Total Area</th>
<th>Total Forested Area</th>
<th>R2 Zoned Area</th>
<th>Current Vegetated R2 Zoned area</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.89 km²</td>
<td>2.22 km²</td>
<td>0.802 km²</td>
<td>0.47 km²</td>
</tr>
</tbody>
</table>

% reduction in forested area = 21.35 %

Subcatchment 2 is the most degraded area of the catchment, as it has higher values for TSS, TN, TP and surface runoff than the other subcatchments. Subcatchment 2 includes the southern side of Back Lake, where Merimbula Township is located. Subcatchment 3 has lower values for all the determinants than both subcatchments 1 and 2. This illustrates the positive effect that low levels of development and a large area of forested area has on the catchment, enabling it to retain lower levels of nutrients and runoff. However, the large area of subcatchment 3 (26.8 km²) compared to subcatchments 1 & 2 would contribute to a higher resilience to changes in land cover. The land cover types that have the largest impact on the values of determinants are irrigated horticulture and dry horticulture.
5.4.1 Surface Flow

For the purpose of measurements, surface runoff is the sum of lateral flow and runoff (Geoscience Australia 2013). The current situation produced from the catchment model for surface flow in the Back Lake Catchment produces the highest values in subcatchment 2 of 159 ML/km²/yr (Figure 24), the subcatchment in which Merimbula Township is situated. Subcatchment 3 is the most densely forested part of the catchment and possesses a surface runoff value of 20ML/km²/yr less than subcatchment 2. Subcatchment 1 has greater surface flow than subcatchment 3. Surface flow is only affected once 10% of the forest area is converted to either cleared land or urban areas. However, a 20% decrease in forested area increases surface flows by 20ML/km².yr, which is equivalent to the current surface runoff in subcatchment 2.

Figure 24: The current situation in the catchment with surface flow as the determinant (ML/km²/yr). The result of a 20% removal of forest from subcatchment 1 and with a land cover of either urban or cleared area is an increase in runoff from 139ML/km²/yr to 159 ML/km²/yr.
5.4.2 Total Suspended Solids (TSS)

TSS has the lowest concentrations in subcatchment 3 with the least amount of TSS transported (Figure 25). Subcatchment 1 has a current value of 10399 kg/km²/yr. The model estimates that if 20% of the forest area in subcatchment 1 is converted to cleared area, TSS will increase to 39,999 kg/km²/yr. This is a substantial increase in the amount of TSS present in the water transported into the lake. However, a change to urban area from forest produces no change, retaining a value of 10,399 kg/km²/yr. This illustrates the impact of unconsolidated sediment on the presence of particles suspended in water, as cleared areas produced significantly larger values of TSS than urban area.

![Figure 25: TSS increases from 10,399 kg/km²/yr to 39,999 kg/km²/yr if there is a 20% change of catchment cover from forest to cleared area (bottom left). The figure on the bottom right shows the impact of a 20% removal of forest to urban area, producing no change in the amount of TSS from the current situation model.](image)

5.4.3 Total Nitrogen (TN)

As shown by Figure 26, TN varies across the 3 subcatchments, with subcatchment 2 containing the highest TN value of 48 kg/km²/yr. Values in subcatchment 1 increase by 350 kg/km²/yr if 20% of the forested area is changed to cleared land. There is no difference in TN if a change to urban area is applied. Values of TN equal the same as
values of TN from subcatchment 2 if 50% of the forest in subcatchment 1 is converted to urban area.

Figure 26: Subcatchment 2 has the highest TN of 299 kg/km²/yr. Subcatchment 1 has a slightly larger TN than subcatchment 3, of 199 kg/km²/yr. A land cover change scenario of a 20% decrease in forest area in subcatchment 1 to cleared area produces no change in TN. (bottom right). The same scenario was modelled with a change to cleared areas. This produced an substantial increase to 549 kg/km²/yr (bottom left).

An increase in TN in the lake causes increases in Chlorophyll a, which is shown by the Current Situation Model from CERAT (Figure 27). Chlorophyll a relates to the biomass of microalgae and phytoplankton which can reflect the health of an estuary.

Figure 27: Current situation model of Back Lake taken from the CERAT tool. Data is for the whole catchment and shows that an increase in TN can lead to higher levels of Chlorophyll a, increasing the risk of eutrophicication.
5.4.4 Total Phosphorus (TP)

The values for TP throughout the catchment vary significantly, with subcatchment 3 having the lowest values of TP runoff of 13kg/km²/yr and values increasing according to the amount of vegetation present in the each subcatchment. Subcatchment 2, which has the highest rates of TP, is the most developed subcatchment. It has a TP value 35kg/km²/yr greater than subcatchment 3. This illustrates the impact of greater urbanisation within the catchment on TP supplied to the lake. Subcatchment 1 has a current value of 20 kg/km²/yr.

![Figure 28: The total phosphorus (TP) in the catchment.](image)

The results from CERAT modelling illustrate the impact that the removal of forested area in the catchment will have on subcatchment 1. It can be seen that conversion from forest to cleared area produces a more drastic increase in levels of TN and TSS more drastically then the conversion from forest to urban. Surface flow changes are not affected with a change from urban or cleared land until a change greater than 10% occurs. A healthy level of nutrients within an estuary will vary between systems.
5.5 Short Cores

Field work in Back Lake indicated that the lake bed is predominantly organic sand in the central basin containing some shell and wood fragments further down the cores. Core 4 was a muddy, peat environment with bands of wood fragments present. Core 5 had a high presence of silt and clay in the top 15 cm before an abrupt change to an organic sandy mud. Of the 8 cores retrieved, most were predominantly organic sand throughout the bottom layers with some distinct changes in top sediment seen in Cores 6, 7 and 8. Figure 32 summarises the stratigraphy of the 8 cores collected. The details of sediment type and colour in the cores are provided in Appendix A. The size and distribution of grain size for Cores 1-5 is provided in Appendix B.

Core 1: Central Basin

Core 1 was extracted from the central basin which is located on the seaward side of the estuary and thus receives sediment from the sea during times when the entrance is open. The central basin is likely to provide relatively uninterrupted sediment supply and minimal surface mixing (Sloss et al. 2009). The core is predominantly muddy sand, with minimal shell and wood material. There are no defined boundaries throughout the core, and the colours range from brown to dark brown (Munsell description). There is an increase in the sand content down core, with silt composition decreases down core from 40% to 18% whilst the presence of sand increases. There is also a higher percentage of clay in the top 3 cm.

Core 2: Small Creek entering North side of Central Basin

Core 2 was taken from the north eastern side of the central basin, where a small creek line drains into the central basin. Core 2 has a higher sand content throughout the core with medium dark brown sand dominant throughout the core. This part of the basin would also receive a higher proportion of sediment from marine action due to its proximity to the barrier. It has well sorted sandy sediment that increases in coarseness down core. Woody material and shell fragments are present from 47 cm to 71 cm.
A. Borrell (2013)

Core 3: Paige’s Creek

Core 3 was taken from the mouth Paige’s Creek, a creek that drains into the central basin and runs through the north western aspect of Mirador Estate. Core 3 has a similar composition to Core 1, containing a higher percentage of silt (30%) content in the top 10cm, and decreasing down core. Silty sand was present in the top 3cm. It was poorly sorted and finer grained than the unit below. Shell fragments were present in the top 10cm. The core has woody material throughout. The sediment was dark in colour and alternated between a silty sand and medium sand. There was a lack of distinct boundaries throughout the core. The XRD analysis showed a fairly similar mineral content between the top 1cm and the sediment at the bottom of the core; with quartz the main mineral present. This supports results from the grain size analysis, which showed a similarity in sand and silt content between the sample taken from the top 1cm and from the bottom of the core at 85cm.

Core 4: Salt Marsh

Salt Marsh is situated on the south west margin of the central basin and is bordered on the southern side by housing. This housing was established prior to 1948. Core 4 was taken from within the salt marsh and is predominantly a dark, organic mud with dispersed shell fragments throughout the core. Woody material was present in poorly sorted bands at 20cm and 24.5cm. A silty layer was present on the top 6cm which was lighter in colour then the sediment below. The XRD analysis showed a higher percentage of quartz and muscovite in the top sample, with quartz decreasing in content and muscovite not present at the 40cm sample.

Grain size indicated that the core was predominantly silt, with the highest content of silt at the top of the core (73%) and decreasing down core to 46%.
Core 5, 7 & 8: Berrambool Creek

Cores 5, 7 and 8 were retrieved from Berrambool Creek, which receives runoff from the adjacent Berrambool Housing Estate. Core 5 has a significant silty clay layer on the top 14.5 cm. At 14.5 cm, there is a well-defined boundary and a change to a dark brown/black sandy mud occurs or the rest of the 100 cm long core. The top 8 cm is a light brown silty loam, with greyish brown clay present at 8 cm. Medium clay with distinct bands occurs until 14.5 cm, reaching a clay content of 44% at 9 cm.

Figure 22 shows the sediment size distribution of Core 5. The increase in the presence of silt and clay content can be seen in Figure 29a in the top 14 cm of the core. From 15 cm to 95 cm, the core is predominantly comprised of sand and silt. The abrupt change in composition correlates with a reduction in organic content as determined by LOI, as seen in Figure 22b.

![Figure 29: a) Sediment size distribution from Core 5 b) organic content of core 5.](image-url)
Core 7 was retrieved from the bank on the side of the Berrambool development. The core has a similar clay layer to that found in Core 5. The clay layer has four distinct bands which have a thick lighter layer overlain by a thin darker layer. The top 4cm consists of a silty, spongy mud, differing in texture and colour to the underlying medium clay bands. The lighter layer of the clay is a medium, sticky clay whilst the darker bands appear finer, with a greater presence of silt (a silty clay loam) (Figure 31a). Core 8 has a shorter layer of muddy sediment and is not the same consistency as the clay layer found in Core 5 & 7 (Figure 31). Core 8 was taken on the bank opposite Core 7, adjacent to the oval.

Grab samples were taken from various locations in the creek, providing information on the clay deposition close to the bank of the creek (Figure 17). The grab samples exhibited a highly variable and patchy deposition of clay and silty mud as seen in Error! Not a valid bookmark self-reference. Grab sample A has 30cm of silty mud with coarse grained material present (pebbles and stones) and 23cm of a medium clay. Grab sample B taken approximately 3 metres upstream has a 3cm silty mud layer on top, followed by 17cm of a medium clay which is deposited on top of an organic loamy sand (Error! Not a valid bookmark self-reference.). The combination of cores and grab samples taken in the creek showed that the deposition of clay was not consistent throughout the creek.

Figure 30: Grab Sample A is 53cm long with a change from silty mud to clay occurring at a depth of 30cm. Grab sample B was 48cm long, with the distinct change from clay to organic loamy sand occurring at a depth of 17cm.
XRD results provided details on the mineralogy of Core 5 (Figure 33: Legend for stratigraphic log on page 65).

Table 11). The top 2cm of the core presented much higher percentages of biotite, kaolin, mixed layer illite and muscovite to 15-16cm. The sample at 15-16cm, taken from below the clay layer showed higher composition of quartz, illite and chlorite. However, the sample taken from a depth of 47cm within the organic, muddy sediment contained a higher concentration of biotite and had a composition of almost 30% mixed layer illite, the highest concentration from within all the cores analysed.

Figure 31: A: Core 7 taken from the bank closest to Berrambool Housing Estate. B: Taken from the far bank, adjacent to the sporting oval.

Core 6: Merimbula Creek

Core 6 was taken further downstream from the Berrambool Creek junction, in order to determine the extent of clay deposition throughout the estuary. Core Six is a coarse river gravel. The top five centimetres of the core is moderately sorted with sediment ranging from 1mm to 10mm. A fine silt is present within the larger clasts, producing a slightly brown appearance compared to the underlying sediment. Between 5cm and 55cm, the core fines downwards with the bottom 25cm exhibiting significantly cleaner sediment. No sediment analysis was carried out on this core as this deposition environment was not going to provide any information regarding the deposition of sediment due to the uniform nature of the core.
Figure 32: Stratigraphic log of the 8 cores collected from Back Lake. Sandy mud was present in the cores from the central basin, and an organic coarse grained sandy mud was prevalent in the fluvial dominated regions. Please see page 66 for core legend.
**Table 11: XRD results providing details of the mineralogy of Cores 1, 3, 4 and 5.**

<table>
<thead>
<tr>
<th>Sample Depth (cm)</th>
<th>Chi Square</th>
<th>Albite (wt %)</th>
<th>Biotite (wt %)</th>
<th>Chlorite (wt %)</th>
<th>Illite (wt %)</th>
<th>Kaolinite (wt %)</th>
<th>Microcline (wt %)</th>
<th>Mixed layer illite (wt %)</th>
<th>Muscovite (wt %)</th>
<th>Orthoclase (wt %)</th>
<th>Pyrite (wt %)</th>
<th>Quartz (wt %)</th>
<th>Siderite (wt %)</th>
<th>Sodium Chloride (wt %)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Core 1 Central Basin</strong></td>
<td>0-1</td>
<td>3.38</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>10-11</td>
<td>3.68</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>15-16</td>
<td>3.98</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Core 3 Paige's Creek</strong></td>
<td>0-1</td>
<td>3.46</td>
<td>0.7</td>
<td>1.4</td>
<td>1.4</td>
<td>0.1</td>
<td>3.0</td>
<td>0.3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>85-86</td>
<td>2.74</td>
<td>0.4</td>
<td>1.1</td>
<td>1.1</td>
<td>-</td>
<td>1.9</td>
<td>1.1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Core 4 Salt Marsh</strong></td>
<td>0-2</td>
<td>3.36</td>
<td>2.8</td>
<td>1.3</td>
<td>3.5</td>
<td>3.6</td>
<td>3.3</td>
<td>8.9</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>40-41</td>
<td>3.55</td>
<td>3.5</td>
<td>3.9</td>
<td>3.5</td>
<td>2.4</td>
<td>0.8</td>
<td>0.3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Core 5 Berrambool Creek</strong></td>
<td>0-2</td>
<td>3.71</td>
<td>5.4</td>
<td>0.7</td>
<td>0.6</td>
<td>5.8</td>
<td>1.4</td>
<td>5.6</td>
<td>10.7</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>15-16</td>
<td>3.95</td>
<td>0.4</td>
<td>3.6</td>
<td>3.1</td>
<td>0.6</td>
<td>0.8</td>
<td>0.3</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>47-48</td>
<td>4.1</td>
<td>6.8</td>
<td>4.7</td>
<td>2.6</td>
<td>2.7</td>
<td>27.5</td>
<td>4.9</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 33: Legend for stratigraphic log on page 65.
Chapter Six: Discussion

6.1 Catchment Land Cover Mapping

The majority of recent development in the catchment has occurred around Back Lake. The increase in cleared and grass areas is the result of land clearing to enable the development of residential estates. There was a notable increase in bare earth between 1972 and 1975, where grassed land was cleared for the development of Berrambool Estate. A 13% reduction in the amount of vegetation between 1972 and 1975 was found. This included clearing on top of the hill now occupied by Mirador Estate, which was revegetated with grasses and some tree growth until it was cleared again in the 1990s.

A study of soil loss by Simms et al. (2003) showed the effects of sediment loss from a catchment with the removal of vegetation. It is predicted that soil loss caused from the increase in cleared areas in the Back Lake catchment in the 1970s, resulted in higher rates of sediment runoff and accumulation in the lake. The mapping of the catchment coupled with the results from the extracted of cores, highlighted the localised nature of the clay deposits in close proximity to the creek and housing, providing convincing evidence of induced sediment due to land cover change. This trend was reflected in the results of this report, with cores extracted from Berrambool Creek exhibiting significant clay horizons.

Sloss et al. (2009) identified increased sediment rates in a catchment that has experienced widespread development through a comparison of two estuaries that exhibited similar catchment area, size and estuary type (See Table 12). The study, which compared sedimentation rates from Lake Illawarra, a highly urbanised catchment, with the relatively undeveloped St George's Basin, found that despite both catchments possessing similar physical settings, sediment rates were 6-10 times higher in Lake Illawarra. The Lake Illawarra catchment retains only 30% of natural forest whilst St George’s Basin catchment retains 82% of the natural vegetation. St George’s Basin exhibited a relatively constant sedimentation rate over the last 500 years, with little change in sediment deposition since European settlement (Sloss et al. 2009). This illustrates the link between urbanisation in catchments and increased sedimentation rates. These studies in the literature illustrate the link between land cover and the
impacts that vegetation removal can have on sedimentation deposition, as was found in Berrambool Creek.

6.2 Analysis of Cores

The cores extracted from the central basin, salt marsh and Berrambool Creek provided details on the history of sediment deposition in the estuary. The cores extracted from Berrambool Creek indicated that there has been a significant change in the type and rate of sediment deposition over time. Based on vegetation classifications from aerial photography, it is inferred that sedimentation was particularly impacted in the last forty years. Cores 5, 7 and 8 provided evidence of change in the type of sediment deposited in the top 15-20cm, representing the most recent deposition. The sediment present in Cores 1, 2, 3, 4 and 6 is relatively consistent with the expected sediment deposition in an ICOLL. The length of the cores extracted allowed the history and recent changes in the nature of deposition to be assessed.

The clay layer present at the top of Cores 5, 7 and 8 consists of kaolin, illite-smectite and muscovite (Figure 33: Legend for stratigraphic log on page 65).

Table 11). The deposition of clay into estuaries is not unusual and sediments from terrestrial origins are usually dominated by clay rich sediments (Hanslow 2001). Typical sediments in a small creek with low flow velocities, such as Berrambool Creek, often comprises organic sediment that includes roots and shells, a product of the accumulation and decomposition of organic material (Nichols & Biggs 1985). However, clay rich sediments evident in the Berrambool Creek core are not present in the downstream core retrieved from the salt marsh. The salt marsh setting has a similar low velocity environment. This trend suggests that a period of increased runoff, via Berrambool Creek, has led to an increase in recent sediment deposition.

The clay minerals present in the sediment removed from Berrambool Creek were chlorite, illite-smectite, kaolin, muscovite and mixed clay layers. Clays are characterised by a 2D structure, and are hydrosilicates composed of cations and anions (Nemecz, 1981). Generally, clays are formed as the product of weathering, sedimentation, burial and alterations (Velde, 1985). Clays will undergo further structural changes once deposited into a new environment (such as a freshwater body) and burial will also
determine how the structure of the clay will transform (Velde, 1985). These factors influence the composition of clay sediments in Berrambool Creek, with the variety of depositional environments present in Back Lake defining clay structure. There were similar minerals from the clay layer deposited in Berrambool Creek present in other sediment samples from the estuary, with almost all cores containing varying percentages of Kaolin and illite (Figure 33: Legend for stratigraphic log on page 65). Table 11). The high presence of these minerals throughout the cores could be reflective of the podzolic Yellow Pinch soils which are the dominant soil type of the Back Lake catchment. The dominant clay type present in Yellow Pinch soils is kaolin and illite-smectite (Davey et al. 1975).

The distinct bands of clay seen in Core 7 are the likely result of individual storm events, during which particularly high volumes of sediment were transported into Berrambool Creek. The 2cm thick light medium clay bands (Figure 29) may indicate deposition in a flood event, and the thinner, darker coloured silty clay bands represent a slowed deposition rates between floods.

6.2.1 Estimating Rate of Sedimentation in Back Lake

Reviewing sedimentation rates in coastal lagoons with similar characteristics can provide an indication of likely deposition rates of coastal lagoons. Assumptions on contributing processes can be made when estimating sedimentation rates in Back Lake, as soil loss responds to a wide array of factors such as land cover, slope and the erosivity of soil (Simms et al. 2003). Soil loss from a catchment influences the amount of sediment accumulated in a water body, as soil eroded from the catchment is highly likely to be deposited in low lying coastal areas (Gwari & Ugoala 2009). A link has been established between catchment land use and an increase in sediment rates in the literature, which indicates that erosion from the catchment enhances the transport of soil to water bodies (Gwari & Ugoala 2009; Sloss et al 2009).

Sedimentation data from similar ICOLLS on the NSW south coast is relatively limited. There are a number of small ICOLLS in close proximity to Back Lake that exhibit similar geomorphic and physical settings (Bournda Lagoon, Middle Lagoon, Wapengo Lagoon, Bunga Lagoon). However, the limited availability of data on sedimentation rates in these systems means that drawing comparisons of sediment rates between these systems is
not possible. Other NSW lagoon systems in which sedimentation rates have been calculated include Lake Conjola, Lake Wollumboola, St George’s Basin and Lake Illawarra (Table 12). Whilst there is large variability present between these estuaries, similarities between these systems provide an opportunity for the estimation of the expected sedimentation rates in the Back Lake.

Table 12: A summary of characteristics of estuaries on the south east NSW coast (Catchment data from Ozcoasts, OEH, 2012)

<table>
<thead>
<tr>
<th>Estuary Name</th>
<th>Catchment Area (km²)</th>
<th>Estuary Area (km²)</th>
<th>Catchment Vegetation (%)</th>
<th>Sedimentation Rates</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Back Lake</td>
<td>31.03</td>
<td>0.38</td>
<td>85.87</td>
<td>Berrambool Creek</td>
<td>Estimated rate</td>
</tr>
<tr>
<td>Lake Wollumboola</td>
<td>33.73</td>
<td>6.33</td>
<td>91.11</td>
<td>Delta 3.63 ± 2.66</td>
<td>Baumber 2001</td>
</tr>
<tr>
<td>Burrill Lake</td>
<td>58.0</td>
<td>4.38</td>
<td>45.64</td>
<td>Lagoon Deposits 1.7</td>
<td>Jones et al. 2003</td>
</tr>
<tr>
<td>Pattimore’s Lagoon (Lake Conjola)</td>
<td>134.3</td>
<td>6.72</td>
<td>90.08</td>
<td>-</td>
<td>Clarke 2012</td>
</tr>
<tr>
<td>Minnamurra River</td>
<td>115.2</td>
<td>1.86</td>
<td>32.38</td>
<td>Cut-off embayment 3.0-8.0</td>
<td>Panayotou 2004</td>
</tr>
<tr>
<td>St George’s Basin</td>
<td>310.6</td>
<td>40.91</td>
<td>82.13</td>
<td>Worrowin Waterway 4.4 ± 0.9</td>
<td>Sloss et al. 2009</td>
</tr>
<tr>
<td>Lake Illawarra</td>
<td>231.9</td>
<td>35.83</td>
<td>30.72</td>
<td>Macquarie Rivulet Pro-Delta 1.8 – 3.2</td>
<td>Sloss et al. 2009</td>
</tr>
</tbody>
</table>

Lake Wollumboola is a coastal lagoon on the south coast, approximately 300 kilometres north of Back Lake (Figure 34). As can be seen in Table 12, the catchment size of Lake Wollumboola is similar to Back Lake; however it has a much greater estuary size. Other factors that the two catchments share include a similar percentage of vegetated catchment and entrance condition. Back Lake and Lake Wollumboola are situated in the temperate zone of the NSW south coast, sharing similar geologic and climatic regimes.
Sedimentation rates determined in Lake Wollumboola can provide insight into sediment deposition in Back Lake. Factors that may induce differing rates of sedimentation include differences in gradient, the coherence of sediment, land cover in the catchment and the occurrence of large events such as floods (Nichols 1989). The Wollumboola catchment has a relatively constant gradient with a maximum slope of 20 degrees (Simms et al. 2003) whilst Back Lake exhibits a hilly catchment with steep gradients that rise to over 100m AHD within one kilometre of the lake and to over 300m AHD in the upper catchment (WMA 1995). This may cause an increased sensitivity to heavy rainfall producing greater runoff of sediment and nutrients into the lake.

Sediment in Berrambool Creek is supplied from the creek line feeding from the west and includes runoff from the adjacent Berrambool Housing Estate and the sporting field. Sediment from the feeding creek is valley fill, consisting of silts, clays and sands (Figure 10). Analysis of aerial photographs suggest that the creek appears to receive less input from fluvial sources in recent times, however the creek may become active when there is heavy rainfall, leading to runoff transporting valley fill into the creek.

Rates of sediment deposition were compared between coastal lagoon systems. The deposition rate of the delta in Lake Wollumboola was approximately 3.6mm/yr. This figure may me more appropriate for the comparison with Back Lake rather than the corresponding sedimentation rates from the central basin due to the differing settings. The rate of sediment deposition in Berrambool Creek would naturally be greater due to a small water area. Rates are also likely to have become far greater due to the cleared riparian zone and the increased inputs of sediment due to development. The generally low fluvial input into Berrambool creek may also contribute to a higher sedimentation rate as an increased residence time of fluvial input allows sediment to accumulate. Higher fluvial inputs are required to flush alluvial material through the system, resulting in a loss of sediment to the marine interface (Nichols 1989). South coast systems that exhibit similar sediment rates can be seen in Figure 11.

A study by Nichols (1989) of 22 coastal lagoons on the United States Gulf and Atlantic Coasts presented data of short term accumulation rates derived from radiometric analysis of cores. An average rate of 3.4mm/yr was found for all lagoons, with most
lagoons varying between 0.7 and 5.0 mm/yr (Nichols, 1989). Lagoons with active deltaic sedimentation received higher values of sediment, up to a maximum rate of 110 mm/yr. All coastal lagoons studied were shallow (<3.0m) and estuary size varied between 0.1 km² and 4350 km². These rates are comparable to the rates found in NSW south coast estuaries (Table 12).

Three different scenarios were used to estimate sedimentation rates in Berrambool Creek, using the amount of clay deposited since 1948, 1972 and 1975. This was conducted as it is unclear if clearing prior to 1948 would have caused similar situations to that of the 1970s. Aerial images showed that some clearance of the area on the north side of Berrambool Creek occurred after 1948 and before 1972. By 1972, it had become stabilised with grasses as a grazing area and then by 1975, the area had been cleared for development, as seen in the aerial images. This provided three possible scenarios for when large amounts of sediment could have been eroded from the area.

6.2.2 Sedimentation Rate Estimate

The depths of the clay layers in Core 5 and Core 7 were used to calculate the sediment rate deposited per year. The clay layers used in this analysis was not present in cores from other sections of the estuary, indicating that the deposition of clay is not a natural process for the estuary. The presence of clay bands was not evident throughout the bottom 80 cm of Core 5, indicating that there was a recent change in the environment leading to unusual deposition events and this is likely to have occurred between 1948 and 1975 due to the clearance of vegetation for development, causing significant changes in land cover.

An estimation of sediment deposition of approximately 3 mm/yr indicates that the change in sediment type to predominantly clay occurred approximately sixty years ago, in the 1950s. It is possible that the supply of clay began at this time period, as catchment clearing was underway at this time. The other possible scenario is that the sediment is due to the widespread clearing in the 1970s that is clear in the observation of a temporal analysis of aerial images (Figure 35).

The sediment rate for Berrambool creek was calculated by using the amount of clay found in the cores 5 & 7. These cores had a depth of 14.5 cm and 18.0 cm of clay respectively, and these two values were divided by the time difference between the present and three rough, possible dates of mass sediment delivery, 1948, 1972 and
1975. The creek is predicted to be accreting at a minimum rate of 2.2 mm/yr and a maximum rate of 4.7 mm/yr (Figure 35).

![Sedimentation Rate Graph](image)

**Figure 35:** Three sedimentation rate scenarios for Back Lake according to the analysis of sediment cores and land cover trends from aerial photography.

![Clearing Adjacent to Berrambool Creek](image)

**Figure 36:** Clearing adjacent to Berrambool Creek that occurred between the years of 1972 and 1975 for the development of Berrambool Housing Estate. This removed the top layer of grass exposing bare earth.
The removal of natural vegetation increases the amount of soil erosion that is able to occur. The high erosivity ratings of the Yellow Pinch soils in the area could cause sediment to be particularly susceptible to erosion during periods of high runoff. The creek that drains into Berrambool Creek consists of valley fill and would be a source of clay and silt rich sediment. High energy rainfall events could also be a catalyst for mass sediment erosion, with heavy storm conditions documented along the south east coast in May and June 1974, causing damage to coastal structures and beaches (Mclean & Hinwood, 1999). A subsequent period of high rainfall was experienced in Back Lake catchment in January 1994 (WMA 1995).

The analysis of Core 5 displays an abrupt change in sediment type seen along the length of Berrambool Creek. The thickness of a significant clay layer alters along the creek with the thickest deposition present on the bank closest to the housing estate, and a notable decrease towards the centre of the creek. It is likely that this human disturbance in the immediate area to Berrambool Creek was responsible for rapid deposition of clays from the cleared areas in storm events. Normal deposition in the creek in a storm event may produce similar sediment types, but the quantity that was present in the cores was not seen elsewhere. Sheet and gully erosion can be seen on the steep slopes of Berrambool Estate as a result of storm water runoff from paved areas (Figure 37) (Haines & Rollason 2009; WMA 1997). This is an on-going source of sediment to Berrambool Creek.

![Figure 37: Gully erosion within Berrambool Estate and a storm water output.](image)

As mentioned in Chapter 2.5.1, impacts from increased sedimentation include the degradation of water quality and damage to biological organisms. No water quality analysis was carried out in Back Lake as part of this study, so it is unknown whether
water quality within Berrambool Creek differs significantly from other parts of the lake that are likely to have lower sedimentation rates. There is a lack of biological material in the top layers of the cores collected from Berrambool Creek, indicating that the change in sediment rate and type may have affected the biology of the creek. The lack of clay presence downstream could be due to the high cohesion properties of clay causing eroded sediment to not travel far from the site of deposition (Nichols & Biggs, 1985).

The cores collected from Berrambool Creek indicate that siltation has occurred and suggest that if the predicted rate of change was to take place across the central basin the repercussions would be much more severe. An increase in TSS in the estuary could result in higher turbidity values, impacting biological communities such as seagrass which is an important ecological organism. The seagrass populations of Back Lake are predominantly present in the central lake and these fragile communities are susceptible to damage from human activities, such as excess sediment runoff (Kennish 2002; Williams & Meehan 2002). The limited flushing ability of Back Lake due to low fluvial inputs results in high residence times for sediment in the system. Coupled with higher sedimentation rates, this will result in an increase in turbidity in the water column, potentially impacting the health and viability of seagrass communities (Nichols & Biggs 1985). The remediation of damaged seagrass beds has largely been unsuccessful in the past and is much more difficult than other estuarine environments to restore, such as estuarine salt marsh systems (Kennish 2002). The difficulty in restoring damage emphasises the need to identify potential impacts and provide solutions to effectively reduce the risk of harm.

6.2.3 CERAT Modelling

CERAT modelling provided estuary water quality values for TSS, TN and surface flow under future scenarios of land cover. Zoning of the area north of Back Lake includes an area of 0.4km² which is currently vegetated. Within the existing R2 zoning in the area, extensive land clearing has occurred supporting the assumption that the zoning of new areas as R2 will lead to a significant removal of the vegetation. The 20% change in vegetated area that is to occur in subcatchment 1 with the continued development of Mirador Estate was modelled and it was found that surface flow was least affected by the changes, demonstrating that surface runoff isn’t as highly influenced by small changes of vegetation compared to the other determinants. Yellow Pinch soils have been rated as highly impermeable (WMA 1995) and would be expected to contribute to high
surface runoff values even under natural conditions. Forest removal on steep slopes will have a larger effect on surface runoff than on more stable slopes.

TN, TP and TSS levels displayed sensitivity to the removal of vegetation in the model, with cleared areas causing higher levels of the nutrients to be supplied to the lake, rather than urban areas. This modelling further supports the theory that sediment deposition was increased during the 1970s period, as there was a large amount of cleared area adjacent to the Berrambool Creek (Figure 36). The models produced outline predicted trends in the catchment that can be used to guide future development practices by highlighting the risk of removing vegetation without providing stabilisation of sediment.

Natural rates of nutrients are the most ideal level to enable healthy estuarine functioning and any increases can be largely accounted to activities within the catchment. Increases in the concentration of nutrients and sediment may increase the risk of the estuary to impacts such as eutrophication (Riedel & Sanders, 2003). This highlights the importance of sediment management practices when removing natural vegetation for development.

6.3 Sediment Management for Back Lake

The importance of sediment management was illustrated by the consistent results achieved from CERAT modelling, with results exacerbated with the conversion of forested area to cleared area. Approaches that address all aspects of sediment management such as erosion control are critical to ensure that all avenues of loss are accounted for (Verstraeten et al. 2002). The LEP zoning in Figure 13 displays the areas that have been zoned low density residential areas as of the 2013 LEP. This involves the removal of 0.4km² of vegetation from the catchment. This part of the catchment drains into Paige’s Creek which discharges into the central basin. Without adequate sediment management strategies, there is a possibility of a significant increase in the runoff of sediment and surface flow, causing gully erosion and sedimentation of the central basin. The results from cores extracted from Berrambool Creek provide an opportunity to identify issues which have arisen in the past from incorrect management of sediment. Sediment controls have been put in place around Mirador Estate in areas which may be subject to soil loss, such as sediment fencing and hard engineering solutions for storm water control (Figure 38).
Yellow Pinch Soils comprise a large portion of the catchment and are present on steep slopes, hillsides and in forested areas (WMA 1995). Yellow Pinch soil possesses high erodibility rating and low permeability qualities, making them particularly vulnerable to erosion due to vegetation removal. Impermeability of the soil will most likely lead to increased surface runoff from areas that contain these soils, washing eroded soil into the adjacent waterways. This has been seen in examples of gully erosion in the areas which have undergone development in the Bermabool and Mirador Estates (Figure 37). Larger particles washed into estuaries are likely to be flushed out the entrance with only fine particles remaining as suspended sediment in the central basin (Nichols & Biggs 1985). However, there is limited evidence suggesting that flushing can moderate sediment loads within estuaries (Radke et al. 2004).

6.3.1 Sediment Control

Existing sediment controls within the Mirador Estate include textured concrete storm water engineering works aimed to slow flow before it is deposited down slope towards the central basin of Back Lake (Figure 38). These structures are aim to slow water velocities before it is transported down slop towards Back Lake. Decreasing water velocity down slope is important in ensuring the effectiveness of Riparian Buffer Zones.
(RBZs), as it has been shown that RBZs are ineffective where runoff is concentrated before entering filtering vegetation (Daniels & Gilliam 1996).

Riparian vegetation has significantly increased along the length of Merimbula Creek since 1948. The regeneration of riparian zones along Merimbula Creek can be seen in the aerial photographs. Merimbula Creek has been the focus of regeneration projects and the shift in primary land use from pastoral land to urban development is likely to have aided the recovery of riparian vegetation along the creek. However, during runoff events in the 1970s, there was very little riparian vegetation present on the banks of Berrambool Creek, as with other segments of Merimbula Creek. The absence of riparian vegetation is likely to have contributed to increased sediment runoff velocities into the creek, supplying greater amounts of sediment to the creek bed. Riparian buffer zones or Vegetated Filter Strips (VFS) are widely considered an effective measure to reduce sediment and nutrient delivery from cultivated areas to water bodies (Hook 2003; Dilaha et al. 1968; Lee et al. 2000; Verstraeten et al. 2006). This can improve surface water quality, reduce suspended sediment concentrations and mitigate the volume of sediment reaching waterways (Lee et al. 2000). The volume of sediment which is able to be retained by riparian zones is influenced by a range of factors including the width of the buffer, the slope present and the density of the vegetation (Hook 2003). Vegetated buffers reduce sediment runoff by slowing velocities and spreading flows (Lee et al. 2000). Vegetation increases the amount of filtration that is able to occur, removing nutrients and pollutants (Lee et al. 2000). Infiltration is an important process in decreasing surface runoff and capturing sediment pollutants such as nitrogen and phosphorus, thus improving the purity of runoff into waterways (Dilaha et al. 1988).

BVSC currently requires agricultural buffer management plans to accompany development consents for rural development consents. Agricultural buffer management plans must contain details such as the extent of the buffer, the type of vegetation to be present in the buffer and how the buffer will be maintained (BVSC 2012).

Conditions of the development around Back Lake include the presence of a natural vegetation buffer zone that is at least 40m wide (Haines & Rollason 2009). Natural vegetation such as deep-rooted woody plants have been seen to be much more effective at trapping sediment as they provide high infiltration capacity (Lee et al. 2000). This emphasises the importance of retaining natural vegetation around water bodies, with both the buffer width and vegetation type, affecting the amount of sediment which can
be trapped (Lee et al. 2000; Verstraeten et al. 2006). RBZs consisting of native vegetation are more effective at trapping sediment than artificially constructed buffer zones.

Additional conditions for development include the implementation of onsite stormwater detention using on site stormwater detention facilities and the reuse of stormwater on site. No stormwater runoff is permitted to be discharged to Back Lake from Mirador Estate. The runoff must be collected and treated prior to release to the natural drainage paths above the core riparian zone. Post detention structures must be designed to ensure that discharges to the lake achieve natural catchment nutrient export rates (Haines & Rollason 2009).

6.3.2 The Role of Management Frameworks

The Healthy Rivers Commission (HRC) prepared an independent inquiry into the management of coastal lakes in NSW in 2002. It aimed at providing a framework that lake managers (councils and agencies) could use in order to effectively manage coastal lakes. It outlined a range of principles that included the need to manage the catchment and coastal lakes as a whole system and the need for accountability, responsibility and obligations of public authorities to be clearly determined in management plans. Four protection plans were outlined for coastal lakes of varying condition. Back Lake was determined as a system requiring significant protection, due to the relatively good condition it remains in. The HRC signification protection framework was aimed at restoring and preserving critical natural ecosystem. The inquiry into NSWs coastal lakes led to the creation of the 'Back Lake Sustainability Assessment and Management Strategy' which was drafted as a sample document in 2009. The plan was a pilot document which was not adopted by the government.

The outcomes to be achieved from a significant protection management framework presents actions intended to ensure the continued health of Back Lake. This included the limitation of any new urban and rural residential development to within the existing boundaries of developed areas and the progressive minimisation of entrance behaviour intervention. It is clear that the reality of some of the objectives outlined for the management of Back Lake are difficult to achieve at best. Problems that may arise include the threat to human property from flooding, and increasing pressure to expand urban areas in the region.
The points of the framework that remain highly relevant to the management of Back Lake include the implementation of stringent stormwater controls in existing developed areas and the mitigation of sediment runoff, particularly adjacent to water courses.

The management strategy developed by Haines & Rollason (2009) for the Department of Environment Climate Change and Water (now the Office of Environment and Heritage (OEH)) provided a thorough analysis of the environments present in the Back Lake catchment and synthesised data for water quality, habitat condition and the functioning of the lake. It also outlined an extensive management plan which covered a range of management areas including estuarine habitat conservation, water quality, visual amenity, entrance condition and cleared land runoff plans. The responsibility of actions areas was allotted to a range of authorities and public groups consisting of BVSC, OEH, the Southern Rivers Catchment Authority, Department of Primary Industries and local community groups.

Management strategies should address all components of an estuary to ensure the continued functioning of complex interactions within an estuary, allowing healthy functioning. This may require a range of authority's involvement that govern particular aspects of the estuary. However, collaboration between groups can be difficult and further exacerbate the ‘fragmented’ approach to estuary management which has been seen throughout Australia (Keneley et al. 2012). Issues that BVSC face in achieving management principles is the complexity of management tasks and the limitations of resources that are required to carry out all aspects of plans such as those proposed by Haines & Rollason (2009).

BVSC currently manages Back Lake under the Local Environment Plan (LEP), allowing the land use of areas within the catchment to be determined by the council. This is the most effective method of managing activities that occur that will directly affect Back Lake. This has allowed council to zone areas which exhibit particularly steep slopes as Environmental Conservation, preventing development to occur whilst the current LEP is implemented.

Management priorities will need to be established for Back Lake that recognise resource limitations to ensure that critical processes will to continue to provide healthy functioning of the estuary (Thom et al. 2011). For Back Lake, one of the most prominent direct threats to the lake is the removal of natural vegetation which provides sediment stabilisation, habitat for biodiversity and aesthetic value. Management of development that ensures that sediment management methods such as sediment barriers,
stormwater control and buffer zones are implemented and maintained could minimise impacts caused by increased sedimentation rates on water quality parameters and benthic organisms.

6.3.2 Limitations of the Project

Land cover was mapped using the spectral bands in aerial photography. The accuracy of the mapping could have been greatly improved with a greater number of bands present in the imagery, such as that present in current satellite imagery, such as Landsat imagery. The presence of an infrared band would allow greater delineation between vegetation and water classes, providing a more detailed and reliable classification. Using such techniques still possess a degree of error. Nonetheless, the ability to differentiate between water and different types of vegetation based on their detailed spectral signatures would be a significant improvement to the mapping of land cover in the catchment.

Limitations present in the capacity of the study have meant that a number of assumptions have been made in relation to sediment behaviour and processes that are expected to occur. The sediment rate estimated is not a true indication of the rate of accretion of sediment in Berrambool Creek. It is likely that the clay bands present in the cores were primarily deposited during discrete rain events, with large accretions occurring over concentrated time periods. However, it does provide an estimate of modern rates that can be compared with modern rates in similar systems. This estimation could be significantly improved with dating of the cores using radiometric methods. This would provide a clearer indication of the rates of sedimentation in the creek and the rate of sedimentation in the central basin could also be determined. Sediment that was deposited prior to the clay deposition could be dated and its age determined. This would allow the natural rates of sedimentation in the creek to be determined, and a more accurate modern sedimentation rate determined. This could provide more conclusive evidence regarding the impact of native vegetation clearing around Berrambool Creek on sedimentation rates.
Chapter Seven: Recommendations and Conclusions

7.1 Conclusions:

The study conducted involved the evaluation of catchment land cover using mapping techniques, predictive modelling of estuarine responses to catchment changes and the extraction of sediment cores with an aim of increasing the understanding of impacts of development on Back Lake. By identifying the causes of possible deleterious impacts from the past, future actions can be made with a larger base of knowledge regarding the sensitivity of the lake and how actions that may compromise estuarine health can be avoided.

The first objective was to determine the extent of land cover change within the catchment. This was achieved by conducting a land cover classification from aerial photography. This analysis of aerial photography highlighted the expansion of development on the north western side of Back Lake and along Berrambool Creek, with the development of Berrambool Estate in the 1970s and Mirador Estate in the late 1990s. Development of these areas involved the widespread clearing of the top soil and the vegetated areas. Aerial photographs confirmed this, with an 11% decrease in vegetated areas between 1972 and 1975. Forest coverage decreased in the catchment from 93% in 1948 to 74% in 1998. The overall forested area of the whole catchment in 2010 was 28.1 km². This presented an increase in forested area between 1999 and 2010 with a forested area of 26.7 km² in 1999.

The second objective was in order to quantify trends that may emerge as a result of the land cover changes identified through the classification conducted, predictive modelling was completed using CERAT, a tool for assessing the risk of eutrophication to estuaries on the NSW coast. Outputs derived from CERAT were generated, using estuary health indicators such as TSS, TP and TN as determinants. It was found that the removal of vegetation from within the catchment caused a significant increase in the concentrations of TSS, TP and TN supplied to Back Lake. The result of a 20% decrease in forest area in subcatchment 1 to be replaced by cleared ground was a 280% increase in TSS volume in the system and a 175% increase in TN concentrations. This confirmed the likelihood that Back Lake has been subject to inputs of excess sediment as a result of clearing and indicated that improper implementation of best practice sediment controls may result in the degradation in Back Lake. These results also indicate that the presence of
vegetation throughout the catchment is directly related to sediment accumulation and that the removal of vegetation from the catchment will have an impact on the physical processes and ecological values of Back Lake. CERAT modelling indicated a high probability of further damage to the estuary if planned future removal of vegetation is not managed correctly. This importance of measures taken to reduce soil erosion is highlighted in avoiding the transmission of excess sediment to Back Lake.

To investigate the extent of the predicted changes to sediment supply to the lake, a series of sediment cores were retrieved from a variety of depositional environments within Back Lake. Clay layers of thicknesses varying from 14.5cm to 23cm throughout Berrambool Creek as determined by a series of short cores and grab samples. This provided evidence that there has been a likely change in sediment type and deposition due to the clearing that occurred around Back Lake. Factors that may have affected transportation of sediment to the creek include the soil type of the region, the slope of the local area and unusual weather events that occurred, causing increased rainfall. The localised nature of the depositions indicated that the clay deposits may be directly related to the clearing that occurred adjacent to the creek.

The sedimentation rates were estimated using a clay depth of 14.5cm and 18.0cm as the depth that has been deposited since then 1940s. Rates from similar systems were used as a comparison of the estimated sediment rate and a sediment rate of 2.2mm/yr – 4.7mm/yr was calculated as the likely deposition. This was comparable to rates of other NSW south coast ICOLLS such as Lake Wollumboola, which was found to have a sedimentation rate of 3.2mm/yr. A lack of data regarding pre-European deposition rates meant that the calculated modern rate of deposition cannot be compared to natural rates to establish the extent of the increase.

Frameworks developed by government departments to improve estuary management are often ambitious and at times, unrealistic. For the effective and relevant management for Back Lake and its catchment, a simplified and unified approach is required that encompasses the most important aspects, enabling positive flow on effects from management actions. Key management areas that could provide these functions include the management of sediment in the catchment to ensure that rates of nutrients and sediment supplied to the lake are not elevated above functional levels and monitoring water level as a quantifiable measure of estuary health.
7.2 Recommendations

Key management strategies for Back Lake should focus on developing a simplified and unified management framework that encompasses key processes in the functioning of Back Lake. Prioritisation of values can ensure protection of key processes which have inherent flow-on effects to other integrated processes. The inclusion of Back Lake in the water quality monitoring in the region is recommended to collect information on parameters such as TSS, TN, TP and turbidity at regular intervals. Monitoring and informed management of water quality parameters has important implications for sensitive ecological communities such as seagrass. Water quality is a good indicator of the health of an estuary and levels of nutrients in the water may flag larger issues through the measurement of turbidity and TSS which reflect sediment supply processes. Data collected can be referred to in the future as a measure of the long-term health of Back Lake, as development in the catchment increases. Gathering accurate and up to date data will also allow real data to be used in assessments of estuary health, rather than relying on indicators in predictive models (such as CERAT). Monitoring changes in land cover through the use of aerial photography is necessary to ensure that regulated management techniques protecting estuarine processes (RBZs and stormwater retention) are implemented with future alterations to land cover.

The strong ecological values that Back Lake retains today should be maintained. A key area that would significantly aid this outcome is the limitation of mass removal/clearance of native vegetation. The proposed R2 zoned areas are currently highly vegetated and development of these areas should avoid concentrated removal of vegetation, particularly over short time periods. This could lead to large amounts of cleared land, increasing the probability of excess sediment and nutrients being transported to the lake.

It is acknowledged that retaining all forest in the catchment is unrealistic and impractical when considering the social and economic needs of the community and region. However, the values obtained from CERAT modelling, estimate substantial increases in the supply of nutrients to the lake could occur with the proposed zoning changes, compromising water quality and estuarine processes. This modelling can be used to guide management strategies and monitoring within the lake. Methods of managing soil loss should be implemented to avoid the loss of soil from the catchment into the lake.
The restrictions that have been imposed on developments should be monitored to ensure that conditions are adhered and to evaluate the effectiveness of strategies. The evaluation of current sediment management techniques could provide valuable information for future sediment management within the catchment. Management strategies are not useful without evaluation of the outcomes achieved.

Soil loss modelling could be used to further identify areas susceptible to soil loss. The potential soil loss in the catchment can be determined with the removal of vegetation using soil loss equations. Predictive modelling of soil loss can guide management strategies to ensure that catastrophic soil loss into waterways is avoided.

Further research into the sediment within the lake could be conducted to provide more detailed information on the presence and distribution of sediment types. The retrieval of additional cores from the upper reaches of Merimbula Creek could determine whether valley fill eroded from creek lines is present in other sections of the catchment and if the clay layers found in this study are restricted to Berrambool Creek. Determining the age of sediment from the cores using a dating method, such as Lead-210 dating, would enable a comprehensive and accurate estimation of sediment rates to be determined. This could provide conclusive evidence of the impacts of clearing within the catchment. The pre-European sedimentation rate in Back Lake could also be determined, allowing a comparison between modern and historic rates of deposition in the lake, further illustrating the impacts of development in the catchment on Back Lake. Dating of the sediment in Back Lake could serve as an example of the likely type and magnitude of changes that may occur in an ICOLL on the NSW south coast with land cover change. This information could be used in the management of other, similar ICOLLS in the region.
References:

www.abs.gov.au/ausstats/abs@nrs.nsf/95553f4ed9b60a374a2568030012e707/3667361675130816ca257b7400045477!OpenDocument


BVSC, (2012). Development Control Plan (Draft). Bega Valley Shire Council, Bega, NSW.


Clarke, A.R. (2012). The environmental history and tidal regime of Pattimore's lagoon, a modified coastal wetland on the southeast Australian coast. BEnvSc Hons, School of Earth & Environmental Science, University of Wollongong.


### Appendix A – Core Logs

<table>
<thead>
<tr>
<th>Core 1</th>
<th>Depth (cm)</th>
<th>Description</th>
<th>Bioturbation</th>
<th>Sorting</th>
<th>Colour</th>
<th>Mottling</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0-5.0</td>
<td>Sandy loam</td>
<td>Sea grass roots</td>
<td>Well sorted</td>
<td>2.5Y 3/1 Dark brown</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>5.0-28.0</td>
<td>Organic loamy sand. Contains a higher proportion of sand to silt then above.</td>
<td>Shell material present (2%)</td>
<td>Moderately sorted</td>
<td>2.5Y 3/2 Very dark greyish brown</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>28.0-77.0</td>
<td>Sandy loam</td>
<td>Fining downward</td>
<td>Moderate sorted sandy silt</td>
<td>2.5Y 3/1 Very dark grey</td>
<td>Some uneven colour but not distinct mottles</td>
</tr>
<tr>
<td>Core 2</td>
<td>Depth (cm)</td>
<td>Description</td>
<td>Bioturbation</td>
<td>Sorting</td>
<td>Colour</td>
<td>Mottling</td>
</tr>
<tr>
<td>--------</td>
<td>------------</td>
<td>----------------------</td>
<td>--------------</td>
<td>----------------</td>
<td>----------</td>
<td>----------</td>
</tr>
<tr>
<td></td>
<td>0-1.0</td>
<td>Coarse grained sand</td>
<td>-</td>
<td>-</td>
<td>10YR 4/3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.0-4.5</td>
<td>Finer sand than above</td>
<td>-</td>
<td>Poorly sorted</td>
<td>10YR 3/1</td>
<td>5%</td>
</tr>
<tr>
<td></td>
<td>4.5-10.0</td>
<td>-</td>
<td>-</td>
<td>10YR 3/1</td>
<td>5%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>10.0-25.0</td>
<td>Fine grained sand</td>
<td>-</td>
<td>10YR 4/2</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>25.0-40.0</td>
<td>Medium Sand</td>
<td>Shell fragments present</td>
<td>10YR 3/1</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>40.0-47.0</td>
<td>Finer sand</td>
<td>-</td>
<td>Well sorted</td>
<td>10YR 3/1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>47.0-49.0</td>
<td>Coarse, organic sand</td>
<td>Woody material present</td>
<td>Moderately sorted</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>49.0-71.0</td>
<td>Coarse grained sand</td>
<td>Woody material present</td>
<td>Poorly sorted</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Core 3</td>
<td>Depth (cm)</td>
<td>Description</td>
<td>Bioturbation</td>
<td>Sorting</td>
<td>Colour</td>
<td></td>
</tr>
<tr>
<td>--------</td>
<td>------------</td>
<td>----------------------------------</td>
<td>-------------------------</td>
<td>--------------------</td>
<td>-------------------------</td>
<td></td>
</tr>
<tr>
<td>0-2.0</td>
<td>Fine sandy silt with coarse grains</td>
<td>-</td>
<td>Moderately sorted</td>
<td>10YR 4/2 Dark greyish Brown</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.0-10.0</td>
<td>Fine, organic mud</td>
<td>Shell fragments present</td>
<td></td>
<td>10YR 2/2 Very dark brown</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10.0-30.0</td>
<td>Increasingly coarse with more sand present</td>
<td>Woody material present</td>
<td></td>
<td>10YR 3/2 Very dark greyish brown</td>
<td></td>
<td></td>
</tr>
<tr>
<td>30.0-40.0</td>
<td>Coarse grained sandy mud</td>
<td>Larger stones present (2-10mm)</td>
<td>Moderately sorted</td>
<td>10YR 4/2 Dark Greyish brown</td>
<td></td>
<td></td>
</tr>
<tr>
<td>40.0-64.0</td>
<td>A rich sandy mud</td>
<td>Woody fragments present (20% coarse fragments)</td>
<td>Poorly sorted</td>
<td>10YR 2/1 Black</td>
<td></td>
<td></td>
</tr>
<tr>
<td>64.0-67.0</td>
<td>Coarse grained sand</td>
<td>Woody fragments present (50%)</td>
<td>Poorly sorted</td>
<td>10YR 2/1 Black</td>
<td></td>
<td></td>
</tr>
<tr>
<td>67.0-90.0</td>
<td>Coarsening downwards</td>
<td>Woody material present</td>
<td>Poorly Sorted</td>
<td>10YR 2/1 Black</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Depth (cm)</td>
<td>Description</td>
<td>Bioturbation</td>
<td>Sorting and Grain Size</td>
<td>Colour</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-----------</td>
<td>--------------------------------------------------</td>
<td>------------------------------------------------</td>
<td>------------------------</td>
<td>--------------------</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0-6.5</td>
<td>Silty loam, organic</td>
<td>Small Shell fragments and shells (5%)</td>
<td>Well sorted</td>
<td>2.5Y 2.5/1 Dark Brown</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6.5-7.0</td>
<td>Loamy sand</td>
<td>Small pebbles 2% (2mm)</td>
<td>Poorly sorted</td>
<td>2.5Y 5/1 Grey</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7.0-15.0</td>
<td>Loam with more sand then above.</td>
<td>-</td>
<td>Well sorted</td>
<td>2.5Y 4/1 Dark Grey</td>
<td></td>
<td></td>
</tr>
<tr>
<td>15.0-20.0</td>
<td>Sandy loam</td>
<td>-</td>
<td>Well sorted</td>
<td>2.5Y 2.5/1 Black</td>
<td></td>
<td></td>
</tr>
<tr>
<td>20.0-21.0</td>
<td>Lighter, fine grained sand</td>
<td>Woody material (5%)</td>
<td>Moderately sorted</td>
<td>2.5Y 4/1 Dark Grey</td>
<td></td>
<td></td>
</tr>
<tr>
<td>21.0-23.5</td>
<td>Sandy loam</td>
<td>Woody material present (50%)</td>
<td>Moderately sorted</td>
<td>2.5Y 2.5/1 Black</td>
<td></td>
<td></td>
</tr>
<tr>
<td>23.5-24.5</td>
<td>Lighter, fine grained sand</td>
<td>-</td>
<td>Poorly Sorted</td>
<td>2.5Y 4/1 Dark Grey</td>
<td></td>
<td></td>
</tr>
<tr>
<td>24.5-37.0</td>
<td>Sandy loam</td>
<td>Woody material present (50%)</td>
<td>Poorly Sorted</td>
<td>7.5YR 2.5/1 Black</td>
<td></td>
<td></td>
</tr>
<tr>
<td>37.0-38.0</td>
<td>Lighter, fine grained sand</td>
<td>-</td>
<td>-</td>
<td>2.5Y 4/1 Dark Grey</td>
<td></td>
<td></td>
</tr>
<tr>
<td>38.0-39.0</td>
<td>Sandy loam</td>
<td>-</td>
<td>-</td>
<td>7.5YR 2.5/2 Very dark brown</td>
<td></td>
<td></td>
</tr>
<tr>
<td>39.0-54.0</td>
<td>Sandy loam with greater clay content then above.</td>
<td>Coarse fragments (some small pebbles 2%, 5mm)</td>
<td>Moderately sorted</td>
<td>10YR 3/1 Black</td>
<td></td>
<td></td>
</tr>
<tr>
<td>54.0-56.0</td>
<td>Coarse grained sand layer</td>
<td>Small pebbles (2-5mm, 2%)</td>
<td>10YR 3/1 Black</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>56.0-76.0</td>
<td>Organic sandy clay loam</td>
<td>Woody material present and coarse fragments</td>
<td>Moderately sorted</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Core 5</td>
<td>Depth (cm)</td>
<td>Description</td>
<td>Bioturbation</td>
<td>Sorting and Grain Size</td>
<td>Colour</td>
<td></td>
</tr>
<tr>
<td>--------</td>
<td>------------</td>
<td>-------------</td>
<td>--------------</td>
<td>------------------------</td>
<td>--------</td>
<td></td>
</tr>
<tr>
<td>0-2.5</td>
<td>Loam with coarse sand</td>
<td>-</td>
<td>Moderately sorted</td>
<td>10YR 4/2</td>
<td>Dark Greyish Brown</td>
<td></td>
</tr>
<tr>
<td>2.5-8.0</td>
<td>Silty loam with medium clay present in sections</td>
<td>-</td>
<td>Well sorted</td>
<td>10YR 2/2</td>
<td>Very dark brown</td>
<td></td>
</tr>
<tr>
<td>8.0-10.5</td>
<td>Fine-grained medium clay</td>
<td>-</td>
<td>Poorly sorted</td>
<td>2.5Y 5/2</td>
<td>Greyish brown</td>
<td></td>
</tr>
<tr>
<td>10.5-14.5</td>
<td>Medium clay, darker in colour than above.</td>
<td>-</td>
<td>Poorly sorted</td>
<td>2.5Y 5/3</td>
<td>Brown</td>
<td></td>
</tr>
<tr>
<td>14.5-24.0</td>
<td>Organic sandy loam, very dark in colour. Fining upwards.</td>
<td>-</td>
<td>Poorly sorted</td>
<td>10YR 2/1</td>
<td>Black</td>
<td></td>
</tr>
<tr>
<td>24.0-28.5</td>
<td>Coarse-grained loamy sand.</td>
<td>Coarse fragments (10%, angular stones 2 – 5mm)</td>
<td>Moderately sorted</td>
<td>2.5Y 5/1</td>
<td>Grey</td>
<td></td>
</tr>
<tr>
<td>28.5-60.0</td>
<td>Organic silty loam</td>
<td>Shell fragments and woody material present (20%)</td>
<td>Poorly sorted</td>
<td>10YR 2/1</td>
<td>Black</td>
<td></td>
</tr>
<tr>
<td>60.0-66.0</td>
<td>Silty clay loam</td>
<td>Shell fragments present (10%)</td>
<td>Well sorted, tightly packed</td>
<td>10YR 2/2</td>
<td>Very dark brown</td>
<td></td>
</tr>
<tr>
<td>66.0-76.0</td>
<td>Organic silty loam</td>
<td>-</td>
<td>-</td>
<td>10YR 2/1</td>
<td>Black</td>
<td></td>
</tr>
<tr>
<td>76.0-77.0</td>
<td>Sandy Clay Loam</td>
<td>Shell fragments and woody material (20%)</td>
<td>Poorly sorted</td>
<td>10YR 2/1</td>
<td>Black</td>
<td></td>
</tr>
<tr>
<td>77.0-95.0</td>
<td>Organic Sandy clay loam</td>
<td>Organic matter prevalent with little shell fragments present.</td>
<td>Moderately sorted</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>96.0-100.0</td>
<td>Sandy loam</td>
<td>Wood material present (5%)</td>
<td>Moderately sorted</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Core 6</td>
<td>Depth (cm)</td>
<td>Description</td>
<td>Sorting and Grain Size</td>
<td>Colour</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-------</td>
<td>------------</td>
<td>------------------------------------------</td>
<td>---------------------------------------------</td>
<td>-----------------</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0-5.0</td>
<td>Stones with fine silt</td>
<td>Moderately sorted (1mm-10mm)</td>
<td>2.5Y 4/3 Olive Brown</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>5.0-30.0</td>
<td>Coarse pebbles and stones. Little silt present (cleaner)</td>
<td>Moderately sorted (1mm-10mm)</td>
<td>2.5Y 6/1 Grey</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>30.0-55.0</td>
<td>Finer than above with some coarse grained material present</td>
<td>Moderately sorted</td>
<td>10YR 4/1 Dark Grey</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Depth (cm)</td>
<td>Description</td>
<td>Bioturbation</td>
<td>Sorting and Grain Size</td>
<td>Colour</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-----------</td>
<td>------------------------------------------------------------------------------</td>
<td>--------------</td>
<td>------------------------</td>
<td>-------------------------</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.0-1.0</td>
<td>Sandy clay loam</td>
<td>-</td>
<td></td>
<td>7.5YR 3/2 Dark Brown</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.0-3.0</td>
<td>Loam with a spongy and smooth texture</td>
<td>-</td>
<td>Well Sorted</td>
<td>2.5Y 3/2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.0-6.0</td>
<td>Silty clay loam, greater clay content than above</td>
<td>-</td>
<td></td>
<td>10YR 4/2 Dark greyish brown</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6.0-10.0</td>
<td>Light medium clay, smooth to touch.</td>
<td>-</td>
<td>Well sorted, fine clay</td>
<td>2.5Y 4/2 Greyish brown clay 2.5Y 5/2 Dark greyish brown</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10.0-18.0</td>
<td>Sticky, silty clay loam layered with a sandy clay loam (darker in colour) in 1cm wide bands.</td>
<td>-</td>
<td>Well sorted, very fine clay.</td>
<td>2.5Y 5/2 Greyish brown 10YR 4/2 Dark greyish brown</td>
<td></td>
<td></td>
</tr>
<tr>
<td>18.0-27.0</td>
<td>Organic sandy loam</td>
<td>Woody material present (5%, 0.5-2cm) and coarse fragments (very small few pebbles -2mm)</td>
<td>Moderately sorted</td>
<td>10YR 2/2 Very dark brown</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Depth (cm)</td>
<td>Description</td>
<td>Bioturbation</td>
<td>Sorting and Grain Size</td>
<td>Colour</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-----------</td>
<td>--------------------------------------------------</td>
<td>--------------</td>
<td>------------------------</td>
<td>-------------------------</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0 - 4.0</td>
<td>Slity loam with some larger sand present</td>
<td>-</td>
<td></td>
<td>7.5YR 3/2 Dark brown</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.0 - 10.0</td>
<td>Silty clay loam, more clay present than above</td>
<td>-</td>
<td>Moderate to Well sorted</td>
<td>10YR 2/2 Very dark brown</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10.0 - 15.0</td>
<td>Light clay</td>
<td>-</td>
<td></td>
<td>10YR 4/1 Dark Brown</td>
<td></td>
<td></td>
</tr>
<tr>
<td>15.0 - 26.0</td>
<td>Organic slity loam</td>
<td>Wood/ root fragments present (2%)</td>
<td>Well sorted</td>
<td>10YR 2/1 Black</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Appendix B – Grain Size Compositions

Core 1

Core 2

Core 3
Grain size distribution for Core 1
Grain size distribution for Core 2
Grain size distribution for Core 3

Grain size distribution for Core 4
Grain size distribution for Core 5

A. Borrell (2013)