To my precious family, in appreciation for their support, laughter and love.
TABLE OF CONTENTS

Table of Contents i
List of Figures and Tables ix
Abstract xvi
Statement xviii
Acknowledgements xix

CHAPTER 1 INTRODUCTION 1
  1.1 Introduction 1
  1.2 Aims 5
  1.3 Outline 6

CHAPTER 2 BACKGROUND AND CONCEPTUAL FRAMEWORK 8
  2.1 Geology and Stratigraphy 8
    2.1.1 Introduction 8
    2.1.2 Sedimentation and Major Stratigraphic Units 10

...
2.1.3  Uplift of Australia’s Eastern Highlands  11
2.1.4  Drainage Pattern of the Clarence River  12
2.1.5  Quaternary Sediments and Geomorphology  13
   2.1.5.1  Coastal Sediments and Geomorphology  13
   2.1.5.2  Estuarine Sediments and Geomorphology  18
   2.1.5.3  Alluvial Sediments and Geomorphology  24
2.1.6  Local Resources and Land Use  28

2.2  Site Formation Processes and the Synthesis of a Geoarchaeological Framework  34
   2.2.1  Introduction  34
   2.2.2  Site Formation Processes  34
   2.2.3  Aeolian Processes  36
   2.2.4  Storm Reworking  38
   2.2.5  Other Alluvial Processes  39
   2.2.6  Bioturbation  43
   2.2.7  Synthesis of a Geoarchaeological Framework  47
   2.2.8  Previous Archaeological Studies and Identification of Potential Research Sites  51

CHAPTER 3  SITE DESCRIPTIONS  55

3.1  Sleeper Island  55
   3.1.1  Land Use and Geomorphology  55
   3.1.2  Vegetation  60
   3.1.3  Cultural Material  60

3.2  Woombah  63
   3.2.1  Land Use and Geomorphology  63
   3.2.2  Vegetation  64
4.1.3 Plover Island

4.1.3.1 Collection of Cultural Material

4.1.3.2 Sediment Collection/Coring

4.1.3.3 Surveying

4.1.3.4 Vegetation Coverage Estimates

4.1.4 Minnie Water

4.1.4.1 Shell Sample Collection

4.1.4.2 Sediment Collection

4.1.4.3 Surveying

4.1.4.4 Vegetation Coverage Estimates

4.1.5 Wooli

4.1.5.1 Shell Sample Collection

4.1.5.2 Sediment Collection

4.1.5.3 Map Measurements

4.1.5.4 Vegetation Coverage Estimates

4.2 Laboratory Analyses

4.2.1 Biological Analyses

4.2.1.1 Percentage Composition by Weight, Size Range and Minimum Number of Individuals

4.2.1.2 Number of Identified Specimens (NISP)

4.2.2 Taphonomic Analyses

4.2.3 Loss on Ignition

4.2.4 Emerson Aggregate Test

4.2.5 Sand:Silt:Clay Ratio

4.2.5.1 Sample Preparation

4.2.5.2 Particle Size Analysis

4.2.6 Flood and Tide Hazard Analyses
4.2.7 Calculation of Erosion Rates 110
4.2.8 Calculation of Erosion Hazard 111
  4.2.8.1 Introduction 111
  4.2.8.2 Method one: Assessment of disturbance processes, their contributory factors and outcomes 122
  4.2.8.3 Method two: A rapid, field-based erosion assessment Methodology 127
  4.2.8.4 Field Trial of the Erosion Hazard Pro Forma 133
  4.2.8.5 Method three: GIS model 134

CHAPTER 5  STRATIGRAPHIC INVESTIGATION AND INTERPRETATION 140
5.1 Characteristics of Quaternary Strata 140
5.2 Age Determinations 141
5.3 Depositional Sequence – Near-coastal Inner Barrier Dunes 143
5.4 Stratigraphic Interpretation 144
  5.4.1 Woombah 144
  5.4.2 Sleeper Island 149
  5.4.3 Plover Island 151
  5.4.4 Minnie Water 152
  5.4.5 Wooli 154

CHAPTER 6  BIOLOGICAL AND TAPHONOMIC ANALYSES 157
6.1 Introduction 157
6.2 Species Composition 157
  6.2.1 Woombah 157
  6.2.2 Sleeper Island 160
6.2.3 Plover Island 161
6.2.4 Minnie Water 162
6.2.5 Wooli 164

6.3 Taphonomy 166
6.3.1 Woombah 166
6.3.2 Sleeper Island 171
6.3.3 Plover Island 173
6.3.4 Minnie Water 174
6.3.5 Wooli 176
6.3.6 Conclusions 177

CHAPTER 7  GEOMORPHIC PROCESSES AND MAJOR IMPACTS 178

7.1 Introduction 178
7.2 Anthropogenic Modifications to the Clarence River Channel 180
7.3 Sea Level 189
7.3.1 Sea Level During Interglacial Stages 189
7.3.2 Causes of Sea Level Rise 194
7.3.3 MIS 5e and Holocene Sea Levels Along the East Coast of Australia 197
7.3.4 Past, Present and Projected Rates of Sea Level Change in Eastern Australia 209
7.3.5 Effects of Current and Future Rates of Sea Level Rise on Study Sites in Northern NSW 211
7.4 Flooding and Tidal Inundation Hazard at Estuarine and Riverine Study Sites 212
7.4.1 Flooding 212
<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.4.2</td>
<td>Tidal Inundation</td>
<td>216</td>
</tr>
<tr>
<td>7.5</td>
<td>Erosion Hazard at the Study Sites</td>
<td>222</td>
</tr>
<tr>
<td>7.5.1</td>
<td>Introduction</td>
<td>222</td>
</tr>
<tr>
<td>7.5.2</td>
<td>Soils</td>
<td>222</td>
</tr>
<tr>
<td>7.5.3</td>
<td>Causes of Erosion on Sleeper Island</td>
<td>233</td>
</tr>
<tr>
<td>7.5.4</td>
<td>Causes of Bank Erosion at Woombah</td>
<td>238</td>
</tr>
<tr>
<td>7.5.5</td>
<td>Use of Farming Machinery at the Woombah Site B</td>
<td>240</td>
</tr>
<tr>
<td></td>
<td>Aboriginal Midden Deposit</td>
<td></td>
</tr>
<tr>
<td>7.5.6</td>
<td>Erosion Rates at Woombah and Sleeper Island</td>
<td>241</td>
</tr>
<tr>
<td>7.5.7</td>
<td>Causes of Erosion on Plover Island</td>
<td>244</td>
</tr>
<tr>
<td>7.5.8</td>
<td>Causes of Erosion at Minnie Water</td>
<td>246</td>
</tr>
<tr>
<td>7.5.9</td>
<td>Wooli</td>
<td>249</td>
</tr>
<tr>
<td>7.5.10</td>
<td>Conclusion – Causes of Erosion at the Study Sites</td>
<td>250</td>
</tr>
<tr>
<td>7.5.11</td>
<td>Validation of the Erosion Hazard Assessment Models</td>
<td>252</td>
</tr>
<tr>
<td>7.5.11.1</td>
<td>Results of the field trial – validation of the rapid field assessment methodology</td>
<td>252</td>
</tr>
<tr>
<td>7.5.11.2</td>
<td>Comparison of results obtained using the rapid field-based erosion hazard assessment and the comprehensive methodology presented in Chapter 4 and Appendix 5</td>
<td>254</td>
</tr>
<tr>
<td>7.5.11.3</td>
<td>Comparison of results obtained using the rapid field-based erosion hazard assessment and the GIS model</td>
<td>255</td>
</tr>
<tr>
<td>7.5.12</td>
<td>Conclusions – Studying the Causes of Erosion</td>
<td>256</td>
</tr>
</tbody>
</table>
CHAPTER 8
RECOMMENDED ACTIONS FOR CONSERVATION OF THE STUDY SITES 258

CHAPTER 9
CONCLUSIONS 261

9.1 Broader Applications of the Methodologies Developed in this Research Project 261

9.1.1 Introduction 261

9.1.2 International Examples 262

9.1.3 Australian Grassroots Programs 273

9.2 Conclusion 277

REFERENCES 285

PLATES AND PLATE EXPLANATIONS 317

APPENDICES 324

APPENDIX 1: CORE DIAGRAMS A1 -1

APPENDIX 2: RESULTS OF SEDIMENT ANALYSES A2 -1

APPENDIX 3: HANDBOOK FOR USE WITH THE EROSION HAZARD PRO FORMA A3 - 1

APPENDIX 4: HISTORIC FLOOD AND TIDE DATA A4 - 1

APPENDIX 5: RESULTS OBTAINED USING THE THREE EROSION HAZARD ASSESSMENT TECHNIQUES OUTLINED IN THE TEXT A5 - 1

APPENDIX 6: GIS EROSION HAZARD ASSESSMENT MODEL (MEDIA)

APPENDIX 7: ETHICS APPROVAL DOCUMENTATION A7 - 1
FIGURES AND TABLES

FIGURES

Chapter 1

1.1: Location of the study sites. 3
1.2: Aerial photographs showing the location of the study sites. 4

Chapter 2

2.1: Regional geology of the study area. 9
2.2: Pleistocene and Holocene geomorphology of the Iluka to Woody Bay sand barrier. 16
2.3: Configuration of the coastline and Clarence River entrances at (a) 1600 yr BP, (b) 1500 yr BP, and (c) 1000 BP. 17
2.4: Composite estuarine system of the Clarence River showing the location of study sites located within the estuary. 21
2.5: Geomorphic subdivisions of the Grafton floodplain. 27
2.6: Clarence Valley Council current land use zonings. 29
2.7: Locations of Morand’s (2001) soil landscapes in the study area. 33
2.8: A flow chart for site formation. 35
2.9: Percolation of fine sediments indicated by the presence of crescentic laminations on the clay coating under the pore spaces. 45
2.10: Thin section taken from the Sangamon Soil in western Illinois showing biogenic sorting of mineral grains by size. 46

Chapter 3

3.1: A: Aerial photograph of a section of the Clarence River estuary showing Sleeper Island. 56
B: Close up of Sleeper Island showing location of Aboriginal shell midden.
3.2: Sleeper Island, adjacent to Palmers Island, showing locations of core samples. 56
3.3 Topographic map of Sleeper Island, adjacent to Palmers Island, showing locations of core samples. 57
3.4: Cattle hoof prints on Sleeper Island. 58
3.5 & 3.6: Bridge connecting Sleeper and Palmers Islands.

3.7: Pooled water in the channel between Sleeper and Palmers Islands.

3.8: West bank of Sleeper Island, showing bank erosion.

3.9: East bank of Sleeper Island.

3.10: A: Site of the cultural deposit on Sleeper Island. B: Part of the lag deposit showing stone tools. C: Part of \textit{in situ} deposit with arrows showing shell material.

3.11: Sleeper Island \textit{in situ} Aboriginal shell midden deposit.

3.12: A: Aerial photograph of a section of the Clarence River estuary showing the Woombah study site. B: Close up of the Woombah study site showing locations of the Aboriginal shell middens.

3.13: Close up of red box in Figure 3.10A showing the location of core samples.

3.14: Topographic map of Woombah sites A (east) and B (west), showing the location of core samples.

3.15: Section of Woombah Site A riverbank deposit.

3.16: Shell material eroding from the Woombah Site A riverbank deposit.

3.17: Woombah Site A Aboriginal midden deposit.

3.18: Woombah Site B Aboriginal midden deposit.

3.19: Aerial photograph of the mouth of the Sandon River showing Plover Island to the north.

3.20: Close up of Plover Island showing the locations of the \textit{in situ} stone artifacts, surface scatter and managed Aboriginal shell midden deposit.

3.21: Plover Island showing the location of core 1P (red dot).

3.22: Topographic map of Plover Island showing the location of core 1P (circled red dot).

3.23: Walking track worn partially through the surface scatter of Aboriginal stone tool artifacts on Plover Island.

3.24: \textit{In situ} stone artifact lens, Plover Island.

3.25: Portion of the stone artifact scatter on Plover Island.
3.26: Retaining wall at the Aboriginal shell midden site, Sandon River camping ground.  
3.27: Plover Island, showing the location of the in situ artifact deposit and the surface artifact scatter. 
3.28: A: Aerial photograph of Minnie Water showing the study site, town, Ilaroo camp ground and beach access points. B: Close up of Rocky Point. 
3.29: Rocky Point Headland (Minnie Water) showing the locaton of core samples. 
3.30: Topographic map of Rocky Point (Minnie Water) showing the location of core samples. 
3.31: A: A section of the exposed face of the midden deposit at Rocky Point, Minnie Water. B: The eroding face of the midden deposit showing the lag deposit at its base. 
3.32: Location of the midden deposit at Rocky Point, Minnie Water. 
3.33: Well worn in situ shell material at the Rocky Point midden. 
3.34: In situ stone core showing points of percussion. 
3.35: Cross section of the location of the Minnie Water Aboriginal midden. 
3.36: Minnie Water Aboriginal midden deposit. 
3.37: A: Aerial photograph of Wooli showing the study site, the village of Wooli and the Wooli River. B: Close up of Harold Lloyd Park. 
3.38: Topographic map of the Wooli study site showing the locaton of core samples. 
3.39: A burrow through the Wooli Aboriginal shell midden showing cultural material which has been brought to the surface as a result of the burrowing process. 
3.40: Photograph of the northern end of Harold Lloyd Park, Wooli. 
3.41: Photograph of a section of one of the trenches dug for sample collection at Harold Lloyd Park. 
3.42: Plan view diagram of the Wooli Aboriginal midden deposit. 

Chapter 6 
6.1: Percentage composition of species by weight – Woombah Site B. 
6.2: Percentage composition of species by weight – Woombah Site A. 
6.3: Percentage composition of species by weight – Sleeper Island.
6.4: Proportion of major edible species by MNI – Minnie Water. 163
6.5: Species composition of the midden and lag deposits at Minnie Water. 164
6.6: Comparison of results – percentage composition by weight and MNI, Wooli midden. 166
6.7: Percentage composition of major midden species by weight, Wooli midden. 166
6.8: Amount of abrasion as a percentage of shell material affected – Minnie Water in situ and lag deposits. 175
6.9: Amount of biological modification as a percentage of shell material affected – Minnie Water in situ and lag deposits. 176

Chapter 7
7.1: A-H: Diagrammatic representation of the anthropogenic modifications to the Clarence River estuary. 183
7.2: The south external breakwater at Yamba. 187
7.3: Moriarty’s Wall, complete with spur directed upstream. 187
7.4: Middle Wall as seen from the south external breakwater. 188
7.5: Close up of the eastern end of Middle Wall, taken from the south external breakwater. 188
7.6: Alignment of MIS 11 and MIS 1 based on northern hemisphere summer insolation trends. 191
7.7: Northern hemisphere summer insolation levels during MIS 11 and MIS 5 and predicted future levels. 191
7.8: Vostok time series and ice volume. 193
7.9: The effects of surface wind stress at the east and west Pacific basin boundaries. 195
7.10: The mechanism of hydro-isostasy and its influence on sea level. 196
7.11: Summary of observed Holocene sea level highstands along the Australian coastline, showing higher amplitudes at bays and gulfs and lower amplitudes at open coastline locations. 196
7.12: Predicted Holocene sea levels for NSW, based on rheological model E14(50). 206
7.13: Predicted sea levels for the Australian coastline at 6000 years BP, based on upper mantle viscosity of $10^{20}$ Pa and lower mantle viscosity of 1022 Pa, and an upper mantle viscosity of $2 \times 10^{20}$ Pa and lower mantle viscosity of 1022 Pa.

7.14: Sea level data from fixed biological indicators, forming a postulated sea level envelope for the east coast of Australia.

7.15: Sea level curves of Lambeck and Chappell, 2001 and Waelbroeck et al., 2002.

7.16: Particle size plot Woombah Site A.

7.17: Particle size plot Woombah Site B.

7.18: Particle size plot Sleeper Island.

7.19: Particle size plot Minnie Water.

7.20: Particle size plot Plover Island.

7.21: Elevation of natural seedling recruitment on an eroding river bank.

7.22: Tree root exposure around the bank of Sleeper Island.

7.23: Erosion-vegetation cover relationship.

7.24: Soil pedestal at the Minnie Water Aboriginal shell midden site.

7.25: Tree root exposure at the Minnie Water Aboriginal shell midden site.

7.26: Field trial of the Erosion Hazard Pro Forma system at the Minnie Water Aboriginal shell midden site.

7.27: Field trial of the Erosion Hazard Pro Forma system at the Sleeper Island Aboriginal shell midden site.
TABLES

Chapter 2

2.1: Area of Protected Lands, land under Voluntary Conservation Agreements, wildlife refuges and other land for wildlife in the Clarence Valley. 30

2.2: Land use by soil type. 31

2.3: The study sites, their geomorphic context and age. 54

Chapter 4

4.1: Selected methods of erosion hazard assessment. 114

4.2: Standard Definitions for GIS Erosion Risk Categories. 138

Chapter 5

5.1: Age determinations obtained from materials located within the Inner Barrier dune complex along the east coast of Australia. 155

Chapter 6

6.1: Woombah Site A – percentage composition of species by weight. 159

6.2: Sleeper Island – percentage composition of species by weight and minimum number of individuals. 161

6.3: Species composition of the Wooli midden. 165

6.4: Attributes of shell concentrations – Woombah Site A. 169

6.5: Attributes of shell concentrations – Woombah Site B. 170

6.6: Type of Saccostrea glomerata fragments present in the Woombah Site A and B deposit samples. 170

6.7: Attributes of shell concentrations – Sleeper Island. 173

6.8: Attributes of shell concentrations – Plover Island lag deposit. 174

6.9: Amount of biological modification as a percentage of shell material affected – Minnie Water in situ and lag deposits. 176

6.10: Attributes of shell concentrations – Wooli. 177

Chapter 7

7.1: Post-European Channel Modifications to the Clarence River mouth. 180
7.2: Late Quaternary sea level measurements along the east coast of Australia. 202
7.3: Number of years until total inundation of Aboriginal shell middens at study sites in northern NSW based on various rates of sea level rise discussed in the text. 212
7.4: Tidal range and corresponding inundation class. 217
7.5: Site elevation, flood height and flood return period. 220
7.6: Site elevation, tidal inundation frequency and inundation class. 221
7.7: Hazard outcomes and factors contributing to erosion at the study sites. 240

Chapter 8

8.1: Conservation recommendations for the study sites. 260

Chapter 9

9.1: Examples of Australian sites where the methodologies developed in this study could be applied. 268
ABSTRACT

A combination of archaeological and geomorphic techniques was used to study erosion hazard at Aboriginal shell midden sites in the Northern Rivers region of New South Wales, Australia. In the absence of artifactual material, biological and taphonomic analyses were undertaken to determine the likelihood a deposit was anthropogenic in origin. These analyses were also used to gain an understanding of site formation processes.

The relationship between, and relative influence of, anthropogenic and non-anthropogenic erosive factors at shell midden sites in different geomorphic settings was used to formulate three erosion hazard assessment methods. Each method was designed to address the needs of a different stakeholder group. The archaeological method includes analysis of the effects of bank erosion, cultivation, anthropogenic and biological excavation, wind and wave erosion. Erosive factors are compared between sites and geomorphic settings. The rapid assessment technique designed for use by Aboriginal Land Councils and local Indigenous communities includes an Erosion Hazard Pro Forma and uses relatively simple geomorphic analyses which can be performed in the field. A handbook containing straightforward, user-friendly instructions on how to complete the Erosion Hazard Pro Forma is also included, along with a scoring system used to quantify erosion hazard and rank the study sites. A GIS model generated using soil, land use, vegetation and elevation data is also used to quantify erosion hazard and rank the study sites.

Agreement between results obtained using the three assessment methods, based on the relative influence of erosive factors, confirms their usefulness as cultural heritage management tools. Study sites at Sleeper Island, Minnie Water, Woombah Site A, Woombah Site B, Plover Island and Wooli are ranked, in that order, from greatest to least erosion hazard. Major factors contributing to erosion at Sleeper Island include boat traffic, steep banks, low site elevation and vegetation coverage and a history of farming. At Minnie Water unconsolidated dunes in close proximity to ocean swell, low vegetation coverage and high exposure to prevailing winds all
influence erosion. Human activity (historic cultivation and excavation) is the major factor causing erosion at the Woombah study sites. These processes have not only disturbed large portions of the midden complex, they have also had a negative influence on vegetation coverage and bank slope. Exposure to prevailing winds, coupled with its situation within a walking track, are the major causes of erosion and disturbance of the surface stone artifact scatter and \textit{in situ} stone artifact deposit on Plover Island. Minimal disturbance at the Wooli Aboriginal shell midden deposit is due to its burial in a low energy environment, gentle bank slope, high vegetation coverage and minimal anthropogenic impact. Research findings indicate vegetation coverage and bank slope are the primary factors influencing erosion at estuarine sites. Elevation (above water level), exposure to prevailing winds and vegetation coverage were found to be the primary factors influencing erosion at coastal sites.

Two sets of conservation recommendations were formulated. The first set comprises general guidelines for management of sites based on their geomorphic setting. Secondly, specific guidelines for management and conservation of the study sites were formulated in accordance with the wishes of the Yaegl Local Aboriginal Land Council. Implementation of these recommendations will ensure effective cultural heritage management at these sites. Further application of the methodologies developed in this study would greatly increase the effectiveness of cultural heritage management at Aboriginal shell middens as well as other types of coastal archaeological sites.
STATEMENT

Unless otherwise acknowledged, all data and interpretations presented in this thesis are my own. I hereby certify that this thesis has not been submitted for the degree of Doctor of Philosophy to any other university or institution.

Hannah Nair
ACKNOWLEDGEMENTS

Associate Professor James Kohen and Dr Paul Hesse have been my supervisors throughout the duration of the research project. I thank them for their valuable discussions, suggestions and general help throughout the duration of the project, and for critically reading the manuscript. I also thank Dr Julia Raftos for her administrative support as an associate supervisor.

I gratefully acknowledge the technical assistance provided in the field by Mr David Harrington, Dr Tan Nair, Dr Paul Hesse, Mr Nathan Gocher, Ms Tessa Campbell and, most importantly, Mr Ferlin Laurie. Ferlin’s passion for, and dedication to, the management and preservation of his Aboriginal cultural heritage is inspirational. His assistance in the field and also in liaising with the Yaegl Local Aboriginal Land Council was invaluable. I also thank the Yaegl Local Aboriginal Land Council for their support and willingness to facilitate the research.

I also sincerely thank Mr Russell Field for his technical assistance in the soils laboratory, Roger Mehr and Sarah Paddington from the DECCW Aboriginal Cultural Heritage Unit, the Clarence Valley Council Floodplain Services and Manly Hydraulics Laboratory for the provision of land use zoning information and flood and tide height/frequency data.

I am very appreciative of the support and encouragement offered to me by my family, from assistance in the field to useful discussions and suggestions relating to various parts of the research. And I especially thank my daughter Sofia, who travelled inside me during the first year of the project, for her love and hugs.

The research was funded by an Australian Postgraduate Award.