Oceanographic Considerations for the Management and Protection of Surfing Breaks

A thesis submitted in fulfilment of the requirements

for the Degree of
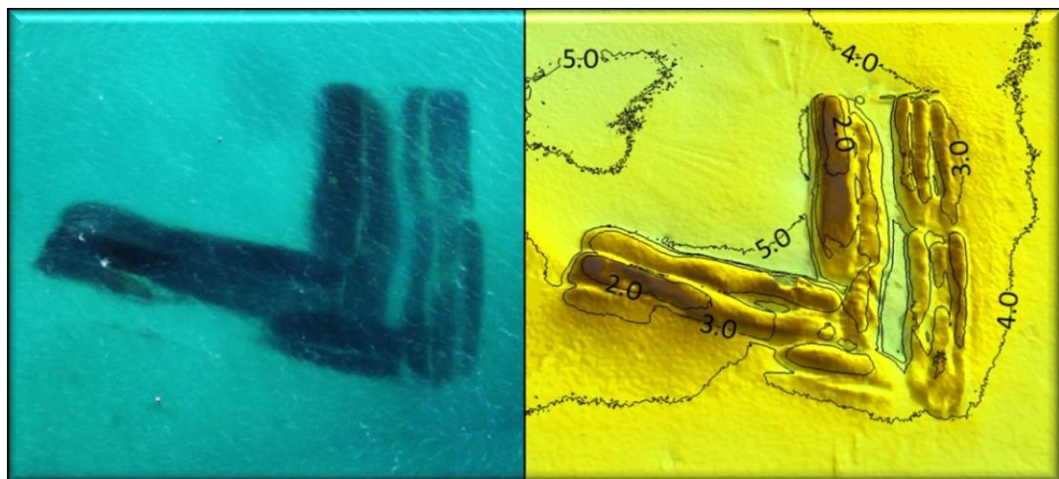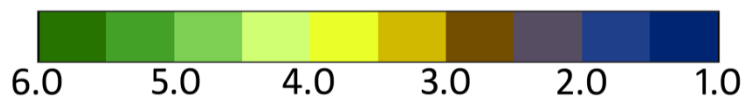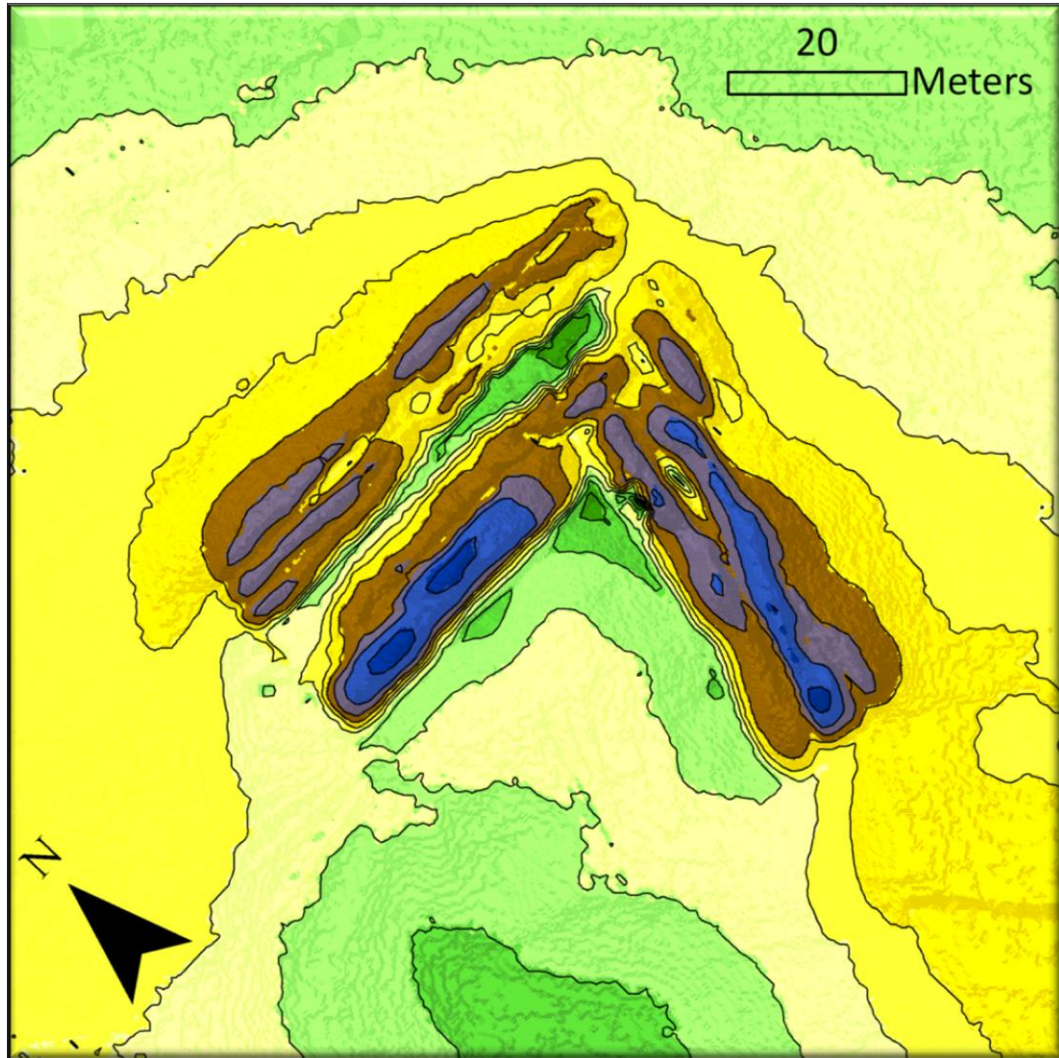
Doctor of Philosophy

in Earth and Ocean Sciences

by

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ABSTRACT

Although the physical characteristics of surfing breaks are well described in the literature, there is little specific research on surfing and coastal management. Such research is required because coastal engineering has had significant impacts to surfing breaks, both positive and negative. Strategic planning and environmental impact assessment methods, a central tenet of Integrated Coastal Zone Management (ICZM), are recommended by this thesis to maximise surfing amenities. The research reported here identifies key oceanographic considerations required for ICZM around surfing breaks including: surfing wave parameters; surfing break components; relationship between surfer skill, surfing manoeuvre type and wave parameters; wind effects on waves; currents; geomorphic surfing break categorisation; beach-state and morphology; and offshore wave transformations. Key coastal activities that can have impacts to surfing breaks are identified. Environmental data types to consider during coastal studies around surfing breaks are presented and geographic information systems (GIS) are used to manage and interpret such information. To monitor surfing breaks, a shallow water multibeam echo sounding system was utilised and a RTK GPS water level correction and hydrographic GIS methodology developed. Including surfing in coastal management requires coastal engineering solutions that incorporate surfing. As an example, the efficacy of the artificial surfing reef (ASR) at Mount Maunganui, New Zealand, was evaluated. GIS, multibeam echo soundings, oceanographic measurements, photography, and wave modelling were all applied to monitor sea floor morphology around the reef. Results showed that the beach-state has more cellular circulation since the reef was installed, and a groin effect on the offshore bar was caused by the structure within the monitoring period, trapping sediment updrift and eroding sediment downdrift. No identifiable shoreline salient was observed. Landward of the reef, a scour hole ~3 times the surface area of the reef has formed. The current literature on ASRs has primarily focused on reef shape and its role in creating surfing waves. However, this study suggests that impacts to the offshore bar, beach-state, scour hole and surf zone hydrodynamics should all be included in future surfing reef designs. More real world reef studies, including ongoing monitoring of existing surfing reefs are required to validate theoretical concepts in the published literature.

ACKNOWLEDGEMENTS

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LIST OF ABBREVIATIONS

α	Wave Peel Angle
ArcGIS	Commercial GIS product
ArcIMS	Commercial GIS image server
ArcSDE	Commercial server-based GIS storage software
ASR	Artificial Surfing Reef
BAG	Bathymetric Attributed Grid
B_I	Wave Breaking Intensity
CMG	The University of Waikato's Coastal Marine Group
CUBE	Combined Uncertainty and Bathymetric Estimator
DBMS	Database Management System
DTM	Digital Terrain Model
EIA	Environmental Impact Assessments
ESRI	Environmental Systems Research Institute
FGDC	Federal Geographic Data Committee
FGDC ESRI	Federal Geographic Data Committee ESRI metadata format
GIS	Geographic Information System
H_B	Breaking Wave Height
ICZM	Integrated Coastal Zone Management
IHO	International Hydrographic Organisation
ISO	International Standards Organisation
LAT	Lowest Astronomical Tide
LiDAR	Light Detection and Ranging
LINZ	Land Information New Zealand
MBES	Multibeam Echo Sounder
MSL	Mean Sea Level
NAVOCEANO	U.S. Naval Oceanographic Office
NOAA	National Oceanic and Atmospheric Administration
NZGD2000	New Zealand Geodetic Datum 2000
NZMG	New Zealand Map Grid coordinate system
R.A.N.	Royal Australian Navy
RAID	Redundant Array of Independent Drives
RTK GPS	Realtime Kinematic Global Positioning System
S.A.I.C.	Science Applications International Corporation
S-57	IHO Digital Hydrographic Exchange Format
SATA	Serial Advanced Technology Attachment
SBES	Singlebeam Echo Sounder
S_L	Wave section length
U.S.A.C.E.	United States Army Corps of Engineers
WBEND	WBEND wave refraction model from the 3DD suite of models
XML	Extensible Markup Language

APPENDICES

Appendix One: DHI Mike 21 Nearshore Spectral Wave (NSW) refraction modelling of Aramoana Beach, New Zealand.

Appendix Two: Mount Maunganui, New Zealand, WBEND refraction model calibration.

Appendix Three: Survey coverage for Mount Maunganui artificial surfing reef surveys.

Chapter 1 - THE VALUE, SCARCITY, AND VULNERABILITY OF SURFING BREAKS

BACKGROUND

Surfing is a major recreational and economic activity involving intimate human relationships with diverse coastal environments (LAZAROW *et al.,* 2007a; p.21). While almost any wave can propel a person towards the beach, for the sport of surfing a special type of wave is required. Surfers need waves that propel them laterally along a wave crest, ahead of the peeling wave breakpoint (WALKER, 1974; BLACK, 2001; MEAD, 2001; SCARFE *et al.,* 2003). FARMER and SHORT (2007) define a surfer as:

> *'any person who interacts physically with the surf for recreation. It includes bodysurfing, bodyboarding, surfboarding, surfskiing, surfboating, all forms of surf lifesaving and lifeguarding, but excludes all surf interaction powered by wind and machines (p. 99).'*

The difference between an ordinary beach with a surf zone and a "surfing break" is the unique combination of what MEAD and BLACK (2001a and 2001b) term "surfing reef components" (seabed features), and their interaction with wind, tides and waves. WALKER and PALMER (1972, p. 42) first scientifically defined a surfing break as:

> *'an area where surfers participate in the sport of surf riding on natural ocean waves. A site includes the take-off, riding, board-recovery, rider-return, and access areas.'*

High quality surfing breaks are vulnerable to coastal development, scarce, and possess economic, sporting and aesthetic value. The recreational, aesthetic and associated economic value of a high quality surfing break to a coastal community is often significant (NELSEN *et al.,* 2007). To maximise surfing amenities and their associated benefits, serious consideration needs to be given to surfing breaks in coastal management. It is essential as many surfing breaks have been affected by coastal development (ANON, 2003; SCARFE *et al.,* Chapter 3). This view, commonly held by the surfing community, is becoming more widely accepted in coastal management. Evidence of this can be seen by coastal management

practices such as the development of Australian National Surfing Reserves (FARMER and SHORT, 2007) and publication of journal special issues on surfing (BLACK, 2001; WALTHER, 2007)

THE ECONOMIC VALUE OF SURFING BREAKS

Although the economic impacts of surfing have not been as extensively researched as the oceanographic processes (*see* Chapter 2 for researched-based surfing literature review), there is ample evidence to demonstrate the associated economic benefits of surfing breaks to coastal communities (LAZAROW, 2007; LAZAROW *et al.,* 2007a and b; NELSEN *et al.,* 2007), and surfing has been identified as a key tourist attraction in many locations (BUCKLEY, 2002a and 2002b). Understanding the value of surfing breaks relative to other activities can help resolve resource management conflicts by providing transparency in decision making (LAZAROW *et al.,* 2007a).

In specific investigations, BAILY and LYONS (2003), and TOURISM RESOURCE CONSULTANTS (2002) quantified the economic impact of artificial surfing reef developments. They reported cost/benefit ratios to the economy of artificial surfing reefs, ranging from 20:1 to 70:1. LAZAROW (2007) has reported that 20 million dollars per year is spent by surfers at the South Stradbroke Island surfing break in the Gold Coast. Further summaries on the economic value of surfing breaks are presented in LAZAROW *et al.* (2007a) and NELSEN *et al.* (2007), demonstrating that they are important contributors to coastal economies.

FARMER and SHORT (2007) estimate in Australia there are three million people who identify themselves as surfers and LAZAROW *et al.* (2007a) estimates that there are between 18 and 50 million surfers globally. Surfing has become a mainstream sport with mass media coverage, associated celebrity and merchandise. Consequently, the tourism and accommodation, food, equipment, clothing and merchandise industries relating to surfing have significant economic value. BUCKLEY (2002a) in the mid-1990s estimated the industry to be worth US$10 billion per annum, and based on the reported growth rate of the activity, this figure is expected now to be significantly larger. Therefore maintaining the sustainability of surfing amenities is not just required for those who ride the waves, but also for the economic and social infrastructure that they support.

THE SCARCITY OF SURFING BREAKS

Surfing breaks are scarce because there are relatively few surfing breaks compared to the length of the world's coastline (PRATTE, 1987; MEAD and BLACK, 2001a). For example, according to one of the largest databases of worldwide surfing spots, www.wannasurf.com[1], there are 313 surfing breaks in New Zealand. Another estimate by MORSE and BRUNSKILL (2004) is that New Zealand has 470 surfing breaks. Considering that there is 18,200 km of coastline in New Zealand (ROUSE *et al.*, 2003), there is only one surfing break every 39 km to 58 km. Many of these surfing breaks are only surfable a few days per month or year when the tide, wind and wave conditions are suitable. HENRIQUES (2005) stated that good surfing breaks are rare, but surfers are not, and this leads to overcrowding at many surfing breaks. This in turn can lead to incidents of surf rage where conflict occurs between surfers (YOUNG, 2000).

Although surfing breaks are rare, high quality, or "world-class" (MEAD and BLACK, 2001a and b), surfing waves, suitable for top amateur and professional surfers (HUTT *et al.,* 2001), are even rarer. For example, the www.wannasurf.com[1] website uses a one to five rating system for surfing quality with five being the highest quality. Out of the 313 New Zealand surfing breaks identified, only 17 % are rated four or above. Considering these issues, the chance of turning up to a surfing break and finding high quality surfing waves is rather low. Given that surfing breaks also are vulnerable to coastal development (SCARFE *et al.*, Chapter 3), they may become even more scarce.

THE VULNERABILITY OF SURFING BREAKS

On a geomorphic scale, surfing breaks are reasonably resilient to natural coastal forces such as waves and tides. The processes and bathymetry that comprise the surfing break evolve over decades to hundreds, possibly even thousands of years, but generally, in the absence of human intervention, surfing breaks are stable within peoples' lifetimes. Although some surfing breaks change naturally at shorter time scales, it is probable that many of the changes at timescales of 5, 10 or 20 years, are influenced by human activities. Examples of various activities that

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[1] Public web surfing forum without scientific quality control. The website is still expected to represent reality reasonably well. Number of surfbreaks as of 2007.

can destroy or improve surfing amenities include the jetting of inlets, the flattening of sand dunes, the dredging of channels, the dumping of artificial nourishment, the armouring of coastlines, the alteration of sediment transport pathways' (and sediment sources and sinks), and general modification of the world's coastlines and catchments.

There have been numerous surfing breaks around the world that have been affected by development (CHAD NELSON [2], *pers. comm.*). The accelerated modification to surfing breaks has been caused by human activities that are single-issue (e.g., boat navigation, coastal erosion) or single-sector (e.g. fisheries, resort development) focused, leading to conflict with surfers. PILKEY and DIXON (1996) comprehensively describe how the lack of integration of the USA government in coastal management, as well as a narrow project focus during the 20th century has lead to significant negative environmental impacts to sectors and issues outside the initial project scope. Surfing is one of these sectors.

An example of this lack of integration was the proposed south jetty extension project at Ponce de Leon Inlet (Florida). The planned proposal failed to adequately address impacts on surfing and tourism in the initial feasibility study, which resulted in significant community concern. A community campaign was launched to save the surfing break which included successful lobbying of the developer (USACE) to include surfers more in the decision making process. An online petition with 3164 signatures (20 September 2007; www.petitiononline.com/surf11/petition.html) summarises their concerns. This level of recognition and concern over the vulnerability of surfing breaks to human intervention clearly indicates a need for methods to manage development issues around surfing breaks.

RESEARCH AIM AND TECHNIQUES

The general purpose of this research is to provide an overview and methods for the scientific management of surfing breaks. This includes the protection of surfing amenities and their enhancement where appropriate. The research is focused on identifying oceanographic processes around surfing breaks. Infrastructure, such as free public access to surfing breaks, toilets and

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[2] Environmental Officer, Surfrider Foundation.

accommodation, as well as water quality, contribute to the quality of a surfing experience, but is outside the scope of this research. Additionally, monitoring the usage of surfing breaks and other more social coastal management techniques are important for decision making around surfing breaks, but not covered in this research.

Within this theme, the specific objectives are to:

1. *investigate research-based surfing literature pertinent to coastal management decision making;*

2. *describe the physical characteristics of surfing breaks and surfing waves;*

3. *identify the range of physical effects coastal engineering activities can have on different types of surfing breaks, and to propose methods to manage the oceanographic aspects of surfing breaks;*

4. *develop improved methods for charting surfing breaks, including the management of relevant environmental data;*

5. *present methods and results of pre-construction baseline bathymetric data collection around a surfing break as an example of a modern surfing break Environmental Impact Assessment (EIA) requirement;*

6. *demonstrate the potential of Geographic Information Systems (GIS) overlay, geoprocessing and geodatabase techniques to store and analyse information for management of surfing amenity; and*

7. *monitor the beach and wave response to an artificial surfing reef using techniques identified and developed in this thesis.*

THESIS STRUCTURE

To achieve the objectives listed above the thesis is comprised of nine chapters, including three submitted papers, two papers accepted for publication and one published paper. They are:

Chapter Two is a peer-reviewed paper accepted for publication in the *Journal of Coastal Research.* The chapter reviews the different categories of research-based surfing literature and provides definitions of key surfing science concepts and an overview of the theoretical research framework. Case studies are used to demonstrate processes occurring around surfing break.

Chapter Three presents a peer-reviewed paper accepted for publication in the *Journal of Coastal Research*. It outlines the need to investigate the sustainability of surfing breaks using examples of coastal development near surfing breaks. This paper proposes that modern coastal management should protect existing surfing breaks, incorporate surfing into coastal engineering, and undertake environmental impact assessments (EIA) using detailed scientific methods.

Chapter Four comprises a peer-reviewed paper submitted to the *Hydrographic Journal*. This paper describes coastal mapping techniques used in this thesis to chart surfing breaks. Accuracy estimates for the multibeam survey system used are calculated and the paper provides a key reference for the survey methodology undertaken in subsequent chapters of the thesis.

Chapter Five is a peer-reviewed paper submitted to the *Hydrographic Journal*. It describes the development of a data management system for hydrographic information using GIS techniques discussed in BREMAN (2002), ESRI (2006) and WRIGHT *et al.* (2007). The method used can be applied store, interpret and distribute other types of environmental information during the management of surfing breaks.

Chapter Six is a peer-reviewed paper presented and published at the Australasian Coasts and Ports Conference 2005. It outlines a pre-construction bathymetric monitoring program that recorded baseline datasets around the Tay Street (Mount Maunganui, New Zealand) artificial surfing reef (ASR). The paper argues that in order to protect and maximise surfing amenities, a good baseline understanding of the environmental conditions is required. The methodology provides a useful method for bathymetric monitoring as part of an EIA process or engineering development.

Chapter Seven describes the oceanographic conditions around the Mount Maunganui ASR. Tides, winds as well as measured and hindcast wave data are collated to understand the oceanographic conditions during surfing and storm events. Key wave events are identified for use as hydrodynamic boundary conditions.

Chapter Eight is a peer-reviewed paper submitted to *Coastal Engineering* and shows the short term morphological response of the Mount Maunganui beach to

the ASR. Nine RTK GPS foreshore and multibeam bathymetric surveys before and during the construction of the ASR show the beach morphology during different stages of reef construction. Hydrodynamic modelling of wave transformations over the reef are also presented.

Chapter Nine summaries the major findings from the research. Specific techniques developed within this thesis are highlighted to show that surfing break management can be enhanced by using modern coastal analysis techniques, GIS, detailed EIA reporting and strategic coastal management planning specifically for surfing.

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Chapter 2 – RESEARCH-BASED SURFING LITERATURE FOR COASTAL MANAGEMENT AND THE SCIENCE OF SURFING – A REVIEW

PREFACE

This chapter reviews the current state of research-based literature on surfing as a background to key concepts and terms used during this thesis. Research-based surfing literature focuses on exploring the various characteristics of surfers, the surfing environment and industry. To date there has not been peer-reviewed research categorising research-based surfing literature. A summary of this type is necessary to provide coastal managers with an overview of the different publications and research areas. Additionally, the characteristics of surfing waves and surfing breaks are described to show how waves, wind and bathymetry combine to turn ordinary waves into surfing waves. This paper relates to the following objectives of the thesis:

1. *to investigate research-based surfing literature pertinent to coastal management decision making; and*

2. *to describe the physical characteristics of surfing breaks and surfing waves.*

This paper has been peer-reviewed and accepted for publication in the Journal of Coastal Research, along with a companion paper describing the impacts coastal engineering can have on surfing amenities (SCARFE *et al.,* Chapter 3). The combined efforts of these two papers develop the argument that surfing breaks are sensitive to nearby activities, and that the management of surfing amenities can be improved using the substantial literature base on oceanographic processes occurring around surfing breaks. SCARFE undertook the literature reviewing, writing, figure and table creation, but the intellectual input by HEALY and RENNIE's in a thesis supervisory and editorial role warranted co-authorship.

The current paper citation is:

SCARFE, B.E., HEALY, T.R., and RENNIE, H.G., *in press*. Research-Based Surfing Literature for Coastal Management and the Science of Surfing – A Review. *Journal of Coastal Research,* accepted for publication and manuscript archived 8 May 2008.

ABSTRACT

Incorporating recreational surfing into coastal management practises is required to protect the seabed features and oceanographic processes that create surfing waves. A review of research-based surfing literature is undertaken to provide a summary of information available to assist in coastal management decision making. The different categories of research-based surfing literature are identified as artificial surfing reef (ASR) design, ASR monitoring, ASR construction, ASR sediment dynamics, biomechanics, coastal management, economics and tourism, industry, numerical and physical modelling, surfers and waves, sociology and physical processes. The majority of this research has been undertaken in the last decade making it a relatively young research area. As a background for non-surfing coastal researchers and managers, the characteristics of surfing waves and surfing breaks are described, referring to relevant literature. Wave height, peel angle, breaking intensity and section length are identified as essential parameters to describe surfing waves. Existing surfer skill and manoeuvre categorisation schemes are presented to show the relationship between surfers and surfing waves. The geomorphic categories of surfing breaks are identified as headland or point breaks, beach breaks, river or estuary entrance bars, reef breaks, and ledge breaks. The literature discusses the various scale bathymetric components that create these surfing breaks. Examples of modelling offshore wave transformations at Mount Maunganui, New Zealand, as well as the measurement micro-scale wave transformations at "The Ledge" Raglan, New Zealand, are presented to demonstrate surfing wave transformations.

ADDITIONAL INDEX WORDS: *Surfing breaks, surfing reefs, surfing wave parameters, wave focusing, coastal management.*

INTRODUCTION

A key reason that coastal management practises are needed is to minimise conflict between coastal space users (e.g. boat users and surfers) and coastal sectors (e.g. ocean recreation and port operations). Incorporating the sport of surfing into coastal management is a relatively new phenomenon that is gradually gaining attention because of the importance of surfing breaks to coastal communities (PRATTE, 1983 and 1987; LAZAROW, 2007; NELSEN *et al.*, 2007; SCARFE *et al.*, Chapter 3). Consideration in coastal management is required because historically there have been many surfing breaks altered or destroyed by coastal development. When surfing amenities are considered in coastal management projects, the process needs to include transparent scientific evidence.

This paper comprises the introductory section of a comprehensive research effort (SCARFE, 2008) devoted to developing tools for the scientific management of surfing amenities. The research reviews the existing framework of knowledge around surfing research and provides definitions of key concepts for the larger body of work. References for research-based surfing literature are consolidated for those with an interest in the research and management of the coastline. In this context, research-based surfing publications explore the various characteristics of surfers, the surfing environment and industry. The first section identifies the different categories of research-based surfing literature. The second section explains the mechanics of surfing waves and surfing breaks from an oceanographic perspective. It discusses the physical processes occurring around surfing breaks, drawing from literature on the topic. This paper updates and expands on the work of SCARFE *et al.* (2003a) on surfing science, notably by adding a coastal management focus.

SURFING SCIENCE RESEARCH HISTORY

With the exception of the detailed foundation research by the University of Hawaii (WALKER and PALMER, 1971; WALKER, *et al.,* 1972; WALKER, 1974a and b) and a few miscellaneous works (e.g. DALLY, 1989 and 1991), most of the 63 scientific surfing publications identified by SCARFE *et al.* (2003a) were published in the last decade. The updated review presented here identified 162 research-based surfing publications and it is evident from Figure 2.1 that the topic is only a recent focus in the coastal literature. This increase in surfing literature can be

attributed not only to surfers trying to understand their environment, but also out of the need to have scientifically credible research to support the concerns of surfing communities that often arise during the coastal management process.
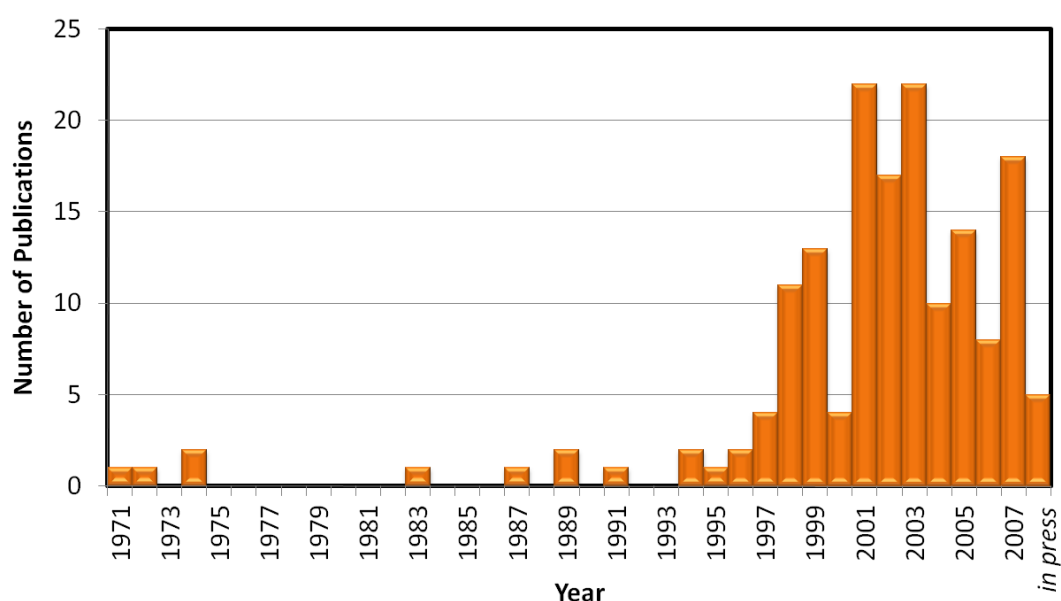
Figure 2.1. Number of research-based surfing publications identified for each year.

Research from the University of Hawaii identified many of the modern concepts and parameters that should be considered when studying a surfing break. One of the most important parameters used to describe surfing waves, the peel angle (α), came out of this research. Studies of Hawaiian surfing breaks using bathymetric charts, aerial photography and various other techniques helped dissect the mechanics of surfing breaks. Much of the modern surfing research and literature on artificial surfing reefs (ASR) has come out of the Artificial Reefs Program (ARP) and subsequent research at the University of Waikato (e.g. ANDREWS, 1997; HUTT, 1997; SAYCE, 1997; BLACK, 2001a; MEAD, 2001; MOORES, 2001; SCARFE, 2002a; SPLENDELOW, 2004). The use of modern scientific methods, especially numerical wave modelling, coastal geomorphology, hydrographic surveying, and photogrammetry, were invaluable for investigating natural surfing breaks, as well as predicting wave and sediment response to artificial surfing reefs. After achieving the main objectives of the ARP, the major findings were published in the *Journal of Coastal Research* Special Issue No. 29 (BLACK, 2001a), along with other surfing research undertaken around this time. Topics included relating waves to surfers (DALLY, 2001a and b; HUTT *et al.,* 2001), relating surfing waves to surfing breaks (MEAD and BLACK, 2001a, b, c), sediment transport and salient response to offshore reefs (BLACK and ANDREWS, 2001a and

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b; TURNER *et al.*, 2001), currents around reefs (SYMONDS and BLACK, 2001) and ASR design and construction (BLACK and MEAD, 2001a; JACKSON, 2001).

Five International Surfing Reef Symposium's have been held since 1996. Not every conference seems to have produced a widely published proceedings, but the third conference in Raglan, New Zealand (BLACK and MEAD, 2003) produced many editorially reviewed papers. Despite the lack of conference proceedings, each of the symposiums has brought together worldwide researchers on coastal engineering and management for surfing, resulting in an exchange of ideas. Also in recent years Delft University of Technology has published a series of Master's theses on designing ASRs for Dutch swell conditions (e.g. WEST, 2002; HENRIQUEZ, 2005; VAN ETTINGER, 2005; OVER, 2006; TRUNG, 2006; Poort, 2007).

Concurrent to the aforementioned literature, attempts were made to build ASRs in El Segundo, California (MOFFAT and NICHOL ENGINEERS, 1989; BORRERO, 2002; BORRERO and NELSEN, 2003; MACK, 2003), Cable Station, Western Australia (BANCROFT, 1999; PATTIARATCHI, 2000, 2002 and 2007), Narrowneck, Gold Coast (BLACK, 1998 and 1999; BLACK *et al.*, 1998a; HUTT *et al.*, 1998 and 1999, AARNINFKOF *et al.* 2003; TURNER 2006; JACKSON *et al.*, 2007), Mount Maunganui, New Zealand (MEAD *et al.*, 1998a, b and 2007; RENNIE *et al.*, 1998; MEAD and BLACK, 1999a; RENNIE and MAKGILL, 2003; SCARFE and HEALY, Chapter 6; BLACK and MEAD, 2007; SCARFE *et al.*, Chapter 8) and Opunake, New Zealand (TOURISM RESOURCE CONSULTANTS, 2002; BLACK *et al.*, 2004). The success of the reef projects has been mixed, but each reef has made significant advances in design and construction methods. For example, the complexity of the design and construction method, as discussed in MEAD *et al.* (2007a), demonstrate significant improvements in the technology since the first attempt in El Segundo.

Many publications on surfing have reviewed the basics of surfing science merely as a background to their research methods. This enables publications to be read without a detailed background to surfing concepts. Although this has lead to repetition in the literature, especially in some of the Masters' theses, it has also resulted in some well-researched synopses on the formation of surfing waves and desirable wave characteristics for surfing. Noteworthy literature reviews are included in WALKER (1974a), COURIEL and COX (1996), BANCROFT (1999),

SCARFE (1999 and 2002a), BLACK (2001a); RANASIGNHE *et al.* (2001), WEST (2002), MACK (2003), MEAD (2003), SCARFE *et al.* (2003a), HENRIQUEZ (2004), HEARIN (2005) and WALTHER (2007).

CATEGORIES OF RESEARCH-BASED SURFING LITERATURE

People have initiated surfing research for a variety of reasons. They may simply be interested in understanding the surfing environment, or they may have been motivated to protect a local surfing break, or manage a social issue surrounding surfing. Others may be looking to enhance surfing amenities in some way. This includes building ASR, incorporating surfing amenities into another coastal development project, or changing any factor that may improve the surfing experience (including toilets, access to surfing breaks, accommodation, parking, water quality etc). Given the significant volume of literature on surfing, it is difficult to summarise all of the work into a single research paper, and therefore various categorises of surfing research have been created (Figure 2.2 and Table 2.1). It is important to appreciate the different categories of information available to make well-informed coastal management decisions.
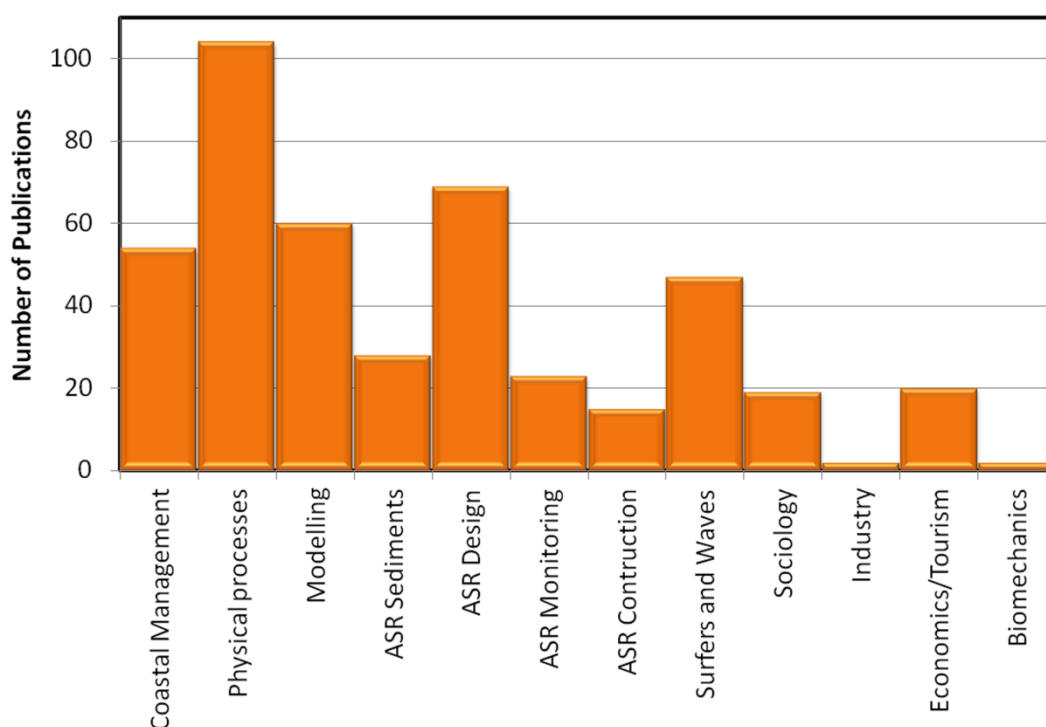
Figure 2.2. Number of citations for each research-based surfing literature category between 1971 and 2007.

Table 2-1. Categories of surfing research-based surfing publications identified from the literature.

Category	Criteria	References
Coastal management	*Coastal management theory, protecting surfing breaks, recreational coastal amenities, environmental impact assessments, surfers and coastal use conflict, examples of impacts to surfing breaks*	ANON, (1999 and 2003); AUGUSTIN (1998); ANDREWS (1997); ANON (2003); BENEDET *et al.* (2007); BLACK (2001a and b); BLACK and ANDREWS (2001a and b); BLACK and MEAD (2001b); BLACK *et al.* (1998a and b); BORRERO and NELSEN (2003); BUCKLEY (2002a and b); CHALLINOR (2003); CHAPMAN and HANEMANN (2001); CORBETT *et al.* (2005); DALLY and OSIECKI (2007); FARMER and SHORT (2007); GEORGE (2004); JACKSON *et al.* (2001 and 2002b); LAZAROW (2007); LAZAROW *et al.* (2007b); LUNTZ (2002); MEAD (2001); MEAD and BLACK (1999a and 2005); MEAD *et al.* (1998b, 2001, 2003a, 2004a, b, c, d and 2007b); MOCKE *et al.* (2003); NELSEN and HOWD (1996); NELSEN and RAUSCHER (2002) NELSEN *et al.* (2007); PRATTE (1983 and 1987); PRESTON-WHYTE (2002); RENNIE and MAKGILL (2003); RENNIE *et al.* (1998); SCARFE and HEALY (Chapter 6); SCARFE (1999, 2002a); SCARFE *et al.* (2003b and Chapter 3); SCHROPE (2006); WALKER and PALMER (1971), WALTHER (2007)
Physical processes	*Oceanographic and sedimentary conditions around surfing breaks including artificial breaks, hydrography, measurement of physical processes, surfing science*	ANDREWS (1997); BANCROFT (1999); BATTALIO (1994); BEAMSLEY and BLACK (2003); BENEDET *et al.* (2007); BLACK (1998, 1999, 2001a, b, 2003); BLACK and ANDREWS (2001a and b); BLACK and MEAD (2001a, b and 2007); BLACK *et al.* (1998a, 2001a, b and 2004); BORRERO (2002); BORRERO and NELSEN (2003); BUONAIUTO and KRAUS (2003); BUTTON (1991); CALDWELL (2005); CALDWELL and AUCAN (2007); CHONG AND SCARFE (2000); COURIEL and COX (1996); DALLY (1989, 1991); HEARIN (2005); HENRIQUEZ (2005); HUTT (1997); HUTT *et al.* (1998, 1999 and 2001); KILPATRICK (2005); MACK (2003); MEAD (2001, 2003); MEAD and BLACK (1999b, 2001a, b, c, d and 2005); MEAD and PHILLIPS (2007); MEAD *et al.* (1998a, b, 2001, 2003a, b, 2004a, b, c, d, 2007a and b); MOCKE *et al.* (2003); MOORES (2001); OVER (2006); PATTIARATCHI (2000, 2002 and 2007); PHILLIPS (2004); PHILLIPS *et al.* (1999, 2001, 2003a, b and 2004); POORT (2007); PRATTE *et al.* (1989); PRESTON-WHYTE (2002); RAICHLE (1998); RANASIGNHE and TURNER (2006); RANASIGNHE *et al.* (2001 and 2006); RENNIE *et al.* (1998); SAYCE (1997); SAYCE *et al.* (1999); SCARFE (1999, 2002a and *in prep.*); SCARFE and HEALY (Chapter 6); SCARFE *et al.* (2002a, b, 2003a, b, Chapter 3, 4 and 8); SPENDELOW (2004); SYMONDS and BLACK (2001); TRUNG (2006); TURNER *et al.* (2001); TURNER (2006); van ETTINGER (2005); VAUGHAN (2005); WALKER and PALMER (1971); WALKER (1974a and b); WALKER *et al.* (1972); WEST (2002); WEST *et al.* (2002)
Numerical and physical modelling	*Modelling of theoretical and real surfing breaks*	BEAMSLEY and BLACK (2003); BENEDET *et al.* (2007); BLACK (1998, 1999, 2001 and 2003); BLACK and MEAD (2001a, b and 2007); BLACK *et al.* (1998a, 2001 and 2004); BLENKINSOPP (2003); BUONAIUTO and KRAUS (2003); CALDWELL and AUCAN (2007); DALLY and OSIECKI (2007); HEARIN (2005); HENRIQUEZ (2005); HUTT (1997); MACK (2003); MEAD (2001, 2003); MEAD and BLACK (1999b, 2001b, d and 2005); MEAD and PHILLIPS (2007); MEAD *et al.* (2001, 2003a, b, 2004a, b, c, d, 2007a and b); MOCKE *et al.* (2003); OVER (2006); PATTIARATCHI (2007); PHILLIPS (2004); POORT (2007); RAICHLE (1998); RANASIGNHE *et al.* (2006); RENNIE *et al.* (1998); SCARFE (2002a and 2008); SCARFE *et al.* (2003b, c and Chapter 3 and 8); SPENDELOW (2004); SYMONDS and BLACK (2001); TRUNG (2006); TUNER *et al.* (2001); van ETTINGER (2005); VAUGHAN (2005); WALKER (1974); WEST (2002); WEST *et al.* (2002)
ASR sediment dynamics	*Sediment and morphological response to an ASR*	ANDREWS (1997); ATKINS *et al.* (2007); BLACK (1998, 1999 and 2003); BLACK and ANDREWS (2001a and b); BLACK and MEAD (2001b and 2007); COURIEL and COX (1996); HEARIN (2005); HUTT *et al.* (1998 and 1999); INNES (2005); MEAD *et al.* (2004b and c, 2007b); MEADGER (2005); MOCKE *et al.* (2003); RANASIGNHE *et al.* (2006); SCARFE and HEALY (Chapter 6); SCARFE (2008);

Table 2.1. continued.

ASR design	*The design of ASRs*	ANDREWS (1997); ANON (1999); BLACK (1998, 1999, 2001a, b, and 2003); BLACK and ANDREWS (2001); BLACK and MEAD (2001a and b); BLACK *et al.* (1998a, 2001a and 2004); BLENKINSOPP (2003); BORRERO (2002); BORRERO and NELSEN (2003); BUTTON (1991); COURIEL and COX (1996); HEARIN (2005); HENRIQUEZ (2005); HUTT (1997); HUTT *et al.* (1998 and 1999); JACKSON *et al.* (2002b); KILPATRICK (2005); MACK (2003); MEAD (2001 and 2003); MEAD and BLACK (1999a, 2001a, b, c, d and 2005); MEAD *et al.* (1998a, b, 2001, 2003a, b, 2004a, b, c, d, 2007a and b); MEADGER (2005); MOCKE *et al.* (2003); MOORES (2001); NELSEN and HOWD (1996); OVER (2006); PATTIARATCHI (2000); PRATTE *et al.* (1989); RANASIGNHE *et al.* (2001 and 2006); RENNIE *et al.* (1998); SCARFE (1999, 2002a); SCARFE *et al.* (2002a, b and 2003a); SYMONDS and BLACK (2001); TRUNG (2006); VAN ETTINGER (2005); VAUGHAN (2005); WALKER (1974); WEST (2002); WEST *et al.* (2002)
ASR monitoring	*Monitoring of effects to surfing amenities, coastal stability, habitat, navigation, swimming safety,*	BANCROFT (1999); BLACK and MEAD (2007); BORRERO (2002); BORRERO and NELSEN (2003); JACKSON *et al.* (2002a, b and 2007); MACK (2003); MEAD *et al.* (1998b, 2004c and 2007a); PATTIARATCHI (2000, 2002 and 2007); RANASIGNHE and TURNER (2006); SCARFE (1999 and 2008); SCARFE and HEALY (Chapter 6); SCARFE *et al.* (2002a; Chapter 4 and 8); TURNER (2006);
ASR construction	*Construction techniques and tolerances*	JENKINS and SKULLY (1994); BLACK (2001b); BLACK *et al.* (2001a); BLENKINSOPP (2003); HEARIN (2005); JACKSON (2001 and 2007); MEAD *et al.* (1998b, 2004a, b, c and 2007a); PRATTE *et al.* (1989)
Surfers and waves	*Describing waves, relating surfers to waves including skill levels, surfboard type, manoeuvres performed, surfability*	BANCROFT (1999); BATTILIO (1994); BENEDET *et al.* (2007); BLACK (2001); BLACK *et al.* (1998a and 2001a); BORRERO (2002); BORRERO and NELSEN (2003); COURIEL and COX (1996); DALLY (1989, 1991, 2001a and b); HEARIN (2005); HENRIQUEZ (2005); HUTT (1997); HUTT *et al.* (1998, 1999 and 2001); JACKSON *et al.* (2002a); KILPATRICK (2005); MACK (2003); MEAD (2001 and 2003); MEAD and BLACK (2001a and c); MEAD *et al.* (2003a, 2004a, b and c); MOCKE *et al.* (2003); MOORES (2001); PATTIARATCHI (2002); PHILLIPS *et al.* (2003); RANASIGNHE *et al.* (2001); SCARFE (1999); SCARFE (2002a); SCARFE *et al.* (2002b, 2003a and b); SYMONDS and BLACK (2001); VAN ETTINGER (2005); WALKER and PALMER (1971); WALKER (1974a and b); WALKER *et al.* (1972)
Sociology	*Sociological aspects of surfing including surfing culture, social protocols at surfing breaks, gender and surfing, localism*	AUGUSTIN (1998); BUCKLEY (2002a and b); ISHIWATER (2002); LANAGAN (2002); LAZAROW (2007); MCGLOIN (2005); NELSEN *et al*, (2007); ORMON (2007); OSMOND *et al.* (2006); POIZAT-NEWCOMB (1999a and b); PRESTON-WHYTE (2002); RIDER (1998); RENNIE *et al.* (1998); STEDMAN (1997); YOUNG (2000)

Table 2.1. *continued.*

Industry	*Surfing equipment and technology, merchandise, clothing, surfing films and magazines, marketing*	BUCKLEY (2002a and b); LANAGAN (2002)
Economics/Tourism	*Discussions on the economic value of surfing breaks, impacts of surf tourism on beach communities, the character or value of surf tourism*	AUGUSTIN (1998); BAILY and LYONS (2003); BREEDVELD (1995); BUCKLEY (2002a and b); CHALLINOR (2003); CHAPMAN and HANEMANN (2001); DOLNICAR and FLUKER (2003); LAZAROW (2007); LAZAROW *et al.* (2007a and b); LEW and LARSON (2005); MCGLOIN (2005); NELSEN *et al.* (2007); POIZAT-NEWCOMB (1999a and b); RAYBOULD and MULES (1999); TOURISM RESOURCE CONSULTANTS (2002); WEIGHT (2003)
Biomechanics	*Fitness, surfing techniques, sporting injuries*	SUNSHINE (2003); TAYLOR *et al.* (2006)

The categories in Table 2.1 reflect the main themes apparent in the coastal literature. The literature reviewed has been incorporated into the categories to facilitate its accessibility to decision-makers and researchers interested in particular themes. Some publications (e.g. doctoral theses or final ASR design reports) cover a variety of topics, traversing more than one category, and may therefore have multiple entries in Table 2.1. To be included the publication needed to make a contribution to the topic. Only literature that has been cited and reviewed is included in Table 2.1. The word "surfing" has been picked up and used in a variety of contexts (e.g. Internet surfing), creating some difficulties when using internet and library database searches for literature on recreational surfing. It is probable that research presented here has some bias in the distribution of article numbers (Figure 2.2) towards physical coastal scientific research because of the background of the authors and their familiarity with this field. Moreover, while the compilation is extensive, the logistics of obtaining some publications that may have been of some relevance means that the table is not exhaustive. However, Table 2.1 and Figure 2.2 do provide a comprehensive overview of the majority of research-based surfing literature and are indicative of the focus and gaps in the field.

Sociological surfing research is important because at many surfing breaks undesirable or antisocial relations exist between surfers as they compete for a finite number of waves. This is often caused by regular beach users attempting to protect their surfing breaks from outsiders and varied social science approaches have been used to analyse the issues. For instance, ISHIWATE (2002) uses Hawaii as a case study to investigate the politics of surfing including topics such as localism and hierarchies in the water. A more experimental approach was adopted by four-time world surfing champion Nat Young (YOUNG, 2000) who concluded from a number of case studies that every surfer has experienced some form of aggression in the surf. It is important to understand some of the positive and negative cultural issues, when planning and managing surfing amenities. However, this literature has not been extensively reviewed here because the broader research focus (SCARFE, 2008) is on oceanographic considerations for coastal management and surfing. For the same reason, the review of literature on the surfing industry and biomechanics is also limited.

In a detailed discussion, MCGLOIN (2005) investigates the relationship between surfing and Australia's national identity, using interviews and literature as research tools. MCGLOIN (2005) believes there has been a shift in ideologies as Australia's identity moves from being based on traditional images, such as bush pioneers and war heroes, to a surfing and beach culture. This cultural change is also identified by LANAGAN (2002), who argues the physical act of surfing has been appropriated by business interests and turned into a commodity to make a profit from lifestyle clothing and accessories.

Surfing, while long considered by many as a fringe sport, has developed into a US$10 billion p.a. industry (mid-1990s) with over 10 million participants worldwide and a 12-16 % growth rate per annum in surfer numbers (BUCKLEY, 2002a). In another study, MCGLOIN (2005) calculates the global surfing industry to be worth $7 billion annually and estimated in 2001 that there were 2 million surfers in Australia alone. Considering the economic value, surfing breaks clearly need to be considered in coastal management. Further evidence of the economic value of surfing is presented in ASR economic impact assessments (e.g. RAYBOULD and MULES, 1999; TOURISM RESOURCE CONSULTANTS, 2002; BAILY and LYONS, 2003; WEIGHT, 2003), a study of the value of a surfing contest (e.g. BREEDVELD, 1995) and by a calculation of the economic value of a surfing break (e.g. LAZAROW, 2007). LAZAROW *et al.* (2007a) summaries various studies on surfing and economics and note that little research on the social and economic benefits of surfing compared with that of recreational fishing, which historically has had much stronger focus in coastal management. To fill this void, NELSEN *et al.* (2007) and LAZAROW *et al.* (2007b) provide methods to calculate the value of surfing breaks, which are subsequently applied to calculate the value of different surfing breaks in Australia and California.

DOLNICAR and FLUKER (2003) identify surf tourism as a prevalent and growing phenomenon, with only a few research investigations on the topic. They include AUGUSTIN (1998) who researched surfing resorts, POIZAT-NEWCOMB (1999a and b) who describes the genesis of surfing tourism, and also BUCKLEY'S (2002a and b) who investigates the impacts of surf tourism on Indonesia's economy. Surfing tourism is connected to the specific features of the natural landscapes and is largely separate from the cultures of the host communities, but has strong economic links to the global fashion and entertainment industries (BUCKLEY,

2002a). Yet in most countries, the strategic management of the surfing breaks is not practised at a government level, even though they provide social and recreational benefits, and support this growing industry. Even in places like Southern California, which is generally regarded as one of the main centres of modern surfing culture, and is home to many of the world's largest surfing companies, until recently surfers have had little political say in the management of their recreational space.

Large participation rates imply that in many locations surfing warrants funding and resources for research, resource management practises, and facility enhancement. For example, BANCROFT (1999) estimated that 16 % of the Western Australian population (300 000 people) surf, which must have a significant social and economic impact. LAZAROW *et al.* (2007b) estimates the global surfing population to be 18-50 million. Although not all countries have resource management frameworks that consider the economic affect of a development (e.g. New Zealand's Resource Management Act 1991), understanding the economics relating to surfing is important for political lobbying. If a surfing break is under threat from an activity, the economic benefits of the surfing break to the community can help to gain support for efforts to preserve the surfing location. This is iterated by LEW and LARSON (2005) who note that information on the economic value of beach recreation is needed to make informed policy decisions. Economic analysis is also important for artificial surfing reef developments as it assists in evaluation benefits of the project. Although it is likely that more literature exists on surfing economics and tourism, the lack of abundance shown in Table 2.1 demonstrates a need to further this area of research. For example, DYER and HYAMS (2001) also noted that little research on surfing and economics exists in the United Kingdom, where a significant number of people surf despite the cold conditions and relatively poor quality surfing waves

CHARACTERISTICS OF SURFING WAVES

SCARFE *et al.* (2003a) considered surfing waves and surfing breaks as distinct entities. Surfers can be related to surfing waves, and surfing waves related to surfing breaks. The parameters that describe surfing waves can be related to the skill level of surfers (HUTT, 1997; HUTT *et al.,* 2001; MOORES, 2002), and the types of manoeuvres that they perform (SCARFE, 2002a; SCARFE *et al.*, 2002b).

Thus the style and skill of surfers can be matched to a type of surfing wave. Similarly, the parameters of surfing waves can be related to the oceanographic and bathymetric features that comprise a surfing break. These basic concepts are pertinent when trying to determine changes to a surfing break from another activity, or trying to design an artificial surfing reef to match a particular type of surfer.

There is a need to scientifically quantify the impacts of an activity on a surfing break and to specify the design criteria for a surfing enhancement project. In the following section different wave parameters are identified that can describe surfing waves. To match surfers to surfing waves, existing schemes relating these parameters to surfing skill and manoeuvres are discussed. Also the effects of wind are reviewed because it can have positive or detrimental impacts on breaking waves. Relating surfing waves and bathymetric features and wave transformation is dealt with separately in a later section.

Surfing Wave Parameters

Over the years various surfing wave parameters have been used in the literature to scientifically describe waves. Because of the increasing number of terms used to describe waves, SCARFE *et al.* (2003a) argued that four main parameters can be used to discuss the general character of waves. Although more complex parameters and relationships between parameters exist (e.g. DALLY, 2001a and b), for simplicity the following parameters below are used to explain surfing waves transformations. The parameters are:

- breaking wave height (H_B);
- wave peel angle (α);
- wave breaking intensity (B_I); and
- wave section length (S_L).

Breaking Wave Height (H_B)

A very important parameter is the breaking wave height (H_B) because it dictates the skill level required to ride the wave and can vary between wave sets, and along the wave because of wave focusing, non-linear wave interactions and wind effects (e.g. SCARFE, 2008). Estimating wave height can be subjective because different groups of surfers develop their own standards of estimating wave heights

(BATTALIO, 1994). However, wave heights used by surfers may not actually have much relevance to the oceanographic measurement from the crest to the trough. For example, CALDWELL (2005) and CALDWELL and AUCAN (2007) discuss the Hawaiian scale which is approximately half the oceanographic height. They calibrated long-term observational data collected using the Hawaiian scale against measured deep water significant heights and showed that the oceanographic measurement was 1.36-2.58 times larger depending on the location.

For scientific surfing studies the oceanographer's measurement is used because it can be measured by instrumentation. Because waves arrive in sets separated by lulls, and surfers generally ride the largest waves in a set, HUTT (1997) recommends using the average of the top 10 % of waves ($H_{1/10}$) for surfing studies. However, the oceanographic measurement of crest to trough at the time of breaking is of the most interest to surfing wave studies, and the method used to measure wave heights in this study. The surfable limits of wave heights are identified by MACK (2003) as 1 to 20 m, although smaller waves can be ridden by highly skilled or lighter surfers. Developments in board technology and use of personal water craft for tow-in surfing have significantly increased the range of wave heights that can be ridden in recent decades.

Wave Peel Angle (α)

Perhaps the most critical parameter to determine whether a wave can be surfed, other than wave height, is peel angle (α). If a peel angle is not within a range that can be surfed, then the wave is said to be un-surfable. In fact, SCARFE *et al.* (2003a) state that the role of a surfing break is to increase peel angle to within surfable limits as low peel angles break too fast to surf. The difference between a surfable beach and a non-surfable beach is often that peel angles are too small. This parameter dictates the speed that the wave break point peels along the wave crest, and is closely related to another parameter, peel rate. Peel angle is often preferred in the literature because it can be more accurately modelled than a peel rate, and is easily measured from aerial photographs (e.g. WALKER, 1974a and b; HUTT, 1997) or oblique video images using more complex techniques (SCARFE, 1999 and 2002a; SCARFE *et al.*, 2002a). Many of the core surfing science studies have used peel angles to define relationships between surfers and waves, or waves and bathymetry. It is important that future research recognises the previous

methodologies and parameters so that they can be compared. This concept was also noted by LAZAROW *et al.* (2007b) for surfing economic studies.

Although most detailed studies identified in the *surfers and waves* category include some description of peel angles, it was first defined as "the included angle between the peel-line and a line tangent to the crest-line at the breaking point" WALKER and PALMER (1971, p. 42). This definition is still accurate. In this context the peel line is the path of broken white water left after the wave breaks. Figure 2.3 shows an adapted figure from WALKER and PALMER (1971) showing the parameters of a peel angle. At time one, the wave break point position on wave crest, C1 is denoted by A. At time two, the wave break point position on wave crest, C2, is denoted by B. As the wave crest C1 advances to position C2, a path of white water is left joining the breakpoints A and B. The peel angle is denoted by the angle α. At position A the wave has a velocity of propagation, $\vec{V}_w$, which is perpendicular to the wave crest. The peel velocity, $\vec{V}_p$ or peel rate, is the velocity the wave breaks, or peels, along the wave crest. Summing the vectors gives the resultant velocity vector, $\vec{V}_s$, which approximates the surfers speed if the surfer remains close to the wave break point.
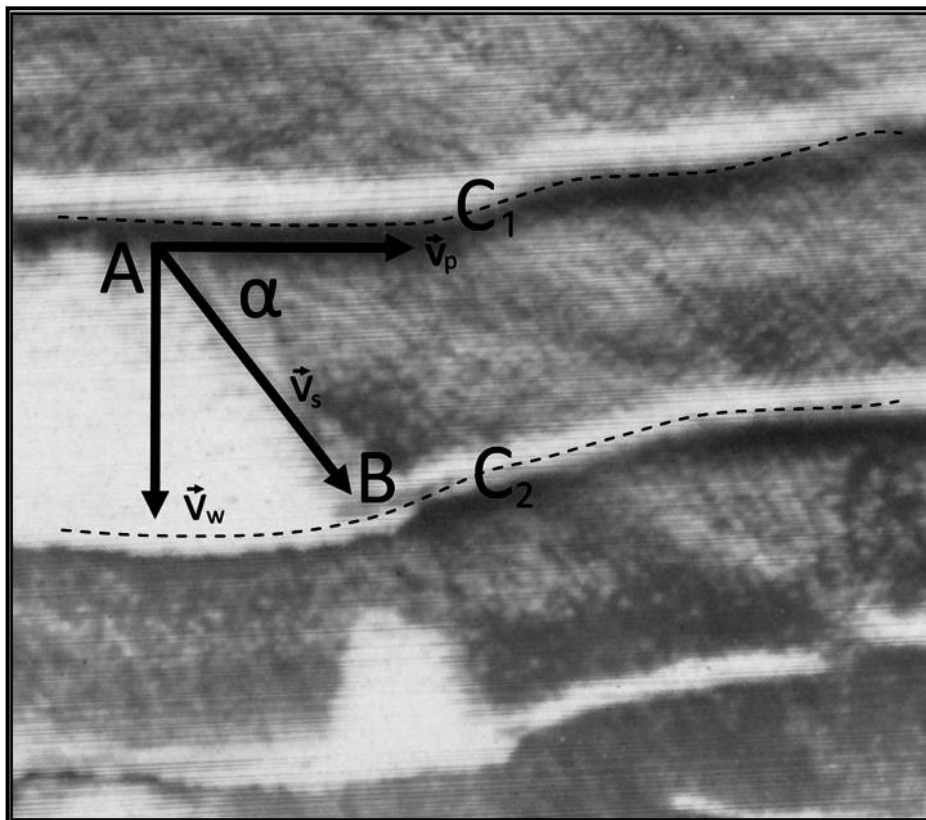
Figure 2.3. Wave peel angle (α), adapted from WALKER and PALMER (1971).

A closeout is a wave where the wave crest breaks simultaneously and is said to have a peel angle of 0°. A closeout wave is only suitable for beginner surfers (HUTT *et al.,* 2001) because surfers can only ride the broken wave white-water, not the unbroken wave crest, which is not challenging for intermediate or advanced surfers. The peel angle in Figure 2.3 is approximately 52°, which is considered fast but surfable. Although peel angles can be too high to challenge more advanced surfers, high peel angles do not necessarily prevent surfers from riding waves, whereas low peel angles do.

Wave Breaking Intensity (B$_I$)

Waves break in spilling, plunging, collapsing and surging forms (KOMAR, 1998), but surfers can only ride spilling and plunging waves. Plunging waves, colloquially termed by surfers as "barrelling waves", need to occur consistently in order for a surfing break to be classed as what MEAD and BLACK (2001a and b) term a "world-class" surfing break. SAYCE (1997) coined the term "breaking intensity" (B$_I$) to describe the intensity at which surfing waves plunge. MEAD and BLACK (2001c) used this concept to investigate the relationship between the open vortex shape (vortex ratio; Figure 2.4) and various parameters. The vortex ratio was calculated from surfing magazine photographs using measurements made with curve fitting routines written in MATLAB, and is essentially the same as breaking intensity. A low vortex ratio is an extreme plunging wave and a high ratio is a mildly plunging wave. A linear relationship between the orthogonal seabed gradient was found that can be used to estimate the vortex ratio:

$$Y = 0.065X + 0.821$$

where Y is the vortex ratio and X is the orthogonal seabed gradient.
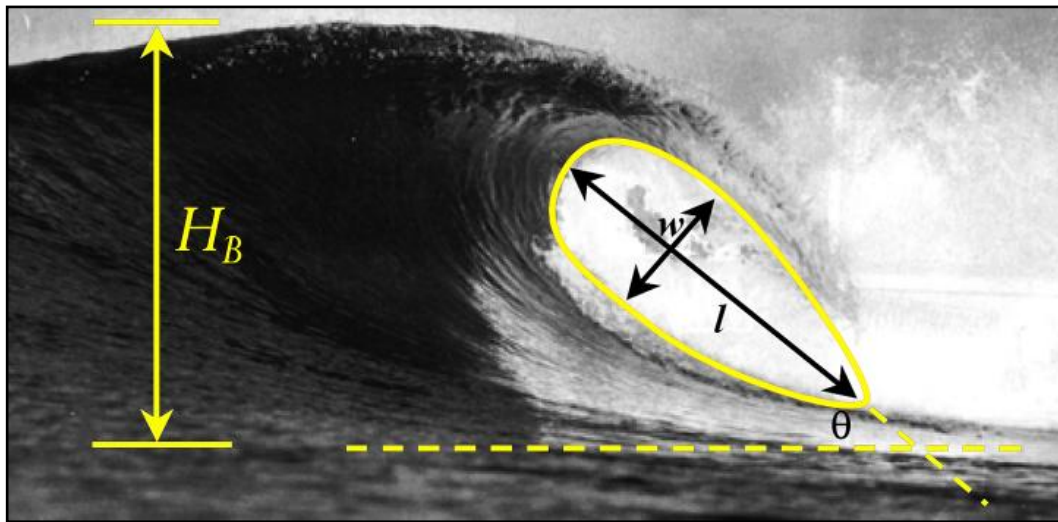
Figure 2.4. Wave breaker intensity (B_I) defined by the vortex ratio of *w* to *l* (after MEAD and BLACK, 2001c).

FAIRLEY and DAVIDSON (*in press*) investigate the effect of steps in the two-dimensional profile of a surfing break on the quality of the surfing wave using wave flume experiments. Previous studies by SAYCE *et al.* (1999) and SCARFE (2002a) at Raglan, New Zealand, show that steps in the profile can modify the wave breaker intensity. FAIRLEY and DAVIDSON'S (*in press*) experiments involved inducing steps into the profile and observing the effects on the breaking intensity. FAIRLEY and DAVIDSON (*in press*)0020review wave breaking theory and conclude MEAD and BLACK'S (2001c) method provides a better prediction of wave breaking for surfing than the common coastal science methods such as the Iribarren number. FAIRLEY and DAVIDSON (*in press*) found inducing steps into the profile increases non-linearity's in the waves and observed that for extreme steps there was a transfer of energy to the higher wave spectrum, adversely affecting the "surfability" of the wave. The "surfability" of a wave represents the level of desirability to a surfer (DALLY, 1989; MACK, 2003). Also the larger the steps, the larger the degree of uncertainty as to the type of breaking wave. They propose maximum steps in an ASR to be between 16 % and 23 % of the wave height.

Wave Section Length (S_L)

By the time a wave crest reaches a surfing break it is sometimes bent or broken when the crest is viewed from an aerial perspective, with variation in height and angle along its length, as in the aerial photo shown in Figure 2.3 and Figure 2.10. This has been shown by BLACK *et al.* (2004) and MEAD *et al.* (2004a) to occur

when using Boussinesq modelling waves passing over complex reefs. The variations can be caused by a messy swell spectrum, local winds, bathymetric effects, non-linear wave-wave interactions, and island sheltering. Although generally surfers desire waves that peel cleanly along the wave crest at a surfable speed, often waves break in sections with a length S_L. A surfing ride is actually made up of a variety of sections, breaking with varying H_B, α, B_I, and S_L throughout the ride. For example, small sections that break at once, with a peel angle near 0°, are not a problem for a surfer provided the surfer can generate enough speed to make it past the section to the unbroken wave crest. In fact, sections can be desirable for advanced surfers, and if the section has a high enough breaker intensity there is a chance of getting a barrel ride. The ability to negotiate a section is related to the surfer's ability to generate enough speed to make it past the section to the unbroken wave crest.

Winds

Wind generates surfing waves in distant locations and when they arrive at a surfing beach the wave period is often long (>8 second), which is favourable for surfing. Local winds can also play an important role in creating or destroying surfing waves (PRATTE *et al.,* 1989). The ideal wind blows directly offshore and steepens the wave face causing plunging, or "barrelling", waves at some surfing breaks. A light offshore wind is also said to groom the wave face to make it smoother (SCHROPE, 2006). Research by both CHEN *et al.* (2004) and FEDDERSEN and VERON (2005) found that an offshore directed wind will delay wave breaking by modifying the breaking-wave height (crest to trough height) to depth ratio (γ_b), with the reciprocal being true for onshore directed wind. FEDDERSEN and VERON (2005) also found that that γ_b can change by 100 % and that waves breaking with offshore directed winds have greater breaking wave heights than for onshore conditions. Thus offshore winds increase the skill level required to surf a given wave. Onshore winds do not necessarily always lower the skill level required because the onshore winds often causes waves to break less predictably making them more challenging to surf.

The delay in breaking caused by an offshore directed wind will reduce the water depth the wave breaks in, increasing the breaker intensity and probability of barrel rides. There will be a maximum offshore wind speed suitable for surfing,

however, because the offshore wind will flatten a weak swell, or make it impossible to catch waves because surfers are blown off the back of the wave when trying to catch a ride. The maximum offshore wind speed was not found in the literature, but MACK (2003) suggested a directionless maximum wind speed of 5 ms^{-1}. Sometimes light local onshore winds can help slightly increase a small swell to a surfable height so the ideal wind condition is also dependent on the swell conditions. Cross-shore and strong winds generally detract from the quality of the surfing waves.

Relating Surfers to Waves

To understand waves at surfing breaks, or design an ASR, the waves need to be suitable for surfers. Not all waves are suitable for surfers of all skill levels, so from the earliest research this has been a topic of discussion. WALKER (1974a) presented a beginner, intermediate and advanced categorisation scheme for skill level based on wave height and peel angle. Advances in surfer skill levels over time, as well as performance of surfboards required HUTT (1997) and HUTT *et al.* (2001) to revisit the scheme for modern surfers. They also added a more quantitative 1 to 10 ranking system. Recently, BLACK and MEAD (*Unpublished Data[3]*) incorporated breaking intensity into the scheme which is shown in Figure 2.5. Another scheme that can be useful when dissecting a natural surfing break, or designing ASRs, was adapted from SCARFE *et al.* (2002b) by SCARFE *et al.* (2003a). The scheme, shown in Figure 2.6, does not include skill level but does relate surfing manoeuvres to section length, peel angle and breaking intensity for the first time.
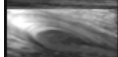
	Rank 2-3	Beginning surfers able to perform basic manoeuvres. Soft breaking waves (spilling breakers). No vortex ratio.	Peel Angle (α) = 60-70°	Low gradient breaks
	Rank 4	Intermediate skilled surfers beginning to initiate and execute standard surfing manoeuvres on occasion. Steep faced, but rarely tubing: Vortex ratio 2.8-3.1	Peel Angle (α) = 55°	Bells Beach (Australia), Indicators (Raglan, New Zealand)
	Rank 5-6	Competent surfer able to execute standard manoeuvres consecutively and advanced manoeuvres on occasion. Some tube sections: Vortex ratio 2.2-2.8	Peel Angle (α) = 40-50°	Kirra Point, Burleigh Heads (Australia)
	Rank 7	Top amateur surfers able to perform consecutive advanced manoeuvres. Fast and hollow tubing waves: Vortex Ratio 1.9-2.2	Peel Angle (α) = 30°	Bingin, Padang Padang (Bali)
	Rank 8-9	Top world surfers able to perform consecutive advanced manoeuvres under extreme and dangerous conditions. Vortex ratio 1.6-1.9	Peel Angle (α) = <27°	Pipeline (Hawaii), Shark Island (Australia)

Figure 2.5. Reef design criteria adapted from BLACK and MEAD (*unpublished from 4th Surfing Reef Symposium proceedings*) for relating surfing wave parameters to surfer skill level.

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[3] Presented at the 4th International Surfing Reef Symposium - Manhattan Beach, California (12-14 July 2005). Conference proceedings are yet to be published.
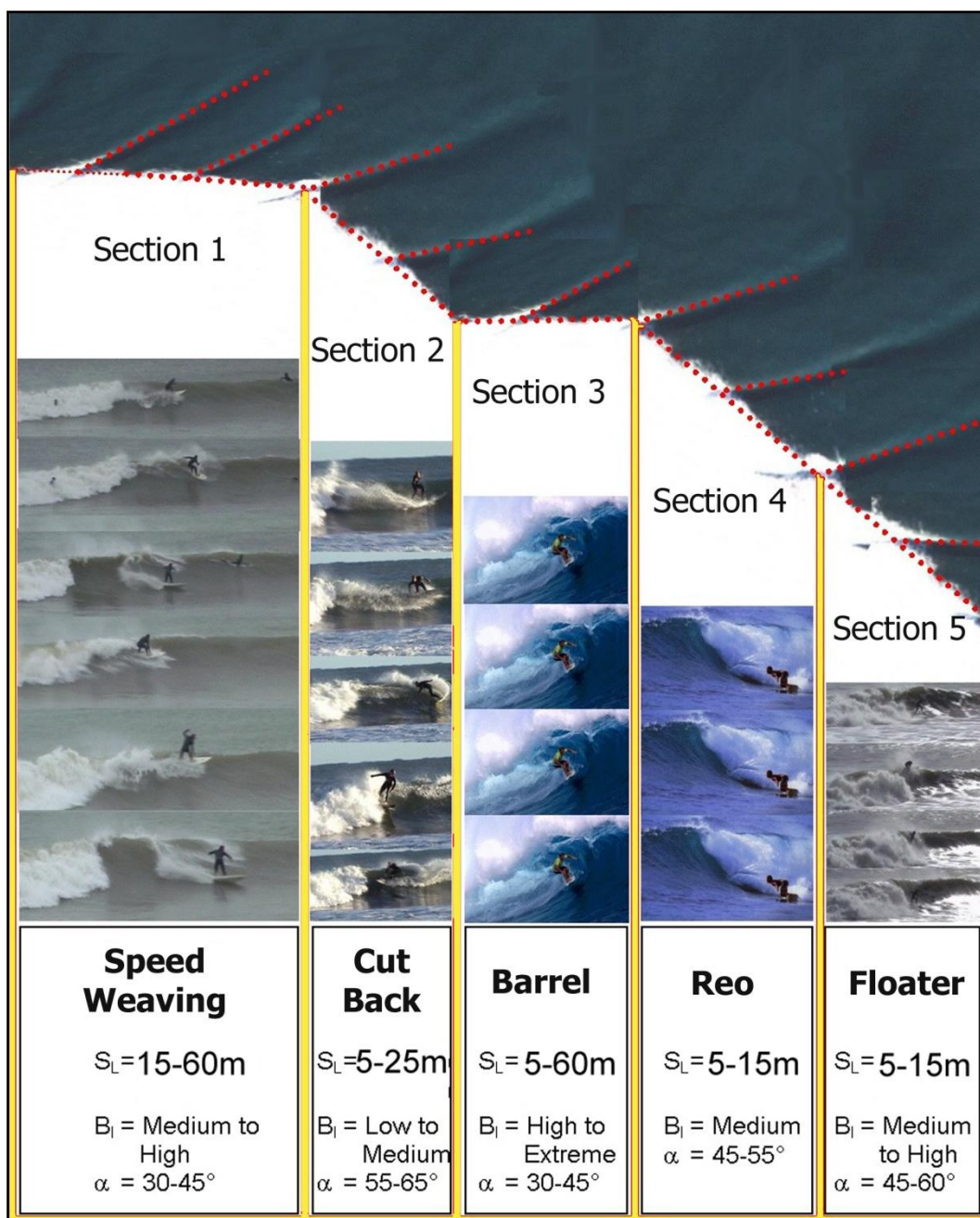
Figure 2.6. Possible configurations of wave sections suitable for different types of manoeuvres. Adapted from SCARFE *et al.* (2002b).

MOORES (2001) was the first to investigate sections and how they relate to the skill level of a surfer, including S_L. Using measurements from rectified video images, MOORES (2001) found that the higher the surfer skill level, the longer the section that can be negotiated, mainly because of the surfer's ability to generate board speed. Thus investigations into sections are closely related to board speed, skill level and peel angle. Both DALLY (2001) and MOORES (2001) have investigated the speed of surfers. The outcome of MOORES (2001) investigation is shown in Table 2-2 and proposes design criteria for the length of a section in an

ASR. SCARFE (2002a) has also looked into sections, but was more concerned with peel angles for different sections and how they influence the types of manoeuvres surfers perform (Figure 2.6).

Table 2-2. Optimum artificial surfing reef design values of wave sections for surfers of different abilities (adapted from MOORES, 2002). Surfers with skill levels 1 and 2 cannot surf waves with sections because it requires the ability to generate speed (HUTT *et al.*, 2001).

Surfer Ability	Wave Height (m)	Section Length (m)	Section Duration (s)	Section Speed (ms^{-1})
1 (low)	n/a	n/a	n/a	n/a
2	n/a	n/a	n/a	n/a
3	2.5	25	1	10
4	2.5	40	1.5	20
5	3	40	2.2	20
6	3	60	2.3	20
7 (high)	3	60	3	20

CHARACTERISTICS OF SURFING BREAKS

The role of a surfing break is to make the waves peel at a suitable peel angle (or rate) and breaking intensity for the size of the wave and the surfer style and skill level. In this section the different categories of surfing breaks and their characteristics are discussed first, followed by a brief overview of currents around surfing breaks. Two examples of physical processes occurring around surfing breaks are then presented to illustrate in more detail the character of surfing breaks and surfing waves.

MEAD *et al.* (1998a) defined five geomorphic categories of surfing breaks and the following definitions have been adapted from SCARFE (1999). They are:

- *Headland or Point Break* –Waves refract around a headland or point before breaking further around the headland or point. The refraction of the waves around the point or headland filters out high frequency waves leaving the longer period waves, which are more likely to be surfable. The wave direction at the surfer take-off zone is usually significantly different to the offshore direction. Examples include: New Zealand's Murdering Bay (Dunedin), and Raglan; California's Malibu and Rincon, and Kirra on the Gold Coast of Australia.

- *Beach Break* – At a beach break, waves break in peaks along the beach caused by offshore wave focusing and nearshore sand bars and rips. Successive waves will break in different locations depending on the current beach-state (e.g. WRIGHT and SHORT, 1984), offshore wave direction, height, period and wave peakiness. Often good beach breaks have control features offshore or nearshore that stabilise the position of sand bars or dictate wave focusing. Examples of beach breaks include the Gold Coast's D-Bar, and New Zealand's Tairua and Aramoana beaches. Tairua is investigated in MEAD and BLACK (2001b) and surfing waves at Aramoana are numerically modelled in SCARFE *et al.* (Chapter 3).

- *River or Estuary Entrance Bar* – Interesting features and processes are required to create peeling waves and river and estuary entrances often create good surfing spots. The ebb tidal delta, out flowing river sediment and tidal currents all interact to sometimes make surfable waves. Tidal inlets are influenced by processes such as wave energy, tidal range, tidal prism, direction and rates of longshore sediment transport, sediment supply and nearshore slope, and are subject to change (FITZGERALD, 1996). Changes to any of these factors can affect surfing conditions for the better or worse. In many locations around the world, river inlets have been jettied and SCARFE *et al.* (2003b and c) showed how this can create surfing breaks. Whangamata Bar (New Zealand), discussed in SCARFE *et al.* (Chapter 3)*,* is an example of a high quality Estuary Entrance Bar.

- *Reef Breaks* – Many of the world's best surfing breaks are reef breaks because the reef provides more consistent wave breaking patterns and allow steeper orthogonal profiles than sandy surfing breaks. Various reefs are discussed in MEAD and BLACK (2001b and c) including Padang Padang (Indonesia) and Pipeline (Hawaii).

- *Ledge Breaks* – Steep rock ledges interrupt wave propagation and create surfing waves breaking with the highest intensity. The waves come from relatively deep water into very shallow water, modifying the way that the waves break. Shark Island (Australia) is a ledge break and often ledge breaks are difficult to surf, except by bodyboarders.

Although these definitions are helpful for non-surfers to understand surfing breaks, there are no clear boundaries between the different types. Sometimes surfing breaks fall under more than one category. For example, often good beach breaks have features, possibly reef, which control the sand bar shape and wave focusing. Sometimes a river bar blends in with a beach break, or a reef break has ledge sections.

Surfing Break Components

Ordinary waves are turned into surfing waves through the process of wave preconditioning and breaking. The preconditioning of waves has been discussed since the early Hawaiian research. MEAD and BLACK (2001a and b) identify several common components in "world-class" surfing breaks that either precondition or cause wave breaking. Identifying the component scale and configuration from detailed bathymetric data and wave refraction analysis is essential for understanding how a surfing break works (e.g. BEAMSLEY and BLACK, 2003; MEAD *et al.*, 2003b; KILPATRICK, 2005), identifying impacts of development on surfing breaks (e.g. SCARFE *et al.,* 2003b; SCARFE *et al.,* Chapter 3), or designing artificial surfing reefs (e.g. MEAD, 2001; SCARFE, 2002a; MOCKE *et al.*, 2003).

The meso-scale surfing reef components identified by MEAD and BLACK (2001a) are ramp, platform, focus, pinnacle, wedge, ledge and ridge. The components were sub-categorized by pre-conditioning or breaking functions. Smaller scale components can exist on larger scale components (Figure 2.7) and this is explored in SCARFE (2002a) and SCARFE *et al.* (2003a). The way surfing reef components of varying scales are superimposed on each other is illustrated in Figure 2.7. The smaller scale components, termed micro-scale components, create wave sections. Common configurations of components identified by MEAD and BLACK (2001b) show how surfable peel angles and breaking intensities are created by the different component configurations. The breaking wave height (crest to trough) during a surfing ride changes because of variations along the wave crest caused by wave focusing over bathymetric components and non-linear wave-wave interactions.
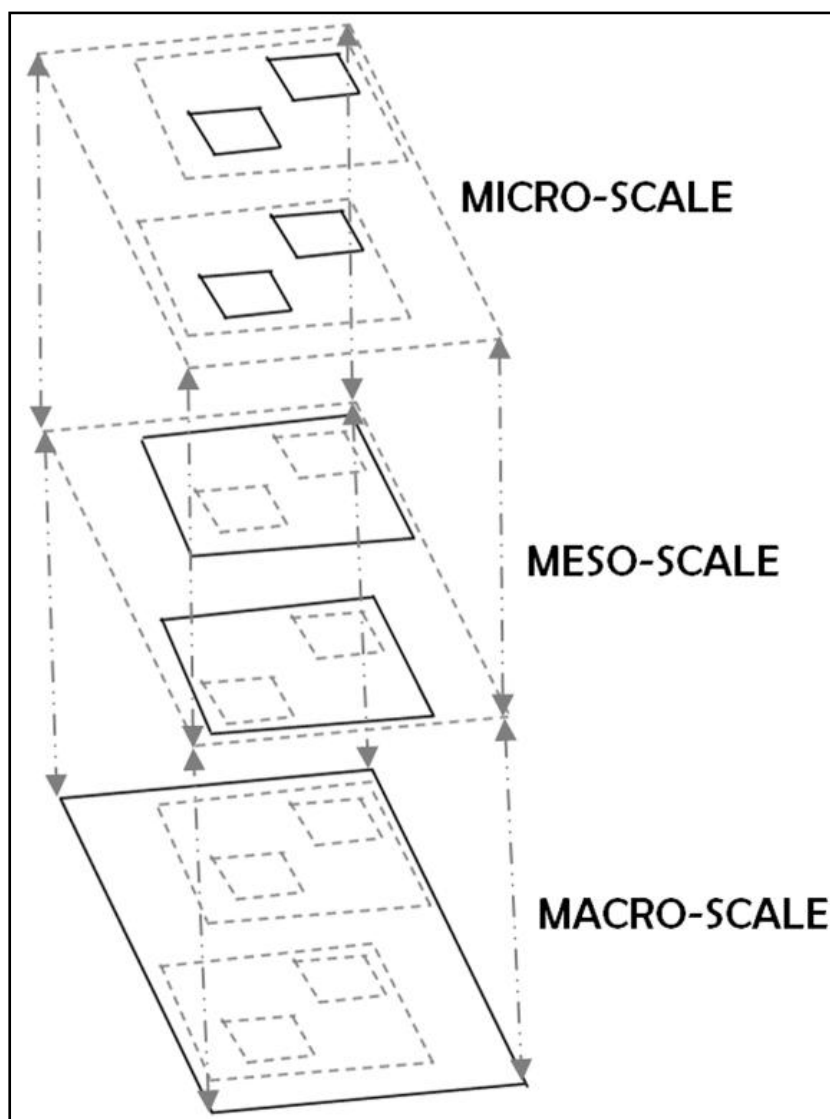
Figure 2.7. Schematic diagram of the different scale of surfing break components, super imposed on each other. From top, micro, meso and macro scale components.

A useful addition to the MEAD and BLACK (2001a and b) categorisation method would be a categorisation scheme relating common wave transformation patterns (e.g., focusing, sheltering, wave-wave interactions) to the configuration of surfing reef components. In a surfing discussion, BENEDET *et al.* (2007, p4.) provide photographs of waves conditions that could be incorporated into such a scheme.

Wainui Beach, Gisborne (New Zealand) is one of New Zealand's premier beach surf breaks and waves are affected by intersecting swells and non-linear wave propagation over a shoal, or focus (Figure 2.8). This type of wave pattern producing good surfing waves is also identified at Ocean Beach, San Francisco (BATTILIO, 1994). The Raglan (New Zealand) surfing breaks, in contrast, require organised and unbroken wave crests approaching oblique to the coast line

(SCARFE *et al.,* Chapter 3). It is possible that the complex offshore wave transformations create the surfing bars and associated rips, which at times are significant in size at Wainui Beach. Modelling and further analysis of the beach is presented in DUNN (2001). The sandbars and rips then interact with the broken and focused wave crests creating surfing waves. Although non-linear Boussinesq modelling of surfing waves is not uncommon (BEAMSLEY and BLACK, 2003; BLACK and MEAD, 2001a; VAN ETTINGER, 2005), it is still an area that requires more discussion and experimentation. These types of wave interactions can create wave sections, and are referred to by HUTT (1997) as the "peakiness" of a swell. These processes are related to beach-state (WRIGHT and SHORT, 1984), which has been investigated around surfing breaks by BLACK and MEAD (2007) and SCARFE *et al.* (Chapter 8), but is still poorly understood in relation to surfing. Intermediate beach-states are likely to be best for surfing because of the more prominent surf zone features.

The orthogonal gradient has been the subject of research during surfing reef design projects because it is important for the wave breaking intensity. By varying the design of the surfing reef components, the orthogonal sea bed gradient can be altered to match the design criteria of a surfing reef. MEAD (2003) show predicted orthogonal seabed gradients for the proposed Lyall Bay (New Zealand) ASR. The orthogonal gradient will change with swell and tide conditions so it is a difficult task to design reef components that deliver expected breaking intensities for the most common wave conditions. As ASR technology improves, fine scale design parameters such as orthogonal gradient are likely to be subject to further research.
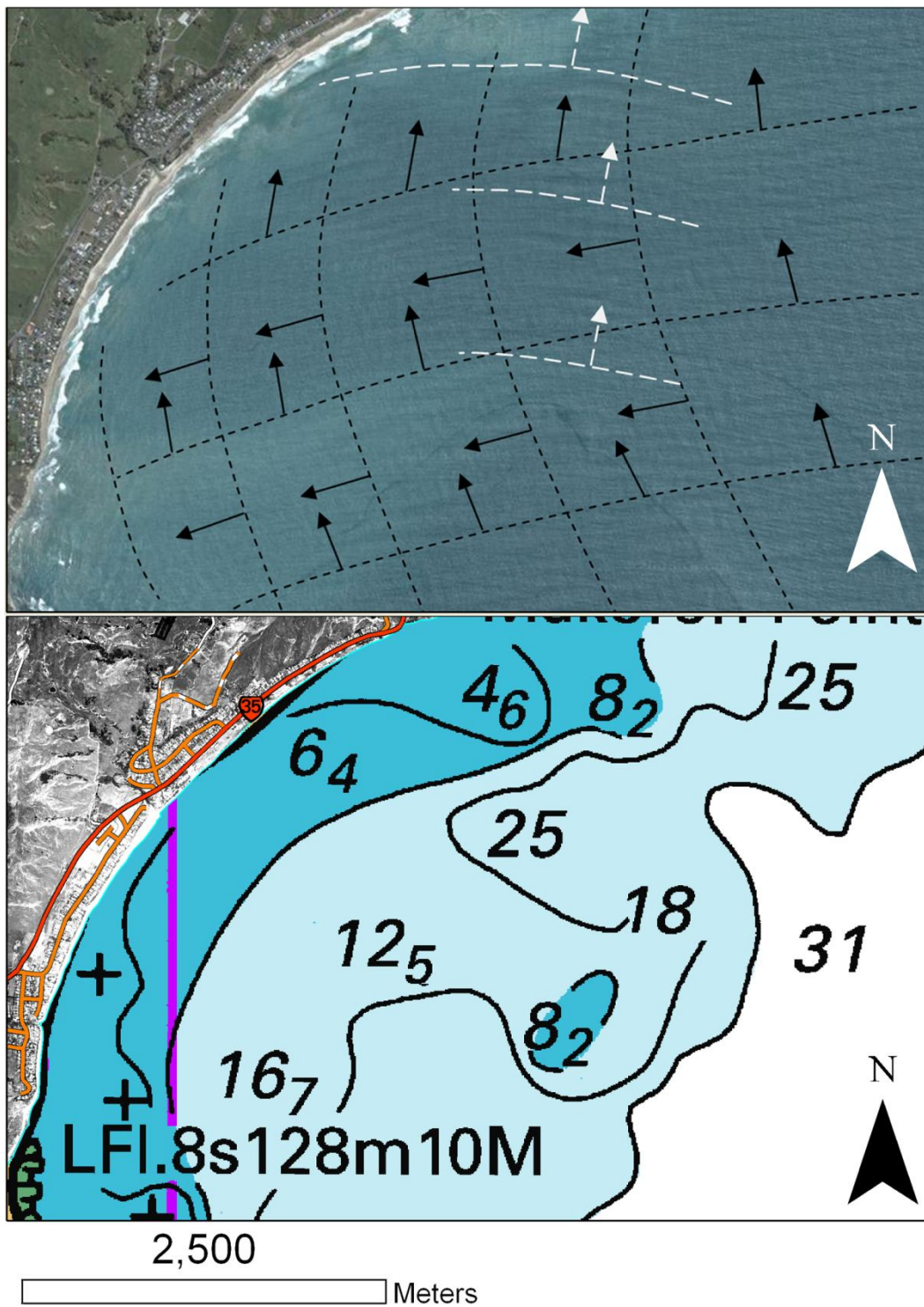
Figure 2.8. Advancing wave crests (top; black and white dashed lines; photography from www.google.com) from southerly and easterly sources converges creating wave non-linearities and complex surf zone process conducive to a good beach surf break. Focusing over the offshore bank (bottom) further preconditions the waves. Bottom navigational chart and aerial photography from Land Information New Zealand.

Currents around Surfing Breaks

Various researchers have physically or numerically modelled wave induced currents around theoretical ASRs (SYMONDS and BLACK, 2001; BLACK, 2003; HENRIQUEZ, 2004; VAN ETTINGER, 2005; TRUNG, 2006). Currents around natural surfing breaks have received less attention. The only substantial work to date is by PHILLIPS (2004) who studied currents and sediment transport around the Raglan headland surfing breaks. By repeatedly surveying a transect, collecting sediment, current and wave data, as well as wave and hydrodynamic modelling, PHILLIPS (2004) identified cells of reticulating current pathways generated by wave-driven forces and bathymetric steering. The observed and modelled currents are related to sediment transport as well as surfing. The return cell circulation is very apparent when surfing the breaks and assists in returning surfers to the take-off location at the end of a surfing ride. Studying natural surfing breaks, as done by PHILLIPS (2004), has the benefit that empirical information about currents during different conditions is known by surfers. This provides a robust and additional data source for validation of model predictions of currents.

HENRIQUEZ (2004) states that considering currents is critical when investigating the "surfability" of a break. Currents can help make the surfing experience better when surfers use the currents to make paddling easier. They can also detract from the surfing experience by making it difficult to paddle, or even dangerous. They also interact with breaking waves, improving or detracting from the "surfability" of a surfing break. For example, currents associated with a rip provide a calm area to paddle through the surf zone. At many surfing breaks, especially during large swells, it would be difficult to ride the waves without utilising currents to get into position to catch waves. BLACK and MEAD (2001a) included a "paddling channel" between the arms of the Narrowneck ASR to minimise interference between waves of each reef arm, and to make it easier for surfers to return to the take off zone. Unfortunately the constructed reef shape did not match the design and the success of the paddling channel is therefore unknown. TRUNG (2006) and VAN ETTINGER (2005) tried to improve "surfability" of an ASR design by reducing currents over the reef with different designs. Morphological evidence of currents around a constructed ASR is included in SCARFE *et al.* (Chapter 8).

Offshore Wave Transformation at Mount Maunganui

Offshore wave focusing is known to affect inshore surfing conditions and has been investigated by a number of researchers (BEAMSLEY and BLACK, 2003; MEAD *et al.,* (2003b) and SCARFE *et al.* (2003b and Chapter 3). Figure 2.9, from modelling by SCARFE (2008), shows how offshore islands, reefs, and the continental shelf affect the propagation of a monochromatic wave before reaching the Mount Maunganui beaches. The two offshore islands, and numerous reefs, transform waves to create variations in wave character along the shoreline. The ebb delta of Tauranga harbour has a significant focusing and rotating effect on the waves creating the best surfing waves in the area. Further east, waves focus to a lesser degree between Tay Street, and Omanu beaches.
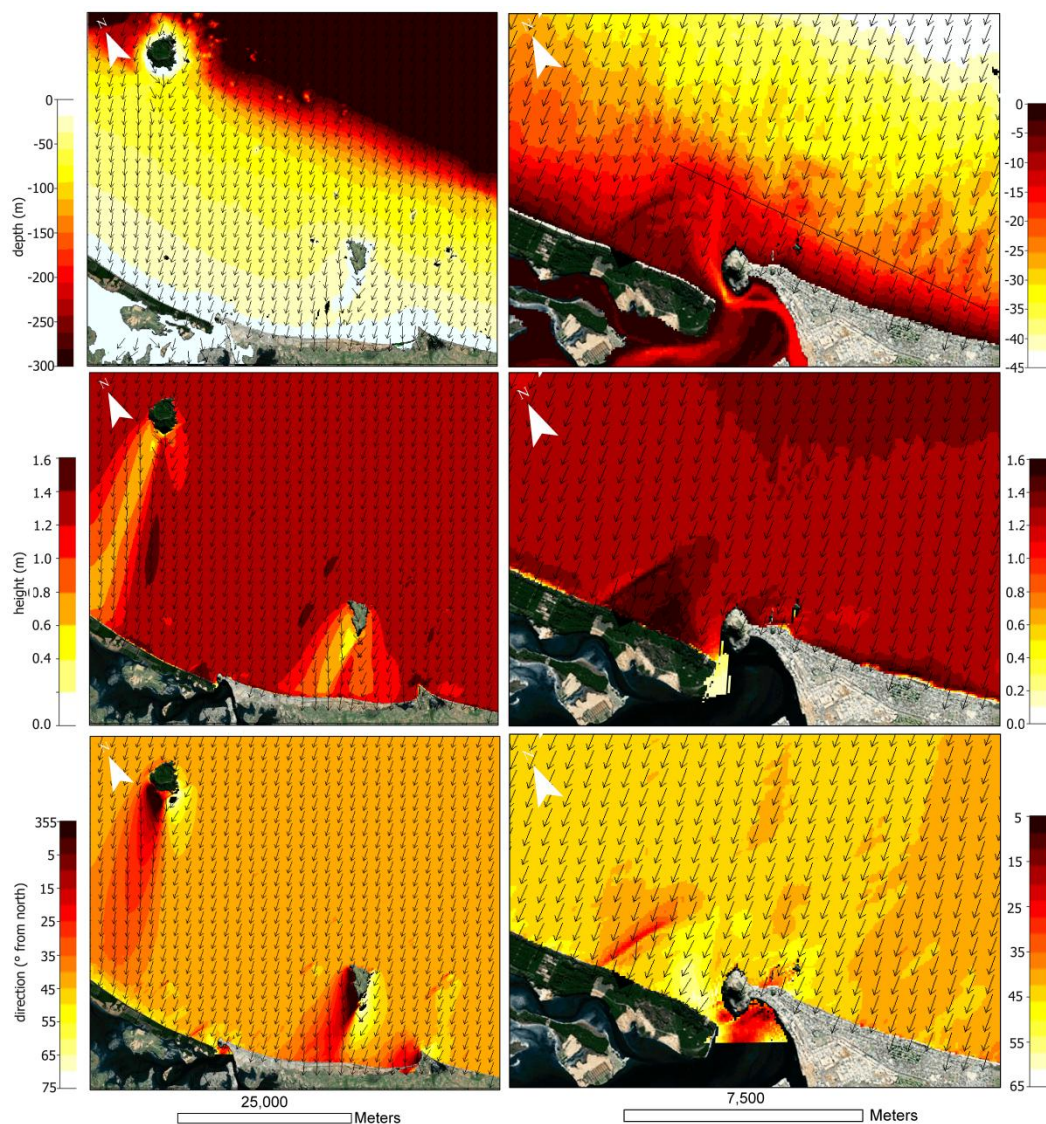
Figure 2.9. Effect of bathymetry and offshore islands on wave heights and angles for a surfing wave event on the Mount Maunganui (New Zealand), ASR from SCARFE (2008; 8am - 4 October 2006).

The offshore islands not only shelter wave energy, but also focus, rotate and break wave crests. The aerial photograph in Figure 2.10 shows the broken, rotated and focused wave crests, which create the peeling waves surfed at the Mount Maunganui beaches. The observed wave patterns are caused by the wave and wind process occurring over the varying scale bathymetric components. Wave focusing has also been predicted for the beaches by SPIERS and HEALY (2007) using refraction modelling. Bands of coarse sediment, or "sorted bedforms", identified using sidescan by SPIERS and HEALY (2007) were considered to be a result of wave focusing, with the larger waves eroding away finer sediments (SPIERS and HEALY, 2007). These were observed in multibeam backscatter imagery by SCARFE *et al.* (Chapter 4) in water depths around 8 m (MSL). The bands were depressed below the ambient seabed by 0.10-0.30 m. Analysis of multibeam backscatter as an indicator of focusing is a new area of surfing research and it is expected that geomorphic indicators (from sidescan, backscatter, shoreline or bathymetry analysis) could be used with numerical modelling to relate wave focusing and bar formations to the "surfability" of a beach.
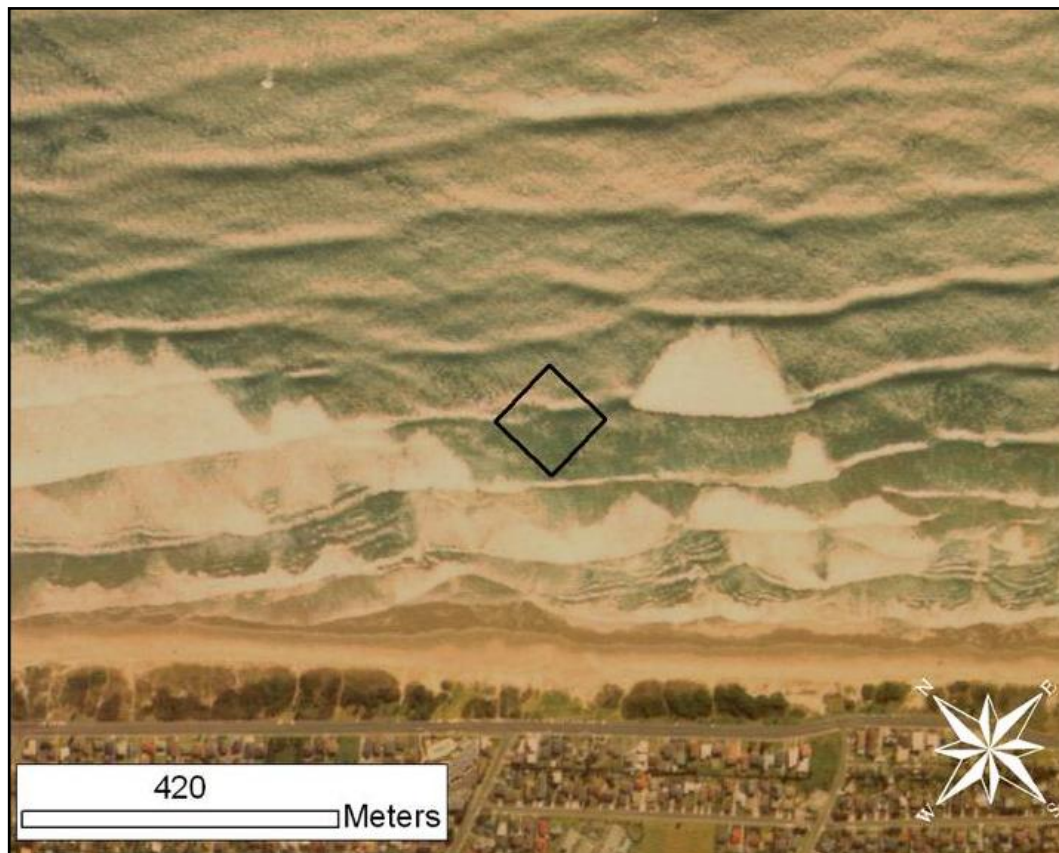
Figure 2.10. Aerial photograph around the Mount Maunganui ASR during a 1.5 m northeast swell showing broken wave crests and other non-linear wave interactions (photo: 6 February 1990, 10:45am).

Measuring Micro-Scale Wave Transformation at "The Ledge"

The Raglan headland, New Zealand, more fully described in HUTT (1997), SAYCE (1997), MOORES (2001), SCARFE (2002a), PHILLIPS (2004) and SCARFE *et al.* (Chapter 3) is made up of a reef/boulder shoreline with a sandy offshore platform below about 5-6 m (MLW). The headland hosts seven high quality surfing breaks. A survey by SCARFE (2002a) utilised accurate RTK GPS water level corrections (SCARFE, 2002b) and showed smooth sand pre-conditioning components, and a complex, undulating shallow-water wave breaking and focusing reef system. This enables the measurement and analysis of wave parameters at Raglan's premier barrelling wave location called "The Ledge" to be undertaken. The classic barrelling waves occur only occasionally and generally the waves break with a lower breaking intensity not suitable for barrel rides, linking up with the next surfing break called Manu Bay.

Since the initial surfing research of WALKER (1974a), photogrammetry has been an important tool in scientific surfing studies. During WALKER'S (1974a) research, bathymetric survey was overlaid with aerial photos and surfer locations to understand the surfing breaks. HUTT (1997) also used aerial photographs to study the Raglan surfing breaks. Aerial photographs can be used to measure directly wave peel angles, track the path of surfing waves relative to bathymetric contours, position surfing take off zones, count surfer numbers, estimate wave direction and refraction patterns as well as derive wave orthogonals for calculating wave breaking intensity. The first discussion on the more involved oblique measurements of surfing waves was by SCARFE (1999), where low cost "off-the-shelf" video cameras were researched to enable measurement of surfing parameters. MOORES (2001) was the first to actually apply an oblique rectification technique to surfing studies. Subsequently, SCARFE (2002a) applied complex oblique photogrammetric techniques to video images at "The Ledge".

Figure 2.11 shows video frames from SCARFE'S (2002a) measurement of breaking wave paths. Wave peel angles and peel rates were calculated by combining the break point locations with numerical modelling of wave orthogonals. Video frames for every second are plotted over the bathymetric features and shown in Figure 2.12. From here the breaking behaviour of individual waves can be related to the bathymetric features, surfer skill, and the types of manoeuvres that they perform. Modelling by SCARFE (2002a) shows that waves focus onto the ledge

and sections with dramatically different wave crest angles (>15°) are created. Waves at "The Ledge" were measured by SAYCE (1997) and found to be 9 % larger than the significant wave height just offshore of the surfing break. To ride a wave at "The Ledge" surfers essentially take-off at the end of a barrelling closeout section. They are able to come out of the barrel section because the peel angle dramatically increases (22° to 69° in the modelled scenario) to a surfable peel angle.

Figure 2.11. Barrelling surfing ride from video at "The Ledge" (Raglan), at 12:34, 30 July 2001 (after SCARFE, 2002a).
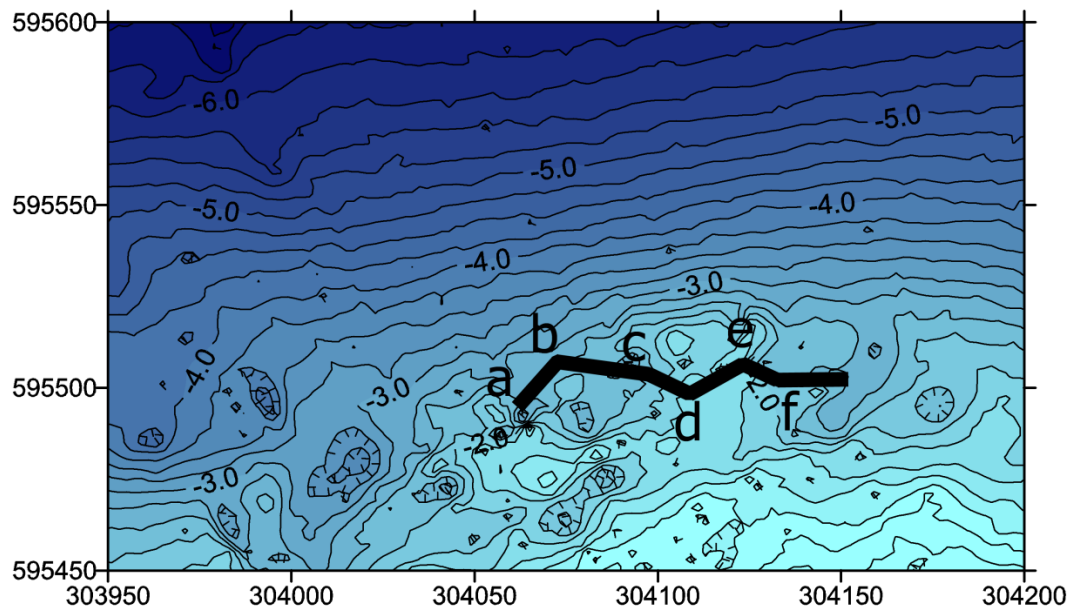
Figure 2.12. Path of breaking wave and peel angles for surfing wave in Figure 2.11 (after SCARFE, 2002a).

Figure 2.13 shows an orthogonal profile through the "The Ledge". The offshore profile in Figure 2.13 shows a similar pattern to many other surfing breaks found in the literature, namely the convex profile that becomes steeper in shallow water. Often in the case of reef surfing breaks the profile is undulating, affecting how the wave breaks for different oceanographic conditions. SCARFE (2002a) found that "The Ledge" profile is made of varying gradients that affect the breaking intensity (Figure 2.13). This was also observed in profiles by MEAD (2001) of Kirra, and by VAUGHAN (2004) of "Whangamata Bar". This complicates the application of MEAD and BLACK's (2001c) B_I formula, indicating the need for more research in this area to incorporate the effect of multiple seabed gradients on the vortex ratio. However, the simple breaking intensity equation from MEAD and BLACK (2001c) still gives a gross estimate of the hollowness of a surfing wave for a given beach gradient.
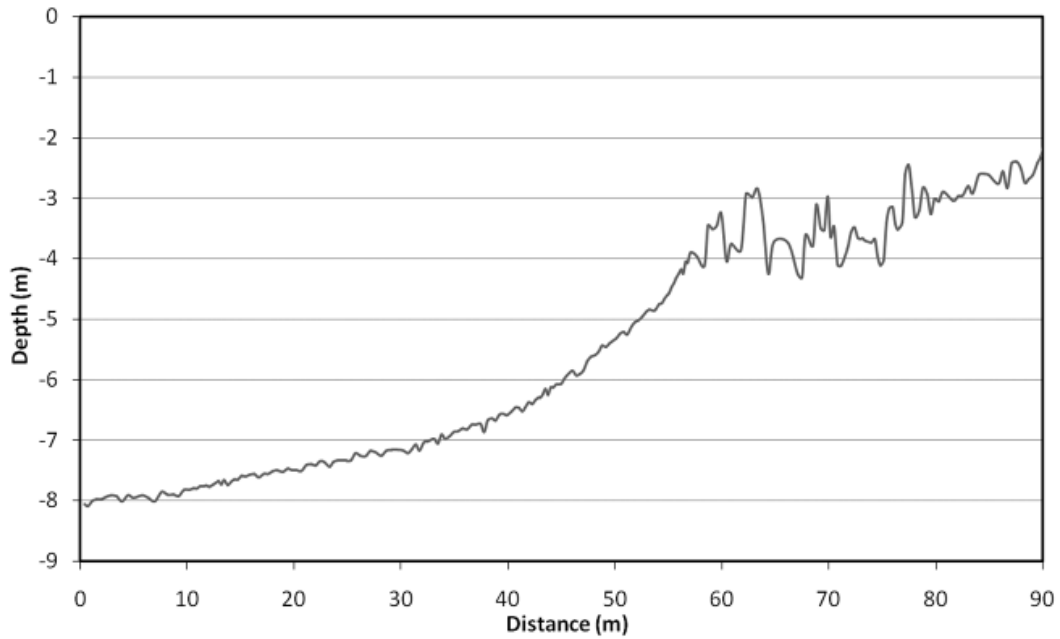
Figure 2.13. Orthogonal profile of "The Ledge" (adapted from SCARFE, 2002a).

The peel angles, breaking intensity and peel rates were shown to vary through the surfing ride. The variations are presented in Figure 2.14 and Table 2-3 and can be used to understand the micro-scale changes occurring during wave breaking. The micro-scale changes can be then related to bathymetric components and other oceanographic processes during the design or monitoring of an ASR, or while assessing the impacts of a coastal activity on surfing amenities.
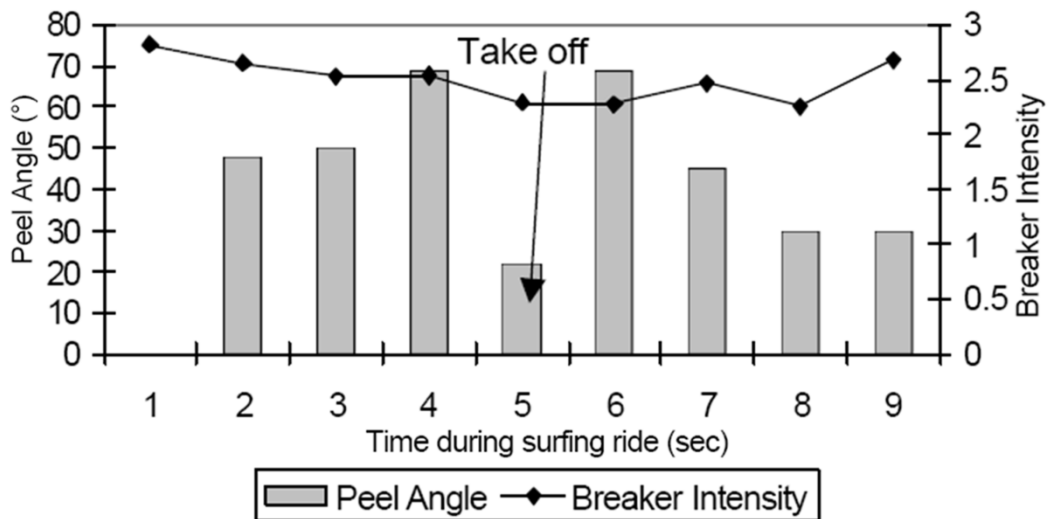
Figure 2.14. Peel angles and breaking intensity during the surfing ride shown in Figure 2.11 and Figure 2.12.

Table 2-3. Peel angles and peel rate during the surfing ride shown in Figure 2.11 and Figure 2.12 (from SCARFE, 2002a).

Time (s)	Peel Angle (°)	Peel Rate (ms^{-1})
1	0	14.4
2	48	11.2
3	50	15.2
4	69	10.5
5	22	16.2
6	69	9.7
7	45	9.8
8	30	6.7

DISCUSSION

BLACK *et al.* (2001b) defined the key goal of surfing reef studies as classifying and numerically ranking surfing wave parameters so that they can be systematically incorporated into artificial surfing breaks. Because every wave is different, and the seabed that comprises a surfing break is often mobile, there are still many unknowns about small scale, or temporal processes. However, the main processes have been identified and researched, sometimes in a lot of detail. The physical processes that differentiate wave transformations at surfing breaks from ordinary beaches are concluded to be reasonably well known, making a significant contribution to this goal. The next frontier for surfing research, discussed by SCARFE *et al.* (Chapter 3), involves maximising the surfing amenities of coastal projects by incorporating surfing into coastal resource management, as well as minimising negative effects of coastal engineering on surfing amenities. To achieve this goal, coastal managers and scientists need examples of methods used to study surfing breaks and various methods are included in the reviewed literature. More importantly, standardised techniques are required to be applied when incorporating surfing into coastal management.

The method used to assign categorises to each paper presented in Table 2.1 and Figure 2.2 allowed a publication to be assigned to more than one category. Papers often include some information on physical process and this explains why this topic has the most publications. A lot of focus has also been put into the design of ASRs rather than the construction, shoreline response or monitoring of ASRs. This may be a reflection of the maturity of ASRs as a research topic. ASR design received considerable attention because ASRs need to be designed before they are

constructed. As more reefs are built and design questions are answered, it is likely that the volume of research on how they are constructed and results of monitoring performance will increase.

Although Figure 2.2 shows several publications on coastal management and surfing, the core topic of many of the publications included in this category are not all specifically for coastal management and surfing. Often the publications will discuss topics such as problems with coastal development or engineering, environmental impact assessments for ASRs, or managing the effects of surfing tourism. The papers still contribute to the topic of how we should manage surfing amenities in some way, but it is not the sole focus of the research. There is urgent need for research on how to manage issues relating to surfing to avoid the problems associated with coastal engineering structures identified by SCARFE *et al.* (Chapter 3). To this end, economic research to support surfers' mandate in coastal management needs more attention in the peer-reviewed literature, and the recent *Shore and Beach* journal (WALTHER, 2007) contributes to this goal. More research on how to calculate the value of a surfing break, economic benefits of ASRs, and the total value of the surfing industry would help gain support for surfing in coastal management. Many of the papers identified may not withstand strong academic criticism because of the location of the publication (*grey literature*), or detail of the study.

Beach Morphology

Considerable research now exists on beach and surf zone processes, yet there remains little specific research on surfing waves at beaches. Although surfing at beaches has been discussed (e.g. BEAMSLEY and BLACK, 2003; KILPATRICK, 2005; SCARFE and HEALY, Chapter 6; WALTHER, 2007; SCARFE *et al.*, Chapter 3) empirical studies of surfing beaches are rare. The beach-state, categorised by WRIGHT and SHORT (1984), is expected to be very important for surfing, and it is likely that certain beach-states are more likely to create surfing waves. Extremely dynamic beaches may have better or worse surfing conditions depending on previous swell events, seasonal variations in sediment supply and wave climate, and even inter-decadal trends such as the Southern Oscillation Index (SOI), and these oceanographic factors will influence beach-state.

HENRIQUEZ (2004) stated that waves that form surfable peel angles when breaking along sand bars are what create surfable beaches. After years of discussions with surfers by the authors, many of them also believe that good sand bars create good surfing conditions. However, research by SCARFE and HEALY (Chapter 6) at Mount Maunganui and SCARFE *et al.* (Chapter 3) at Aramoana, New Zealand show that these surfing breaks are relatively free of surf zone features that would cause peeling waves, putting this commonly held belief in doubt. Refraction modelling by DUNN (2001) for a coastal erosion study at one of New Zealand's best surfing beach breaks, Wainui Beach, also supports the hypothesis that offshore wave focusing is often the controlling process for good surfing conditions at a beach.

SCARFE *et al.* (2003a and b) state that in order for waves to peel suitably for surfing there needs to be a gradient in the wave height and/or contours oblique to the incoming wave crests. It is likely that at different surfing breaks the contributions of offshore processes or nearshore focusing and wave breaking features (bars or rips) to create peeling waves varies. For example, an ebb-delta focuses and breaks waves at the "Whangamata Bar", (SCARFE *et al.,* Chapter 3) but offshore focusing will also make a contribution to the "surfability" of the beach. At Aramoana, offshore focusing and wave-wave interactions play more of a role in the creating of the surfing waves than the nearshore wave breaking features.

CONCLUSIONS

During this review the main drivers for the development of scientific surfing research have been discussed. These include incorporating surfing into coastal engineering (e.g. ASRs) and protecting existing surfing breaks. Different types of research-based surfing literature are identified and 162 citations are categorised in Table 2.1. The findings show that the physical processes around surfing breaks are well researched. Physical and numerical modelling of surfing waves has featured often in the literature, including analysis of existing surfing breaks. Although ASR design has received a lot of attention, the construction, monitoring, resource management process, or beach response to a reef, have not been covered in as much detail. As a result, when coastal conflict occurs near surfing breaks surfing amenities often suffer. What is lacking is specific literature on how to manage

coastal conflict issues around surfing breaks (e.g. SCARFE *et al.,* Chapter 3). More research on economics, socio-cultural issues, coastal management, and the oceanographic effects of coastal development on surfing is required if the world's natural surfing breaks are to be preserved.

Surfing has been scientifically explained by breaking the topic into surfing waves and how they relate to surfers, and surfing breaks and how they relate to surfing waves. Breaking wave height (H_B; crest to trough), wave peel angle (α), wave breaking intensity (B_I), and wave section length (S_L) are four surfing wave parameters that can be used to describe surfing waves. Other parameters exist but these ones are favoured to maintain consistency in the literature. The effect of local winds at a surfing site is briefly discussed and although wave-wind interactions have been researched in the oceanographic literature, surfing wave/wind interactions have not been the topic of specific research.

The different types of surfing breaks are presented and literature on the bathymetric components of surfing breaks and their effect on surfing waves has been reviewed. Two examples of natural surfing breaks are presented to further illustrate how surfing waves form and how they can be analysed. To better understand ASR design, as well as surfing breaks in general, we recommend that more research on beach morphology and surfing be undertaken.

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Chapter 3 - SUSTAINABLE MANAGEMENT OF SURFING BREAKS - CASE STUDIES AND RECOMMENDATIONS

PREFACE

The review process undertaken in Chapter 2 identified a lack of dedicated literature on the effects of coastal engineering to surfing breaks, and how to manage coastal space conflict issues around surfing breaks. This chapter presents various examples of surfing breaks altered by coastal engineering to demonstrate the nature and potential impacts, contributing to this literature void. The effects on surfing breaks demonstrated by the chapter are both positive and negative, but not preconceived. The lack of strategic management of surfing breaks is contrary to modern thought on protecting and enhancing natural resources. Coastal management methods are discussed to further the knowledge of oceanographic methods for protecting surfing breaks, including environmental impact assessments. This paper relates to the following objectives of the thesis.

3. *To identify the range of physical effects coastal engineering activities can have on different types of surfing breaks, and to propose methods to manage the oceanographic aspects of surfing breaks.*

The paper has been peer-reviewed and accepted for publication in the Journal of Coastal Research, along with a companion paper reviewing literature on surfing science and coastal management (Chapter 2). Various issues around the management and engineering of surfing breaks are identified in this paper, which are addressed using modern scientific methods in subsequent chapters of the thesis.

Ideas in this paper were initially presented at the 4th International Surfing Reef Symposium at Manhattan Beach, California (12 -14 January 2005). The proceedings were to be published as a special issue of the *Journal of Coastal Research,* but unfortunately the issue never eventuated. The paper went through a peer-review process as part of the conference, as well as for the final published version reprinted here. As lead author SCARFE's created the paper in a manner that fulfils the requirements of the thesis, but the intellectual input by HEALY and RENNIE's in a thesis supervisory and editorial role warranted co-authorship. MEAD was involved in the initial paper design in 2004, and contributed to the analysis of

the case studies (particularly Raglan and Palm Beach), also warranting co-authorship.

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ABSTRACT

Despite their large numbers worldwide, surfers as a coastal interest group have largely been ignored during coastal management decision making. Surfers are however, increasingly being considered in coastal management decisions as the social, economic, and environmental benefits of high-quality surfing breaks are realised. Examples of surfing breaks that have been improved or compromised by coastal engineering are presented here to demonstrate the fragility of surfing breaks to coastal development. Integrated coastal zone management techniques are suggested as an approach to sustain recreational amenities associated with surfing breaks. Surfers can benefit from integrated coastal zone management practices that balance the coastal space requirements of various coastal user groups. This paper advocates detailed and standardised assessments of the environmental impacts that coastal activities can have on the quality of surfing waves as part of modern integrated coastal zone management practices. Baseline information must also be collected to develop an understanding of the physical processes around a surfing break. To facilitate baseline studies, and ongoing monitoring of surfing breaks, this paper identifies the types of surfing and oceanographic factors that need to be considered. The need for regional and central governments to strategically protect surfing breaks using legislation, reserves and coastal management plans is explored. It is recommended that further surfing research investigate ideal coastal management techniques for different resource management frameworks.

ADDITIONAL INDEX WORDS: surfing reefs, coastal space, recreational space, coastal amenities, integrated coastal management (ICM), environmental impact assessment (EIA), geographic information system (GIS), coastal engineering, wave focusing, coastal development.

INTRODUCTION

In a detailed analysis, SMALL and NICHOLLS (2003) found that the coastal population density is approximately three times the global average and that it is commonly believed that coastal migration is continuing and growing. LAZAROW (2007) estimates that 86 % of Australians live within 30 minutes of the coast, while in small island nations the entire population is coastal. Development to support growing coastal populations puts pressure on many resources, including the natural features that create surfing waves (e.g. PRATTE, 1987; ANON, 2003; LAZAROW *et al.,* 2007; MEAD *et al.,* 2007). It is asserted by this paper that the features that form a surfing break are a resource that possesses recreational amenity values. Surfing breaks need protection as these amenity values are important resources for coastal communities, both socially and economically (LAZAROW, 2007; LAZAROW *et al.,* 2007a and b; NELSEN *et al.*, 2007). Some environmental legislation (e.g. New Zealand's Resource Management Act (RMA), 1991; Section 7c) already requires the protection and maintenance of these recreational amenity values.

Not all surfing breaks are entirely natural. They can be created, modified or destroyed by human activities such as the construction of seawalls (e.g., Saint Clair, Dunedin, New Zealand), jetties (e.g., Mission Bay Jetties, San Diego, California), boating infrastructure (e.g., Manu Bay, Raglan, New Zealand), piers (e.g., Oil Piers, Ventura, California), and beach nourishment (e.g., "The Cove" Sandy Hook, New Jersey). It is not surprising that many existing surfing breaks are unnatural because there are few environments that have not been impacted to some degree by human activity. Whether or not the environmental impact is favourable, the environment possesses some degree of artificiality after the alteration (FRENCH, 1997). While the engineering effects can be positive on surfing wave quality (e.g., The Superbank, Gold Coast, Australia), more often the surfing breaks are compromised (e.g., Saint Clair, Dunedin, New Zealand), or even destroyed (e.g., El Segundo, California). Discussions on this issue are rare in coastal literature (e.g. BENEDET *et al.*, 2007).

The main purpose of this paper is to demonstrate the need to sustainably manage surfing amenities using detailed studies of physical processes and to recommend coastal management methods for surfing breaks. Social research such as

monitoring changes in surfing break usage (e.g., counting surfer numbers) and surfer demographics are also important, but are outside of the scope of this work. Other issues central to surfers but not covered in this research include water quality and amenities such as car parks, showers, clubrooms and beach access. This research is primarily focused on the oceanographic processes that cause surfing waves to form and activities that are likely to affect the "surfability" (WALKER, 1974; DALLY, 1989; HUTT *et al.*, 2001; MACK, 2003). This paper forms part of a larger research effort by SCARFE (2008) focused on developing methods for the oceanographic management of surfing amenities. The specific tasks undertaken in this paper are:

- A review of examples of development around surfing breaks to highlight the effects coastal engineering can have on surfing breaks.
- An exploration of integrated coastal zone management (ICZM) techniques to maximise surfing amenities.

CASE STUDIES OF SURFING AND DEVELOPMENT

Every year surfing breaks are compromised by coastal engineering projects that do not consider impacts to surfing. This is not surprising as there is a lack of dedicated publications on the subject (SCARFE *et al.,* Chapter 2). A few non-peer-reviewed publications on surfing break protection are available (e.g., NELSEN and HOWD, 1996; MEAD *et al.,* 2004), but it is still a new area of coastal research. For example, a conference paper by PRATTE (1987) overviews the problem of surfing breaks and coastal development and technical reports (BLACK *et al.,* 1998; SCARFE *et al.,* 2003a) investigated physical effects that boat infrastructure has on surfing breaks.

In a reviewed article on the topic, LAZAROW (2007) investigates the economic value of surfing breaks as well as conflicts between surfing and other coastal activities. The topic is further investigated by LAZAROW *et al.* (2007a and b) and NELSEN *et al.* (2007), who provide useful discussions and methods for coastal managers. Oceanographic processes important for surfing are not discussed in these publications yet these processes are a necessary consideration to successfully include surfing in coastal management. Another discussion by FARMER and SHORT (2007) noted that despite the rapid growth in the number of Australian surfers and the size of the surfing industry, little has been done to

protect the surfing breaks. FARMER and SHORT (2007) have rekindled interest in surfing reserves as a coastal management technique. The first surfing reserve in Australia was created in 1973, but in 2005 still only one of Australia's more than 10 000 beaches was a dedicated surfing reserve. Presently there are four reserves with another 24 proposed (FARMER and SHORT, 2007). The reserves are gazetted by the Department of lands as a reserve and the boundary extends from the high water mark to 500 m seaward. The reserve is managed by a board of representatives of the surfing area and "it formally recognises the site as an area of surfing significance and quality surf; it recognises the long and close links between surfers and the surf and it will assist in the long term preservation of the site for future surfers (FARMER and SHORT, 2007; p. 99)." However, no statutory protection is included by making the surfing break a reserve. BUCKLEY (2002a and 2002b) also discusses surfing and management issues, with a focus on tourism and surfing in Indonesia.

To further contribute to the topic of surfing and coastal management, this work presents six case studies (Figure 3.1) highlighting the potential oceanographic effects that coastal engineering can have on surfing breaks.
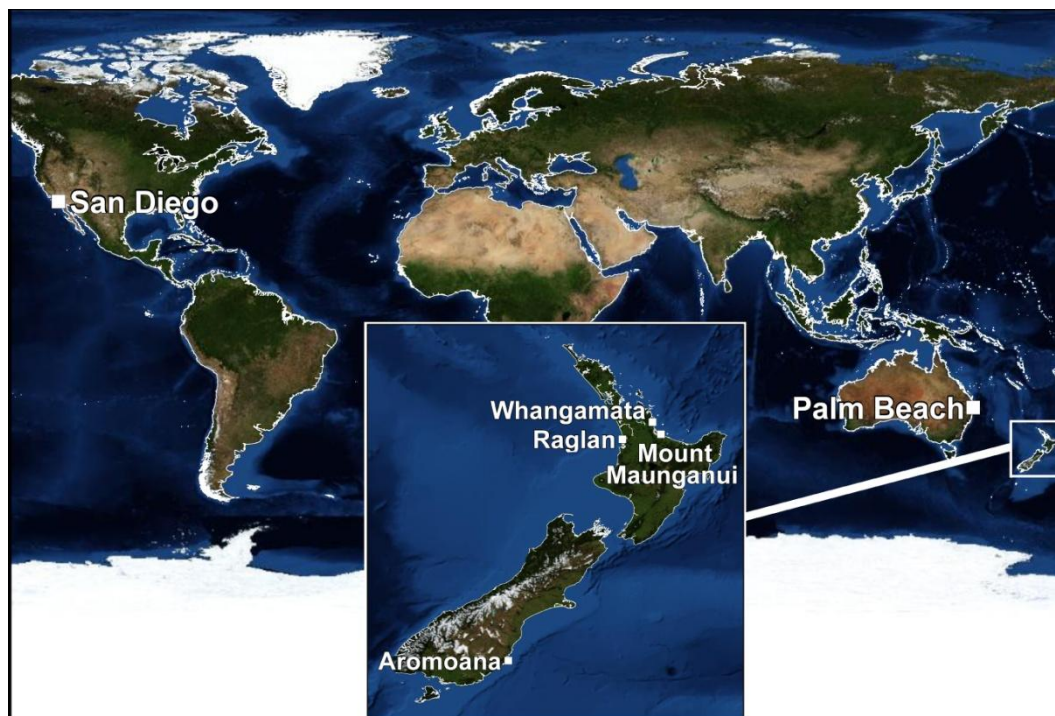
Figure 3.1. Location of case studies of surfing and coastal management discussed in this research.

Case Study 1 – Manu Bay Boat Ramp, Raglan (New Zealand)

Some of New Zealand's most iconic and extensively studied surfing breaks are on the north end of the Raglan headland (Figure 3.2; SAYCE, 1997; HUTT, 1997; MEAD, 2001; MOORES, 2001; SCARFE, 2002a; PHILLIPS, 2004; MEAD and PHILLIPS, 2007; SHAND *et al.,* 2007). When oceanographic conditions are suitable (*see* HUTT, 1997; SCARFE, 2002a), surfing waves peel perfectly along the boulder and reef shoreline, creating seven surfing breaks. However, a small engineering structure has had a negative effect on the most easterly surfing break called Manu Bay.
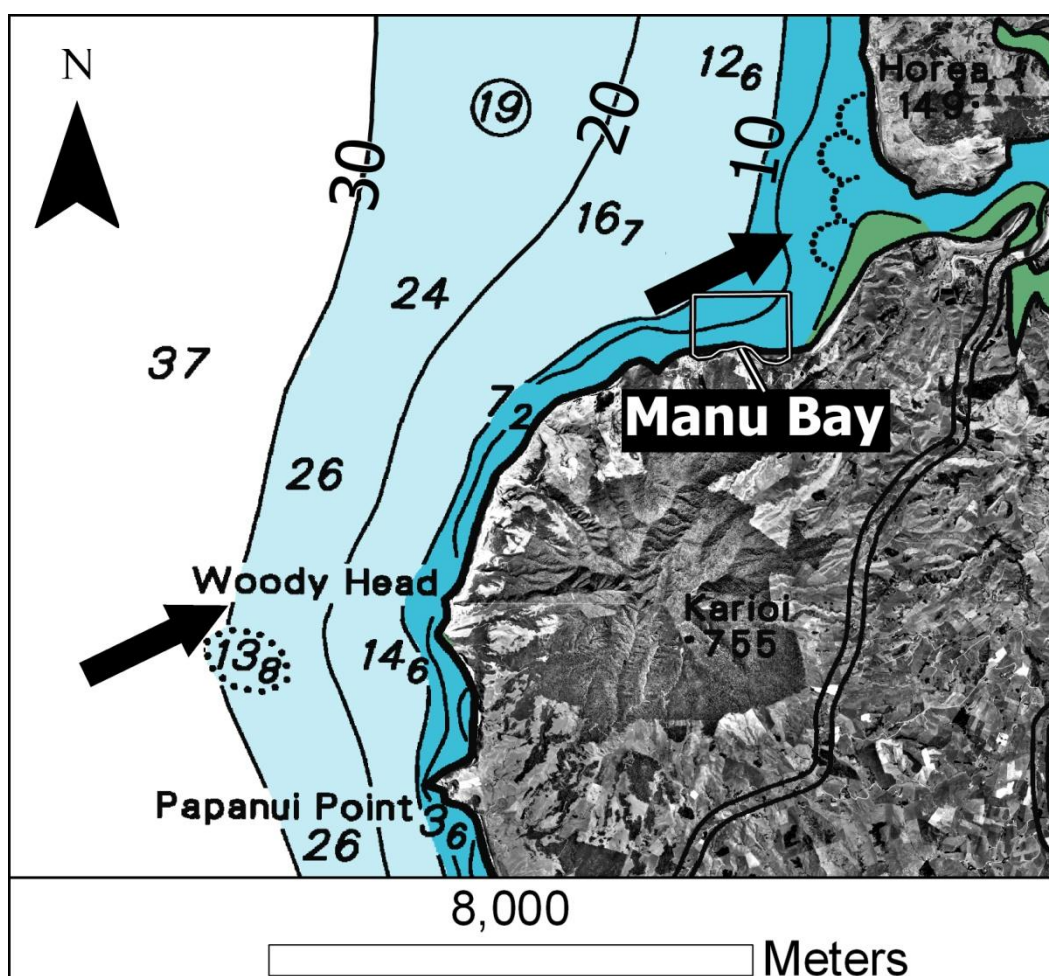
Figure 3.2. Raglan headland with aerial photography and navigational chart adapted from data from Land Information New Zealand. The arrows represent the average of 28 years (1979-2007) of mean wave directions at 40 m and 11 m depths. The coverage of the 2001 survey of Manu Bay (Figure 3.5) is also included on this figure.

Manu Bay is a consistent surfing break that can be surfed in a range of conditions. The average of various wave parameters (Table 3-1) has been calculated from modelling data created by GORMAN *et al.* (2003a and b) and GORMAN (2005). As

waves transform from the deep to shallow water they are predicted to reduce in height and directional spread, as well as increase in mean direction, but not peak direction. Since surfers ride the largest waves in a set (HUTT, 1997), it is possible that these peak waves are most important to surfing studies. Although, nearshore wave focusing is not included in the model simulations, the results still begin to describe how the wave character changes as the waves propagate from deep to shallow water.

Table 3-1. Average value of wave parameters for 1979-2007 from modelling data by GORMAN *et al.* (2003a and b) and GORMAN (2005).

Parameter	Depth 100m		Depth 40m		Depth 11m	
	Average	Standard Deviation	Average	Standard Deviation	Average	Standard Deviation
Significant Wave Height (m)	1.80	0.81	1.61	0.77	1.60	0.76
Mean Period (s)	6.9	1.2	7.2	1.3	7.4	1.3
Mean Direction (° CW from N)	61.8	18.9	66.9	17.4	68.3	17.4
Peak Direction (° CW from N)	58.6	14.5	59.4	14.5	59.7	13.8
Peak Period (s)	11.4	2.4	11.5	2.3	11.5	2.2
Directional Spread (degrees)	31.8	11.2	27.0	7.9	25.6	7.5
Spectral Width	0.531	0.082	0.543	0.083	0.527	0.078

* CW from N = the angle is clockwise from north and describes the wave direction approaches toward

The consistency of swell makes the estuary bar often impossible to navigate, requiring the construction of a breakwater and boat ramp at the end of the Manu Bay surfing break during the 1960s. Waves are smaller in the sheltered bay than farther south along the headland, making the boat ramp position a seemingly sensible location (Figure 3.3). However, the breakwater construction directly affects the end of the surfing ride during some high tide conditions, with further impacts to the natural current patterns, sedimentary morphology, and consequently the surfing ride. The loss of ride length (and wave shape) was caused by two engineering activities. First, discussions with local residents and the council revealed that the shoreline reef was dredged, dynamited, or both. No actual records of the construction were found to exist. The second activity was the breakwater construction.

Figure 3.3. Oblique photos of the Manu Bay surfing break showing impact of the boat ramp on shoreline and wave breaking patterns; (a) 2001 high tide photo (*from* SCARFE *et al.,* 2002) (b) 2007 low tide photo (SAM STEPHENS, *pers. comm.*). The areas of breaking and calm waves are important to the shoreline and seabed morphology, and hence surfing conditions.

One of the most famous surfing films of the 1960's, *Endless Summer* (BRUCE BROWN FILMS, 1990), includes footage of Manu Bay before the boat ramp construction. Frames from the film were captured, enlarged and enhanced using the Topaz Moment version 3.2 software (Topaz Labs) and subsequently merged together. Although the film only shows one overview shot of Manu Bay (Figure 3.4), it is reasonably clear that the boulder shoreline that currently exists to the northwest of the boat ramp was present at the current boat ramp position during the film. The image in Figure 3.4 only shows moderate-sized waves, which stop breaking around the boat ramp location, but during bigger swell events the surfing waves were likely to continue to peel past the current boat ramp position.

Figure 3.4. Video frames captured from 1960's *Endless Summer* (BRUCE BROWN FILMS, 1990) showing the Manu Bay shoreline before the boat ramp construction.

The configuration of surfing break components was initially discussed in MEAD and BLACK (2001a and b) and this type of analysis can be used to understand what has happened to the Manu Bay surfing break after the boat ramp development. Based on a hydrographic survey by HUTT (1997), MEAD and BLACK (2001b) identified the macro-scale components of Manu Bay as a large wedge with a ridge that creates "The Ledge" surfing break. SCARFE (2002a) recharted the surfing break using more accurate methods (SCARFE, 2002b) to show further complexity in the reef and sand surfing break (Figure 3.5a). The hillshade diagram (Figure 3.5b) shows a consistent colour where the seabed is smooth and sandy. Nearer the shore the undulating reef has more variation in the shading. Various holes and mounds, enlarged in Figure 3.6, are also highlighted by the hillshading.
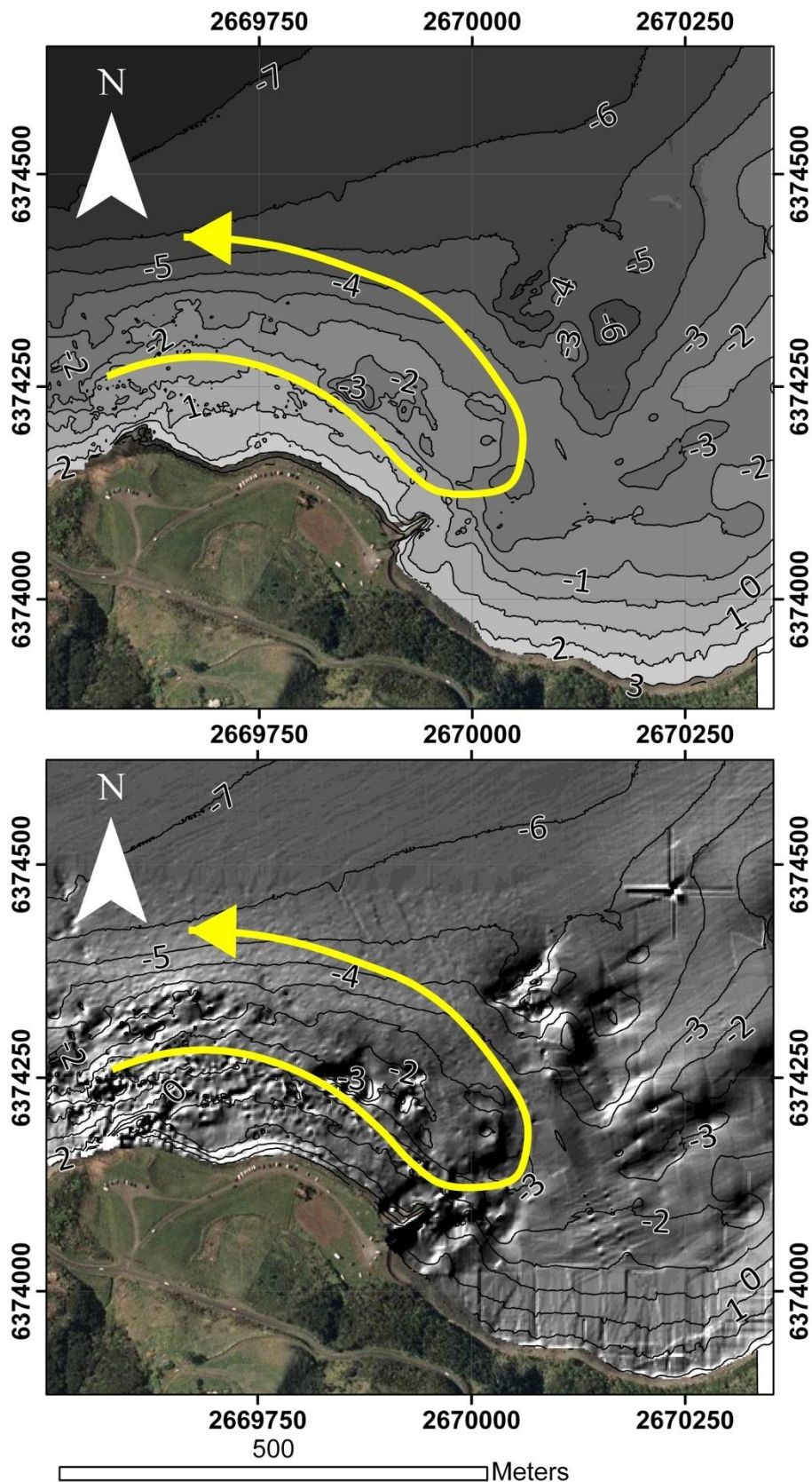
Figure 3.5. Bathymetry (a) and hillshade (b) of Manu Bay surfing break. The arrow represents the circulating current induced by wave processes and steered by bathymetric features. There are bathymetric depressions (holes) around and offshore of the breakwater. Background aerial photography sourced from Terralink International Limited. Coordinates in New Zealand Map Grid, depths relative to Chart Datum (LAT).
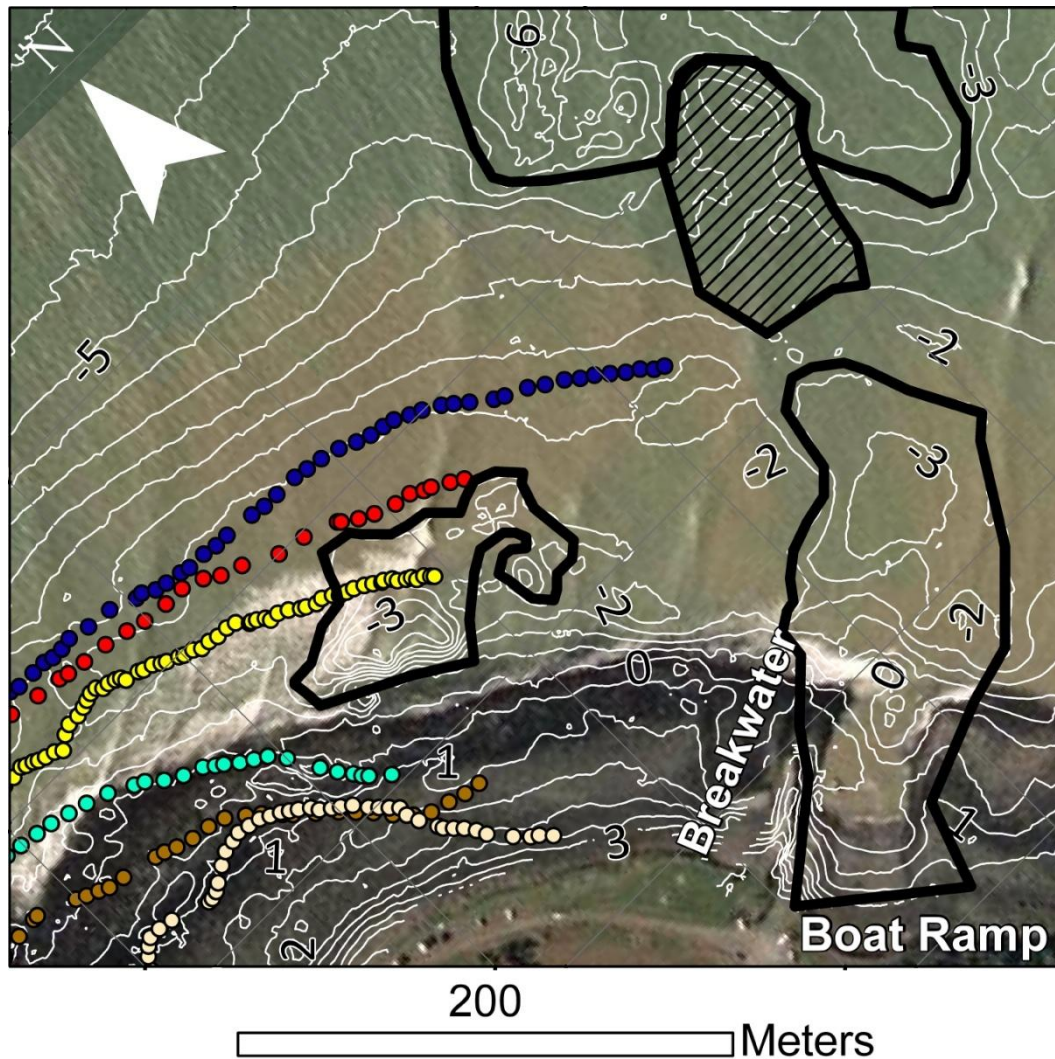
Figure 3.6. Bathymetric contours around boat ramp. The dark polygons show areas of deep water with the stripped polygon representing a shoal area. The dots represent the path of breaking surfing waves from HUTT (1997) during different stages of the tide. The deeper breaking waves are during low tide conditions and the shallower breaking waves during high tide. 2002 aerial photography of very small non-surfing waves and sourced from Terralink International Limited. Depths relative to Chart Datum (LAT).

The ridge feature that causes the extreme wave breaking at "The Ledge" is relatively small with a surface area of 3 200 m², while the wave breaking component of the wedge (+1 to −2.5 m Chart Datum) is approximately 70 000 m². The main wedge is actually two wedge components separated by a platform. These wedges are the main wave breaking components and function differently during different swell events, and tide level due to the meso-scale tidal range (3.0 m spring). The two wedges are approximately 30 000 m² (shallow shelf/wedge) and 40 000 m² (deep shelf/wedge) in size, and they allow surfing waves to peel along the contours. Considering the size of the ledge and wedges, the hole around the breakwater (5 800 m²), and the hole immediately offshore

(15 500 m²), are large features in comparison to the actual surfing break components, making them worthy of further investigation during management of any issues relating to this surfing break.

Wave breakpoint measurements taken from aerial photographs by HUTT (1997) were calculated through the tidal cycle and they are overlaid with the bathymetry from SCARFE (2002a) in Figure 3.6. The 1996 aerial photos were taken during a 1.2 to 1.5 m significant wave height (H_{sig}) swell event at six stages of the tide. The waves therefore only break a small way around the headland. Notice how the three higher tide measurements break on the upper wedge, while the three lower tide measurements break on the lower wedge. The platform between the two wedge components is approximately 50 m wide in the offshore regions and expands to 80 m wide eastward, pushing the lower tide waves offshore. At the end of the path of the mid-tide breaking waves in the HUTT (1997) measurements, there is a 4 m deep hole that modifies the wave and current patterns. The effects of the shelf and hole on wave transformations during low tide conditions are clear in Figure 3.3a. The platform pushes the breaking waves offshore and the hole creates an area of calm water, with further impacts to current circulations.

In the net, 175 000 m^3/yr of sediment move around the Raglan surfing breaks (PHILLIPS, 2004). This is made up of 275 000 m^3/yr in an easterly direction in the surf zone area, and 100 000 m^3/yr to the west further offshore in a recirculating sediment/current pathway. The westerly flow is generated by the interaction of wave-drive forces and bathymetric steering (PHILLIPS, 2004). The width of the circulating cell was found by PHILLIPS (2004) to vary with swell size and tide level. Large wave events at low tide generate the strongest currents flowing east along the headland. However, the strongest westerly currents were found when the tide is the highest. Considering the significant volume of sediment moving around the headland, any construction modifying currents (e.g. the breakwater and dredging) can cause morphological changes due to bathymetric steering of currents and impacts to surf zone hydrodynamics. During large swell conditions, strong wave driven currents, which would normally flow down the headland unimpeded, are directed offshore by the breakwater and dredged boat ramp.

It is likely that the recirculating sediment pathways, measured and modelled by PHILLIPS (2004; Figure 3.5), cause some erosion of the seabed in areas of strong

currents. Although the mechanisms for the creation of the holes noted in Figure 3.6 cannot be resolved in this study, any modification to the currents by the dredging or breakwater potentially can change the seabed morphology some distance from the engineering. This point is iterated by SCARFE *et al.* (Chapter 8). Since the largest hole identified in Figure 3.6 is directly perpendicular to the boat ramp and dredged area, it is likely that the engineering had some influence on the hole formation. The shoal area just north of the breakwater hole could have been created as the currents slow and sediment drops out of suspension, similar to the way a delta is formed at an inlet.

In summary, the breakwater can affect the coastal processes and surfing in three possible ways: (i) directing the sand and smaller gravels offshore by the recirculating sediment pathways, reinforcing the hole to the north of the boat ramp breakwater; (ii) controlling the location of an eddy or rip that erodes a hole in the sand and boulder wedge; and (iii) providing a structure that blocks natural wave and current movements around the headland. This first process has lead to erosion of the boulder beach south of the boat ramp and it is currently stabilised by a failing seawall.

Case Study 2 - Palm Beach Reefs, Gold Coast (Australia)

Three large-scale offshore reefs were planned as coastal protection devices at Palm Beach, Gold Coast, Australia (TOMLINSON *et al.,* 2003). Palm Beach is an important surfing area, with three of the top 10 professional surfers on the World Tour residing at Palm Beach in 2004 (MEAD *et al.,* 2004). Inevitably potential impacts of the project on surfing amenities, poor public participation, and lack of alternative options led to a 1200-person protest on the beach. Although the reef project attempted to develop an integrated and multifunctional coastal management strategy (TOMLINSON *et al.,* 2003), it is apparent that this was not the case as such a large-scale protest would not occur if public consultation was adequate.

The environment impact assessment (EIA) concluded that inshore surfing conditions would be unaffected by the presence of the three reefs along the beach, and surfing improvements were predicted by TOMLINSON *et al.* (2003). However, no investigation or discussion in the design reports quantified the existing surfing conditions. Thus if the reefs were built it would have been difficult to really prove

how the development impacted surfing. An independent review (MEAD *et al.,* 2004) found a failure to relate existing scientific surfing literature to the design or to demonstrate an understanding of coastal processes during the design process. Local concerns were poorly answered with a fact sheet with questions and answers that were unsupported by evidence, badly researched, and often incorrect with respect to existing knowledge of oceanography and surfing wave processes (MEAD *et al.,* 2004). Repeated statements that the reefs would not impact surfing amenities were made. Since the three 250 m long reefs' primary function was to break waves prior to them breaking on the beach, it was impossible that the reefs would not impact on the inshore surfing waves. Modelling simulations and reviews of existing literature demonstrated that waves breaking on the reef, as well as those passing over the reef, would be significantly modified, causing a significant change to the existing surfing conditions in the area.

The design of the proposed reefs can be seen in Figure 3.7 and MEAD *et al.* (2004) found that the reefs would not break waves suitable for surfing. In addition, it was predicted that inshore surfing conditions would be negatively impacted due to wave focusing and wave-induced currents. The "wings" at each end of the reef were designed to mitigate against end effects of the reef but MEAD *et al.* (2004) found that the design would impact surfing as it did not consider refraction, assess dominant wave directions and height, or draw from the abundant amount of available literature. The review report and public protest resulted in the last-minute abandonment of the project, demonstrating the importance of developers and consenting agencies seriously considering impacts on surfing amenities during coastal management. The Gold Coast City Council (GCCC) concluded that construction would not go ahead without the consent of the local stakeholders, including the surfing community.
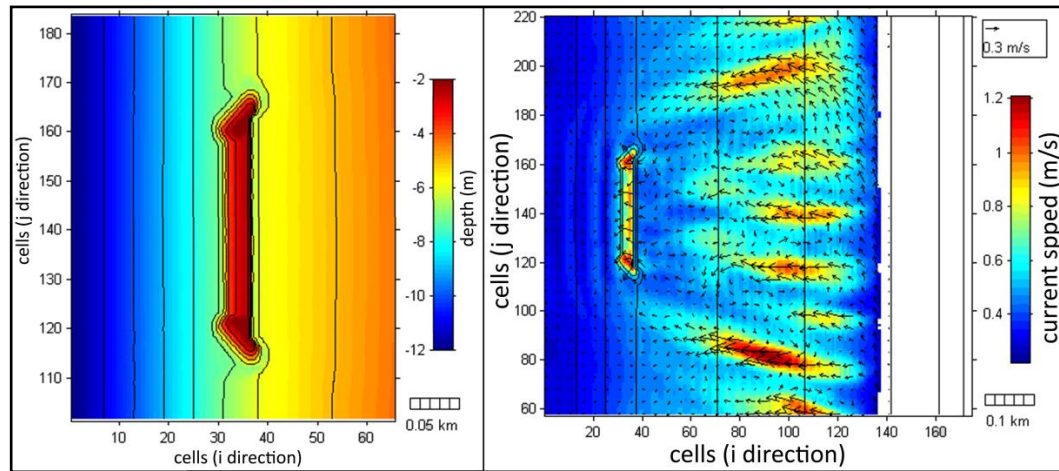
Figure 3.7. Model grids showing design of the coastal protection reefs (bathymetry; left) and predicted wave induced currents (right) for a 1.2 m wave condition (*from* MEAD *et al.,* 2004).

Case Study 3 - Mission Bay Jetties, San Diego (California)

Jetties are a common type of coastal engineering that can modify surfing wave quality (SCARFE *et al.,* 2003a and b; BUONAIUTO and KRAUS, 2003; RAICHLE, 1998). In the case of Mission Bay (Figure 3.8), the northern jetty creates a consistent and high quality surfing break that can have good waves even when surfing conditions on the adjacent beach to the north are often poor (SCARFE *et al.,* 2003a). The surfing waves immediately north of the jetty peel for a significantly longer time than farther north at Mission Beach, and they break with higher intensity. The surfing take-off point is reasonably consistent, whereas the wave peak and breaking location vary significantly at the beach breaks. Surfers desire predictable, clean waves where the wave break point peels along the wave crest at a surfable but challenging speed, and jetties can aid in the formation of these types of waves. Although the Mission Bay jetties improve surfing quality, a proposal to further improve vessel navigability almost destroyed the surfing break (PRATTE, 1987).
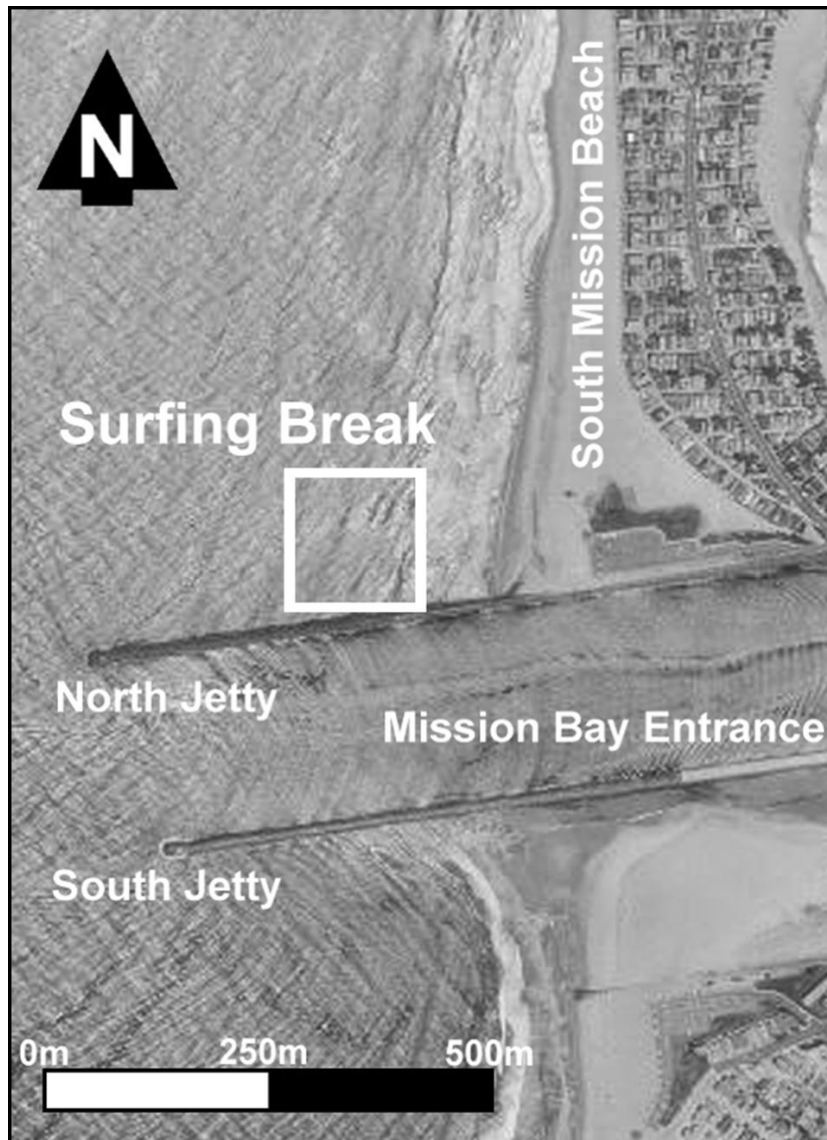
Figure 3.8. Aerial photograph of Mission Bay jetties and location of the surfing break created by the northern jetty wall.

The orientation of a jetty to the dominant wave direction has a large impact on the surfing conditions (SCARFE *et al.,* 2003b), and this is evident at the Mission Bay Jetties. The obtuse angle between the beach and the northern jetty catches waves. Waves compress against, and reflect off the jetty wall causing focused wave energy. In comparison, the southern jetty is at an acute angle to the beach, creating different wave refraction, diffraction, shoaling and other preconditioning wave processes. Thirty-six years of wave data collected by the Scripps' Coastal Data Information Program (Figure 3.9) shows the variety of wave directions the jetties are exposed to. The bidirectional spread is caused by differing winter and summer swell sources for Southern California and the effects of the offshore San Clemente Island.
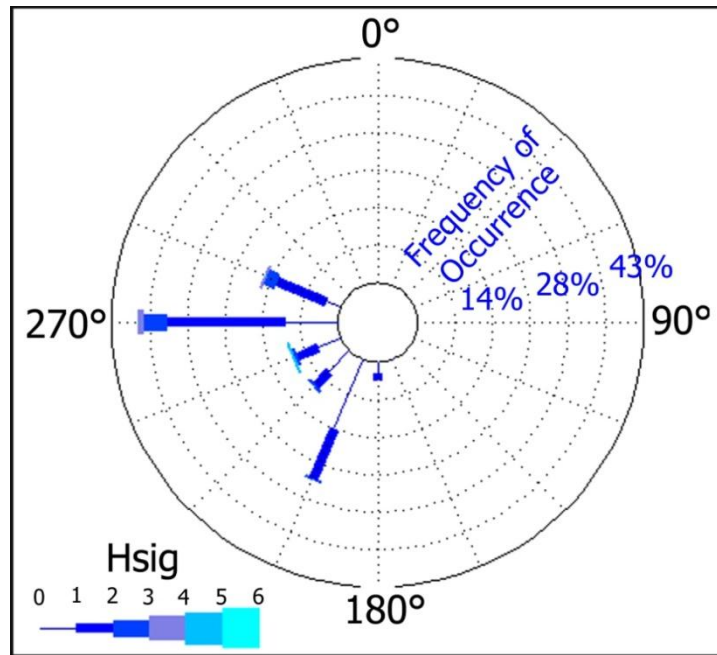
Figure 3.9. Directions and significant wave heights (H_{sig}) for waves in 198 m depth, offshore of Mission Bay. Wave rose sourced from the Coastal Data Information Program (www.cdip.ucsd.edu) using data from 1981-2007.

The northern jetty has been categorised by SCARFE *et al.* (2003b) as a Type 1 jetty (Figure 3.10). This type of surfing break has a long jetty wall that transforms the surfing wave crest before the wave breakpoint peels along the build up of sand (termed a fillet) that forms against the jetty. Type 1 jetty inlets, such as the one between the two jetties, do not have a significant ebb delta to modify wave energy. In this case, there may not be a significant delta because of the low rainfall and lack of sediment supply in California (WILLIS and GRIGGS, 2003).
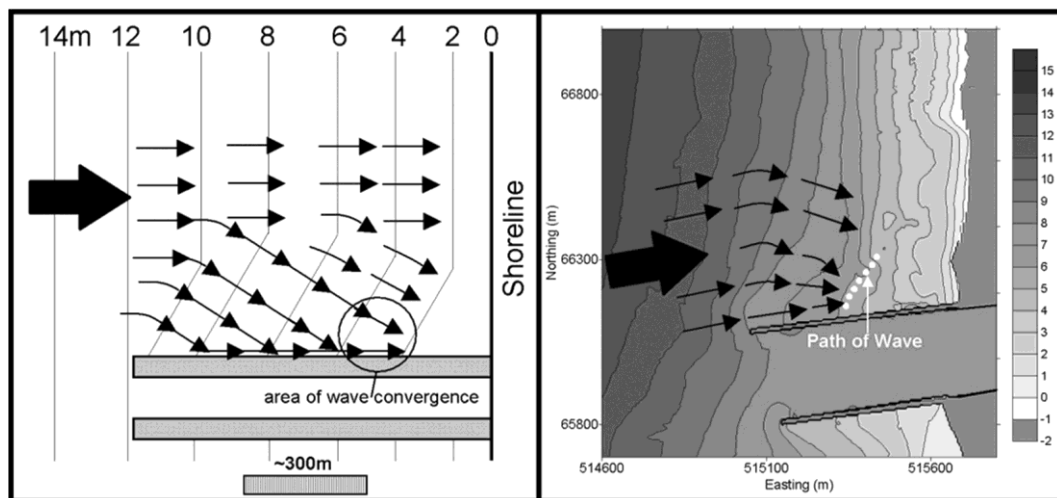
Figure 3.10. Mission Bay jetties is categorised as a Type 1 jetty where a long jetty wall and delta absent inlet cause surfing waves to peel along the sand fillet against the jetty (from SCARFE *et al.*, 2003b).

Jetties require modifications and maintenance, and considering coastal sectors (such as surfing) outside the main project scope during the management of these jetties can help positively affect coastal users. This includes the impacts on wave refraction, diffraction, shadowing and surfing break components, when dredging, extending or modifying an existing jetties design. In order for surfing to be included in jetty management, more research is required that builds on previous work on the topic (SCARFE *et al.,* 2003a and b; BUONAIUTO and KRAUS, 2003; RAICHLE, 1998). The study of natural surfing breaks will also contribute to this goal, such as the fillet-like sandbar and long natural jetty-like structure of the Moturiki Island tombolo at Mount Maunganui (discussed later), which resembles an artificial break created by jetties. Thus, dissecting surfing breaks such as at the Main Beach at Mount Maunganui help us understand how to incorporate surfing into coastal engineering structures.

Case Study 4 – Main Beach, Mount Maunganui (New Zealand)

The Main Beach at Mount Maunganui, New Zealand (Figure 3.11) is an example of a surfing break that is currently subject to artificial nourishment. The nourishment is placed immediately offshore of the beach (5-10 m depth) as a dredge despoil site that also offsets the loss of littoral sediment trapped in the dredged navigation channel of the Port of Tauranga (SPIERS, 2005; SPIERS and HEALY, 2007). The effects of this nourishment to surfing amenities are unknown as information was not recorded on the surfing conditions before the nourishment began. The lack of serious surfer complaints at the Mount Maunganui beaches, all of which are affected in some way by dredging or nourishment, suggests that effects may have been minor. However, this illustrates the importance of collecting relevant baseline information on existing surfing breaks if future changes are to be properly assessed, including surfing breaks suitable more for novice and intermediate surfers, such as this location.
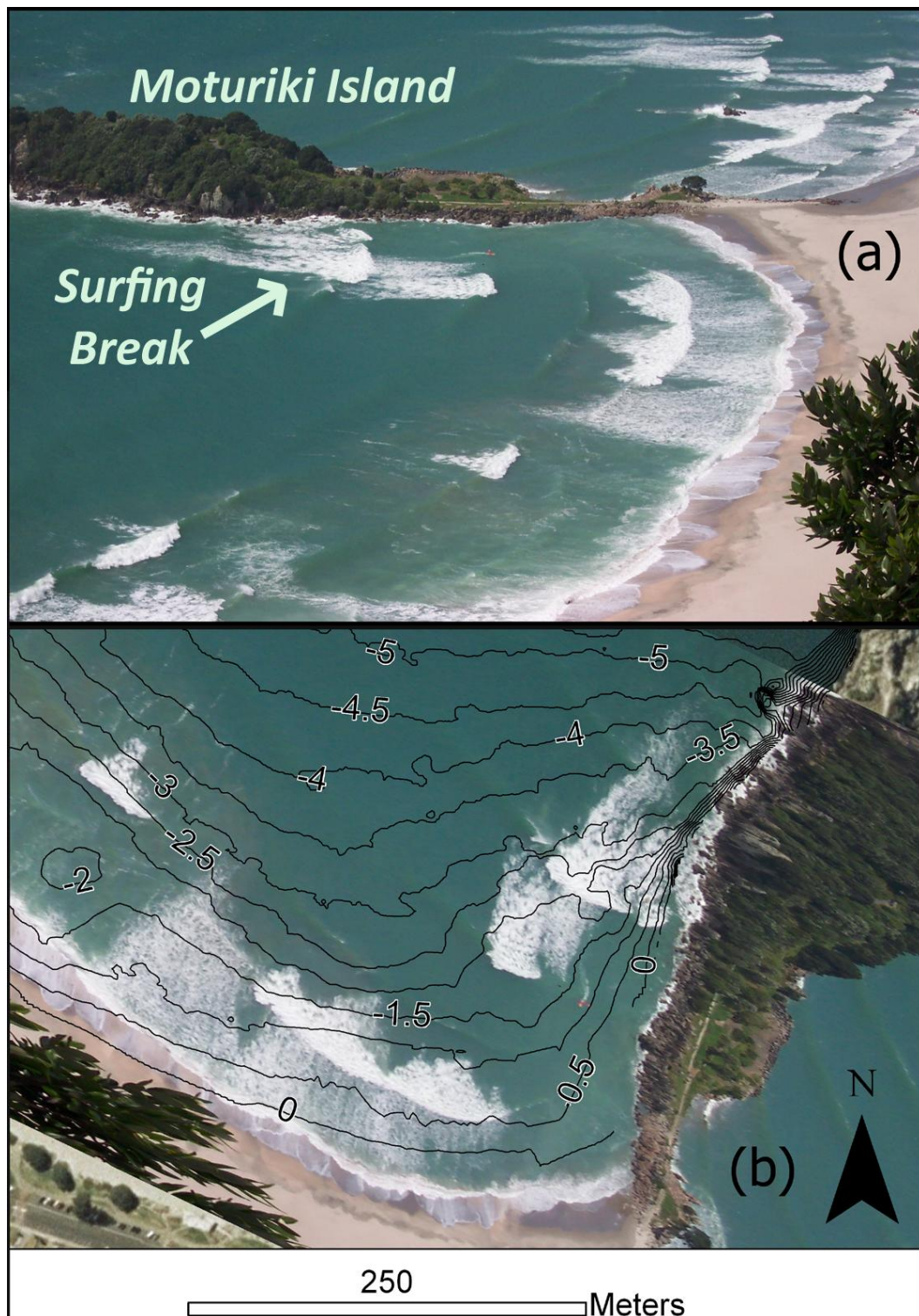
Figure 3.11. Oblique image of wave event at 12:15 p.m., 5 October 2004, creating good beginner, or longboard surfing waves (a) oblique image of breaking waves, and (b) rectified image overlaid on contours from a multibeam survey of the beach. Wave conditions were 2.36 m (H_{sig}), 7.7 sec (Tsig), 10° mean direction with a tide level of 0.69 m (MSL). A good alignment between the breaking waves and a sandbar can be seen. Note that waves were focusing on the edges of the beach rather than in the centre of the beach due to the offshore focusing patterns. The dredge disposal site is immediately offshore of the bottom image.

Moturiki Island connects to the beach with a tombolo and plays a critical role in the creation of the surfing break identified in Figure 3.11. A buildup of sediment against the island has been measured using multibeam echo soundings (SCARFE, 2008), and this feature causes wave breaking with a low "breaking intensity", suitable for beginner or longboard (Malibu) surfing. A study of wave conditions during storm and surfing events found that this surfing break is ridable more often during northerly wave events (SCARFE, 2008). The monochromatic wave model WBEND from the 3DD suite of models (BLACK and ROSENBERG, 1992; BLACK, 1997 and 2000) was used to predict wave refraction (Figure 3.12; Appendix Two). The effect of the offshore islands on wave patterns at the Mount Maunganui beaches can be clearly seen. During the wave event shown, a band of high wave energy approaches the Main Beach from the north-northeast, creating suitably preconditioned waves for breaking on the sandbar against Moturiki Island.
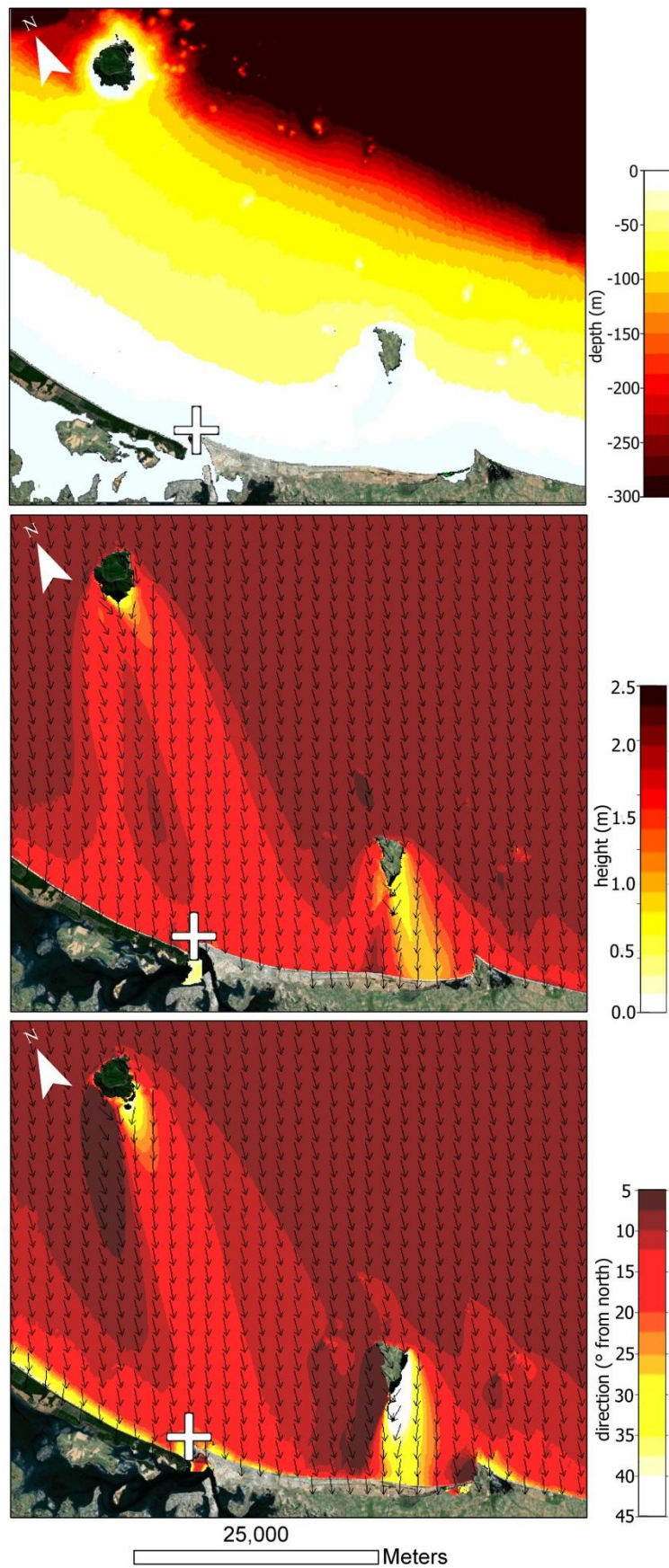
Figure 3.12. Offshore depth, wave height and angle predictions for surfing waves in Figure 3.11. Note the effect of the offshore islands and band of higher wave energy directed at the Main Beach (cross symbol).

Although it is unknown to what extent the surfing break has been modified, DALLY and OSIECKI (2007) and BENEDET *et al.* (2007) discuss how nourishment has the potential to improve, sustain or destroy the quality of surfing waves. If the level of nourishment was increased or reduced significantly, the beach could evolve with unknown effects to surfing amenities. If "targeted nourishment" was used, it is possible that nourished sediment could be placed to precondition and break waves, further improving surf quality. Although using different terminology, the concept of "targeted nourishment" is discussed by DALLY and OSIECKI (2007). The discussion by DALLY and OSIECKI (2007) involves placing fill directly into the surf zone to create a system of artificial shoals. However, SPIERS (2005) shows how an offshore spoil mound modifies wave focusing, as does the Aramoana case study below (*see* next section). Thus "targeted nourishment" extends the DALLY and OSIECKI (2007) definition to include any nourishment that modifies the preconditioning or breaking of surfing waves. Nourishment could also be stabilised with geotextile sandbags to create sedimentary and reef features suitable for surfing, such as in the "multipurpose sediment controlling structures" discussed by SCARFE *et al.* (Chapter 8). Such geotextile containers have been installed by MEAD *et al.* (2007b) and shown to modify inshore surfing bar formation by BLACK and MEAD (2007) and SCARFE *et al.* (Chapter 8). The interactions between beaches and surfing, or nourishment and surfing have not been heavily researched (SCARFE *et al.*, Chapter 2) and thus the concept of "targeted nourishment" is still experimental. The work of BENEDET *et al.* (2007), BLACK and MEAD (2007) and SCARFE *et al.* (Chapter 8) on the use of the WRIGHT and SHORT (1984) beach-state models and surfing needs to be extended for successful design of "targeted nourishment".

Case Study 5 – Aramoana Beach, Dunedin (New Zealand)

An example of artificial nourishment, combined with a large engineering structure around a surfing break is found at Aramoana Beach, Dunedin, New Zealand (Figure 3.13 and Figure 3.14). The surfing break is adjacent to a 1350 m long jetty that stabilises the Otago Harbour entrance and the surfing break is no longer natural, but still possesses important surfing amenities. The tidal harbour is 4 600 ha in size (calculated using ArcGIS version 9.2), creating a large ebb delta. The navigation channel is dredged for the Port of Otago, and one of the spoil grounds is immediately offshore of the Aramoana surfing break. Currently the

shoal rises to around 6 m below the surface. A hydrographic survey from KILPATRICK (2005) and the refraction modelling undertaken here are used to show that surfing waves form due to extreme wave focusing, and that the spoil ground is likely to have improved surfing conditions at the surfing break.
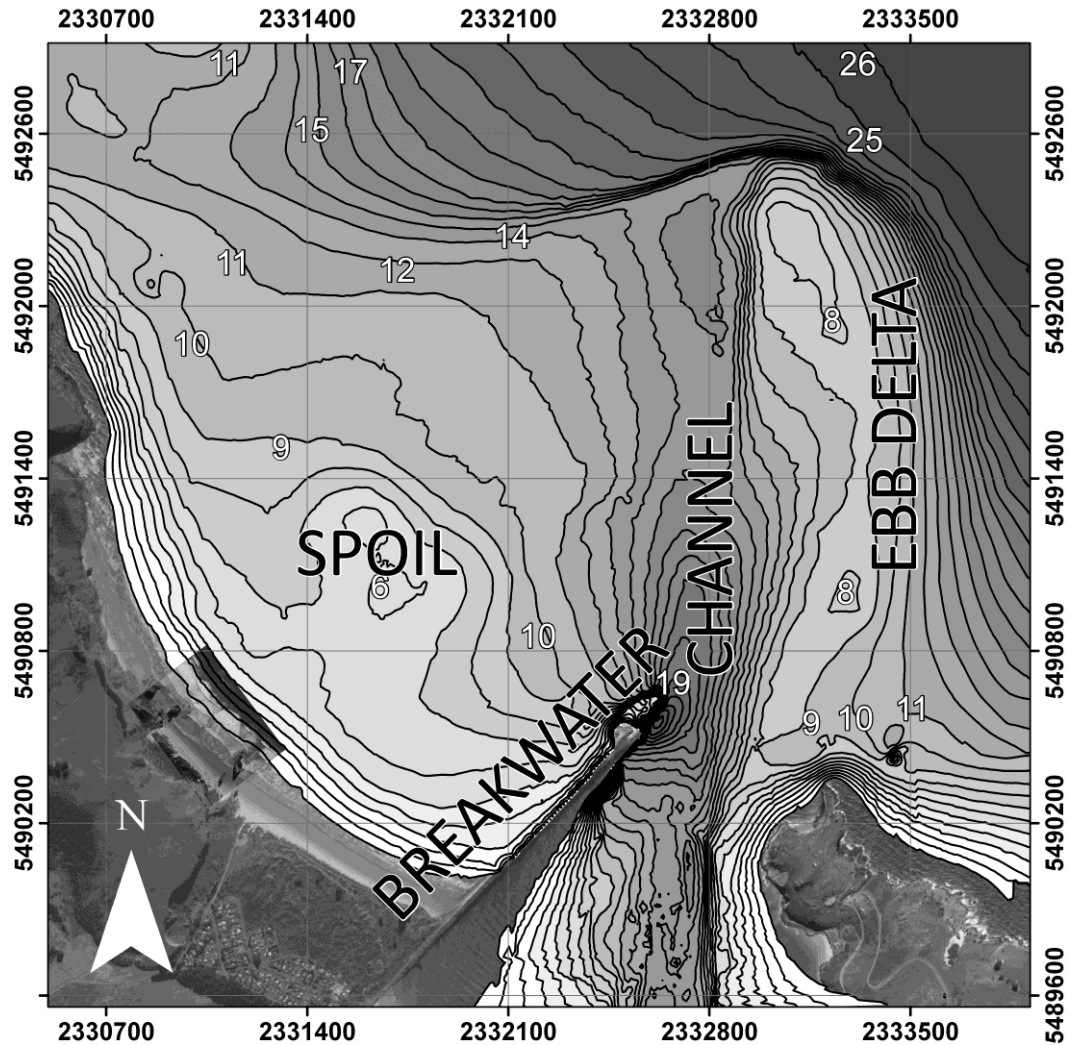
Figure 3.13. Macro-scale bathymetry and features around the Aramoana surfing break. The position of the surfing break is highlighted by the small aerial photograph taken by KILPATRICK (2005), to the southeast of the spoil mound.
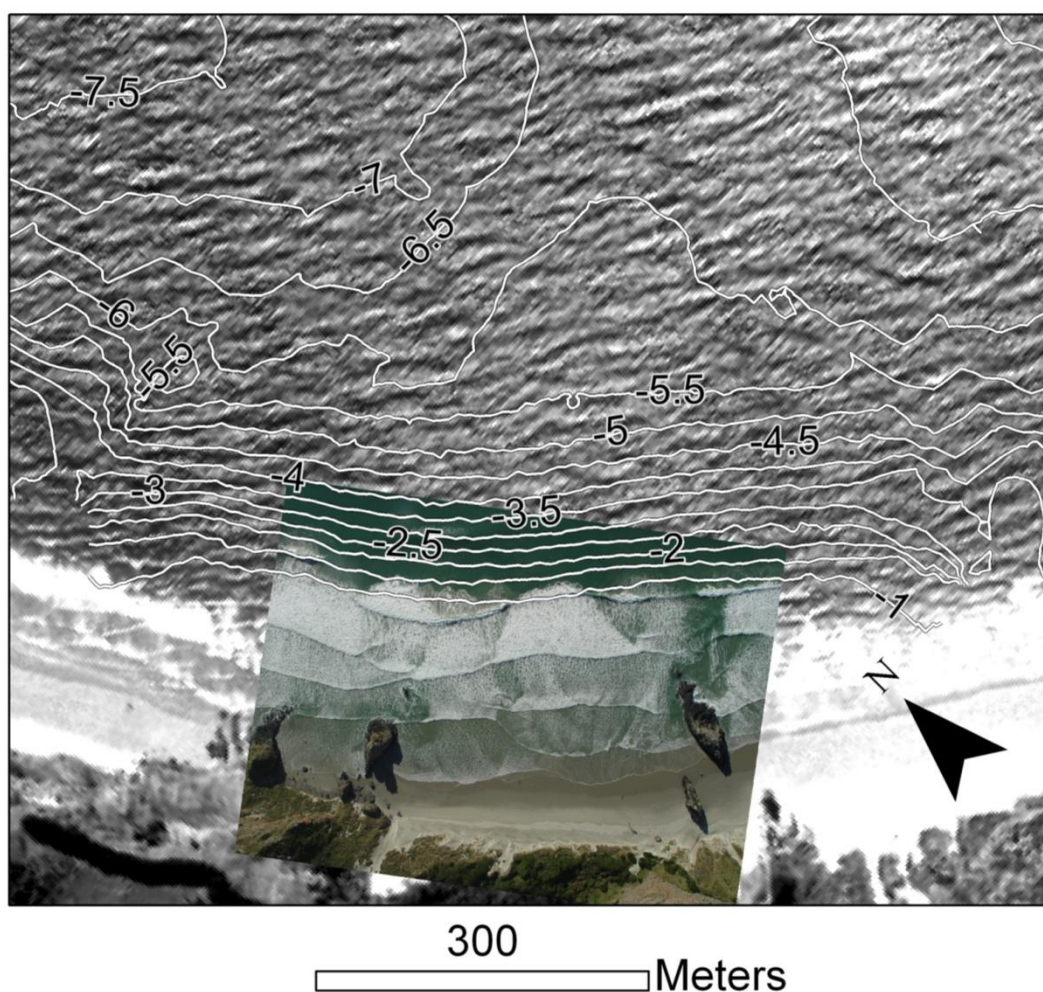
Figure 3.14. Meso-scale bathymetry and features around the Aramoana surfing break surf zone. The position of the surfing break is highlighted by the small aerial photograph taken by KILPATRICK (2005) and the spoil ground is immediately offshore of the image.

The area inshore of the spoil ground is an extremely good surfing break that can only be surfed during northerly swells, which are less frequent than southerly swells. The combination of the delta, the spoil ground and the equilibrium the beach has formed with the jetty, help to create extremely good waves that break on a beach. The survey of the surf zone by KILPATRICK (2005) showed almost no features to cause wave breaking, and therefore surfing waves are created almost completely by offshore preconditioning over the offshore features. Over time as the entrance continues to be dredged, and spoil is deposited offshore the surfing break, it is possible that the character of the surfing waves could change. So although the engineering activities are likely to have improved surfing conditions, the impacts of continued dredging and nourishment of the beach are unknown.

KILPATRICK (2005) compiled existing survey data from the Port of Otago, and undertook a hydrographic survey of the surf zone using RTK GPS water level

corrections (*see* SCARFE, 2002b) to identify the main surfing break components of the surfing break. Five good surfing events were photographed, including positioning the surfing break with aerial photography from a helicopter. Modelling undertaken here with the MIKE21 nearshore wind-wave model (NSW) is used to show how the identified components transform waves during the surfing events. MIKE21 NSW is a wind-wave model that describes the propagations, growth and decay of nearshore waves (DHI SOFTWARE, 2003).

Since the Otago region is almost devoid of wave data, hindcast information from GORMAN (2005) was used to drive the model boundary. Hence no calibration data was available for the model, but the results still show the general refraction patterns and magnitude of focusing. More research is required to investigate the nuances of the surfing break, and to validate the model's accuracy. However, five surfing events have been modelled by SCARFE (2008; *see also* KILPATRICK, 2005 and Appendix One) with the premier surfing condition (Event 2; Figure 3.15) from 19 June 2005 presented here. This is a large surfing event with offshore winds producing clean, surfable waves that were variable in size (KILPATRICK, 2005).

Figure 3.15. Photograph of surfing event two from KILPATRICK (2005). The surfing wave occurred at 4:06pm NZST (19/06/2005) and the photo is an example of extremely good surfing waves breaking on a beach break from offshore focusing. The conditions on the day were tide = 1.76 m (chart datum), direction = 80°, H_{sig} = 1.70 m, period = 12.3 sec and winds = offshore.

KILPATRICK (2005) was able to compile a bathymetry dataset around the spoil ground from 1980, before the spoil mound was created. Thus a direct comparison of wave transformations with and without the spoil ground has been undertaken. The modelling results (Figure 3.16) show convergent focusing of waves over the ebb tidal delta creating a prominent band of focused wave energy that varies somewhat in focusing location along the beach depending on wave direction. An oblique photograph from the helicopter flight by KILPATRICK (2005) was rectified, allowing precise positioning of the exact surfing area relative to the contours and model output. The main surfing area is between the -1.5 m and -3.5 m relative to chart datum (~lowest astronomical tide [LAT]) and although this will not always be the largest area of wave focusing, it is a popular surfing location. The location of wave focusing from 19 June 2005 is aligned perfectly with the main surfing location. The location and degree of the focusing will change between sets of waves but Figure 3.16 should still represent the mean focusing patterns well.

The wave transformations improve the surfing through two process: (i) wave focusing creates a gradient in height along the wave crest, promoting wave peeling as the region of larger wave height breaks farther offshore before the sections with smaller wave heights (BATTALIO, 1994; BEAMSLEY and BLACK, 2003; MEAD *et al.*, 2003; SCARFE *et al.*, Chapter 2), (ii) the spoil ground slightly rotates the waves causing less of an angle between the wave orthogonal and the surf zone contours. Table 3-2 shows focused wave heights for each simulation at the main surfing area. Wave focusing is not as apparent at the main surfing area in Examples 4 and 5 (*see* KILPATRICK, 2005), as the spoil mounds focus the wave farther northwest along the beach due to the southeasterly origin of the swells. The gradient in the wave crest can be seen in Figure 3.15. Table 3-3 shows waves are approaching less perpendicular to the surf zone contours when the spoil mound is present. This does not relate to an increase in peel angle of exactly the same size, but it will generally increase peel angles improving "surfability".
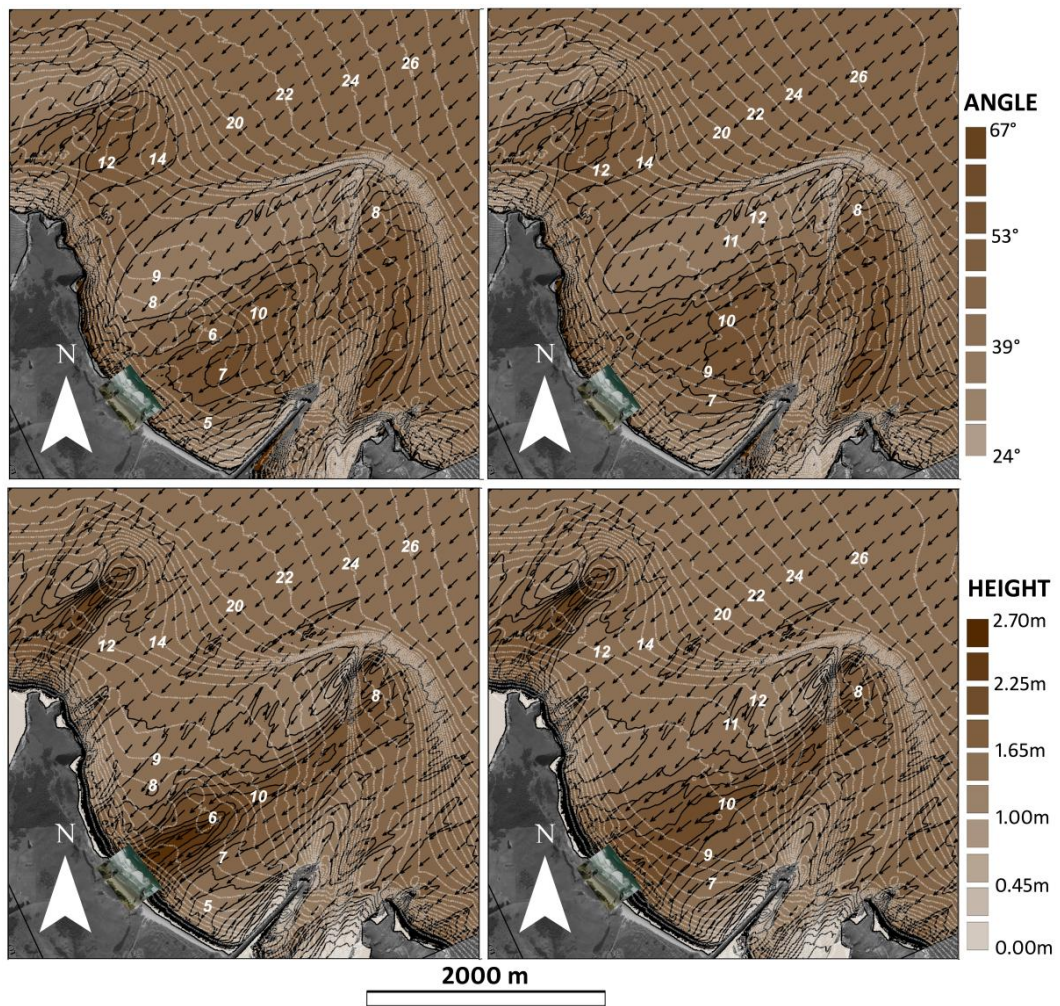
Figure 3.16a. MIKE 21 NSW model predictions showing extreme wave focusing over Otago Harbour ebb tidal delta which is enhanced by the spoil ground just offshore of the surfing break (left with spoil mound, right without spoil mound). Model boundary conditions: tide = 1.76 m (chart datum), direction = 80°, H_{sig} = 1.7 m, period = 12.3 sec. KILPATRICK (2005) wave event 2.
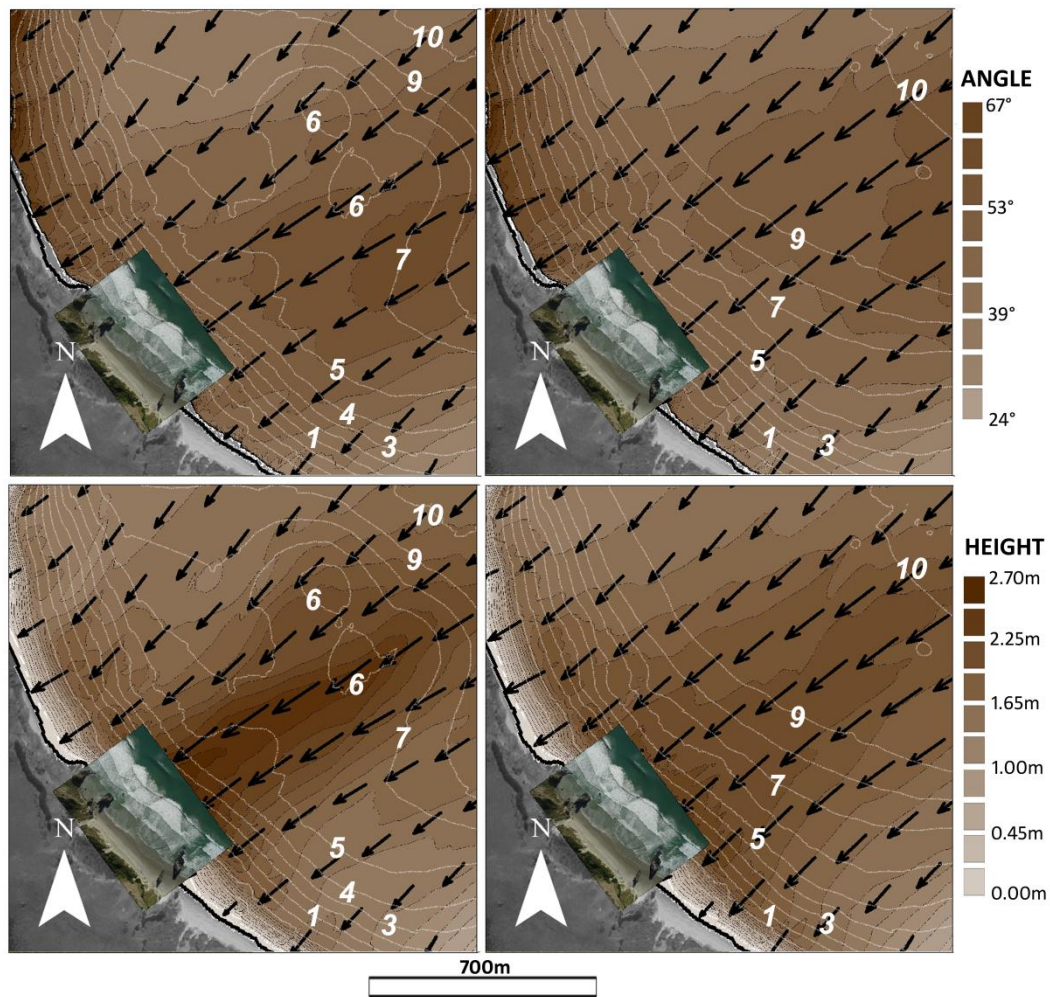
Figure 3.16b. MIKE 21 NSW model predictions showing extreme wave focusing over Otago Harbour ebb tidal delta which is enhanced by the spoil ground just offshore of the surfing break (left with spoil mound, right without spoil mound). Model boundary conditions: tide = 1.76 m (chart datum), direction = 80°, H_{sig} = 1.7 m, period = 12.3 sec. KILPATRICK (2005) wave event 2.

Table 3-2. The degree of wave focusing with and without the spoil ground directly offshore the main Aramoana surfing area.

		Wave height (m)	Increase in wave height
Event 1	*With spoil ground*	3.27	7.2%
	Without spoil ground	3.05	
Event 2	*With spoil ground*	2.72	22.5%
	Without spoil ground	2.22	
Event 3	*With spoil ground*	3.44	7.2%
	Without spoil ground	3.21	
Event 4	*With spoil ground*	2.13	3.4%
	Without spoil ground	2.06	
Event 5	*With spoil ground*	1.93	-0.5%
	Without spoil ground	1.94	

Table 3-3.Effect of the spoil ground on wave directions at the Aramoana surfing break.

	Wave direction with spoil ground (°)	Wave direction without Spoil ground (°)	Difference (°)
Event 1	50	43	7
Event 2	53	47	6
Event 3	54	51	3
Event 4	65	62	3
Event 5	67	64	3

Case Study 6 – The "Whangamata Bar", Whangamata (New Zealand)

Whangamata is located on the Coromandel Peninsula (New Zealand) and the coastal development history of the area, along with human interactions with the natural environment is covered in QUINN (2007). The beaches (Figure 3.17) are popular for surfing and the "Whangamata Bar" is one of the best surfing breaks in the region. QUINN (2007) discusses the iconic nature of the surfing break to surfers, and the opinions of different opposing parties on the marina development have been captured in a five part radio documentary by the Auckland, New Zealand radio station 95BFM. Unfortunately the consenting agency or the developer is not included in the documentary to provide a completely balanced discussion.

Figure 3.17. Location of the "Whangamata Bar" surfing break, proposed marina, offshore focusing reef (shoals at 6.5 m from 12 m deep), and harbour inlet. Background map stream over the internet from ArcIMS geographic data server of Land Information New Zealand.

"Whangamata Bar" differs from the beach surfing locations at Whangamata Beach because waves break on an ebb tidal delta (Figure 3.18). The delta transforms ordinary waves into surfing waves through a series of processes including wave focusing (BEAMSLEY and BLACK, 2003; MEAD *et al.,* 2003), wave rotation (BLACK and MEAD, 2001), and wave breaking (BLACK and MEAD, 2001c; VAUGHAN, 2005). Depending on the oceanographic conditions the take-off area and path of the surfing wave will vary. More information on the behaviour of the surfing break is included in VAUGHAN (2005).
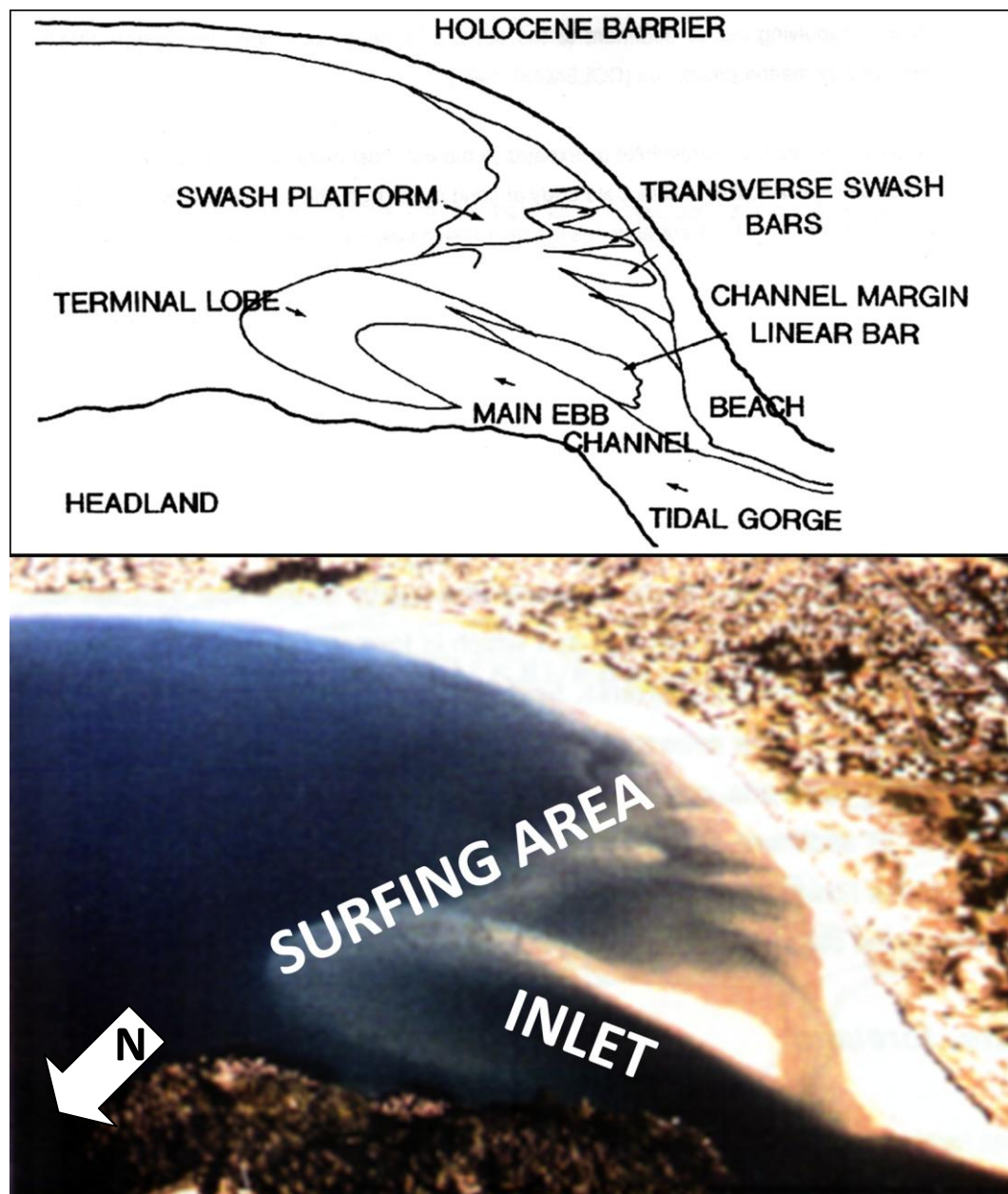
Figure 3.18. Morphological features of the ebb delta (top) and main surfing area and navigation channel (bottom; adapted from SHEFFIELD, 1991). The navigation channel area is used by surfers to access the surfing break and by boats entering and leaving the harbour.

The harbour is one of many rapidly infilling estuaries in the area. Hot Water Beach and Opoutere are two nearby estuaries that are completely filled (SHEFFIELD *et al.,* 1995). The surrounding catchment is 56km² with ridges up to 690 m high and steep valley slopes that are easily eroded (SHEFFIELD *et al.,* 1995). Much of the catchment has been cleared, accelerating the natural rate of infilling of the estuary (SHEFFIELD, 1991). Understanding infilling rates is important for sustainably managing the surfing amenities relating to the delta.

The harbour inlet has been categorised by HUME and HERDENDORF (1993) as a type 4, single spit, barrier-enclosed estuary created through fluvial erosion. The characteristics of this type of inlet generally include small freshwater inputs and spits that are formed based on the littoral drift characteristics of the coast, with limited exchange of water between the estuary and the sea (HUME and HERDENDORF, 1993). The shape and location of the ebb delta move in a dynamic equilibrium based on wave, wind, current and sedimentary forces. More specifically this equilibrium is controlled by tides, infragravity wave energy, wind-driven circulation, fluctuations in sediment supply, river inputs and wave-induced processes. This equilibrium will be affected as processes such as sediment infilling, and potential climate change and sea level rise occur. Exchanges of sediment between the ebb and the flood deltas are likely to occur, influencing the ebb delta morphology and consequently surfing amenities.

The rock headland, Te Karaka Point (Figure 3.17), stabilises the channel and sandbar, which is a factor in the consistency of the delta location and surfing wave shape. From a surfing amenity and coastal management perspective, the delta is delicate and can potentially be affected by changes in the estuary, and the catchment, including the cumulative impacts of multiple activities. For instance, a causeway construction in 1976 modified the natural harbour character and is blamed for the growth of mangrove habitat in the area (QUINN, 2007). Thus establishing the cause-effect relationships among different activities is difficult. A simple method employed here shows the migration of the ebb delta over time, but does not link the observed changes to any cause.

Analysis of four georeferenced aerial photographs between 1944 and 2002 shows that the delta's channel margin linear bar has moved away from the headland (Table 3-4). The shoreward tip of the bar was essentially parallel with the headland between 1973 and 2002, but was at an angle to the headland in 1944. The available aerial photographs show that the bar's crest has moved approximately 70 m away from the headland between 1944 and 2002. The reasons for the movement have not been investigated here but could include construction of a causeway, sedimentary inputs from land use change, swell effects and possible spring-neap or longer-term tidal variations.

Table 3-4. Changes in the distance of the channel margin linear bar from the rock headland, Te Karaka Point. Measurements made from shoreward and offshore end of visual bar. Distances calculated using GIS measurements from historical aerial photographs.

Year	Shoreward tip (m)	Offshore tip (m)	Average (m)
1944	125	185	155
1973	197	226	212
1993	197	187	192
2002	217	224	221

* Measurements made from shoreward and offshore end of visual bar.

† Distances calculated using GIS measurements from historical aerial photographs.

The Whangamata harbour is an important mooring location for recreational boats, hence the inlet and ebb delta are a mixed user coastal space (MATHER and RENNIE, 1997). Conflict between local surfers and boat users has been evident in recent years as the different groups share a coastal resource. This conflict (*summarised* in QUINN, 2007) was highlighted when a fishing competition between 8 and 10 of February 2007 coincided with good surfing conditions on the 8 and 9 February. The fishing contest involved 142 boats, and the inlet channel was being used concurrently by both surfers and fishermen (KIWI SURF, 2007; p. 22). Surfers were riding waves peeling to the south (toward the beach) and north (toward the inlet channel) and the space conflict is highlighted by a recreational fishing vessel passing through the surfing break in Figure 3.19.
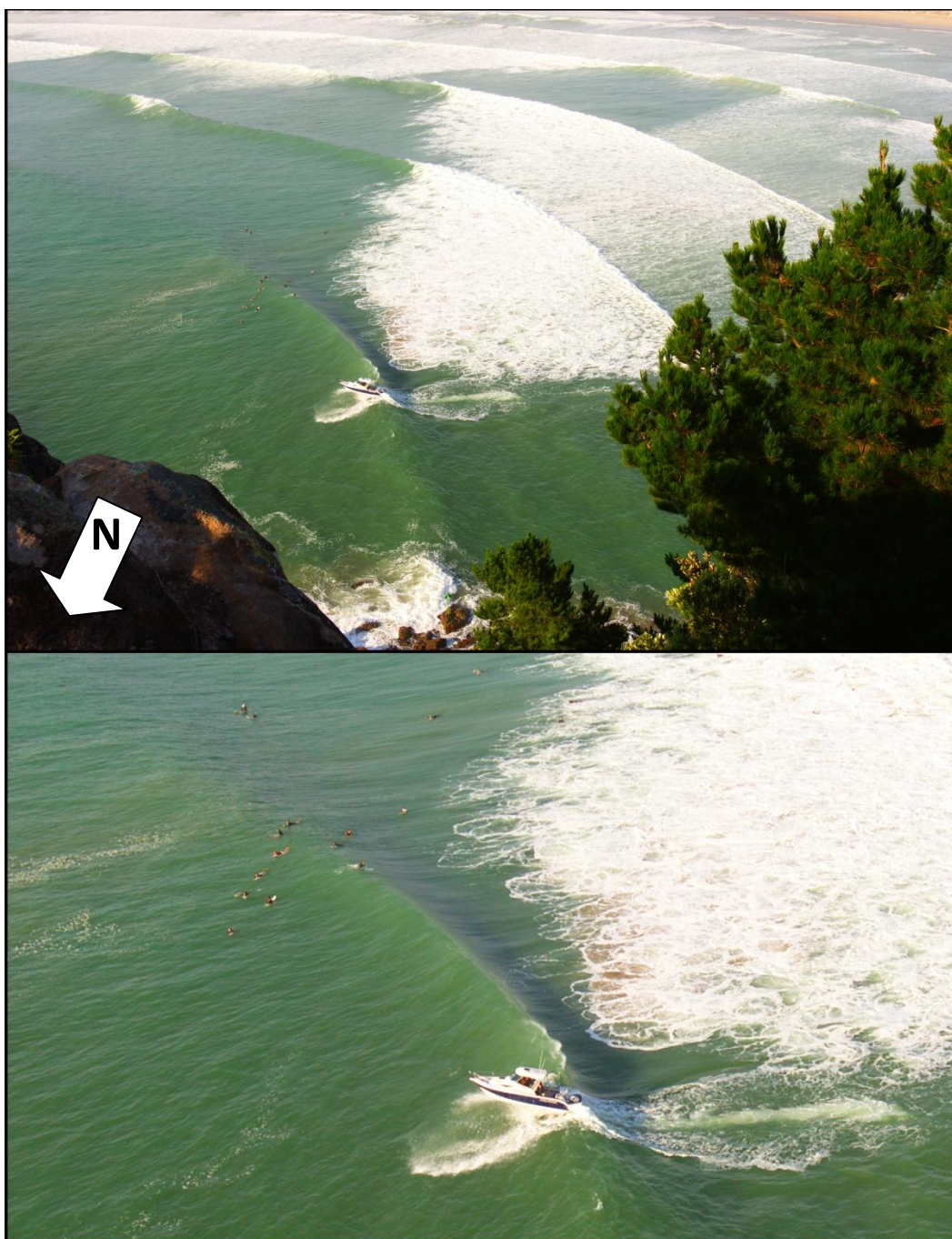
Figure 3.19. Coastal space conflict between surfers and boats when a February 2007 recreational fishing competition coincided with a good surfing swell. Photo source: John Wilson.

Problems with existing boating facilities led to the planning of a marina development in 1992. It was argued that the marina would alleviate problems associated with the current moorings in the main channel of the harbour by providing a safe, all-tide alternative for boats (WHANGAMATA MARINA SOCIETY, 1995). Surfers and local Maori (the indigenous people) have particularly vigorously, but unsuccessfully, opposed the development throughout the statutory permitting process (CHRISTENSEN and BAKER, 2007; KAPUA, 2007). Opposition from the surfing community exists because of the importance of the harbour

hydrodynamics, sediment transport pathways, and delta system to the surfing on the "Whangamata Bar".

In a near-final decision, the Minister of Conservation halted the project due to the various potential negative environmental effects. Subsequently, an unprecedented decision in New Zealand environmental law was made and the Court of Appeal overturned the Minister of Conservation's decision to decline the application on procedural grounds and consequently, under extreme political pressure, the Minister for the Environment (acting under an also unprecedented delegation from the Minister of Conservation) approved the development. The marina's resource consent is now being exercised and enables the reclamation of wetlands and the dredging of 167 000 m^3 of sediment, plus 6 000 m^3 of annual maintenance dredging (QUINN, 2007).

To date there has not been a detailed assessment of the individual or cumulative effects on surfing of the various coastal engineering activities and other land use changes that are affecting the hydrodynamics and sediment morphology of the harbour, and hence the ebb delta. A lack of strategic planning of surfing resources in the area contributes to the defensiveness of the surfing community to the development of the harbour.

Although it is beyond the scope of this study to assess the actual impacts of the marina development on surfing, three activities that could affect an ebb delta surfing break like "Whangamata Bar" when developing a marina in an estuary have been identified. They are:

(i)   construction of the marina and dredging of the harbour navigation channels;

(ii)   dredging of the ebb delta; and

(iii)   dumping of nourishment offshore or near the Whangamata beaches.

Marina construction and harbour dredging could change the tidal prism, by modifying the ebb and flood delta character. This issue has been addressed by the New Zealand courts and impacts were not considered significant due to the small change in tidal prism and remote location of the dredging. However, the Minister for the Environmental added a condition to monitor the impacts of the marina development on the ebb delta, highlighting the importance of this mechanism

when considering activities in the vicinity of surfing breaks. The effects of dredging might be adverse for a different type of development or at another surfing location. The second activity that could potentially impact the marina is the possible requirement for future dredging to maintain navigable channels, including dredging the channels, inlet and the delta. Considering that the estuary is infilling, this second activity needs to be managed in a strategic manner that considers the oceanographic impacts to the surfing break. This is especially true if the surfing break itself is directly dredged for navigation. The third activity that could occur is the dumping of dredged sediment in a manner that changes the surfing waves. This could be placing dredged material on the neighbouring beach, offshore of Whangamata or on the delta. Although from a coastal erosion point of view, nourishing a beach makes sense, placing sediment where it is likely to reach the surf zone could potentially alter the shape of the delta, and hence the surfing break components. This was shown to occur at in a positive manner at Aramoana but the activity could also have negative impacts.

Now that the marina is likely to proceed, monitoring of any impacts to the ebb delta is the next concern for surfers. This includes the cumulative effects of multiple coastal activities that can impact surfing amenities. A surf monitoring study of this type needs to have three aspects:

(i) developing a baseline understanding of surfing wave character, the skill level of surfers able to use the surfing break (during different conditions e.g. wave height), oceanographic processes around the surfing break, important bathymetric features and sedimentary patterns;

(ii) monitoring changes to the character of surfing waves over time including surfing parameters discussed in SCARFE *et al.* (Chapter 2), and changes in skill level of surfers able to surf the waves; and

(iii) monitoring changes to the wave, current and sedimentary patterns that control the shape, size and location of the delta over time, and hence dictate surfing conditions.

An oceanographic study around similar surfing break to the "Whangamata Bar" has been undertaken in Mundaka, Spain (Figure 3.20; CEARRETA *et al.,* 2005) and this study is of high relevance when designing a monitoring program. The Mundaka surfing break's main wave breaking component is the channel margin

linear bar of the ebb delta surfing break, or the crest of the wedge surfing component, and this is very similar to "Whangamata Bar". The inlet channel and channel margin linear bar are stabilised by a rock headland, further showing the similarities between the two locations, although there is a noticeable difference in the scale of the wedge crest, or channel linear marginal bar (Whangamata is 130-200 m; Mundaka is 400 m), as well as the contributions of river sediments. CEARRETA *et al.* (2005) collected and analysed numerous types of the environmental information of importance to a surfing break monitoring program, especially at Whangamata, including the following:

- aerial photography

- wave refraction

- hydrographic soundings

- wave climate

- wind climate

- sediment grain size analysis

- suspended sediments

- tides

- in situ currents measurements

- Acoustic Doppler Current Profiler (ADCP) measurements
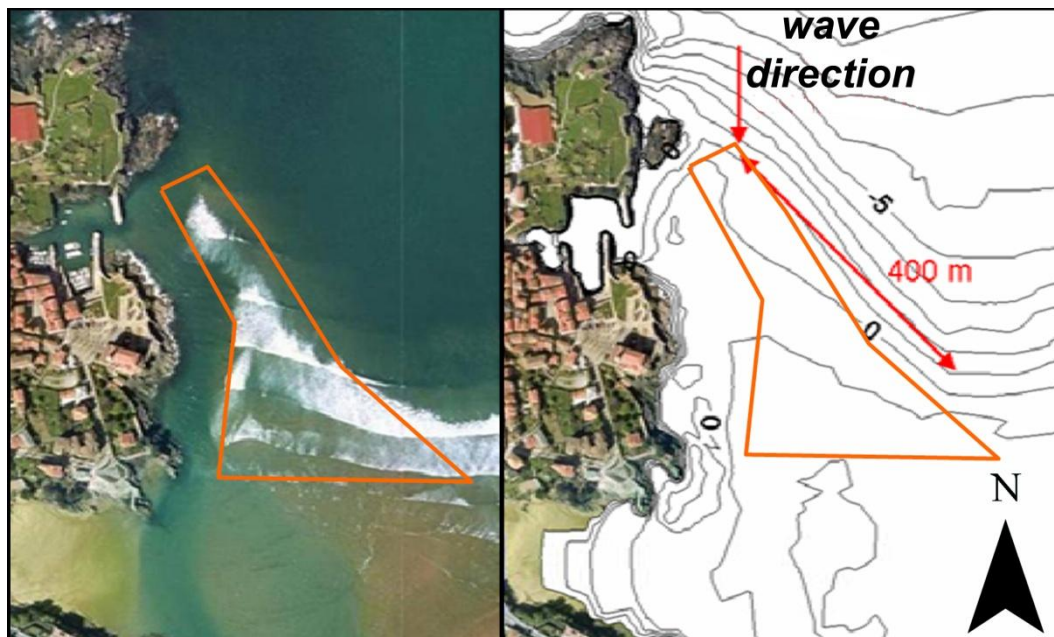
Figure 3.20. Aerial photography and survey of the Mundaka surfing break, and an ebb tidal delta's channel margin linear bar (*adapted from* CEARRETA *et al.* 2005). The polygon area represents the channel margin linear bar, or wedge crest of the surfing break.

INTEGRATED COASTAL ZONE MANAGEMENT (ICZM) AND SURFING BREAK PROTECTION

The preceding case studies have shown that surfing breaks can be altered, created or destroyed by coastal engineering. The unplanned effects on surfing breaks illustrate the need to proactively protect surfing breaks and to embrace opportunities to enhance them where appropriate. The case studies have also illustrated that not all engineering effects result in bad surfing outcomes. In fact, GEORGE (2004) in a discussion of artificial surfing breaks, listed more than 60 coastal engineering projects in the United States that had inadvertently improved the quality of surfing waves, or indeed created a surfing break where one did not previously exist. It is likely that with a few engineering design modifications, many more of the coastal engineering projects could have improved surfing amenities.

The UNITED NATIONS (1992), through Chapter 17 of Agenda 21, has advocated an inclusive, integrated approach to the management of multiuser coastal zones. Integrated Coastal Zone Management (ICZM)[4] is widely seen as an approach to achieving this. Essentially ICZM practices are adopted to:

> *"establish and maintain the best use and sustainable levels of development and activity use in the coastal zone, and, over a period of time, improve the physical status of the coastal environment in accordance with certain commonly held and agreed norms (HEALY and WANG, 2004; p.231)".*

Modern ICZM practices (JACOBSON and RENNIE, 1991; CICIN-SAIN, 1993; RENNIE, 2000 and 2003; WOOD, 2003; HEALY and WANG, 2004) integrate the coastal space requirements of various coastal user groups, and can be to the benefit of recreational surfing. One of the most important aspects of ICZM is that it is forward looking and aims to preserve resources for future generations (HEALY and WANG, 2004). The definition of resources is extended here to include the natural features and processes that create surfing waves. An example of a project attempting to integrate multiple benefits is discussed in HEALY *et al.* (2002). The project's main objective was to redesign a coastal port, although the project also

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[4] ICZM is also termed Integrated Coastal Area Management (ICAM) or Integrated Coastal Management (ICM)

included amenity values as an ancillary redesign consideration. Surfing enhancement was considered, but has yet to be given any detailed design consideration and economic factors have placed the development on hold.

The reactive participation of surfers during the planning of proposed coastal engineering activities at Palm Beach and Whangamata has been significant. Although strategic consultation with surfers was not necessarily undertaken by consenting authorities, the impact of lobbying from surfers on the final outcome has been noticeable. The case studies indicate the importance of an integrated approach. However, specific discussions of ICZM and surfing are not apparent in the peer-reviewed literature examined as part of this project (*see* SCARFE *et al.,* Chapter 2). Problems that have been identified by HEALY and WANG (2004) in the absence of ICZM, such as unnecessarily reactive management, cumulative impacts and fragmented geographic planning, are noticeable in the presented case studies.

The Environment Impact Assessments (EIAs), Assessment of Environmental Effects (AEE) or Environmental Impact Reports (EIR) are an anticipatory, participatory, integrative environmental management tools that provide decision makers with an indication of the potential consequences of development (WOOD, 2003). It is essential that EIAs be based on the now-significant volume of science on surfing research (*see* SCARFE *et al.,* Chapter 2). There are more than 100 EIA systems worldwide and although they differ in detail, the basic principles are similar (WOOD, 2003). They are usually required by law as part of the environmental permitting for an activity and are a very tangible step in the ICZM process. They involve an investigation into the effects of an activity on the environment and are a central tenet of ICZM (HEALY and WANG, 2004). All potential effects, to all sectors of the environment need to be considered in detail so the impacts can be avoided, remedied or mitigated. Investigating impacts to biophysical bottom lines during EIA is a mechanism to protect surfing amenities. An EIA should consider any sheltering, focusing or rotation of wave energy offshore of the surfing break. This offshore region is termed a "swell corridor" and waves travel and transform through the corridor on the way to a surfing break and are affected by reefs, islands and other bathymetric features.

At a higher planning level, a Strategic Environmental Assessment (SEA) is a form of EIA that assesses the impacts of the policies and rules in plans, the effect of plans, and the effect of programmes of work that might involve several individual projects (WOOD, 2003). An SEA can result in the setting of parameters for EIAs of projects and determine the nature of activities in an area. Consideration of surfing resources and amenities in an SEA provides opportunities to ensure that surfing-specific baseline data collection is incorporated into project and programme preparation, the prevention or avoidance of activities that adversely affect surfing breaks, and the inclusion of surfing and its enhancement as a consideration in EIAs. For the purposes of this paper, reference to EIA encompasses both the specific project EIAs and the broader SEA process unless specifically separated.

In the New Zealand context for instance, an EIA is undertaken for any activity to ensure that it meets the provisions of the relevant RMA plans and policies. The provisions of the plans are set through a SEA process but have not traditionally placed much attention on surfing. However, in New Zealand, central government has included the protection of surfing breaks in its draft 2008 coastal policy statement[5]. Over time this statement will guide their management at a regional level through plans and policies, to the benefit of surfers. Unfortunately the statement only identifies very few surfing breaks and submissions are being made to amend this statement to include many more surfing locations. The statement is reproduced below as follows:

> "Policy 20 Surf breaks of national significance:
>
>> *The surf breaks at Ahipara, Northland; Raglan, Waikato; Stent Road, Taranaki, White Rock, Wairarapa; Mangamaunu, Kaikoura; and Papatowai, Southland, which are of national significance for surfing, shall be protected from inappropriate use and development, including by:*
>>
>>> *(a) ensuring that activities in the coastal marine area do not adversely affect the surf breaks; and*

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[5] Submissions to the draft lodged by the New Zealand Surfbreak Protection Society (www.surfbreak.org.nz) included significant contributions based on this thesis. Submissions opposing the policy are also likely to have been lodged and therefore final wording could change.

> *(b) avoiding, remedying or mitigating adverse effects of other activities on access to, and use and enjoyment of the surf breaks (DEPARTMENT OF CONSERVATION, 2008)."*

Although the impacts of an activity on environmental assets such as biodiversity are often included in EIAs, impacts on surfing breaks have traditionally been ignored. For example, at the time of constructing the Manu Bay boat ramp all environmental permits were obtained and the boat ramp was built legally. Although EIAs were beginning to be used 30 years ago (WOOD, 2003), a serious investigation of impacts of the boat ramp to surfing waves was not undertaken because EIA techniques for surfing breaks did not exist and were not required during the permitting process. Where impacts to surfing have been acknowledged, they are usually only reviewed superficially. Statements such as 'there will be no negative effects to surfing wave quality' are made without any scientific rationale (MEAD *et al.,* 2004).

An excellent example of a poor EIA on surfing conditions was that undertaken for Chevron's El Segundo (California) coastal oil refinery (NELSEN and HOWD, 1996). The oil refinery was at threat from erosion and Chevron sought permits for construction of a groin to retain sediment. Local surfers also required use of the same coastal space. Several experts on coastal processes predicted no negative impacts to surfing with the possibility of an improvement to surfing conditions (NELSEN and HOWD, 1996). Surfrider Foundation, acting on behalf of local surfers, raised concerns with the groin construction in spite of the experts' assessment. This resulted in the California Coastal Commission (CCC) permitting the development, but with a unique condition that if the initial EIA was incorrect and there were adverse impacts on surfing conditions, funds had to be provided by Chevron to mitigate with an artificial surfing reef (NELSEN and HOWD, 1996). Unfortunately for the surfers the El Segundo reef never significantly improved surfing conditions (BORRERO and NELSEN, 2003; MACK, 2003) because of the construction budget, limited existing knowledge of surfing wave transformations and reef construction techniques. A detailed EIA with alternative design considerations that address the various coastal users biophysical bottom lines could have resulted in a better outcome for surfers and the industry associated with the surfing break.

EIA Checklist and Overlay Techniques

The methods employed in the EIA process should be designed with two main criteria in mind: adding rigour to the process, and effectively communicating the nature of the effects (MORGAN, 1998). Four basic methods have been developed over the years as aids to EIA: checklists, overlays, matrices and networks. Each of these has advantages and disadvantages and each has evolved and become more technically and technologically sophisticated. The generic checklist is of interest here because it can be designed for a particular type of project (e.g., new artificial surfing reefs) or for types of environment (e.g., reef versus sand surfing breaks). Checklists provide a simple method for impact identification and ensuring that important effects are not overlooked. These may be general (able to cover any project and environmental type), generic, or specific (a 'one-off' checklist designed for a particular project or setting; LEE, 1989; MORGAN, 1998). Overlays are also particularly relevant as they address spatial characteristics not easily captured in other methods (MCHARG, 1969). Now overlays are largely expressed through use of Geographic Information Systems (GIS) and are an effective way to understand and communicate complex processes around surfing breaks. Matrices tend to be sophisticated versions of checklists in tabular format that make transparent the cause-effect assumptions of linkages between specific actions undertaken during a project and their assumed effects. They also underpin multi-criteria evaluations. Networks can show cause-effect relationships diagrammatically and provide the basis for systems modelling.

Among the keys to effective use of any of these methods in ICZM is the identification and collection of relevant data (FRIHY 2001; TIWI 2004). Our research suggests a generic checklist of the information required for EIAs relevant to coastal activities near surfing breaks could easily be used in conjunction with GIS overlay methods to manage threats to surfing amenities. The discussion in this paper is limited to parameters relevant to checklists and overlays.

The EIA method of a checklist can be used to identify types of information that should be included in a surfing EIA. Table 3-5 shows the main coastal activities and structures observed on the coastline that can alter wave quality and this can be used decide if a checklists of effects to surfing of such activities needs to be undertaken. The various surfing and oceanographic factors that should be considered when one of these developments occurs near a surfing break, and for

use in a checklist, are shown in Table 3-6. An example of the environmental data types that could be used in a checklist when evaluating impacts to surfing are shown in Table 3-7.

Table 3-5. Coastal activities and constructions that can have an impact on surfing conditions.

Artificial nourishment	Port developments	Jetty construction or extensions	Outfall pipelines
Breakwaters	Piers	Boat ramps	Marinas
Seawalls	Dredging	Dumping of dredge spoil	Groynes (groins)

Table 3-6.Surfing and oceanographic factors that can be used when undertaking a surfing EIA.

Bathymetry	Sediment transport pathways	Wave refraction/ diffraction/ shoaling	Breaker intensity
Wave climate (inshore and offshore)	Sediment grain sizes within littoral cell	Peel angles	Breaking wave height ratio (H/d)
Surfer numbers and seasonal variations	Precise location of surfing rides	Tidal patterns and long term water level trends	Surfable days per year
Wind patterns	Surfer skill level	Storm surge	Wave and tide induced current patterns

Table 3-7.Generic list of environmental data types that can be collected when undertaking a surfing EIA.

Surfing break component schematics	Bathymetry data	Digital Elevation Models (DTM)/Digital Terrain Models	Suspended sediment concentrations
Topographic data (e.g., contours, LIDAR data)	Hydrodynamic modelling of oceanographic conditions	Sediment grain size data	Wave data
Side scan images	Oblique photos of surfing waves	Video of surfing waves	Aerial photos
Documents/ reports	Water quality data	Tidal data	Current data

Additional considerations for the design of checklists will exist, but the presented tables still provide a starting point for coastal managers. Information obtained for

such parameters can be published and built into coastal plans, and SEA practises as well as GISs and other database systems. It is important to recognise that while some spatial data can be readily collected at short notice, data on people's use of areas may be much less readily available. Well-prepared surfing interest groups should invest in ongoing collection of such data so that it is readily available in case their surfing breaks are threatened (e.g., NELSEN and RAUSCHER, 2002). Techniques for gathering such information are available, although still somewhat experimental (e.g., KLEIN *et al.* 2003; POLETTE and RAUCCI 2003; THOMSON, 2003).

GIS has made giant technological leaps forward in recent years and is being promoted as a key tool for ICZM (BARTLETT and SMITH, 2005; WHEELER and PETERSON, 2007) with specific reference to the need for appropriate spatial data infrastructure (LONGHORN, 2005). Development of geoprocessing techniques and models, 2D and 3D visualisation, geodatabasing, and data communication over the internet, as well as integration with modern computing strategies, enables powerful analysis and communication of spatial data. The point-and-click nature of a lot of modern GISs makes these systems available to a wide range of users. Many users, such as people viewing Internet based street maps, may not even realise they are using GIS. The greater ability to analyse and visualise the environment around surfing breaks using GIS adds transparency and can aid in the protection and enhancement of surfing breaks, especially during the EIA and monitoring process.

The use of overlay techniques for studying surfing breaks has been undertaken since the first scientific study by WALKER and PALMER (1971). Overlay techniques therefore have application to surfing studies beyond solely EIA requirements. The application of a coastal-specific GIS is covered in BREMAN (2002) and a marine specific geodatabase schema is presented in WRIGHT *et al.* (2007). The marine geodatabase schema allows exchange of common marine datasets between different GIS users and is important to consider when designing a surfing GIS in the ArcGIS (Environmental Systems Research Institute Inc. (ESRI), 2006) software environment. Various industries and environmental issues are explored in BREMAN (2002), including a surfing-specific GIS developed by NELSEN and RAUSCHER (2002) for the environmental surfing organisation Surfrider Foundation. The Surfrider GIS stores and distributes information about

the location and access to surfing breaks, as well as land-use patterns, pollution sources, beach erosion information, marine habitats and wave characteristics around surfing breaks. Having information available from a GIS supports their mandate to protect surfing breaks and the rights of surfers to use surfing resources. Surfrider is currently working with the U.S. National Parks Service to locate all the surfing breaks in the National Parks, and collect information on the number of users (CHAD NELSEN, *pers. comm.*). In the current research ArcGIS version 9.2 (ESRI, 2006) has been used to process geographic information and to understand the case studies presented earlier. ArcGIS version 9.2 is also used to process, store, interpret and visualise information around surfing breaks by SCARFE (2008).

Linking to existing coastal data will be a critical part of a surfing GIS and this has been made easier by the various sources of geographic information that are now streamed over the internet to GIS software. Figures 3.1, 3.5, 3.6, 3.12, and 3.17 all use information from either www.geographynetwork.com or www.nztopoonline.linz.govt.nz ArcIMS servers either during the construction of the geographic information, or during the development of final thesis figure. Another coastal management study involving a GIS has been implemented in Xiamen Bay, China, and JIANG *et al.* (2004) present a discussion on coastal GIS and clear GIS imagery that could be used in a surfing GIS. For example, geodatabasing of photography and incorporation of coastal numerical modelling.

The preceding techniques at the strategic and project level should be used in coastal plans to identify surfing break locations, the physical processes that cause the quality waves to form and the threats to the wave quality. Early consultation and consideration of effects on surfing breaks is recommended not only to minimise conflict between parties, but also to ensure that surfing amenities are recognised and optimised. In this context, surfing amenity is optimised by protecting against threats as well as taking up opportunities to enhance surfing breaks where appropriate.

DISCUSSION

Historically there has tended to be a single-issue (e.g., the protection of coastal real estate) or single-sector (e.g., marine transportation) management approach applied in coastal engineering projects (e.g., JACOBSON and RENNIE, 1991; PILKEY

and DIXON, 1996). A lack of integrative participatory approaches has meant that those stakeholders without a strong political voice (*discussed* in LAZAROW *et al.*, 2007b) have often been ignored in coastal management. The unplanned impacts to surfing amenities caused by coastal engineering are evidence that recreational surfers have been one of these stakeholder groups.

Negative responses to traditional coastal engineering practices are driving the development of integrated engineering methods that work with, rather than against, nature and that benefit multiple coastal user groups. Practices that take into account more than one objective and include visual amenity, biological enhancement and recreational concerns will continue to develop in the future. It is expected that as more detailed EIAs of coastal projects are undertaken, weaknesses in the use of traditional coastal engineering technology around surfing breaks will be highlighted and there will be an effort to include recreational surfing in engineering designs. As multiple objectives are taken into account, innovative and holistic engineering techniques such as wave rotating structures, submerged reefs, submerged groins and stabilized artificial nourishment may be seen as preferable solutions to many coastal engineering problems. The artificial surfing reef concept (ASR; WALKER *et al.*, 1972; PRATTE *et al.,* 1989; BLACK, 2001a and b; MEAD, 2001) is an example of a coastal engineering technology that can minimise environmental effects by attempting to mimic natural processes, and benefit multiple coastal users. Although the ability to reproduce natural environments with ASRs is still being tested (SCARFE *et al.*, Chapter 8).

During observations by the authors of various conflicts between development and surfing, it appears that authorities and developers often only consider serious investigations to impacts on surfing amenities as a reaction to environmental lobbying. This is contrary to the ICZM principles which require consultation with affected parties in the initial stages of the development and a strategic rather than reactive approach to environmental effects. Surfers Against Sewage (UK; WHEATON, 2006), Surfrider (global), and the Surfbreak Protection Society (New Zealand) are examples of surfer-led groups that have developed to advocate surfers concerns due to a lack of strategic leadership from central and regional governments. Their causes would be greatly supported through the inclusion of surfing in coastal management in a strategic manner. The lack of historical advocacy for surfing is covered in LAZAROW *et al.* (2007b).

To effectively include surfing amenities in ICZM there needs to be legislative frameworks for considering surfers' objections to coastal activities to be considered. A regulatory approach is recommended generally for coastal management at various national and international levels by GOLDBERG (1994) to minimise conflict due to competing for coastal zone space. GOLDBERG (1994) suggests that regulation should also exist where currently there is no conflict in order to preempt possible future conflict. Spain was used as an example where 42 % of the coastline (at time of publication) was unoccupied and laws and policies had been formulated to minimise unregulated development. With the exception of the surfing reserves implemented by FARMER and SHORT (2007), no known regulatory techniques for managing issues around surfing breaks have been found in the literature. It is hoped that more examples how to manage coastal management issues eventuate from New Zealand's proposed Coastal Policy Statement (DEPARTMENT OF CONSERVATION, 2008) as it is implemented.

The Australian requirement for a surfing site to be a surfing reserve is that 'it is recognised by the local community for the quality and consistency of it's surfing and it's long-term and ongoing relationship between surf and surfers (FARMER and SHORT, 2007, p. 100)'. The definition of a surfing reserve also includes 'the beach and adjacent surf zone, including features that intrinsically enhance aspects of the surfing experience, including structures such as surf clubs or places considered sacred by surfers for a particular reason (FARMER and SHORT, 2007, p. 100)'. FARMER and SHORT'S (2007) definition of a surfing reserve could be extended to include the wave breaking, preconditioning and sheltering of a surfing break.

CONCLUSIONS

Case studies of surfing breaks that have been both improved and compromised by coastal development have been presented to illustrate the need to nurture surfing resources. Impacts to surfing outlined using the case studies will continue to occur unless proper provisions in coastal management are made. This will be especially important to realise for protection of surfing in some counties where coastal management decisions are made based on economic rather than environmental effects. Surfing breaks could be too easily discounted from everyday decision making by short-term cost-benefit-based arguments for relatively high economic returns to a community result from major engineering works. However, the work

of LAZAROW (2007), LAZAROW *et al.* (2007a and b) and NELSEN *et al.* (2007) show that the economic benefits of surfing breaks to coastal communities can be significant.

It has been proposed in this paper that the requirement of ICZM to balance the needs of various interest groups can be better achieved through innovative and nontraditional coastal engineering practices that provide multiple benefits to many users. The artificial surfing reef concept is used as an example of an engineering technique that can facilitate ICZM and monitoring of such a structure is included in SCARFE *et al.* (Chapter 8). Another ICZM mechanism is the EIA process, which provides an avenue for surfers to address concerns relating the impacts of coastal developments on surfing breaks. To assist with the preparation of an EIA, various common activities that can affect the surfing wave quality listed (Table 3-5), and a list of surfing and oceanographic factors (Table 3-6) and environmental data types important for surfing (Table 3-7) are presented. As part of this EIA process it is important to collect baseline information, and this is discussed further in SCARFE and HEALY (Chapter 6) and SCARFE (2008).

For the best environmental result, recognition is required of surfing amenities as specific natural resources in coastal plans and environmental legislature to facilitate their protection and enhancement. For example, a coastal plan that identifies surfing break locations, the physical processes that cause the quality waves to form and the threats to the wave quality, gives greater weighting to any concerns that a coastal engineering project may jeopardize the surfing break. Early consultation and consideration of effects to surfing breaks is recommended not only to minimise conflict among parties, but also to ensure that surfing amenities are maximised. In this context, surfing amenities are maximised by protecting against threats as well as taking up opportunities to enhance surfing breaks where appropriate.

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Chapter 4 - CHARTING OF THE COASTAL ENVIRONMENT – A CASE STUDY ON MAPPING SURFING BREAKS

PREFACE

Bathymetry has a large influence on how surfing waves form, and within the surf zone bathymetry changes over time due to natural and artificial forces. Bathymetry is a critical environmental data type for undertaking both environmental impact assessments (EIA) and monitoring of environmental effects, as discussed in Chapter 3. Depth is a parameter in equations that make up hydrodynamic models, further showing the importance of seabed shape for surfing studies. It is required for bathymetric component analysis, wave hindcasting, refraction/diffraction modelling, peel angle and breaker intensity calculations, artificial surfing reef baseline studies and construction monitoring, as well as for analysis of surfing bar and rips. Thus, the collection of baseline bathymetry information (*see* Chapter 6), and ongoing monitoring (*see* Chapters 7 and 8), is critical when a surfing break is under threat, or when incorporating surfing into engineering works.

As a background to the hydrographic survey data used in numerical modelling and morphology analysis in later chapters, this chapter discusses a hydrographic surveying methodology to collect bathymetry around surfing breaks. The discussion is focused on surfing, but since the survey method is applicable to a range of hydrographic survey applications, it also includes information from non-surfing research to develop an explanation of the method. The paper relates to the following objective of the thesis:

4. *To develop improved methods for charting surfing breaks, including the management of relevant environmental data.*

SCARFE has prepared this paper with supervision and editorial input from HEALY and RENNIE in the sprit of thesis supervision. IMMENGA has been heavily involved with the mobilisation of the hydrographic system and data collection, and although was not involved in the writing of the paper, still has provided intellectual input worthy of co-authorship.

The paper is currently being peer-reviewed and the citation is:

SCARFE, B.E., HEALY, T.R., IMMENGA, D.K.H., and RENNIE, H.G., *in press*. Charting of the Coastal Environment – A Case Study on Mapping Surfing Breaks. Submitted to the *Hydrographic Journal* 10 January 2008.

ABSTRACT

Hydrography has its origins in navigational charting, dredging and marine construction, but hydrographic datasets are used for many other applications. This includes surveying of the coastal margins for environmental studies. A single beam and multibeam echo sounding system is described for use in shallow-water environment studies. Charting of surfing breaks is discussed to describe the nuances of environmental applications. The study of surfing breaks is important for maintaining and enhancing recreational amenities associated with surfing breaks because surfing breaks are often affected by coastal engineering. The Mount Maunganui (New Zealand) artificial surfing reef is used as a case study. A bathymetric control point concept is presented to ensure the nine surveys of the reef are accurate. RTK GPS water level measurements have been used for the surveys and lessons gained from eight years using the technology are presented. Environmental surveys have different accuracy and quality control requirements than navigational charting and engineering surveying. To quantify the accuracy of the survey methods used, a GIS based accuracy calculation method is described. In shallow water (<20 m) and calm conditions the multibeam system can achieve better than 0.20 m accuracy (95 % confidence). This accuracy diminishes when the sea state deteriorates. Sounding reliability diagrams are identified as a method to enhance the metadata quality of a hydrographic dataset.

INTRODUCTION

The purpose of a hydrographic survey is "to depict the relief of the seabed, including all features, natural and man-made, and to indicate the nature of the seabed in a manner similar to topographic maps of land areas (INGHAM and ABBOTT, 1992' p. 3)", and although hydrography's origins are in areas such as navigational charting, dredging and marine construction, hydrographic soundings are used for many other applications (ABBOT, 2001; BYRNES *et al.*, 2004; DENNY *et al.*, 2007). INGHAM and ABBOTT (1992) identify that environmental surveying will become increasingly important to hydrographers and shallow water environmental charting is the topic of this paper.

A subset of environmental surveying is charting surfing breaks and this area is increasingly receiving attention (e.g. HUTT, 1997; MEAD and BLACK, 2001; SCARFE *et al.*, 2002; SCARFE, 2008) as surfers become more involved in coastal management. Surfing is important to coastal communities for economic, tourism and cultural reasons, and management of these resources is required as many surfing breaks have been affected by coastal development (SCARFE, 2008; LAZAROW *et al.,* 2007; NELSEN *et al.*, 2007). The majority of bathymetric studies around natural surfing breaks have been for developing design criteria for artificial surfing reefs (e.g. HUTT, 1997; MEAD and BLACK, 2001; SCARFE *et al.*, 2002). Other surfing surveys have been commissioned as part of artificial surfing reef design projects (e.g. HUTT *et al.,* 1998; MEAD *et al.*, 2004). A more recent surfing focus in hydrography is protecting surfing breaks (e.g. SCARFE, *in prep*). Perhaps the most detailed and repetitive surveys of a surfing break to date are presented in SCARFE *et al.* (Chapter 8).

The specific objectives of this paper are to:

 (i)   develop a coastal charting process including control, echo sounding and topographic surveying of coastal margins;

 (ii)   investigate the use of Real-Time Kinematic (RTK) GPS for heave and water level corrections, including inclined plane modelling of the geoid-ellipsoid separation; and

(iii)   quantify the accuracies of the survey methods.

SURVEY PROCESS OVERVIEW

For environmental surveys the high accuracy, shoalest depth approach often used in the coastal zone for navigational charts is not always necessary. Although high accuracy, dense soundings are required for many applications, valuable geomorphic information can still be derived from soundings with lower accuracy or density. Often imagery of bathymetric shape is more important than the absolute depth, which is required for vessel clearance or an engineering application. For example, MEAD and BLACK (2001) used a low specification sounder and autonomous GPS to identify the main bathymetric components common to some of the world's best surfing breaks. The survey system was portable for international travel and provided data to develop fundamental concepts on how surfing waves form. In contrast, SCARFE and HEALY (Chapter 6) used high density multibeam to create an accurate baseline dataset for monitoring of the beach response to an artificial surfing reef. Thus the application of the hydrographic dataset is important when specifying the density and accuracy requirements of a survey for environmental purposes.

To describe coastal surveying for environmental studies, the coastal survey process used by the Coastal Marine Group (CMG, Department of Earth and Ocean Sciences, University of Waikato) is discussed. There has been over a decade of surfing break charting and research by the CMG, as well as numerous other shallow water environmental surveys (Table 4-1). Many of the techniques discussed here are of interest to all shallow water charting applications, including coastal (beaches and harbours) and inland (lakes and rivers) waterways. So although surfing research is the focus, much of the discussion can be applied in a more generic shallow water charting context.

Table 4-1. Examples of environmental surveys undertaken by the Coastal Marine Group (CMG) since 2000. Surveys are in New Zealand unless stated otherwise.

Location	Environment
Tauranga Harbour	estuary
Waikato River	river
Bay of Plenty offshore reefs	reef
Narrowneck (Australia) artificial surfing reef	beach/surfing reef
Port of Auckland	port channels
Lake Rotorua	lake
Lake Karapiro	lake
Lake Tarawera	lake
Lake Rotoiti	lake
Raglan	surfing breaks
Opotiki	beach/inlet
Port of Gisborne	port embayment and channels
Poverty Bay	beach
Tuamotu Island, Poverty Bay	surfing break
Whangamata	estuary/beach/surfing break
Whitianga	estuary/beach
Orewa	estuary/beach

The CMG operates sidescan, a single beam echo sounder (SBES), and multibeam echo sounder (MBES) surveys from two survey vessels, together with various other oceanographic instrumentation. The larger vessel, Tai Rangahau (Figure 4.1) is used most often for MBES surveying because of the enclosed cabin and extra working space. Sidescan, MBES and SBES surveying from Taitimu (Figure 4.2) is still manageable, but space is traded for manoeuvrability, portability and reduced operating costs. The sidescan system (KLEIN 595 Dual frequency 100/500 KHz Side Scan Sonar with Triton Imaging Inc. Suite) has been outlined in various CMG publications and summarised in SPIERS (2005) and WOOD (2005).

Figure 4.1. The 9 m catamaran "Tai Rangahau" has a bow mounted MBES, and stern mounted SBES. The vessel was purpose built as a surveying and diving vessel.

Figure 4.2. The 6 m Pontoon vessel, "Taitimu", is a multi-task craft with a bow mounted MBES and a stern mounted SBES.

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The SBES system consists of a Knudsen MP 320 dual frequency 33/200 KHz sounder with a Trimble MS750 RTK GPS using HYDROpro v2.3 for data logging and processing (Figure 4.3). A key reason for using the HYDROpro software is the handling of RTK GPS tides or water levels, and its integration with Trimble Geomatics Office for network control surveys and inclined plane modelling. A recent upgrade to the Knudsen sounder allows a dual frequency digital sounding trace to be streamed over a Small Computer Systems Interface (SCSI) connection. The echo sounding trace can be logged for post survey analysis using the Knudsen SoundSuite software. Logging of the dual frequencies enables better determination of bottom depths where the seabed is complex (reef/coral) or covered in weed. Also it gives a 2D picture of the soft sediment characteristics in the superficial sediment layers, which is important for many types of environmental surveys. The penetration depth is dependent on the sediment type.
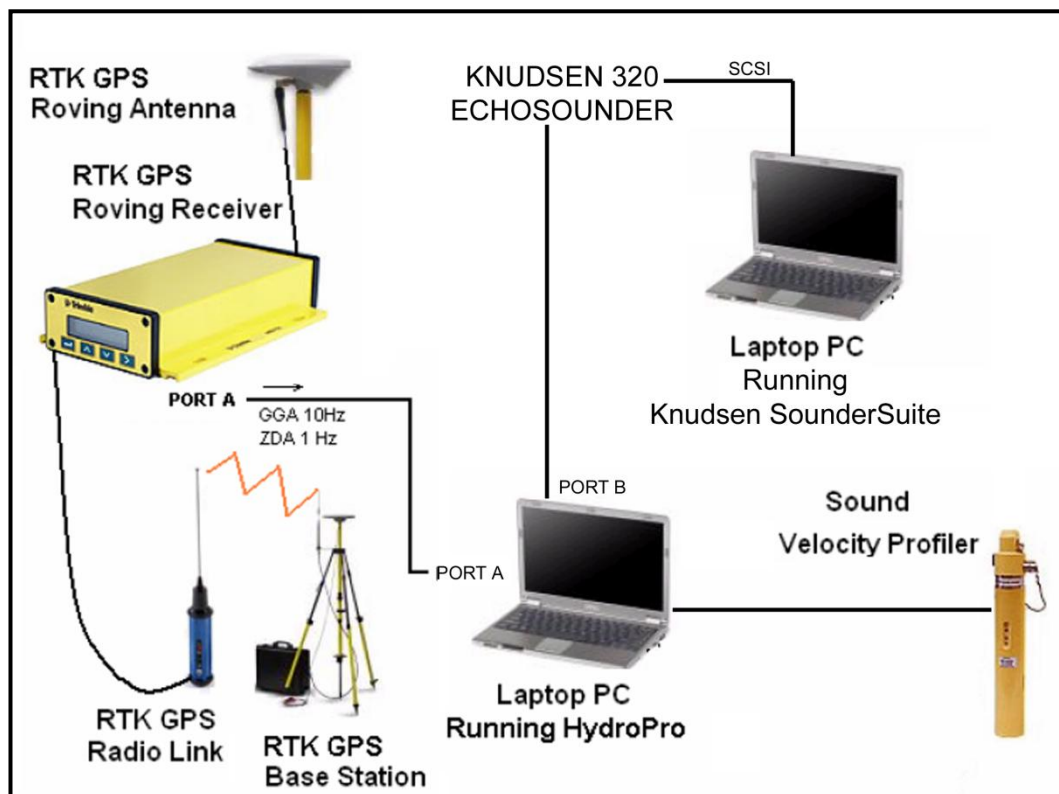
Figure 4.3. Components of the SBES survey system (*adapted from* Figure 4.4).

MBES techniques are covered by many authors including overviews of the shallow-water capabilities (HUGHES-CLARKE *et al.,* 1996; EEG, 1999) and future trends (MAYER, 2006). The MBES system (Figure 4.4) described here is a Simrad EM3000 and was acquired in 2003. To date the system has been used in the

shallow water harbour, beach, lake and river environments. The MBES system is a much more complicated array of hardware and software than the SBES system and at the core of the system is a Simrad EM3000 transducer and processing unit. This unit processes input from the GPS, transducer and motion sensor, and is then transmitted via a network link to a Windows 2000 based Triton Imaging Inc. processing computer. The Triton Imaging Inc. processing computer displays real-time waterfalls of 2D and 3D depths, backscatter (HELLEQUIN *et al.,* 2003), and colour binning of sounding. The Triton Imaging Inc. suite achieves this using a combination of ISIS, BathyPro Realtime and DelphMap software packages. The SBES system is run periodically and concurrently with the multibeam as an independently collected and processed dataset. This is critical for quality assurance, especially when working in an area for the first time. The two systems share the same GPS so are not completely independent, but still provide valuable redundancy to identify setup and processing errors.
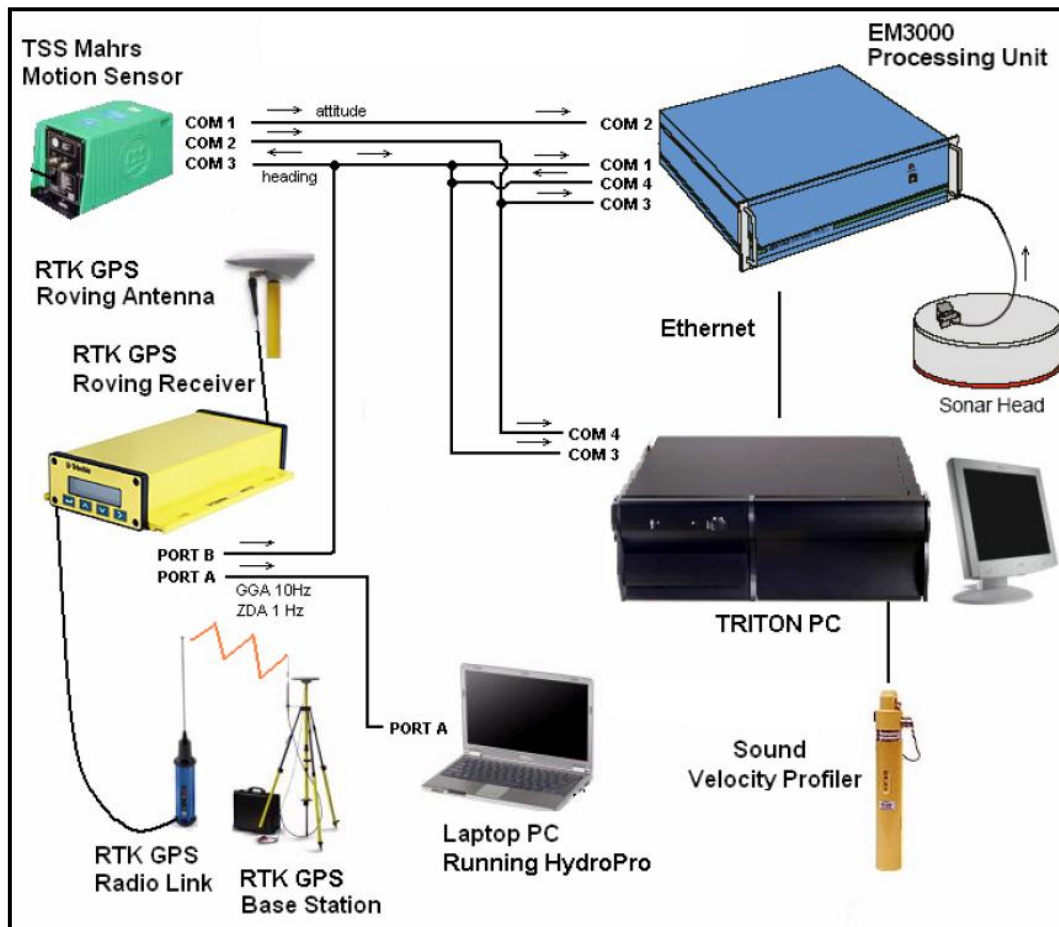
Figure 4.4. Components of the MBES system (*adapted from* MCRAE, 2007).

PRECISE RTK GPS WATER LEVEL CORRECTIONS

RTK GPS is increasingly used for measuring water level corrections during hydrographic surveys. Early tidal measurements were undertaken by ASHKENAZI *et al.* (1990) and DELOACH (1995), and heave was measured by KIELLAND and HAGGLUND (1995). More recently RAMOS and KRUEGER (2006) have investigated tidal measurements and WERT (2004) presents results of further processing of GPS measurements to improve accuracy. With perhaps the most complex technology, CANTER and LALUMIERE (2005) show how combined GPS and initial sensors can provide extra redundancy and significantly more accurate attitude corrections.

SCARFE (2002a) discussed water level corrections as a concept that includes tide, wave, lake, river and other water level fluctuations, including heave compensation. The water level combines the total correction for tide, squat, heave, long period waves, surf-zone set up/set down and harbour oscillations (sieching). For SBES, SCARFE (2002a) found that measurement of separate tide and heave was theoretically flawed as the water level at one instant is a combination of various factors including tide and heave. This is particularly true for small vessel SBES surveying where the GPS antenna is directly above the transducer, like the SBES system used on Tai Timu. The word tide implies that the measurement technique is limited to tidal area, although RTK GPS water levels are applicable to lakes and rivers also. While a somewhat academic discussion, the water level concept of SCARFE (2002a) is worth noting as it pertains to whether different survey systems should measure a "combined" or "separated" (tide, heave, squat etc.) water level.

Using the "combined" method, each sounding is accuracy timed to the water level correction to yield a reduced depth. SCARFE (2002a) developed a calibration method to align SBES and 3D RTK GPS positions with 10-40 millisecond accuracy, and validated the accuracy of the Trimble MS750 (TRIMBLE NAVIGATION, 1999) to measure accurately while in motion. Although a small degradation in accuracy using the low latency mode was found at high rates (20 Hz), the accuracy is more than acceptable considering the other errors inherent in hydrography. The performance of GPS receivers in motion is also covered in

TAYLOR *et al.* (2004). Thus although the combined approach is preferred for the Tai Timu SBES, HYDROpro currently only supports the "separated" method.

The accuracy is optimised when the RTK GPS antenna is mounted directly above the SBES transducer, and there is a short level arm between the two sensors (Figure 4.5). As the vessel pitches and rolls errors will be induced and a vertical separation of less than 2-3 m is recommend between the antenna and GPS for best results. Where the transducer and GPS antenna are horizontally separated, as often occurs with larger survey vessels, measurement of a combined water level at the transducer is not possible, and a tidal record only can be measured because any heave calculation will be valid to the GPS antenna and not the transducer. The effect of using the combined approach when there is a separation between sensors will be an apparent latency between depths and heave measurements.
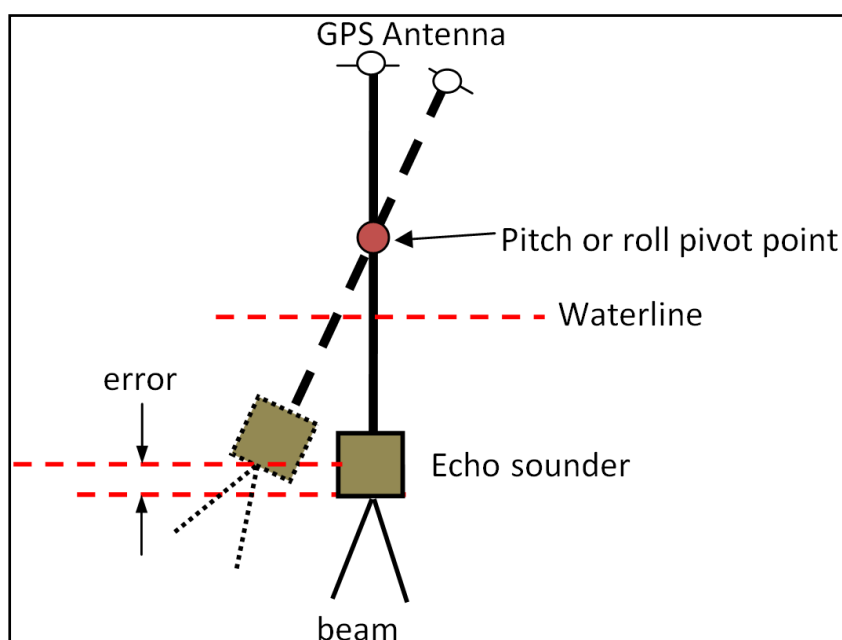
Figure 4.5. Mounting of RTK GPS Antenna above an SBES to minimise lever arms and maximise accuracy when using RTK GPS to measure water levels.

A drawback of the "separated" approach for SBES is that realistically an accurate RTK GPS measurement, timed perfectly with a sounding (*see* SCARFE, 2002a), is deconstructed into two separate signals, which for some survey setups will induce errors. This is especially true during vessel pitching and rolling. Using the "combined" approach is good for a small vessel such as Tai Timu where the distance between the sensors is short and the antenna is directly above the transducer

The "separated" approach is used with the MBES systems because of the distance (5.75 m) between the SBES and RTK GPS antenna. Since a single GPS cannot output remote heave, as common on inertial systems, the SBES is not corrected for heave. Attitude and heave are measured by the TSS Mahrs motion sensor for use with the MBES but not applied to the SBES at this stage. The RTK GPS heave measurements are not used for the MBES system as the Mahrs provides heave. The SBES is used as a check and accuracy statistics generally show consistent agreement between the SBES and MBES, as heave errors are averaged out during the error calculation process.

Inclined Plane Method

VAN WOERDEN *et al.* (1986) identified timing and accuracy as the two major issues with using GPS for heave compensation. SCARFE (2002a) proved the ability of the Trimble MS750 receiver to tackle these two issues. A third important issue discussed here is compensating for the geoid-ellipsoid separation. The separation is the distance between the WGS84 ellipsoid and a local orthometric datum (HYDROGRAPHIC DEPARTMENT, 1975) based on the geoid. The ellipsoid is an approximation of the earth's surface and the geoid is a surface of constant potential energy that coincides with mean sea level of the ocean (Figure 4.6; INGHAM and ABBOTT, 1992; LI and GÖTZE, 2001). FEATHERSTONE and STEWART (2001) also discuss issues with using GPS for heights relating to the geoid.
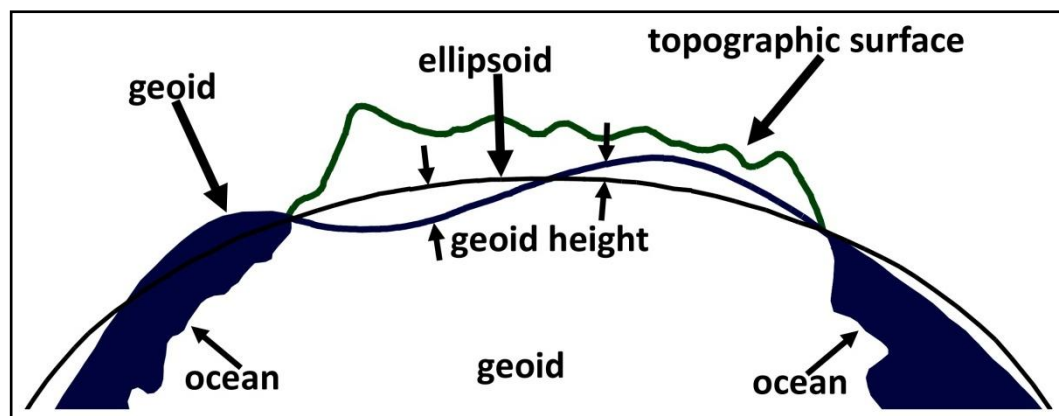
Figure 4.6. Ellipsoid, geoid and topographic surface of the earth (*adapted from* LI and GÖTZE, 2001).

FEATHERSTONE (2000) noted that during the 1990s interest in determining the geoid increased due to the increase in GPS use. Geometric and gravitmetric approaches exist to measure geoid-ellipsoid separations (CHEN and LUO, 2004)

and a geometric approach is used here. The geometric approach calculates the separation from points with heights known relative to the ellipsoid and geoid. A combined approach using both methods is presented in FEATHERSTONE (2000). FIG (2006) identifies two steps in developing a geoid-ellipsoid model: (i) measuring the geoid-ellipsoid separations at a series of point, and (ii) interpolating between the points. Extrapolation outside of the points (e.g. offshore a beach) can be done when appropriate error analysis is undertaken. However, an alternative method is used here to reduce water levels to an orthometric datum using a calibrated inclined plane, as this is supported by the Trimble software available to the CMG. Over small distances (< 300 km^2) the geoid-ellipsoid separation can be approximated by a plane between the two surfaces, using an inclined plane.

The inclided plane method is implemented within the SBES and MBES systems and rather than interpolating between points, a plane is fitted between the geoid-ellipsoid separation calibration points. Trimble Geomatics Office and HYDROpro software are used to create and apply the model. Although HYDROpro can create the model, Geomatics Office integrates with GPS and network adjustments making model creation easier. HYDROpro then applies a correction from the inclined plane model in realtime to convert WSG84 heights to a local datum.

The number of marks required will depend on the accuracy required for the water level corrections, the amount of existing information and the budget available to survey extra marks. As the size of the area covered by the model increases, the geoid-ellipsoid will not be able to be modelled using a plane. When using the Trimble software in survey areas where the geoid varies significantly, or the survey covers a large area, more than one inclined plane model may need to be made to optimise accuracy. It is important to quantify errors from large inclined plane models. More complex mathematical models could be used to calculate geoid/ellipsoid corrections over larger areas, although this feature was not available in existing software used by the CMG.

Scale of analysis must be taken into consideration when trying to understand the geoid behaviour around a survey area. The variation between the earth geoid and the WGS84 ellipsoid can be visualised at various scales. Figure 4.7 shows the North Island of New Zealand with the geoid separation contours overlaid. The raw geoid information was obtained from The Satellite Geodesy research group at

the Cecil H. and Ida M. Institute of Geophysics and Planetary Physics, Scripps Institution of Oceanography, University of California San Diego. Figure 4.7 shows that the geoid around Mount Maunganui is around 30 m different to the ellipsoid.
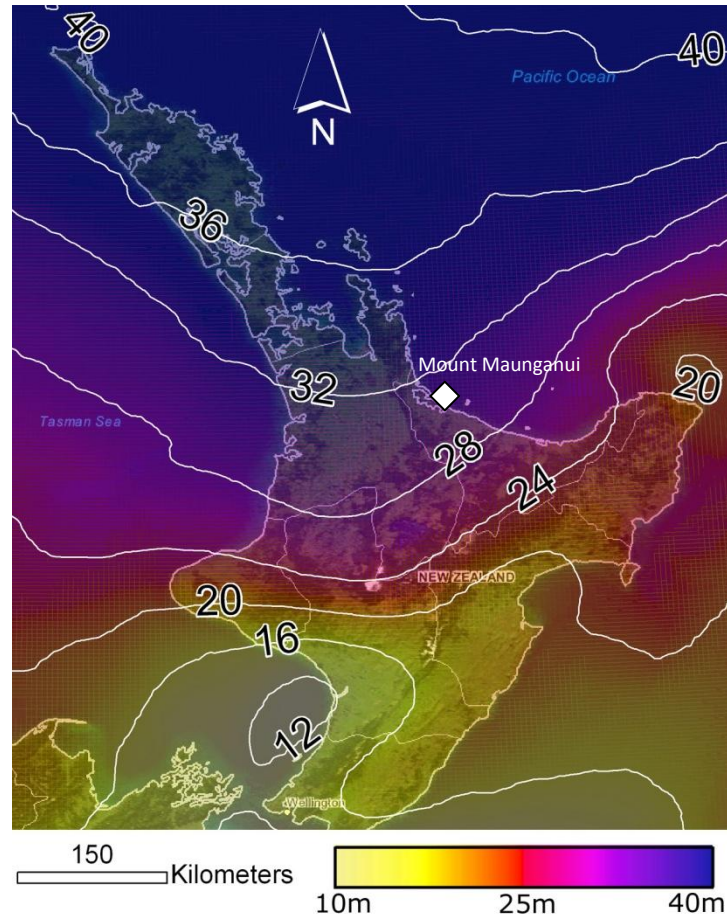
Figure 4.7. Separation (m) between the earth's geoid and the WGS84 ellipsoid for the North Island of New Zealand. Satellite imagery from www.geographynetwork.com via ArcIMS server.

Survey marks from the Land Information New Zealand (LINZ) geodetic database that had both ellipsoid and orthometric heights were downloaded (www.linz.govt.nz) and used to make a first approximation of local variations in the geoid. With this smaller scale analysis (Figure 4.8) a more accurate value of 30.90 m can be read. To improve the model a series of 37 RTK GPS and static GPS observations (Trimble MS750 with TSC1 data logger) to existing orthometric marks were undertaken around the survey site and adjusted in a control network using Trimble Geomatics Office. The fine scale model (Figure 4.9) shows differences from the coarse interpolation (Figure 4.8) of up to 0.15 m around the survey site. More discussion on the creation of the Mount Maunganui inclined plan model is presented in SCARFE and HEALY (Chapter 6).
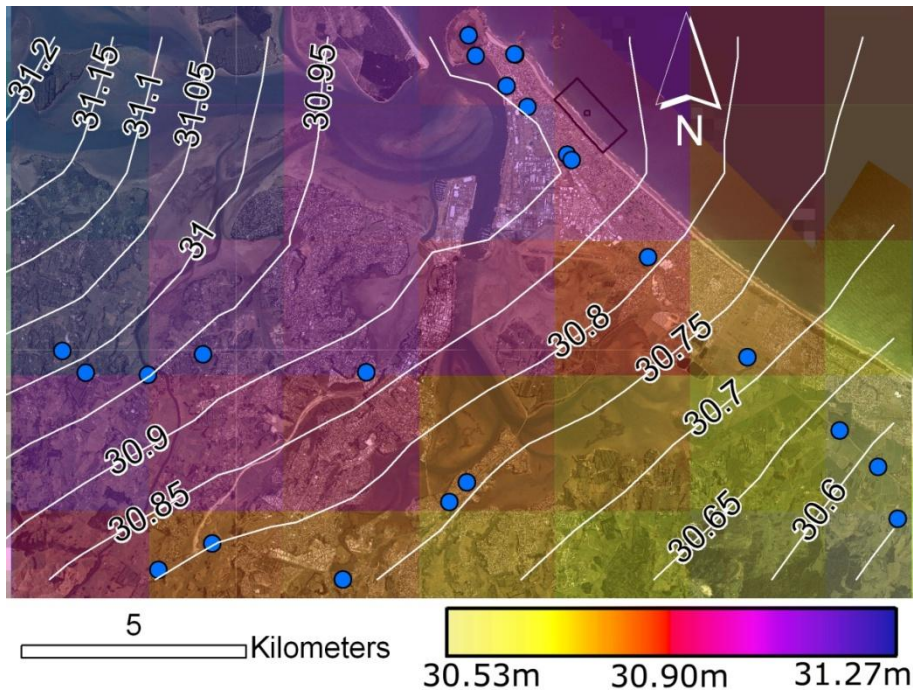
Figure 4.8. Separation between the earth's geoid and the WGS84 ellipsoid for the Mount Maunganui/Tauranga region. Geoid data from www.linz.govt.nz. Aerial photography sourced from Terralink International Limited. The survey area is left of the north arrow.
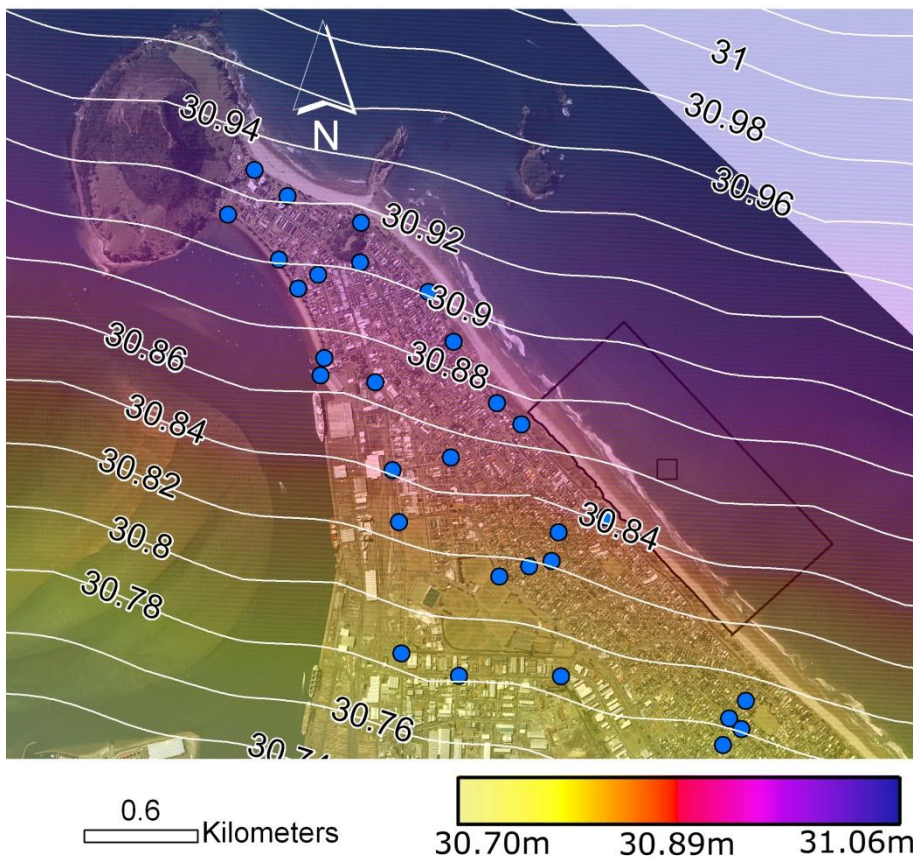
Figure 4.9. Separation between the earth's geoid and the WGS84 ellipsoid for the Mount Maunganui beaches and Port of Tauranga navigation channels. Geoid measurements from network adjusted RTK GPS observations and existing orthometric heights. Aerial photography sourced from Terralink International Limited. The survey site is the black box along the beach.

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RTK GPS Water Level Accuracy Analysis

When using the "separated" method, the RTK GPS tide can be validated against predicted tides, nearby tide gauges, boards or co-tidal models. Having a tide record is a good gross check on the datum of the water level correction. During 5 days of surveying Whitianga harbour and Buffalo Beach (New Zealand), 11 comparisons were made of the RTK GPS tide against a tide board (Table 4-2). An inclined plane model was created for the area and a regression between the two datasets was undertaken (Figure 4.10) with an agreement between the two measurement within the expected accuracy of the RTK GPS. Thus a high degree of confidence can be had in the RTK GPS water level record of the survey, even though the model was not optimised for the location of the tide board and covered a 450 km² survey area.

Table 4-2. Comparison of RTK GPS water level measurements and tide board observations during a coastal environmental survey.

Date (2007)	RTK GPS level (m)	tide board level (m)	average error (m)
17-Sep	0.95	0.91	-0.04
17-Sep	0.91	0.90	-0.01
17-Sep	0.97	0.96	-0.01
17-Sep	1.89	1.87	-0.02
18-Sep	0.79	0.80	0.01
18-Sep	0.83	0.80	-0.03
19-Sep	1.64	1.68	0.04
19-Sep	1.66	1.68	0.02
19-Sep	1.78	1.76	-0.02
1-Oct	0.99	1.00	0.01
2-Oct	1.36	1.32	-0.04
		Average error	*-0.01*
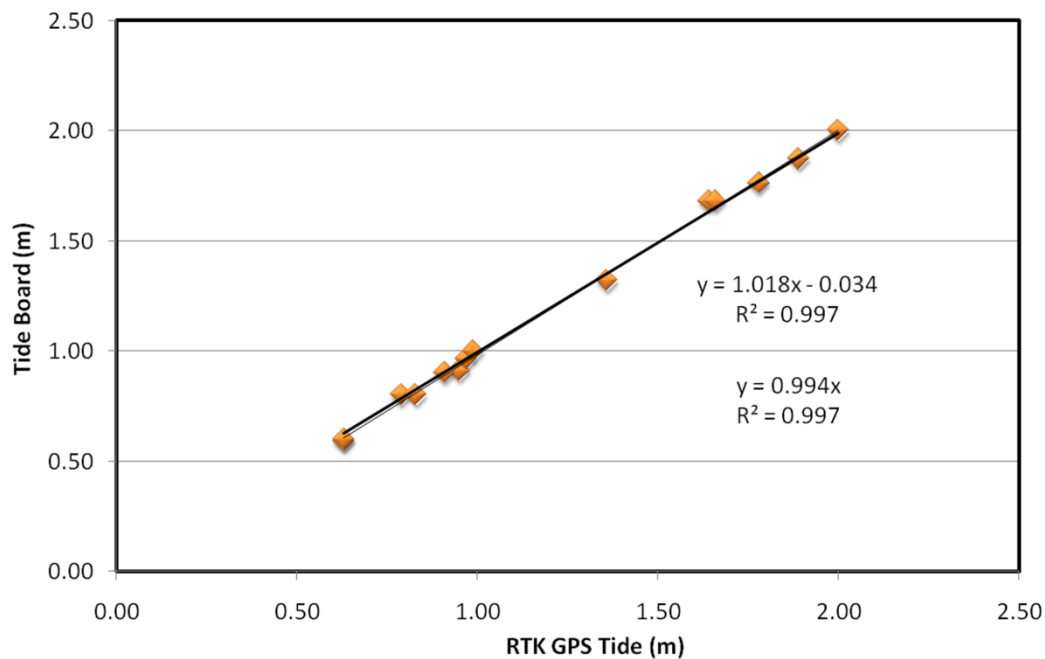
Figure 4.10. Regression between RTK GPS water levels and marina tide board observations (Whitianga Datum 1994) collected during survey.

A stationary water level recorder measuring at a single point can achieve much better resolution and accuracy than RTK GPS. Water level records collected by the CMG often contain significant variations (0.02-0.20 m) from a normal tidal curve (Figure 4.11, Figure 4.12 and Figure 4.13). This is also evident at varying magnitudes in the published RTK GPS tidal records by SCARFE (2002a), WERT (2004) and RAMOS and KRUEGER (2006). Spikes, offsets and other water level variations mean that making a direct comparison between a RTK GPS record and point measurement is not possible. Point source records are often reasonably smooth as the water rises and falls with the tide or other processes (e.g. surges in a river). An RTK GPS water level may have artefacts in the record. The artefacts can be significant if the vessel squat is constantly varying with changes in speed and direction, such as when driving short lines or in enclosed areas, or in swell.
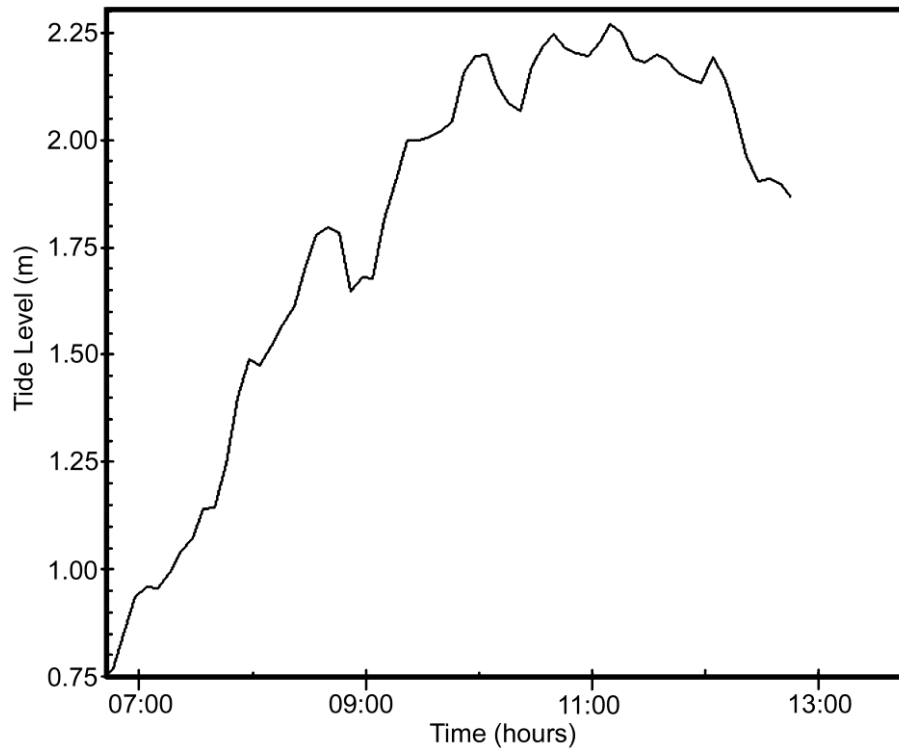
Figure 4.11. Raw RTK GPS water level record for a Whitianga Harbour (New Zealand) on 1-2 October 2007. Step down at around 9 p.m. is because tide level outside the entrance (<8:45p.m.) is greater than inside the entrance (>8:45p.m.). The vertical drop is approximately 0.12 m. Small variations from a perfectly curved tide are present and caused by boat motion and an inconsistent water surface over the survey area.
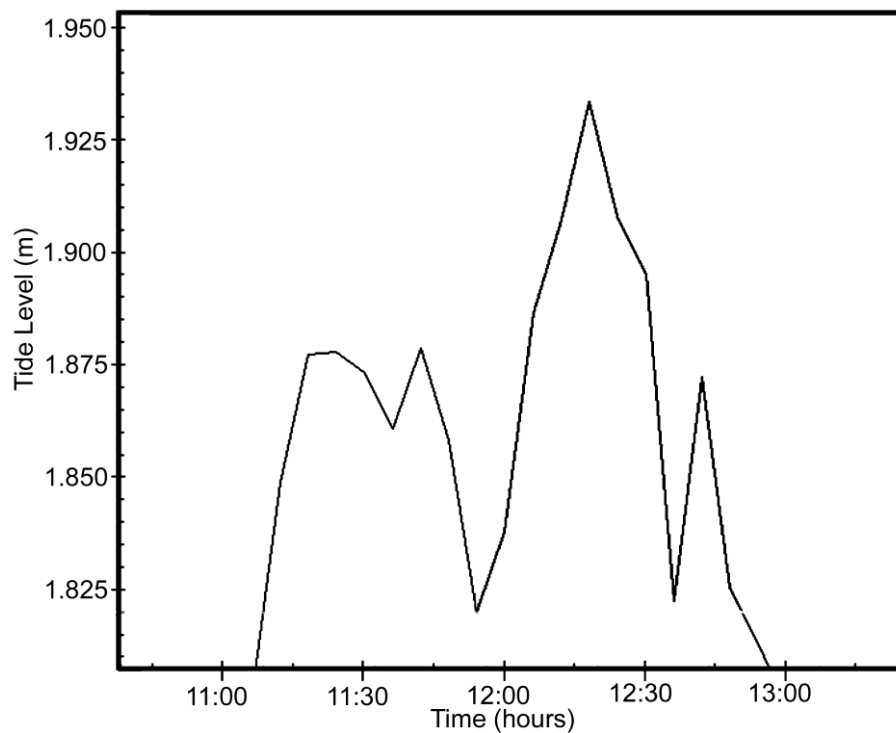
Figure 4.12. Raw RTK GPS water level record for a Whitianga Harbour (New Zealand) on 10 October 2007. Dips and peaks are caused by the survey vessel travelling with, against, or perpendicular to the swell.
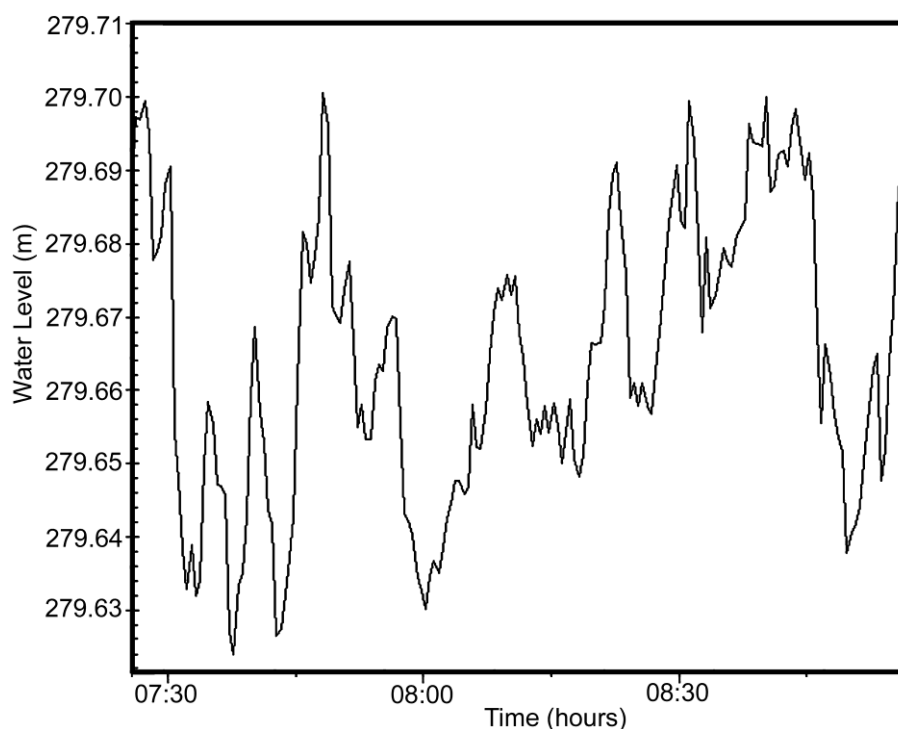
Figure 4.13. Water level using 30 sec sampling from a Lake Tarawera (New Zealand) survey showing spatial variations in water levels of 0.07 m and vessel motion artefacts of 0.01-0.02 m.

To demonstrate the effect of spatial variations on the smoothness of an RTK GPS water level, RTK GPS measurements covering Lake Tarawera (New Zealand) were converted to an interpolated water surface using manual methods (Figure 4.14). The WGS84 heights were converted to a mean sea level datum using the inclined plane method. It is not possible to show this measurement technique in the coastal environment due to tidal effects. The spatial variations in water levels over the lake show a significant gradient from one side of the lake to the other. The cause of the water level variation has not been investigated at this stage but this figure demonstrates that by moving around a survey area water levels can change, resulting in a record that is not necessary that smooth like a point source measurement (e.g. tide gauge). While surveying either side of inlets variations of 0.10-0.20 m have been observed (Figure 4.11). Wind and hydrodynamic effects have shown similar magnitude variations inside and outside of a marina basin.
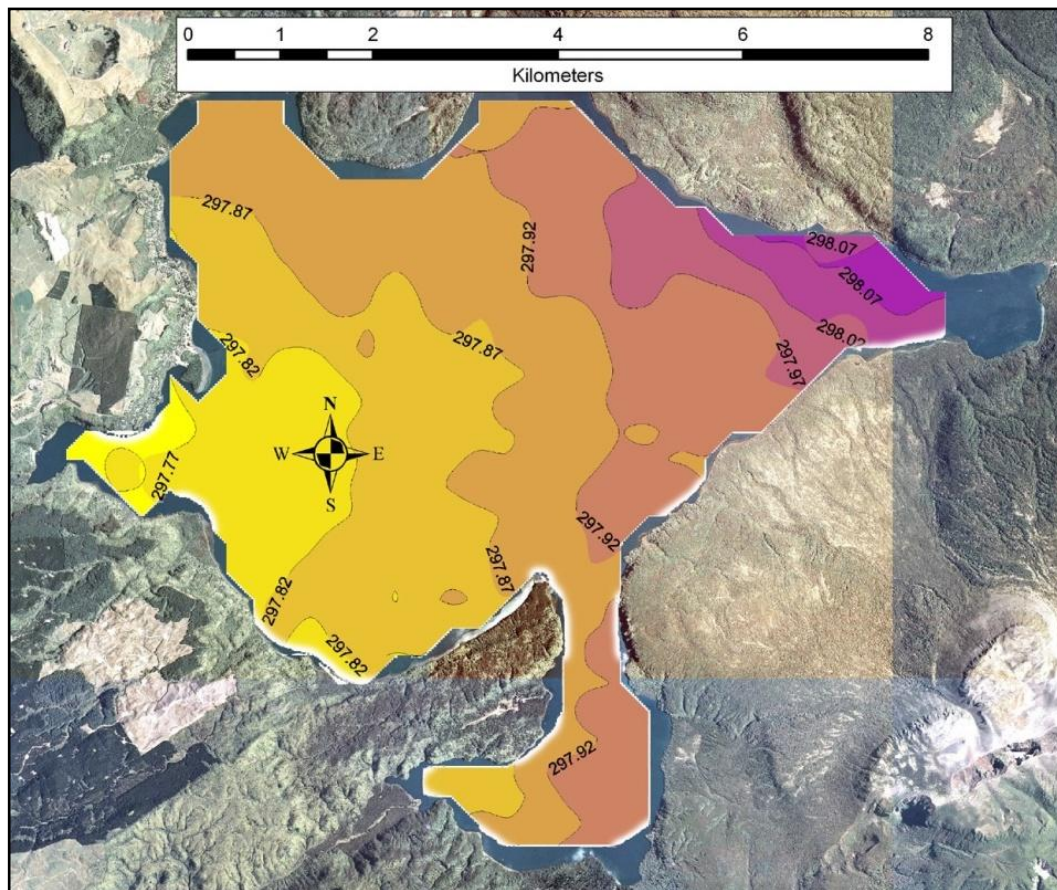
Figure 4.14. Lake Tarawera water levels measured with RTK GPS relative to an orthometric datum showing variations in lake surface that are difficult to correct for with traditional gauges.

GIS ACCURACY CALCULATION METHOD

Nothing can be measured exactly and acceptance of a particular measurement method depends on the precision required for a specific application. For example, the length of an object can be measured visually, with a ruler, microscope, and many other methods, each with different accuracy and precision characteristics. The precision required and degree of effort exerted to obtain a measurement is dependent on the application. The inability to measure exactly is particularly apparent with hydrographic surveying because multiple measurements are made simultaneously including depth, tide, heave, pitch/roll, speed of sound, vessel offsets and horizontal position and all errors contribute to the total error budget, which is covered in more detail in MYRES (1990).

An established method for quantifying the total *a posteriori* errors from different hydrographic error sources is from crossline analysis (IHO, 1998). Crosslines provide statistical testing of the transducer's calibration parameters, verification of water level correction, and evaluation of the speed of sound (BJORKE, 2007). The

redundancy is an advantage of swath systems for accuracy calculations (SEBASTIAN and TAYLOR; 2005) and a GIS method is presented here that automates the calculation of accuracy statistics.

SEBASTIAN and TAYLOR (2005) apply the following two crossline methods for swath mapping:

(i)   calculation of the average error between survey data and crosslines; and

(ii)   calculation of the error of individual beams from comparison to crossline nadir beams.

The first method provides robust estimates of the total error. The second method gives additional information that can be used to identify tide, speed of sound and other error sources. Since 1967 the U.S. Naval Oceanographic Office (NAVOCEANO) has been manually comparing soundings using crosschecks and it is only in recent times that more automated methods have been developed (SEBASTIAN and TAYLOR, 2005). Similar experiences, but at a much shorter time scale, have been had by the CMG. Initially a very manual method was used where overlapping soundings were identified and entered into a spreadsheet to calculate the root mean square error between survey data and crosslines. The next evolution was comparison between the crosslines and soundings binned into cells using Surfer (Golden Software), and analysed in a spreadsheet. This was a significant improvement from the manual method by allowing analysis of 1000s and 10 000s of soundings to be compared, instead of 10s or 100s possible with the manual method. The semi-automated method has been refined over the years and subsequently used by WOOD (2005) for analysis of the accuracy of a 55 km river survey. The process still required two software applications and many laborious processing steps. Now the process has been significantly more automated using ArcGIS (ESRI, 2006) with methods discussed further in SCARFE *et al.* (Chapter 5). The scale of error analysis is now possible for millions of soundings, with potential for larger datasets using more automated batch processing. Once the information is in the ArcGIS environment it can be used for spatial and non-spatial calculations, symbolised, and viewed in 2D and 3D with other geographic and non-geographic data (Figure 4.15).
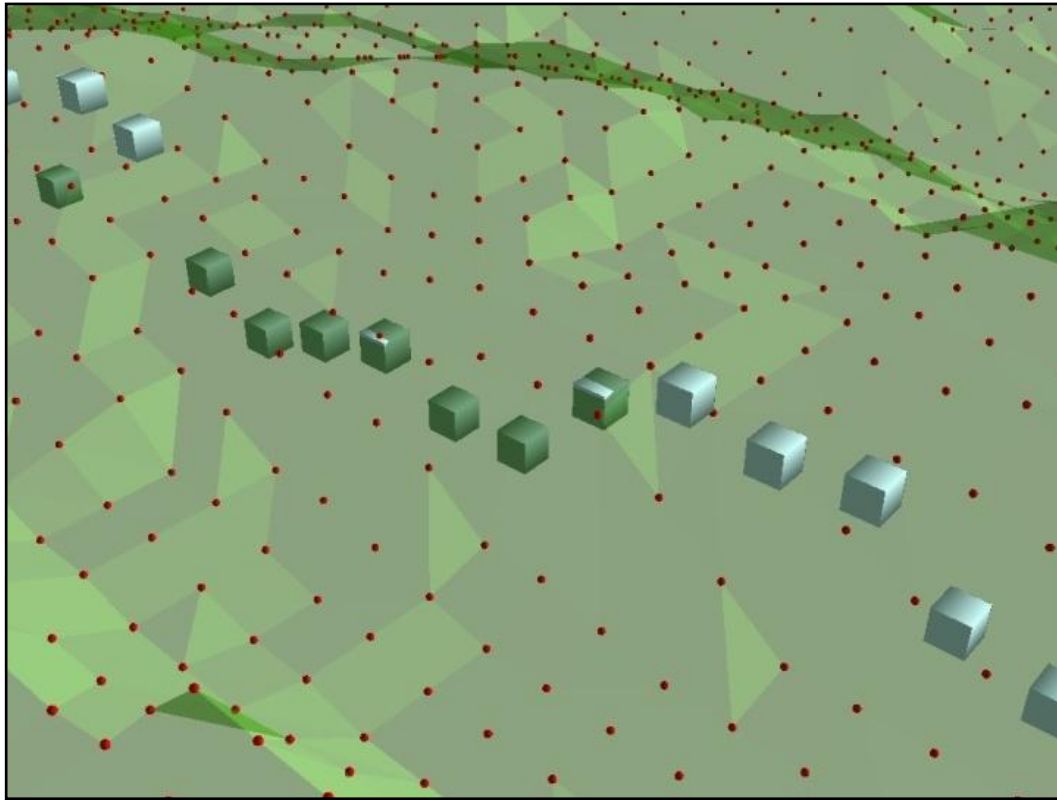
Figure 4.15. 3D GIS visualisation of MBES (red dots), and SBES (larger squares). A semitransparent MBES digital terrain model (DTM) colours the SBES above the MBES surface grey and below the DTM dark green.

The GIS method developed here calculates average error and is essentially a check on the datum, speed of sound, vessel offsets and processing method. Soundings are binned into cells with differences calculated between datasets. The spacing between soundings for different depths is therefore important when calculating accuracy. Figure 4.16 shows the spacing of the EM3000 soundings at different depths surveyed to date. The accuracy calculation requires near flat seabed as small differences in horizontal position of soundings can result in large depth differences on steep slopes. The precision of the horizontal coordinates used to position SBES is usually dictated by the specifications of the positioning system (HARE, 1995). MBES have a more complex error budget than single beam systems because of the additional sensors that are required in order to compute the depth and position of each sounding (HARE, 1995). While horizontal accuracy of SBES systems are mostly limited to the accuracy of the GPS (assuming minimal pitch/roll), horizontal errors in MBES systems also contain extra error sources from measurement of the vessel attitude and beamforming.
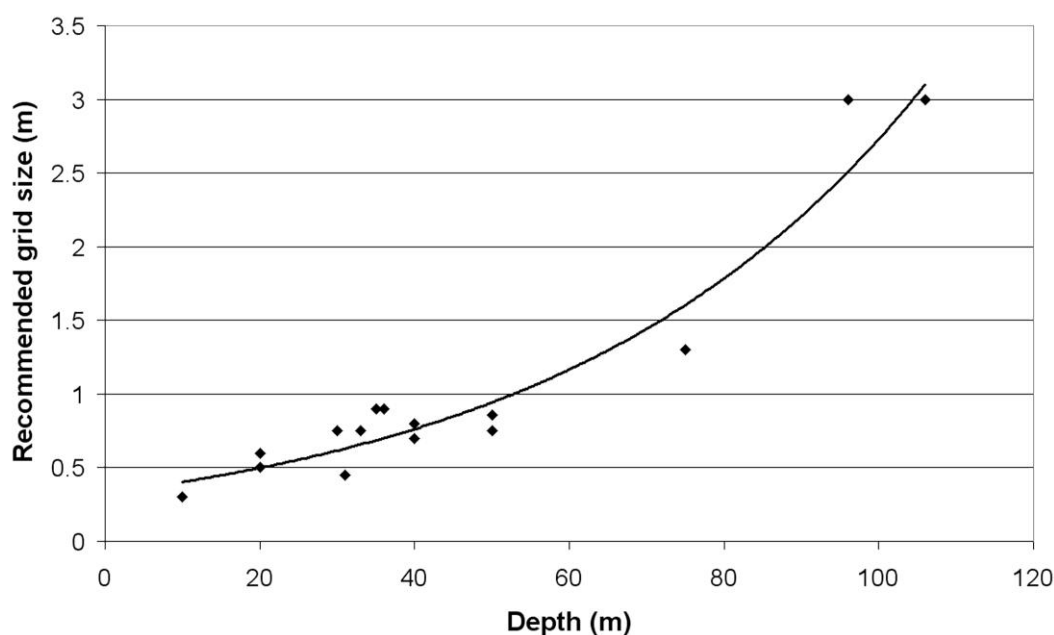
Figure 4.16. Spacing of multibeam echo soundings for EM3000 based on tests undertaken in this study.

The SBES does not require the complicated motion sensor and beam steering of the MBES and simply measuring the draft and RTK GPS antenna height accurately while at survey speed and speed of sound is all that is required for a good survey. Soundings in a MBES system undergo a lot more corrections and rotations for various offsets and motion effects, increasing the likelihood of equipment or human errors. Thus the SBES is a good gross check on the processing and setup of the MBES.

After applying the GIS method to various datasets it has been found that smaller errors occurring inside harbours than at the beaches, due to wave effects. The August 2006 survey inside Tauranga Harbour resulted in a 95 % confidence interval of 0.24 m, compared with 0.42 m at the beach during small swell (<0.5 m). During 16 survey expeditions to the area various accuracy calculations have been undertaken and generally inside the harbour an accuracy of 0.15-0.25 m (95 % confidence interval) is achieved for depths less than 15 m. The variation in accuracy is solely caused by the sea state and 0.15 m is a good estimate of achievable accuracy in shallow, calm water locations. Outside the harbour the accuracy reduces because of wave effects, even during periods of calm sea, because of infragravity wave energy. Accuracy values of 0.25-0.45 m (95 % confidence interval) is generally achieved in depths less than 20 m. During calm conditions 0.25 m can be achieved, and surveying is rarely undertaken when individual heave measurements are larger than 1 m.

The MBES setup has also been validated against Port of Tauranga SBES collected in August 2004. Figure 4.17 shows GIS visualisation, as well as summary statistics created using the GIS method. This calculation had 937 overlapping points available and a regular distribution of error around a 0.10 m mean was found. Comparison with concurrent SBES using the CMG's system generally also identifies this 0.10 m datum difference as the multibeam transducer offset has a misalignment with the RTK GPS water line of 0.10m. Thus this error is corrected for during MBES processing.
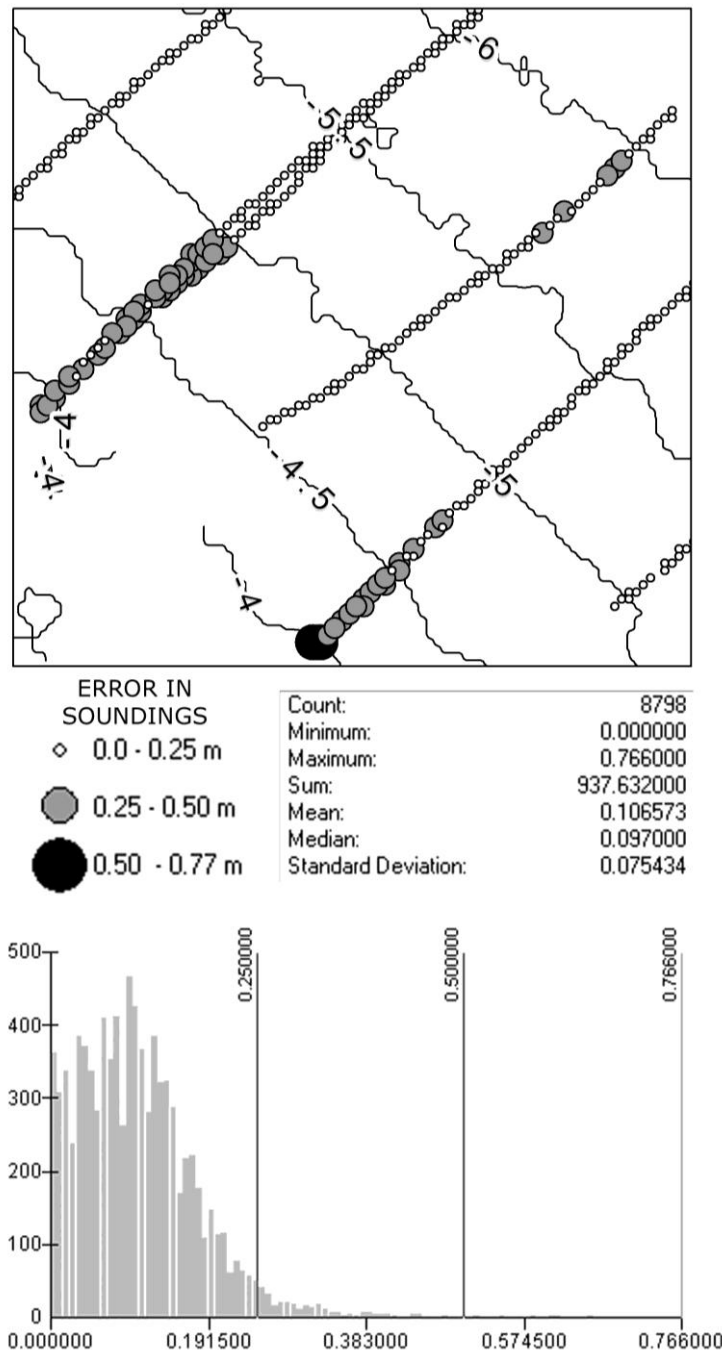
Figure 4.17. Survey accuracy for August 2004 MBES survey compared to Port of Tauranga SBES survey.

Slope affects the results when using this GIS accuracy method, and this is also noted by SEBASTIAN and TAYLOR (2005). Thus the accuracy analysis process also identifies and removes soundings on steep slopes using spatial calculations, such as the control reef (Mount Maunganui) in Figure 4.18.
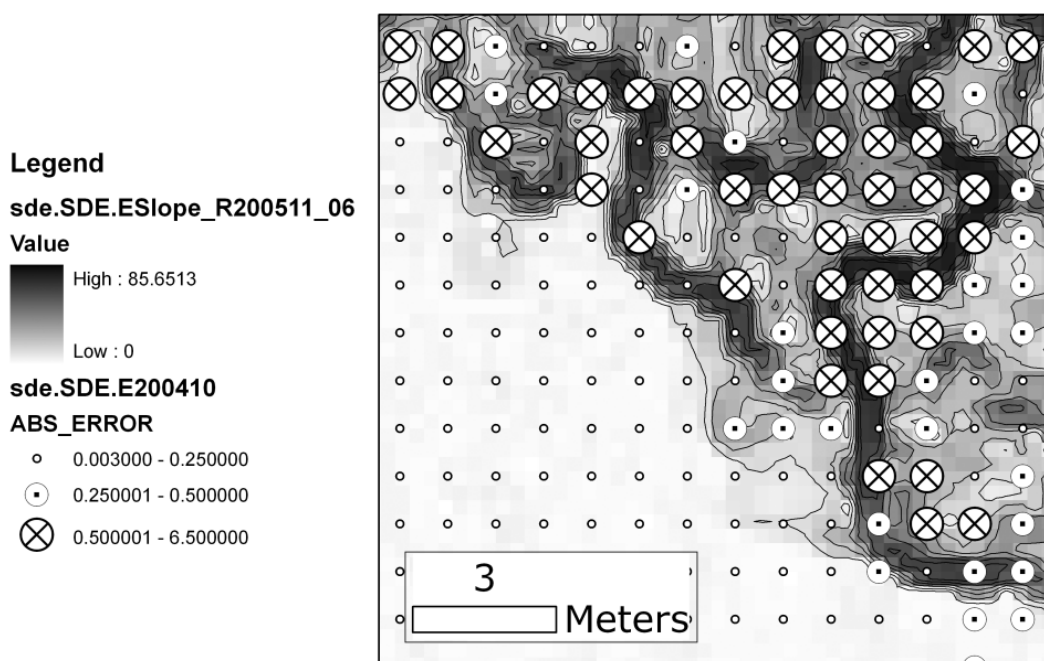
Figure 4.18. Background grey shaded imagery is the seabed slope (degrees) of the control reef (Mount Maungnaui), with accuracy estimates from a crossline analysis symbolised as circles. Note how larger errors exist for steeper slopes.

Many regulations, standards and accepted best practises are applied during cadastral surveying. Similarly, controls over the production of navigational charts also exist. However in the field of earth/environmental sciences there is less control over the quality of surveys. The integrity of the survey is often left to a scientist without a formal surveying background. This can lead to inadequate reporting of information that may be required by people who will use the survey in years to come. It is critical that hydrograph metadata (*see* SCARFE *et al.*, Chapter 5 for a review) are recorded. This enables future users of a chart or soundings to have some idea of the chart's accuracy. This is as much to give credit to a good survey as to raise caution about a poor survey.

The three main contributors to the quality of a final surfing break chart are:

(i)   vertical sounding accuracy;

(ii)   horizontal positioning of sounding accuracy; and

(iii)   percent of seafloor covered.

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A common key on a navigational chart to understand the accuracy of the base sounding data and survey coverage is a reliability diagram. These have been discussed for surfing studies by SCARFE (2002b) and help to depict the three main contributors to the quality of a surfing chart. This gives readers of research on surfing an understanding of any caveats in the research from insufficient or low accuracy surveying data. A surfing break reliability diagram is published in SCARFE (2002b).

CHARTING SURFING BREAKS

A significant amount of research has been undertaken in the last decade to understand how the bathymetry of surfing breaks transforms ordinary waves into surfing waves (*see* SCARFE e*t al*., Chapter 2). There now is a significant volume of scientific literature being applied to increase the benefits to surfing of coastal projects. Analysis of bathymetric data from a wide range of hydrographic surveying methods is critical to understand the complex, but predictable, wave transformations. SCARFE *et al.* (Chapter 3) identify the different processes occurring around surfing breaks, as well as environmental data types that can be used during a study of a surfing break. Bathymetry was identified as environmental data type critical to how surfing waves form. Often surf zone bathymetry changes over time due to natural and artificial forces. If the social and economic benefits of surfing breaks are to be preserved (*see* LAZAROW *et al.,* 2007; NELSEN *et al.,* 2007), these natural and artificial processes need to be understood and managed.

For surfing studies there are many different methods available that can be used to collect bathymetric data. The quality, complexity and cost of each technique varies. The technique adopted depends on the budget as well as the availability of the equipment and operators with the necessary technical expertise. Hydrographic survey techniques to obtain bathymetric data can range from simple and inexpensive to complicated and costly. At the macro level, general seafloor contours from navigational charts or fair sheets can be used to help develop wave climates for different surfing breaks. Offshore focusing over bathymetric features and sheltering behind islands can cause significant variations in wave climate along a coast and some beaches are more likely to have quality surfing waves because of this offshore preconditioning (SCARFE *et al.,* Chapter 2). Depending on

the scale of the chart, analysis at a meso level is likely to require extra soundings to be collected to identify meso-scale components in the bathymetry. To investigate the micro scale changes in wave character, or "sections" (*see* MOORES, 2001), accurate, densely distributed soundings are required. The micro-scale preconditioning and wave breaking components create variations in wave height and angle along a wave crest, which combine with variations in seabed gradient to form wave sections. Surfing waves are made up of sections that peel with greater or lesser speeds and break with lesser or higher breaker intensity. Dense, accurate soundings are also required to measure achieved artificial surfing reef construction tolerances and to monitor the impacts of the reef on the beach (e.g., SCARFE and HEALY, Chapter 6).

Bathymetric Reference / Control Points

For surveys to monitor an artificial surfing reef built at Mount Maunganui (*see* SCARFE, 2008) a bathymetric control point (Figure 4.19) was made from a natural reef. A bathymetric control point is a concept that is presented here to provide a permanent underwater reef that can be used as a direct link to the land based survey coordinate and datum system. Each successive survey of the beach used this natural reef to calibrate and validate the position and datum of soundings collected during the MBES surveys. The surveys were undertaken to better understand how a beach responds to an artificial construction in the surf zone. High absolute and relative accuracy was achieved during the study.
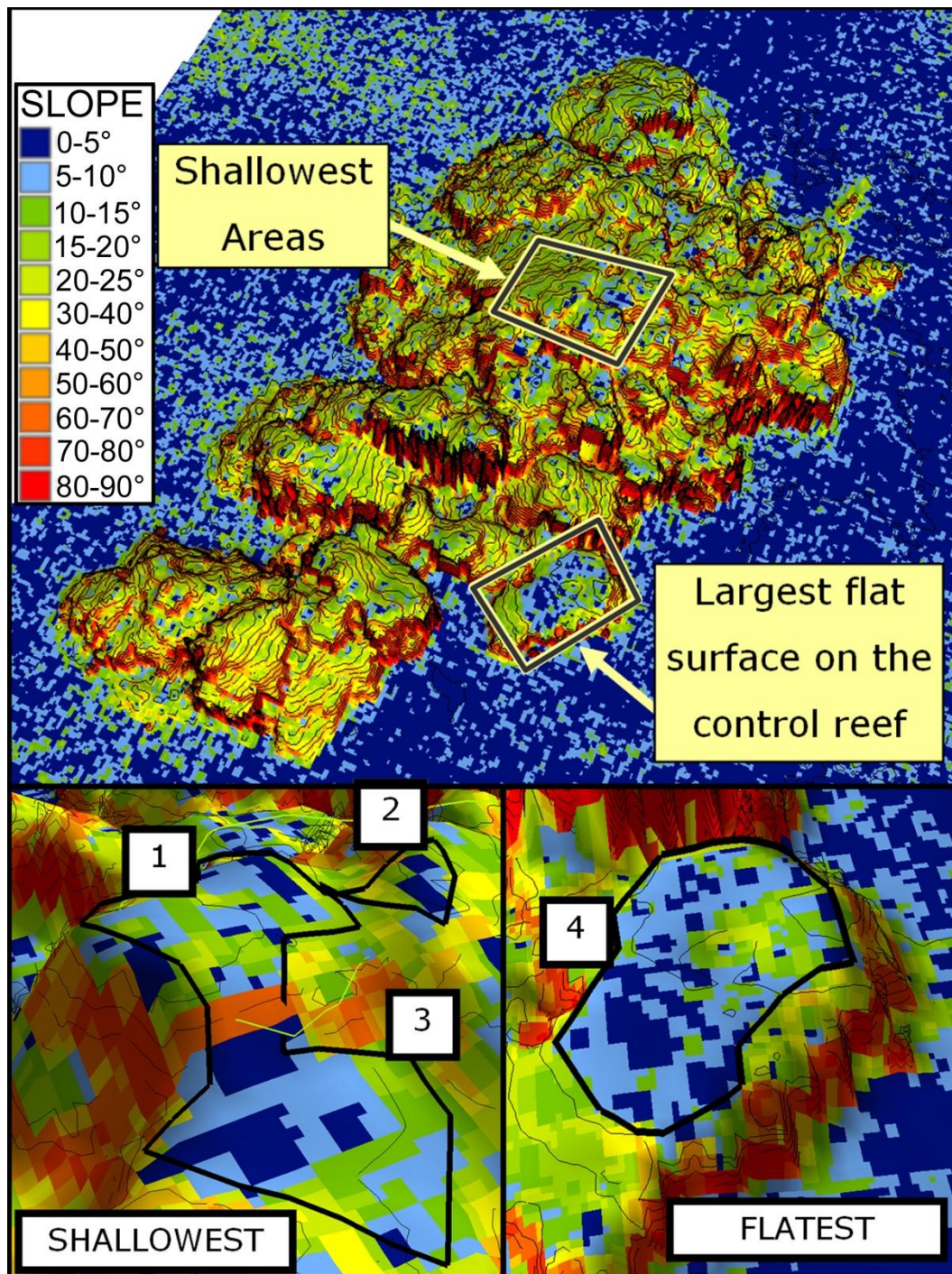
Figure 4.19. The slope of the bathymetric control reef used to validate survey data. The surfaces with the lowest gradients are best for datum checks and are highlighted with the colour blue. The numbers are the calibration areas for this reef.

Multibeam soundings collected over the control reef during the studies of SCARFE and HEALY (Chapter 6) and SCARFE *et al.* (Chapter 8) were processed using the Combined Uncertainty and Bathymetry Estimator (CUBE) algorithm by MCRAE (2007), within the CARIS BASE Editor (v 1.0) multibeam processing software. Automation of MBES processing, not necessarily the topic of this paper, can be significantly improved using the CUBE algorithm (CALDER, 2003; CALDER and

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MAYER, 2004; CALDER and SMITH, 2004; MALLACE and ROBERTSON, 2007). Comparisons between the control reef and successive survey showed that some of the areas of the reef were better for control than others for the GIS accuracy method described earlier. A slope analysis was undertaken to find the flattest areas. Two regions were identified (Figure 4.19) and these were the shoalest flat points of the reef, and the largest flat rock area. Although many parts of the reef can be used to provide control, an area greater than 20 m² was found to be required to create a datum check using the GIS method.

Mount Maunganui Artificial Surfing Reef Monitoring

Although the CMG's research interests are broad, the first large scale hydrographic survey was the 1996 survey of the sand and reef surfing breaks in Raglan, New Zealand (HUTT, 1997). At the time this was the most detailed survey of a surfing break to date. Now the Mount Maunganui reef monitoring (SCARFE *et al*., Chapter 8) is likely to be the most comprehensive charting of a surfing break.

Depending on the purpose of the survey, multibeam soundings can be collected with anywhere between 30 and 200 % coverage of the seafloor. In this context, a survey with 200 % coverage has sounded the entire seafloor twice. There is a significant drop in efficiency as the percentage of seafloor coverage increases. Often there are unavoidable small gaps in the survey coverage as variations in depths will cause the swath coverage to change in width. Rapid corrections to the survey vessel cause motion artefacts in the data and therefore gaps must be filled with a separate survey line. Navigating the survey vessel to fill gaps can take considerable time, and it is not always necessary for environmental surveys. When filling gaps some areas end up having 100-400 % coverage because to navigate to the gap, already surveyed areas must be covered again. In the hydrographic context, 400 % coverage involves the same area being covered 4 times with echo soundings. For environmental and surfing applications, shallow, gently sloping beaches can be surveyed without aiming for overlap between lines. The seabed features will still be accurately depicted with lines that do not overlap. Where reef or other complex seabed features exist, more survey coverage can be dedicated to these areas. Imaging of bedforms can still be done and although there will be gaps in the data, it is still possible to quantify the location and scale of bedforms.

Land and intertidal measurements are undertaken using the same MS750 RTK GPS, but mounted in a backpack with a Trimble TS1 data logger (Figure 4.20). The intertidal measurements complete the picture of how the measured soundings link to land features by enabling an interpolated digital terrain model (DTM) to be created. Although for navigation purposes these intertidal areas are of lesser importance, they are critical morphological features for surfing and other environmental surveys.

Figure 4.20. Topographic survey of intertidal and dry beach (high water to toe of dune) using backpack mounted RTK GPS.

Figure 4.21 shows typical sounding coverage as a reliability diagram for the surveys of the beach around the artificial surfing reef. The coverage achieves an excellent depiction of the dry and intertidal beaches, the surf zone bars and rips, as well as the offshore bar. Between 5 and 10 m depths, 50 m line spacing is used. For the shallower areas 25 m line spacing is used. The beach is surveyed using the RTK GPS with shore parallel lines at the dune toe, high water, low water and with two lines between the high and low water lines. The result of this survey coverage is a complete DTM of the beach that can be used in morphology analysis, numerical modelling, as well as to extract cross-sections. Of the nine beach surveys undertaken, the soundings and RTK GPS intertidal measurements overlapped only once. This gap needs to be interpolated, and for some surfing break surveys an additional measurement technique (e.g. jet ski) in the extreme shallows will be required.

Figure 4.21. Spacing of MBES runlines on around the Mount Maungaui artificial surfing reef. The spacing of the runlines gets greater the further apart as the water gets deeper. RTK GPS point spaced at 2 m were used on the beach.

Around the surfing reef itself there are a lot of redundant measurements and multibeam soundings are generalised into 0.25 m bins. This gives extremely high resolution imagery of the reef and surrounding morphology. A 3D visualisation of the January 2007 survey can be seen in Figure 4.22 to compare well to an oblique aerial photograph around the same time. Settlement, subsidence and bulging of the geotextile sand bags can be seen between surveys. It is the first time an artificial surfing reef has been charted using MBES and the survey data is providing valuable research on how to construct these structures. More information on the reef is included in BLACK *et al.* (2007), MEAD *et al.* (2007) and SCARFE *et al*. (Chapter 8).

Figure 4.22. The Mount Maunganui artificial surfing reef (70 % complete; January 2007). Each arm of the reef is around 80 m in length. The left image is an oblique aerial photograph (from www.mountreef.co.nz) and right image ArcGIS 3D imagery of MBES survey (MSL; Moturiki Vertical Datum 1953).

The Triton Imaging Suite allows for the creation of a backscatter geotif. The backscatter contains artefacts from a generic backscatter correction applied to the soundings (Figure 4.23), but still can provide valuable information to an environmental study. A white line through the centre beams is clear in Figure 4.23, but also the backscatter picks up depressed (0.20-0.30 m) areas of coarse grained sediments. SPIERS and HEALY (2007) identified similar features as "rippled scour depressions" or "sorted bedforms" using side scan sonar at a larger scale. The depressions are caused by wave focusing (SPIERS and HEALY, 2007) and are important indicators of coastal processes around the reef. Improved processing and analysis capabilities for the backscatter exist, which will remove this white stripe, but the imagery still confirms the presence of the features.

Figure 4.23. Backscatter evidence of wave focusing from coarse grained sediment patches, depressed up to 0.30 m from the ambient seabed level. Contours show depths relative to mean sea level.
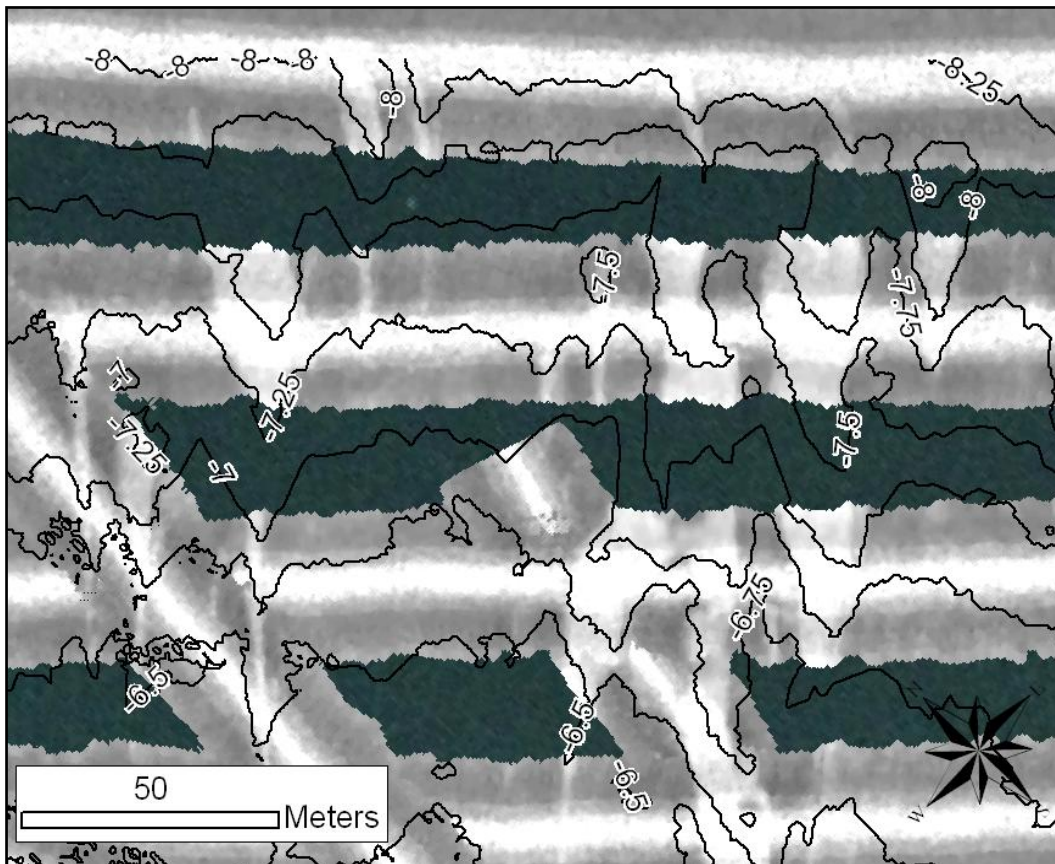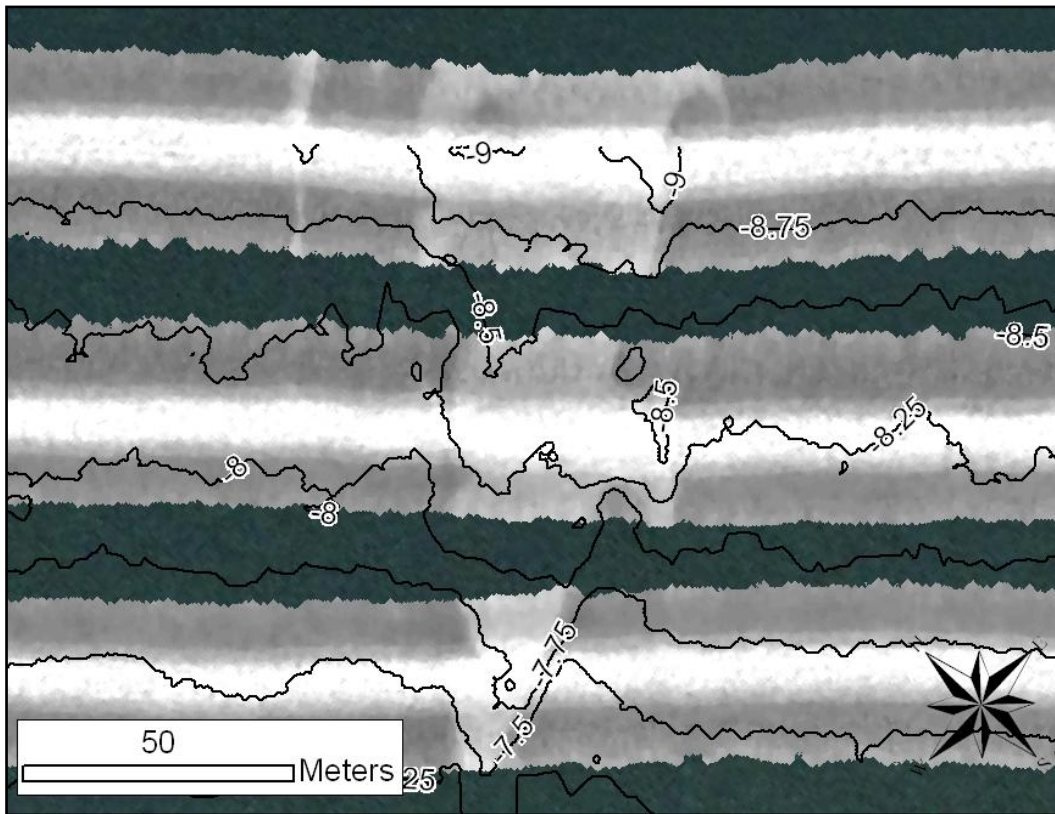
DISCUSSION

As well as various shallow water mapping discussions, experience from eight years of using RTK GPS, including an incline plane method for geoid-ellipsoid separation modelling, has been presented. Various lumps and spikes have been found when comparing RTK GPS records with traditional water level recorders. Although it is difficult to achieve the 1-2 cm accuracy of fixed tide gauges, RTK GPS has the benefit of measuring directly where the sounding is taken. Contributing factors to differences between RTK GPS water levels and record tides were not found to be summarises in the literature, and therefore the errors sources, accuracy range, error type and recommendations for maximising accuracy are identified in Table 4-3

Table 4-3. Factors contributing to differences between measured RTK GPS water levels and traditional fixed location tidal gauges.

Contributing factor	Accuracy range	Error type	How to minimise
RTK GPS accuracy	0.00-0.05 m	Equipment	Dependent on GPS receiver specifications
squat variations during turning and velocity changes	0.00-0.30 m but dependent on vessel size	Survey procedures	Do not log water level measurements during turning or when not travelling at survey speed
fluctuating fuel levels	0.00-0.30 m but dependent on vessel size	Dynamic	Quantify error size and correct using a dynamic squat corrections
change in position of personnel on small survey vessels	0.00-0.30 m but dependent on vessel size	Survey procedures	Maintain consistent positions during data logging
accuracy of the RTK GPS to measure positions when at motion	0.00-0.05 m	Equipment	Restriction dependent on GPS receiver
swell and sea waves	0.00-0.50 m for small to moderate swells	Environmental	Only survey in small swells for optimum accuracy
surfing or travelling into waves	0.00-0.20 m, increasing with swell size	Environmental	Only survey in small swells for optimum accuracy
infragravity wave energy	0.00-0.20 m, increasing with swell size	Environmental	Only survey in small swells for optimum accuracy
surf zone setup	0.00-0.20 m, increasing with swell size	Environmental	Only survey in small swells for optimum accuracy
harbour oscillations (sieches)	0.00-0.20 m and dependent on geometry of harbour	Environmental	Only survey in small swells for optimum accuracy

The contribution of each factor to the observed differences can be small or significant. Potentially the biggest factor is spikes from swell and sea waves.

Infragravity and far infragravity wave energy (KOMAR, 1998) can superimpose an oscillation on the tidal component of the water level record. Infragraivity energy increases with the swell size and can be created offshore and travel towards the shore, bounded to a swell. It can also be created in the surf zone by the wave breaking processes. Long period oscillations in RTK GPS records have been particularly apparent when surveying near the surf zone, even during small wave conditions (<0.50 m). Surveying into swell, or surfing with swell, as well as travelling perpendicular to waves can all impact on the final water level record. Thus there is an element of art and experience that is required when setting tidal averaging periods and planning RTK GPS tide surveys during swell. When GPS measurement are coming in at high rates (>5 Hz) there are a lot of redundant measurements and the final water level record can be improved by filtering less accurate measurement (e.g. when the antenna changes direction suddenly; SCARFE, 2002a) and/or using post processing filtering and smoothing techniques as undertaken by WERT (2004).

After reviewing the surfing literature listed in SCARFE *et al.* (Chapter 2), different sources of bathymetric data have been used to study surfing breaks:

   (i)   navigational charts;

  (ii)   MBES surveys;

 (iii)   low cost fishfinder GPS systems;

 (iv)   dumpy level and tape;

  (v)   total station;

 (vi)   RTK GPS toposurvey;

(vii)   non-heave corrected soundings;

(viii)   heave corrected soundings; and

 (ix)   aerial photos – digitizing.

However, the ability of LiDAR (GUENTHER *et al.*, 2002; MOYLES *et al.*, 2005) and MBES to provide dense soundings is impressive, as shown by the imaging of the Mount Maunganui surfing reef. A MBES survey of a natural reef in the Tauranga habour (New Zealand; Figure 4.24) shows a complex architecture that could modify wave breaking if part of a natural surfing reef. Similarly, if the bedforms imaged in Figure 4.25 were around a surfing break, this could indicate locations

of areas with differing wave induced current patterns. The ability of the MBES to produce images of complex shapes is shown by the 3D image of a sunken tug boat (Taioma) in the Bay of Plenty (New Zealand).
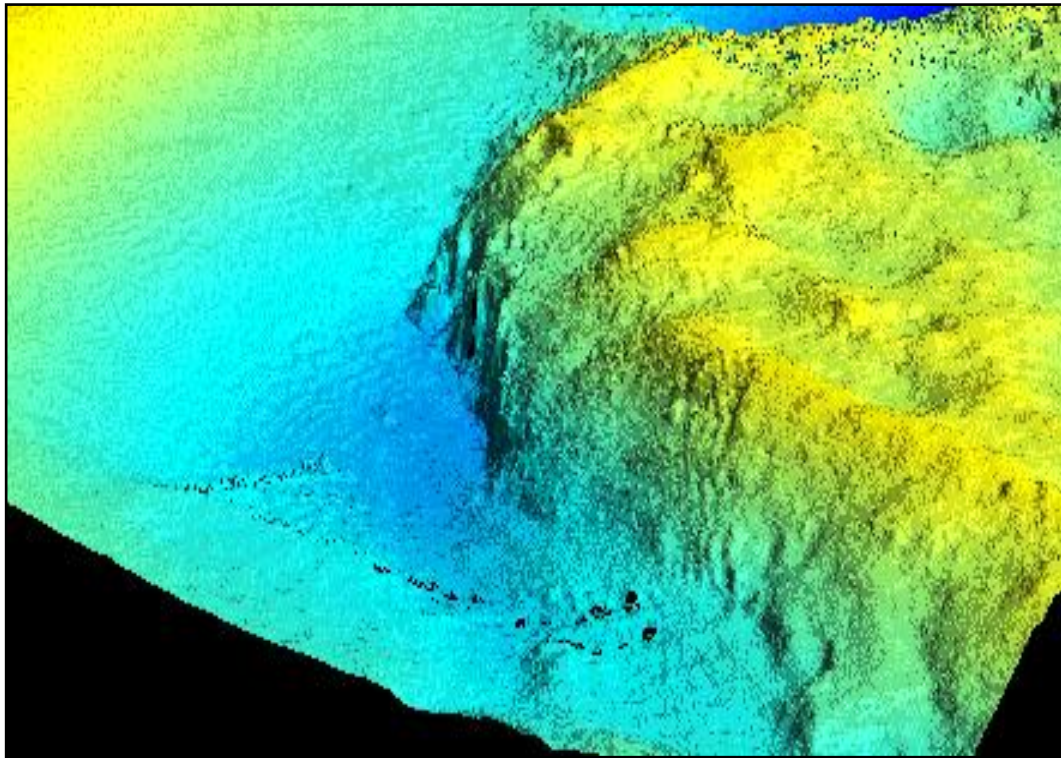
Figure 4.24. A reef in the Tauranga harbour entrance shows how MBES can image complex reef architecture.
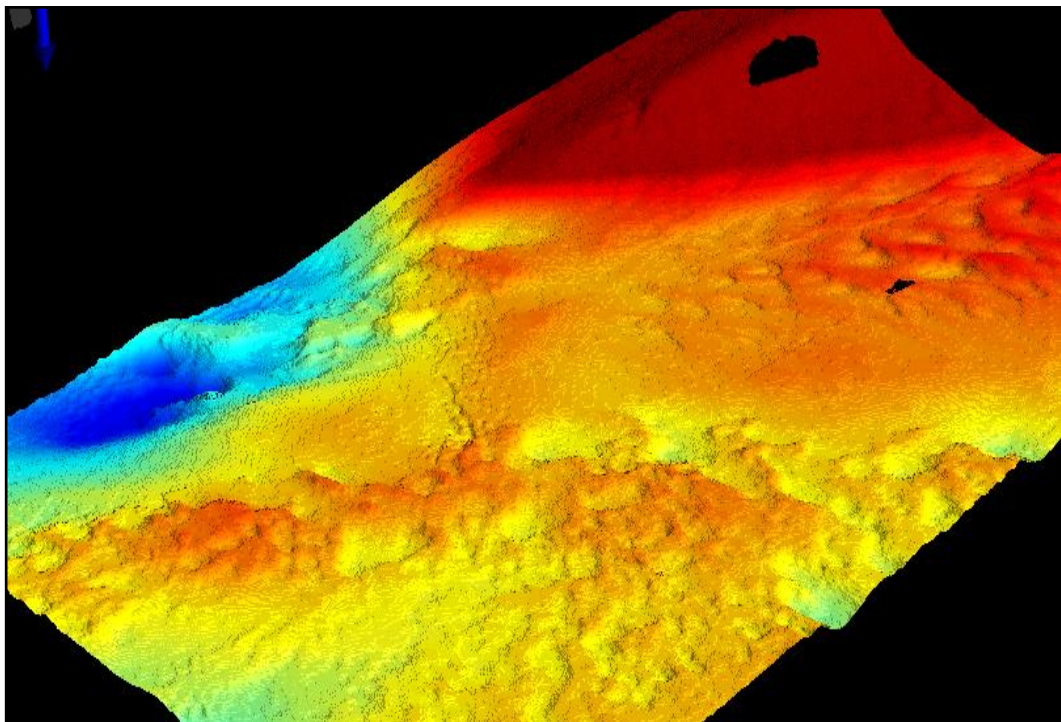
Figure 4.25. Bedforms are indications of current and sedimentary patterns, and can be accurately imaged in shallow water using MBES.
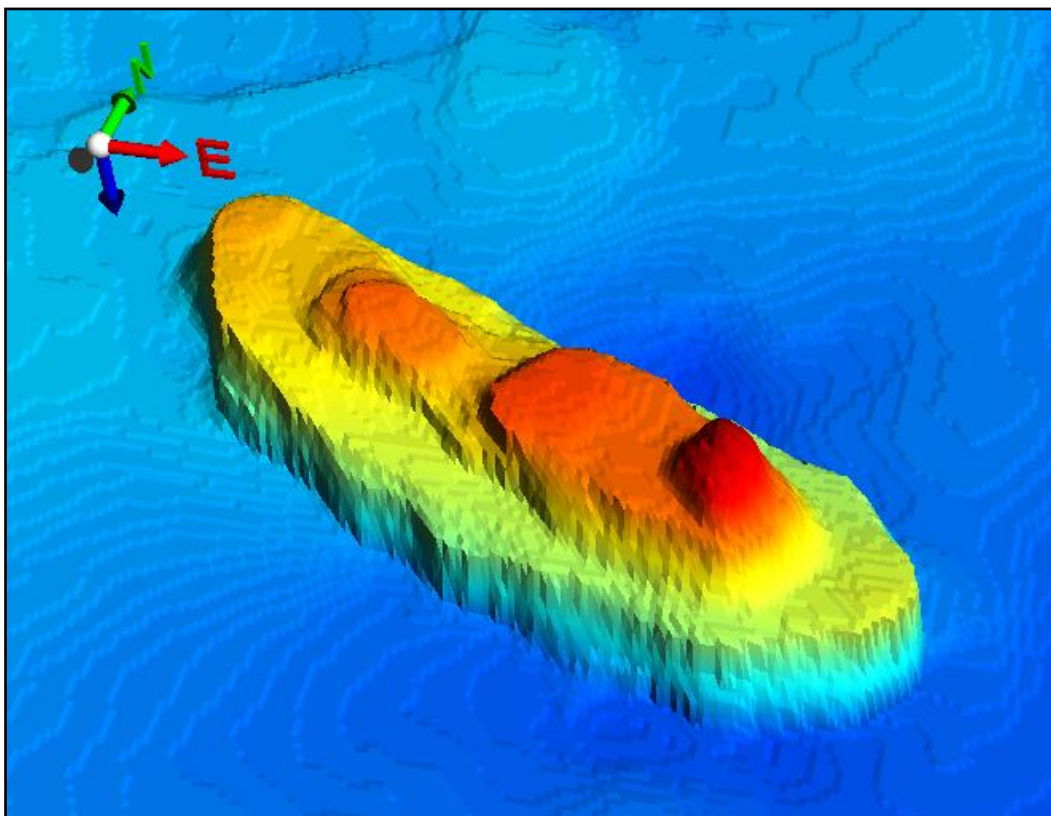
Figure 4.26. Taioma tug vessel submerged for diving offshore Motiti Island in the Bay of Plenty (New Zealand).

Another argument for MBES and LiDAR for charting surfing breaks is the efficiency. The Aramoana (New Zealand) surfing break was charted by KILPATRICK (2005) and the bathymetry (Figure 4.27) shows that there is no abrupt wave breaking features at the beach to create the high quality peeling waves. There is a slight curve in the beach contours but the surfing waves are mostly created by offshore wave focusing (SCARFE *et al.*, Chapter 3). The survey dataset is made up of 110 lines, 200 m long (22 km total distance), covering an area of 12 hectares. This created 8500 discrete soundings over the area with a spacing of 2.5 m along the survey line, at 5 m between lines. At a survey speed of 5 knots, this would take between 2.5 and 3 hours depending on the speed of turning and settlement time into each runline. The main study area of multibeam surveys for a surfing study by SCARFE (2008) was 88 hectares in size. This area took 17 lines, 1600 m long (27 km to distance) to cover with 50-60 % percent multibeam coverage. This area takes around 3 hours to survey at 5 knots, making it around seven times more efficient. Greater coverage is achieved and other information such as 3D relief and backscatter. Another advantage of the MBES is that shore parallel lines allow the shallows to be covered during high tide. The shore

perpendicular employed by KILPATRICK (2005) method gives good data to model the seabed profile but not all lines can be done at high tide. The northwest lines of the survey are able to go around 70 m shallower towards the beach than the southeastern lines because of the lower tide level when surveying the southeastern area. A drawback of the MBES is that archiving, visualising and analysing the soundings requires a lot more effort, as discussed by SCARFE *et al.* (Chapter 5).
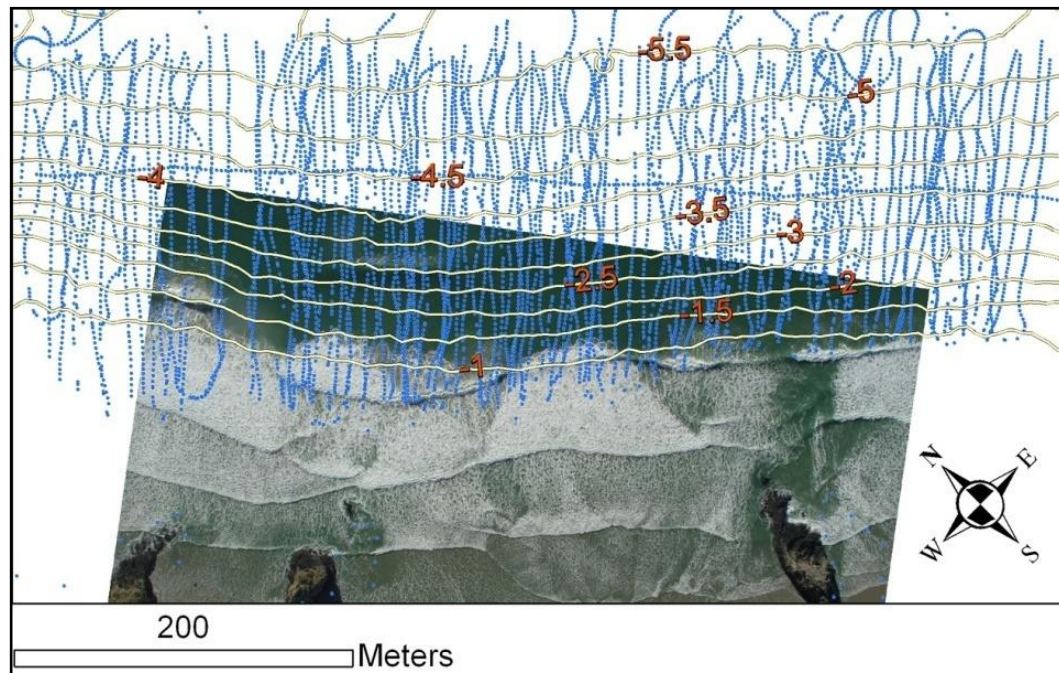
Figure 4.27. Depth contours and reliability diagram created for the Aramoana (New Zealand) surfing break from soundings by KILPATRICK (2005). Aerial photograph taken during a surfing event positions the surfing break by KILPATRICK (2005). The blue dots represent the SBES measurements.

CONCLUSIONS

The information presented in this paper is applicable to different types of environmental surveys. The discussion has used the application of surfing break charting to explain the survey process, which has slightly different aims and methods to traditional hydrographic applications. As already mentioned, the majority of the surveys are coastal process orientated, interested in features, morphology and processes. This means that often the surveys are more qualitative than quantitative and high relative accuracy is often more important than absolute accuracy.

For charting the shallow water environment, a SBES and MBES system has been developed and described. This includes detail on the use of RTK GPS that has not

been widely discussed. In order to quantify the accuracy of sounding dataset, a GIS method has been developed that can compare millions of soundings. To further control the quality of the datasets, the concept of bathymetric control points has been presented and was applied to the hydrographic datasets during monitoring of the Mount Maunganui artificial surfing reef. As well as accuracy, distribution of soundings is identified as important metadata to include with environmental survey datasets. The navigational chart idea of a reliability diagram is suggested as a method for communicating sounding density.

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Chapter 5 - An Approach to Hydrographic Data Management using Customised GIS Applications and Geodatabases

PREFACE

Chapter 3 identified various environmental data types that can be used to understand oceanographic processes around surfing breaks. Environmental data needs to be archived, processed, visualised and interpreted to make informed coastal management decisions. Geographic Information Systems (GIS) was highlighted in Chapter 3 as a key technological tool in assisting with this process and bathymetric data was identified as an important environmental data type. Although this chapter focuses on bathymetry, the method can be applied to the other environmental data types identified in Chapter 3, to manage and protect surfing breaks.

This chapter contributes to achieving the follow objectives outlined in Chapter 1:

4. *to develop improved methods for charting surfing breaks, including the management of relevant environmental data.*

6. *to demonstrate the potential of Geographic Information Systems (GIS) overlay, geoprocessing and geodatabase techniques to store and analyse information for management of surfing amenity.*

HEALY and RENNIE have been involved in an editorial and supervisory nature with this paper, and BROOKS undertook the computer programming for the application development, as well as provided input into the design of the geodatabase schema and development framework. The paper is going through a peer-review process and the current citation is:

SCARFE, B.E., HEALY, T.R., RENNIE, H.G., and BROOKS, S., *in press.* An Approach to Hydrographic Data Management using Customised GIS and Geodatabases. Submitted to the *Hydrographic Journal,* 19 Dec 2007.

ABSTRACT

A Geographic Information System (GIS) approach is used here to archive, process, visualise and analyse hydrographic soundings and metadata, including the development of a custom GIS application. The GIS method uses ArcGIS Desktop v9.2 with an ArcSDE geodatabase running on a SQL Server 2005 database management system (DBMS). The client-server computer architecture allows the storage, backup and distribution of soundings to be undertaken by more powerful server computer, while visualisation and analysis of the data is undertaken by the client computers. The GIS solution can be integrated within other GIS and software over a network or via the internet. Soundings can be searched, identified, edited, exported or converted to new data products from within client GIS software. The GIS method prototyped here shows potential for disseminating soundings to a number of uses, and future research will need to optimise the GIS performance.

INTRODUCTION

It is widely accepted that multibeam echo sounders (MBES; Hughes-Clarke *et al.*, 1996; Mayer, 2006) and Light Detection and Ranging (LiDAR; Brock *et al.*, 2002; Guenther *et al.*, 2002; Moyles *et al.*, 2005; Young and Ashford, 2006) create data management issues. The issue of modern hydrographic data processing and management is subject to much discourse in the literature, including processing methods and hydrographic data formats. This includes Allen and Ferguson's (2005) review of experiences with the National Oceanic and Atmospheric Administration (NOAA), the U.S. Naval Oceanographic Office's (NAVOCEANO) data problems (Depner *et al.,* 2002; Cronin *et al.,* 2003), and Gareau *et al.*'s (2003) of the scope of the hydrographic data management problem.

The hydrographic management system developed here has been used with data collected by the Coastal Marine Group (CMG; Department of Earth and Ocean Sciences) of the University of Waikato (New Zealand). The MBES, fully described in Scarfe *et al.* (Chapter 4), was purchased in 2003 and it quickly became apparent that a single computer could not undertake all the tasks required for a hydrographic data management system. Although the techniques used in this study apply to all terrain measurements methods (LiDAR, photogrammetry, GPS, etc), the present research is focused specifically on data from MBES.

Since various acronyms are used in this paper, Table 5-1 summarises definitions for ease of reading. Objectives of the current research are to:

 (i)   design an approach to store echo sounder survey data and metadata;
 (ii) design geographic processing methods to transform soundings to archived data products; and
(iii) develop a prototype application to automate the creation of data products, and maintenance of metadata.

Table 5-1. Table of acronyms used in paper.

GIS	Geographic Information System
ArcGIS	Commercial GIS product
ArcSDE	Commercial server-based GIS storage software
DBMS	Database Management System
MBES	Multibeam Echo Sounder
SBES	Singlebeam Echo Sounder
LiDAR	Light Detection and Ranging
NOAA	National Oceanic and Atmospheric Administration
NAVOCEANO	U.S. Naval Oceanographic Office
CMG	The University of Waikato's Coastal Marine Group
CUBE	Combined Uncertainty and Bathymetric Estimator
ESRI	Environmental Systems Research Institute
LINZ	Land Information New Zealand
FGDC	Federal Geographic Data Committee
XML	Extensible Markup Language
ISO	International Standards Organisation
FGDC ESRI	Federal Geographic Data Committee ESRI metadata format
S-57	IHO digital hydrographic exchange format
R.A.N.	Royal Australian Navy
BAG	Bathymetric Attributed Grid
S.A.I.C.	Science Applications International Corporation
ArcIMS	Commercial GIS image server
RAID	Redundant Array of Independent Drives
SATA	Serial Advanced Technology Attachment
NZMG	New Zealand Map Grid coordinate system
NZGD2000	New Zealand Geodetic Datum 2000

HYDROGRAPHIC GIS METHOD

HECHT (2000; p.71) defined geographic information as "an information entity providing a qualitative description of a location together with a quantitative, measureable geographic reference containing positional and topological information, and its relationships to other geographic information entities." Geographic Information Systems (GIS), utilising geographic information, are key tools when building a successful environmental data management system. A "GIS is the combination of skilled people, spatial and descriptive data, analytic methods, computer software and hardware, all organised to automate, manage and deliver information through a geographic presentation (ZEILER, 1999; p. 46)". Real world spatial relationships are the defining characteristic of a GIS and a sound GIS system can provide the basis for spatial modelling and simulation. Here the focus is the development of environmental data management systems.

Although several software vendors provide solutions for many components of a hydrographic work flow, GAREAU *et al.* (2003) found management of hydrographic information and metadata to be less well supported. To fill this void, GIS has been discussed in various hydrographic papers to complement off-the-

shelf software and to extend data management and analysis capabilities (Table 5-2). GIS is not limited to data management and Cronin *et al*. (2003) also say that to effectively plan a survey operation, hydrographers must have the capability of visualising survey information in a GIS-like environment. GAREAU *et al.* (2003) proposed that data can be managed using the strengths of disparate systems and data sources using dedicated or *ad hoc* methods, and GIS has the capability to undertake a central management role.

Table 5-2. Research identified and reviewed on hydrographic GIS.

FURNESS and HALLS (1989)	BOBBITT *et al.* (1997)
FALCONER (1990)	GOLDFINGER *et al.* (1997)
KALL (1991)	BOURGEOIS *et al.* (1999)
KOO (1991)	HECHT (2000)
MASSON (1993)	CRONIN *et al.* (2003)
WENTZELL (1995)	MILLETT and EVANS (2003)

Data processing and management at NAVOCEANO are being addressed on a number of fronts as it is predicted that the volume of data will continue to exponentially increase (DEPNER *et al.,* 2002; CRONIN *et al.,* 2003). This includes computer hardware and software improvements and the use of area based editing (DEPNER *et al.,* 2002; CALDER and SMITH, 2004). In this context, area based editing is an automatic MBES processing method that attempts to address concerns of efficiency, objectivity, robustness and accuracy using the Combined Uncertainty and Bathymetric Estimator (CUBE) method (CALDER and MAYER, 2003; CALDER, 2003). The CUBE method was applied to assess the accuracy of the CMG MBES in McRAE (2007). Spatial data infrastructure (SDI) is a commonly used phrase to describe the hardware and software used to store geographic information (LONGHORN, 2005). The SDI needs to enable the sharing of information between different stakeholders as diverse as health epidemiologists, geological surveyors, air traffic controllers and coastal managers (LONGHORN, 2005). A hydrographic example showing GIS analysis of coastal morphology is included in WHEELER and PETERSON (2007).

The premise behind the design of the GIS system used in this research is the potential for use of a DBMS and a distributed computer network (client/server). This arrangement is recommended by ZEILER (1999) for large scale, multiuser GIS. A distributed computer network is a collection of computers set up with

client-server architecture, connected in a manner that can potentially communicate with any other system (SHELDON, 2001). The internet is another example of a distributed computer network. The web browser is a web-client application that connects to servers in geographically diverse locations through telecommunication networks. Distributing the work load of computers is also undertaken by NAVOCEANO and the sensor, computer and networking configurations used by two NAVCOEANO survey vessels are shown in CRONIN *et al.* (2003).

In a client/server system the distribution, backing up and updating of the data is the responsibility of the server, which usually has more processing power, storage and memory capabilities than the lower specification client computers, as well as server grade hardware (e.g. faster hard drives). This allows the resources of the client computer to focus on the core application of visualising, querying, processing and discovering data on the server, as well as to integrate with other software applications concurrent to the GIS.

The considerations for deploying a GIS using ArcGIS technology are listed by PETERS (2007) as:

1. understand the technology;
2. GIS user requirements;
3. system architecture design;
4. system development;
5. prototype function testing;
6. initial system deployment;
7. system performance testing; and
8. production deployment.

The present research has successfully completed the first 6 stages of GIS development, with some progress on the system performance testing. PETERS (2007) described the system architecture of a GIS as comprising various links in a chain. A weakness in any link in the chain will lead to a loss in performance. For example, using a 54 K wireless network may limit performance when large volumes of network data are being transferred. Replacing this network with a 1 GB connection that uses network cable will likely reduce/remove network bottlenecks.

The components identified by PETERS (2007) are:

- servers

- network

- database management system (DBMS)

- geodatabase

- storage

- clients

- ArcSDE

- applications

The configuration of components that comprise the GIS designed in this research is shown in Figure 5.1. The ArcGIS environment is used to achieve the research objectives because of its ability to integrate with a database management system (DBMS), geoprocessing capabilities, and the enterprise level development tools. Geoprocessing is the ArcGIS term for "a GIS operation used to manipulate data" by performing "an operation on a dataset, and returning the result of the operation as an output dataset (ESRI, 2006, p.115; WADE and SOMMER, 2006, p. 89)". In this context, enterprise level GIS is a system that integrates many users to manage, share and use spatial data and related information for a variety of needs including to create, modify, visualize, analyse and disseminate information (WADE and SOMMER, 2006). The system consists of a Microsoft SQL Server 2005 DBMS (WATT, 2006) with an ArcSDE spatial database engine to convert the non-spatial DBMS to a multi-user, versioned, ArcGIS geodatabase (described below). SQL Server 2005 is a multi-component relational DBMS centred around a high-performance database engine (WATT, 2006). ArcSDE is an application server for storing and managing spatial data as rows and columns in database tables, within the DBMS. The DBMS structure allows the ArcGIS client software (e.g. ArcClient, ArcMap, ArcScene, ArcGlobe) to access the data as raster imagery, point, line, polygons, metadata and other data formats more fully described in ZEILER (1999) and ESRI (2006). ArcSDE uses cooperative processing where data is processed by both the client application and the ArcSDE server (ESRI, 2005).
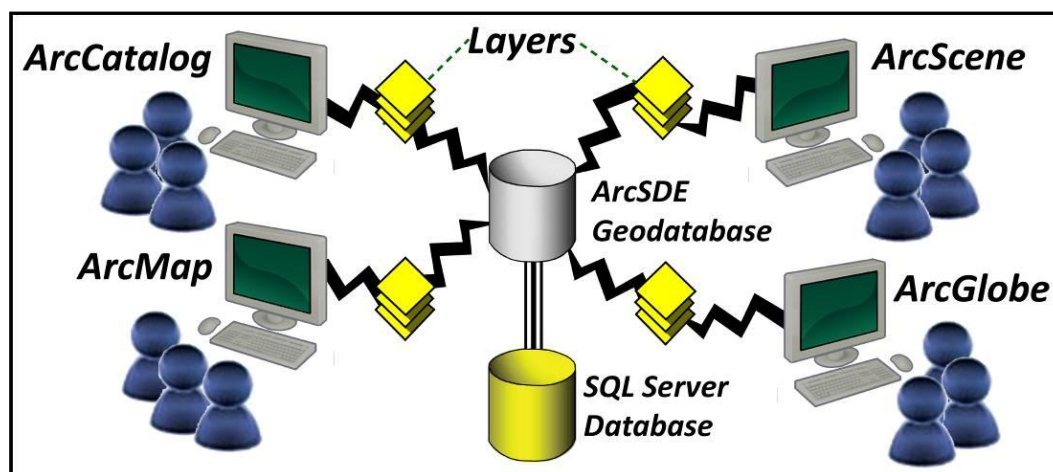
Figure 5.1. Configuration of the hydrographic GIS. Data is stored in an SQL Server 2005 DBMS (yellow) using an ArcSDE spatial database engine to convert the DBMS to a geodatabase (grey). The geographic data is viewed using an ArcGIS client software (e.g. ArcCatalog, ArcMap, ArcScene, ArcGlobe) with settings for querying and symbolising geographic information stored in Layers (yellow squares).

Each of the ArcGIS client software applications in Figure 5.1 can be used to view, edit and manage data within the geodatabase. The underlying DBMS handles the user permissions for access to the database, and different user roles can be assigned. Data within the 2D mapping client (ArcMap) and the 3D visualisation clients (ArcScene, ArcGlobe) are held in a "container" called a data frame (ESRI, 2006). Within the data frame various ArcGIS "Layers" (*see* ESRI, 2006) reference a data source, in this case in a geodatabase. The "Layer" is a view, or query to the geodatabase that stores various geographic and tabular datasets. "Layers" store display, symbolise and take advantage of spatial querying functionality for geographic data. These are ideal for filtering subsets of data from an enterprise level geodatabase.

Data Formats

LONGHORN (2005) suggested a coastal SDI needs to be developed within larger regional and national SDI. While this would depend on the nature of the application, it appears generally valid for hydrographic data as there are numerous hydrographic exchange formats and data strategies that must be considered. Some data formats are published in an open source form, while others are propriety to specific software or organisations. Additionally, various metadata standards exist to describe geographic datasets. Metadata are units of information about information and are used to provide descriptions of the content, context and

characteristics of data (LINZ, 2004a). Metadata is commonly stored in relational databases, as ASCII or binary files, documents, reports or in an XML format. The major uses of metadata identified by the Federal Geographic Data Committee (FGDC, 1998) are to:

  (i)   maintain an organisation's internal investment in geospatial data;

 (ii)   provide information about an organisation's data catalogues, clearinghouses, and brokerages; and

(iii)   provide information needed to process and interpret data received from an external source.

In a networked environment metadata describes and tracks changes to geographic data sets, and maintains the value of data as it is transferred to other users by conveying the nature of the data sets (LINZ, 2004a), including accuracy. Information in metadata broadly falls into the following categories:

  (i)   *What* – title and description of the data set;

 (ii)   *When* – when the data set was created and the update frequency;

(iii)   *Who* – data set originator or creator and supplier;

(iv)   *Where* – the geographic extent of the data set based on coordinates, geographic names, or administrative areas; and

 (v)   *How* – how to obtain more information about the data set, order the data set, available formats, access constraints, etc (LINZ, 2004a).

It is important to review existing metadata standards to use metadata in the most scaleable manner and within existing data frameworks. This saves investment in development of metadata attributes and allows better interoperability. Various important geographic metadata standards identified for the development of a hydrographic database within the New Zealand context are:

- FGDC digital geospatial metadata standard (FGDC, 1998);
- FGDC ESRI digital geospatial metadata standard (ESRI, 2003);
- ISO (2003 and 2007) geographic metadata standards;
- LINZ geographic metadata standard (2004a and b); and
- LINZ's hydrographic metadata standard (LINZ, 2002).

Although other standards exist, the ISO (2003) standard is perhaps the governing document for large scale (multi-country, multi-discipline) geographic metadata. Also important is the FGDC standard (FGDC, 1998) as it has been in use for a

number of years, and many attributes and concepts have been carried through to the ISO (2003) standard. Within the ArcGIS environment various metadata formats are supported and a variation on the FGDC standard (FGDC ESRI) is implemented within the software (ESRI, 2003). The LINZ (2004a and b) standard is built on the ISO (2003) standard, with the addition of attributes relevant to the New Zealand context.

Even though data in the prototyped GIS will be stored in a geodatabase, the source hydrographic data may come in various formats and will first need to be migrated into the geodatabase. The source data can be ASCII-based, binary, databased, open source, or in a proprietary format accessible only through use of specific software. Preserving data standards is the fundamental task in creating a data management system. Hydrographic data standards need to be identified when migrating between data formats and various formats include:

  (i)   S-57 (IHO, 2000);

 (ii)   Hydrographic Transfer Format (R.A.N., 2001);

(iii)   Navigation surface concept (SHEPARD and SMITH, 2003; ARMSTRONG *et al.,* 2004);

(iv)   Bathymetric Attributed Grid (BAG) open source navigation surface (BRENNAN *et al.*, 2005);

 (v)   Generic Sensor Format (FERGUSON and CHAYES, 1995; S.A.I.C, 2003); and

(vi)   Propriety software formats (ArcGIS, Surfer, Triton Imaging Inc., HYPACK, CARIS etc).

The navigational surface concept is an important data format concept to discuss in the context of hydrographic information. It has been developed to improve management, archiving, speed of processing of hydrographic data, and to allow creation of data products (ALLEN and FERGUSON, 2005). The concept has been adopted in the Open Navigation Surface Project by BRENNAN *et al.* (2005), which provides open source tools for the use with the BAG navigational surface format. With the navigational surface approach, survey data are archived as a certified digital terrain model rather than validated echo soundings (ARMSTRONG *et al.,* 2004). The use of navigational surfaces reduces the amount of data that needs to be manipulated by hydrographers by allowing targeting of areas with higher statistical uncertainty (ALLEN and FERGUSON, 2005). Subsequently charting

products are created from scale-appropriate generalizations of the elevation model (ARMSTRONG *et al.,* 2004). A navigation surface is integrated into the hydrographic processing software CARIS HIPS and SIPS, based on work by SMITH (2001 and 2003, *in* ARMSTRONG *et al.*, 2004) and SMITH *et al.* (2002, *in* ARMSTRONG *et al.*, 2004). In CARIS the navigational surface is known as a Bathymetry Associated with Statistical Error (BASE) surface (ALLEN and FERGUSON, 2005). An early application of the navigational surface method combined different data types including MBES, singlebeam echo sounders (SBES) and lead line survey data and is presented in SHEPARD and SMITH (2003).

GIS GEODATABASE DESIGN

GIS represents the real world by modelling natural features and processes using specific geographical data types (ZEILER, 1999). Rivers are modelled either by using line features denoting the river centreline, or by using polygon features representing the river boundary. A geodatabase is an object-orientated data model "that represents geographic features and attributes as objects and the relationships between objects, but is hosted inside a relational DBMS" (ESRI, 2004a; p.115). A geodatabase data model helps categorize and structure various environmental data types so that they can be represented in ways invaluable for decision making (WRIGHT *et al.*, 2007). The object-orientated method is preferred to file-based methods because geographical features are entities and can interact with other geographical entries by building complex relationships (WRIGHT *et al.*, 2007).

Geodatabases in ArcGIS (fully described in ESRI, 2006) can be managed at four levels: Personal (Microsoft Access Jet DBMS; 2.1 GB size limitation), File-based (file structure, 1 TB size limit), Workgroup ArcSDE (Microsoft SQL Server Express DBMS) and Enterprise ArcSDE (various DBMS options; geodatabase size limit is the DBMS size limit). ArcSDE geodatabases support versioning and multiple user simultaneous editing. An advantage of using a geodatabase format is that the model includes a framework to create intelligent features that mimic interactions and behaviours of real-world objects (ZEILER, 1999). This idea is further developed in WRIGHT *et al.* (2007) for marine data.

Using Enterprise Geodatabase system administration some tasks are managed directly by the DBMS including delivering and backing up data, reporting and database maintenance. Making use of a DBMS allows ArcGIS software to take

advantage of developments in DBMS technology (ZEILER, 1999) such as replication. Although ArcGIS is interoperable with many data formats, the most flexibility, efficiency and best data integrity is achieved using geodatabases. With the proposed GIS design, the hydrographic data is live and accessible at all times, even when it is being edited. It can be copied or distributed over a network or the internet (with the addition of ArcIMS or ArcGIS Server *see* ESRI, 2006).

The main file-based hydrographic database of the CMG is currently stored on a server with RAIDed hard drive technology and backed up with tape drives. A schema for folders has been adhered to since the purchase of the CMGs MBES, and thus the data is secure and partially self documenting because of the folder structure. However, overtime the project based folder management method is becoming a fragmented array of datasets with limited searching and visualising capabilities. The geodatabase approach provides a consistent, scalable and seamless data schema with data access capabilities. Mapping visualisation using the DBMS approach overcomes many of the problems with the current file based method, and eleven major benefits of geodatabases to the hydrographic community and these are covered in MILLET and EVANS (2003).
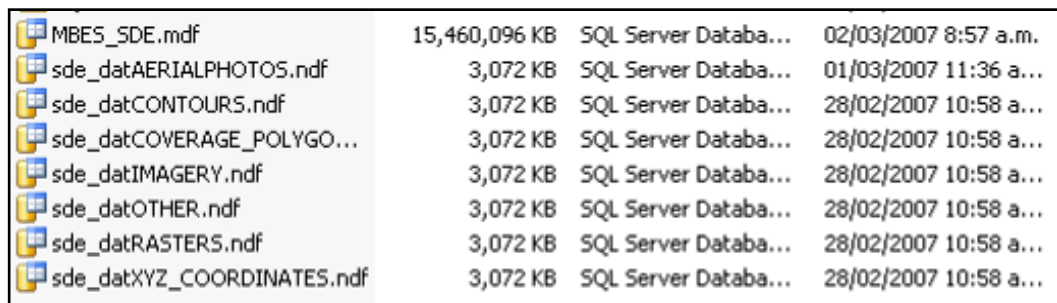
When using an ArcGIS geodatabase, different generic data models can be used when designing a geodatabase (MOREHOUSE, 1999). They are:

 (i)   cell based or raster representation;

 (ii)   object-based or feature-based representation;

 (iii)   network or graph-element representation; and

 (iv)   finite-element or TIN representation.

Various data formats can be used to model a bathymetric or topographic surface including raster, TIN and "terrain" formats. "A raster is a regularly spaced matrix of cells that may have associated attribute information: (ZEILER, 1999; p.38). A triangulated irregular network (TIN) method efficiently represents a surface by varying the data density depending on the complexity of the "terrain" (ZEILER, 1999; p.41). A discussion on the two methods for MBES processing is covered in DE WULF *et al.* (2007). The "terrain" format is a multi-resolution storage TIN contained in a geodatabase, based on features within a feature dataset (ESRI, 2006). Data formats of use in terrains are point, multipoint, polyline, and polygon feature classes. "Terrains" are a new data storage type with ArcGIS v9.2 and

multiple types of data interact to create multi-resolution TINs. As the user zooms in and out, only the current display extent, at a predetermined resolution, is provided to the ArcGIS client applications. The different formats are further described in ESRI (2006) and within the comprehensive ArcGIS software help. Terrain will only support visualisation of data and further analysis will require the data to be converted to a raster or TIN surface.

The geodatabase can be viewed at different levels. At the file-based level, the SQL Server 2005 DBMS data files can be seen in Figure 5.2. The main database file (*.mdf) can have additional files (*.ndf) to span the database over several drives with different data types in each file. A database transaction log file (*.ldf) also exists. In this case, the data is stretched over a RAIDed SATA array of hard drives to access the data quickly. The DBMS stores numerous types of information including tables (Figure 5.3; left image), stored procedures and views. The geodatabase level view can be seen in Figure 5.4 and an array of supported data formats can be previewed, geoprocessed and managed using ArcCatalog. Figure 5.5 shows the top level GIS map view of MBES and SBES overlaid on a geodatabased aerial photograph, queried using "Layers".

MBES_SDE.mdf	15,460,096 KB	SQL Server Databa...	02/03/2007 8:57 a.m.
sde_datAERIALPHOTOS.ndf	3,072 KB	SQL Server Databa...	01/03/2007 11:36 a...
sde_datCONTOURS.ndf	3,072 KB	SQL Server Databa...	28/02/2007 10:58 a...
sde_datCOVERAGE_POLYGO...	3,072 KB	SQL Server Databa...	28/02/2007 10:58 a...
sde_datIMAGERY.ndf	3,072 KB	SQL Server Databa...	28/02/2007 10:58 a...
sde_datOTHER.ndf	3,072 KB	SQL Server Databa...	28/02/2007 10:58 a...
sde_datRASTERS.ndf	3,072 KB	SQL Server Databa...	28/02/2007 10:58 a...
sde_datXYZ_COORDINATES.ndf	3,072 KB	SQL Server Databa...	28/02/2007 10:58 a...

Figure 5.2. File system view of the SQL Server 2005 DBMS (*.mdf, *.ndf, and *.ldf) where the geodatabase resides.
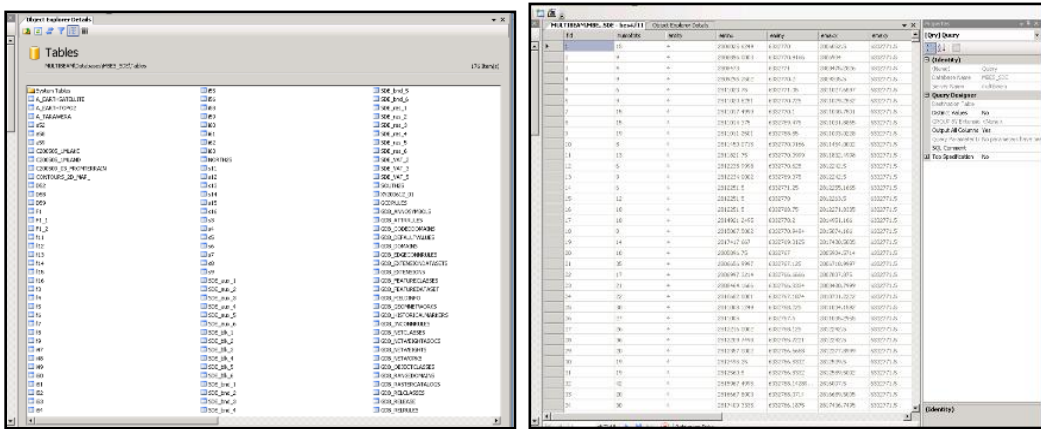
Figure 5.3. SQL Server 2005 DBMS view of the geodatabase.

Name	Type
MBES_SDE.BES4.A_TARAWERA	SDE Raster Catalog
MBES_SDE.BES4.CONTOURS_MOT	SDE Feature Dataset
MBES_SDE.BES4.MBES_2005EBOP09	SDE Feature Dataset
MBES_SDE.BES4.A_EARTHSATELL…	SDE Raster Dataset
MBES_SDE.BES4.A_EARTHTOPO2	SDE Raster Dataset
MBES_SDE.BES4.CONTOURS_2D_…	SDE Raster Dataset
MBES_SDE.BES4.NORTH25	SDE Raster Dataset
MBES_SDE.BES4.SOUTH25	SDE Raster Dataset
MBES_SDE.BES4.XY200612_01	SDE Feature Class

Figure 5.4. ArcSDE Geodatabase view using ArcCatalog to show a combination of rasters, raster catalogs, feature class's, and feature data sets.
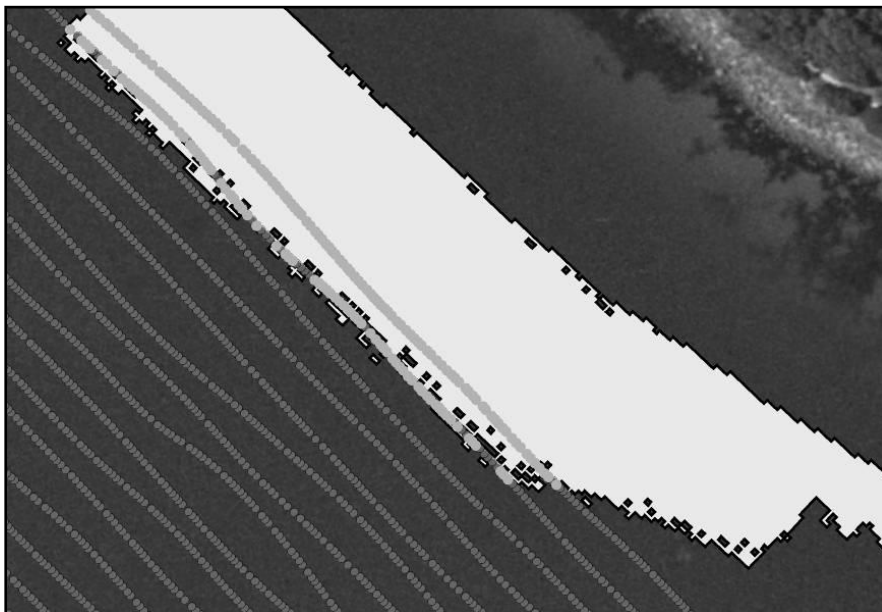
Figure 5.5. ArcMap view showing an aerial photograph, SBES and MBES coverage from the geodatabase.

Relational Metadata Database Schema

For this project individual metadata attributes are contained within a relational metadata database, enabling relationships and joins between the metadata and the geographic data within a geodatabase. Although various well research and designed hydrographic metadata standards exist, a relational metadata database schema suits the current hydrographic workflow of the CMG. As this is a prototype project, the metadata only aimed to store pertinent information about the soundings for the purposes of the CMG. Evolving the metadata to match existing hydrographic and geographic metadata standards would be part of future work if the project is further developed. Storage of metadata as XML, within a geodatabase, is another possible future option. The current metadata database still provides information on the origins and quality of the soundings information, previously not easily obtained for the Coastal Marine Group's hydrographic data.

The relational metadata database was prototyped initially in Microsoft Access 2000 for ease of development at the time. The Access database was then migrated to SQL Server 2000 for further refinement. The metadata describes information relating to a hydrographic dataset including the survey vessel, datum, region, GPS, survey cruise, geoid model, measurement method, organisations involved, personnel and coordinate system. The database schema is normalised to second normal form and includes relationships between table attributes. The normalisation process reduces the amount of redundant data that is stored in the database. Metadata for geographic datasets can be retrieved using joins and relationships to common indexed, integer attributes.

Geodatabase Schema

ArcGIS is collaborating with academia and industry to create ArcGIS geodatabase schema that can be used with specific industries as an initiative to promote and support geodatabase standards. Currently there are 31 existing data models with the ArcMarine model and the S-57 standard for Electronic Navigational Charts being of immediate interest to this development. Additional models of interest for marine applications are hydro, groundwater, climate and weather, and petroleum (WRIGHT *et al.*, 2007). These data models can be used as a base for geodatabase schema design and modified to suite a specific application. The benefits of using the marine data model are outlined in WRIGHT *et al.* (2007).

The geodatabase schema utilised here is based on the ArcMarine model. The model contains 14 features, 16 tables and 13 relationship classes to model a variety of coastal and deepwater data sources (Table 5-3). The primary purpose of this project was to archive a sounding, or interpolated sounding grid, and thus the bathymetry and backscatter data type is of most interest. Specifically, the sounding is stored in a point feature class called SurveyPoint, which is fully described in WRIGHT *et al.* (2007). The X, Y coordinates are stored in geometry table of the feature class, with the Z value being stored as an attribute of the point called ZValue. CruiseID attribute is used to relate the feature to the relational database table Cruise. Additional attributes have been added to the ArcMarine scehma (FileID and RegionID) to provide further linkages to the relational database and additional integer attributes for indexing.

Table 5-3. Marine data types of ArcMarine data model (*adapted* from WRIGHT *et al.*, 2007).

Data Type	*Feature Type*
Shorelines	polyline feature class
Tracks and Cruises	polyline feature class
Time Durations Features	polyline and polygon feature class
Time Series Locations	point feature class
Instantaneous Measured Points	point feature class
Location Series Observations	multipoint and polyline feature class
Survey Transects	polyline feature class
Scientific Mesh	point feature class
Mesh Volumes	polygon feature class
Bathymetry and Backscatter	raster, TIN, "terrain" or point feature class

Geodatabase performance can be improved using both attribute and spatial indexing (ESRI, 2006). The spatial index is used to retrieve features within a feature class by referencing the underlying grid cells where the features are stored. ArcSDE "accesses spatial data based on highly efficient spatial search functions, provides geometric data validations, and works with heterogeneous hardware and network environments (ESRI, 2005; p.30)." The SoundingPoint schema used here has indexing on the integer OBJECTID, ZValue, CruiseID, FileID and RegionID

attributes giving numerous options for tuning the speed of the DBMS, including clustered indexing at the DBMS level. The use of attribute indexing helps to filter features where the search criteria can be applied to millions of features.

Currently data is primarily stored in New Zealand Map Grid (NZMG), with various data sources in other projections. NZMG grid was initially used because of its interoperability with collaborative organisations and use of NZMG aerial photographs as key georeferencing information. ArcGIS has the ability to project data on the fly, and simultaneously displaying or geoprocessing datasets from different coordinate systems. However, for the New Zealand context, a geographic coordinates system such as NZGD2000 (based on WGS84; GRANT and BLICK, 1998) is a preferred option and existing data could be reprojected as part of a migration to a production environment. Using a geographic coordinate system will overcome any distortions caused by a projected coordinate system and is a more modern datum.

The main datasets created and stored in the geodatabase are point soundings, a cell-based raster of binned soundings, a polygon representing the coverage of soundings and contours (Figure 5.6). Additionally, "terrain" datasets are used to create continuous digital terrain models of the survey data. 2D and 3D images of MBES "terrain" datasets are shown for the Mount Maunganui (New Zealand) artificial surfing reef (Figure 5.7) and Lake Tarawera (New Zealand; Figure 5.8). The different datasets enable survey data to be located and viewed on a globe or map, exported or geoprocessed. Viewing large quantities of soundings can be slow, particularly in viewing 3D, and the different dataset types can speed up the searching and visualisation datasets for different viewing scales and dataset sizes.

Figure 5.6. Images of geodatabased MBES data products for a canal development in Whitianga (New Zealand). Clockwise from top left: SoundingPoint feature class, cell-based raster, sounding coverage and contours. The soundings are filtered to display only every 5th point, and this can be set to vary with viewing scale using "Layer" settings.
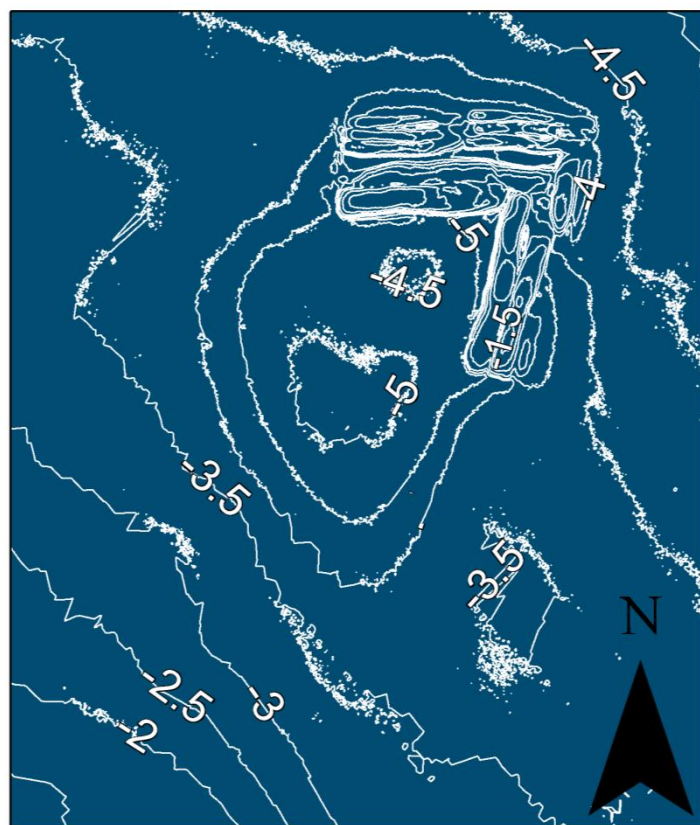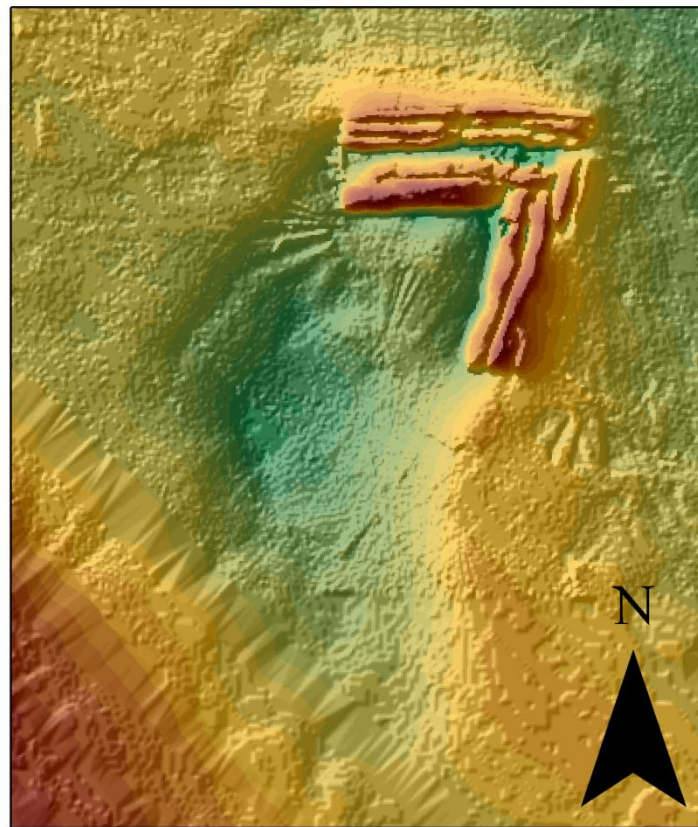
Figure 5.7. Shaded surface and contours of Mount Maunganui (New Zealand) artificial surfing reef (January 2007; 70 % complete) created from interpolated "terrain" data. Datum is meters below mean sea level.
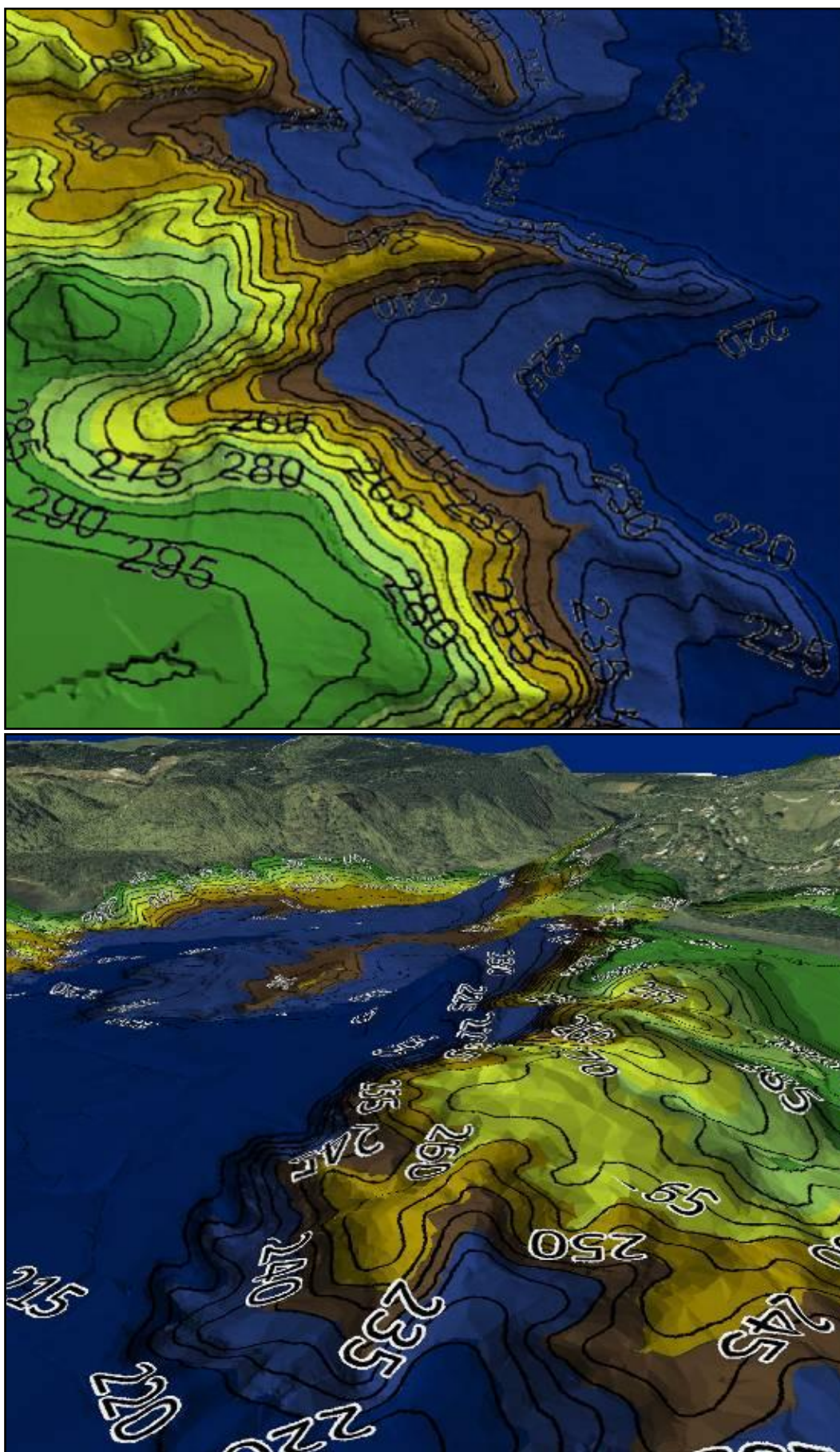
Figure 5.8. 3D view of combined topography and multibeam bathymetry of Lake Tarawera (New Zealand) from a 22 million point "terrain" dataset. Datum is meters above mean sea level.

MODELBUILDER^{TM} AUTOMATION

Users can work with ArcGIS at a variety of levels:

  (i)   Point and click;

 (ii)   Model Builder;

(iii)   Scripting;

(iv)   ArcGIS customisation; and

 (v)   ArcEngine.

The most obvious and flexible level is the use of a mouse and keyboard (or graphical tablet) as this allows users' complete flexibility of the GIS work flow. Sometimes GIS geoprocessing tasks take time to complete and using the GIS at this level for multiple geoprocessing tasks is slow. When there are many quick, but repetitive geoprocessing tasks to undertake manual methods are not ideal and batch processing of GIS task needs to be undertaken. The strength of this method is in the ability to design ideal GIS workflows for repetitive tasks, or to undertake one off, or infrequent tasks.

Where there are tasks undertaken on a routine and repetitive basis, there is the opportunity to automate the task, or provide a more streamlined and customised work flow. When a repetitive task is identified, it can be incorporated into a "model" created with the graphical tool ModelBuilder^{TM} (Figure 5.9). Various definitions of model exist but this research refers to the ESRI (2006, p.40) definition which is a 'graphical way of creating and expressing a multistep process or method.' ModelBuilder^{TM} has been used here to design a geoprocessing algorithm for creating the geodatabase schema within an existing geodatabase. The graphical method has also been used to migrate soundings from text files to the various GIS data products presented in Figure 5.6 and Figure 5.7. Examples of additional models that have been used SCARFE (2008) are:

  (i)   Accuracy calculations between two data sets;

 (ii)   Merging of numerous data sets by deleting overlap and merging point feature classes; and

(iii)   Daily morphing interpolation between raster surfaces for animation of morphology.

Figure 5.9. ArcGIS ModelBuilder[TM] showing geographic data sets (blue), transformation process (yellow) and new GIS layers (green).

The migration of soundings and metadata to a GIS geodatabase, as well as creating derived GIS products, accuracy statistics and other validation routines can be a very long process. However, a lot of manual repetition undertaken during this process can be automated using ModelBuilder[TM]. ModelBuilder[TM] automation can minimise human error as self documenting geoprocessing routines enforce the integrity of the transformations. A model can now be saved in an ArcToolBox, within a folder or in this case a geodatabase, which enables all information to be centrally located for backing up. ModelBuilder[TM] has been used to automate various tasks including creation of the GIS products in Figure 5.6, Figure 5.7 and Figure 5.8. They have been made from a single text file after the setting of some model parameters. The process is has worked for file sizes in the scale of 10's of millions.

CUSTOM GIS APPLICATION

ArcGIS is made based on common libraries of shared GIS software components called ArcObjects (ESRI, 2004b). ArcGIS gives users control over these ArcObjects when using ArcGIS Desktop, ArcToolBox tools, or with a Component Object Model (COM) compliant scripting language (e.g. Python, VBA, Microsoft VisualStudio). Undertaking of repetitive tasks can be automated with ModelBuilder[TM], but more flexibility, speed and power can be found by customising ArcGIS clients (ArcMap, ArcScene, ArcCatalog and ArcGlobe), or creating standalone GIS applications with ArcGIS Engine. Models created and refined in ModelBuilder[TM] can be exported as Python, JScript or VBScript code and incorporated into the development. By developing custom GIS applications,

forms, wizards and menus can guide the user through the data management processes to minimise mistakes and make any manual steps as flexible and easy as possible.

A development has been undertaken here to show how a Microsoft VisualStudio application, accessing a SQL Server 2005 DBMS/ArcSDE server, can be run from within the ArcMap environment, including geoprocessing (Figure 5.10). The development environment chosen is ArcGIS Developer using Visual Studio 2005 but could have been any number of GIS products and development environments. The choice was made to use Visual Studio 2005 with Visual Basic.NET code because ArcGIS supports and interfaces well to the .NET framework. The .NET framework is a programming model for building applications in the Microsoft Windows environment. A primary aim of the development was to drive ArcObjects and VB.NET provides a simple, rapid way to do this, as the development environment is a higher level language than say C++. Visual Studio 2005 also interfaces seamlessly with SQL Server. All these factors reduced development time. Rapid development of the software can be achieved using the Visual Studio 2005 IDE form design by manipulating the .NET user interface components. These are then tethered to components that handle the business logic, or tasks of the application, which in turn is linked to separate data access components that handle the storage and retrieval from the database. The application undertakes the following tasks:

 (i)   Create empty relational metadata database;

 (ii)   Capture metadata and update relational metadata database (Figure 5.11); and

(iii)   Transform a directory of text files to various GIS data products (Figure 5.6) within geodatabase schema.
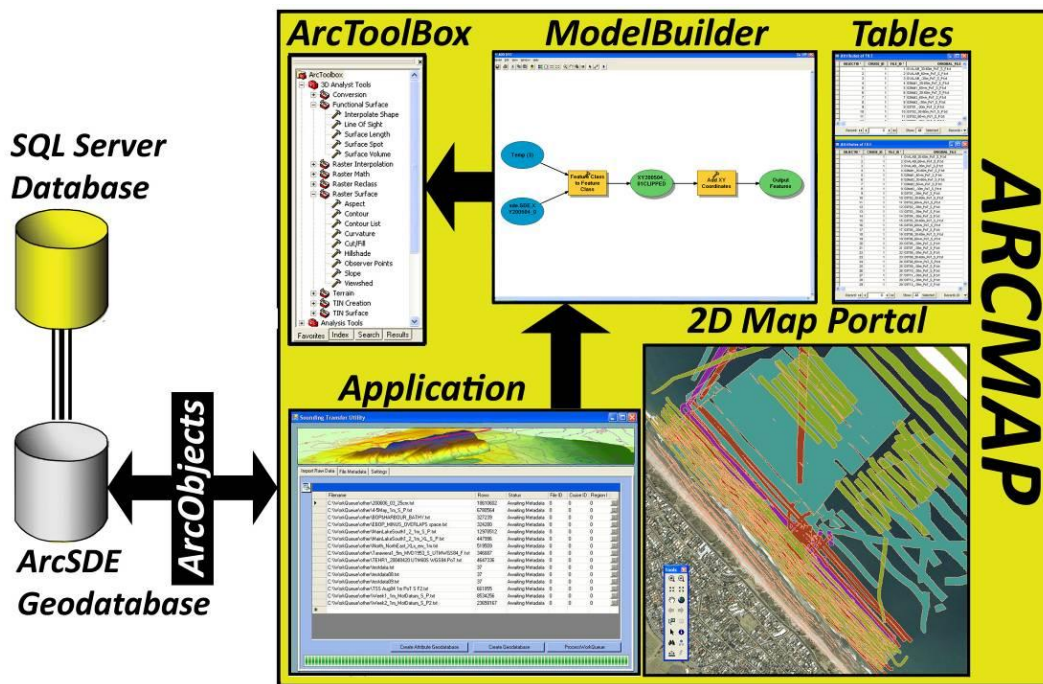
Figure 5.10. ArcToolBox tools geoprocess geographic data in the geodatabase, which is stored in the SQL Server DBMS. The ArcTools are driven by models created in ModelBuilder, and triggered by the ArcMap customised application.

Figure 5.11. Metadata forms created in VisualStudio.NET to facilitate population of the relational metadata database.

DISCUSSION

Limitations of the size of the hydrographic database and number of uses are dependent on the server hardware specifications. The current research would be a complement database such as "Taniwha", which holds hydrographic metadata for

Land Information New Zealand (LINZ, 2002). This GIS can be expanded depending on the quantities of data and the number of users. There will be a limit to the number of users, storage or processing throughput a single server can have. More servers can be added, including servers with specific roles (e.g. distributing aerial photography). This is referred to as a database cluster, and a series of database nodes distribute the workload between servers, and/or replicate data sets for increased data security. The cost of this performance and stability improvement is the extra cost of hardware and software (WATT, 2006). The system designed here can be further scaled to reach a wider audience including the use of web based GIS with the ArcIMS image server software. Geographic information on database clusters can be stored at geographically diverse locations, connected over the internet using ArcIMS. For large scale, well funded distributed computer GIS networks, client and server computers will have a specific role and task. For efficient use of computer hardware resources and software license, often client and servers need to have multiple roles, although this is not always an ideal situation.

There are various advantages found by using off the shelf MBES processing software during various phases of a survey, including survey planning, making sounding files, quality control, production of charts and animations. After all, these types of software exist to do these tasks. They have many other users to help fund and develop features of the software. However, including modern GIS capabilities to merge, clip, analyse and archive the soundings, as well as share and present results, can give more ability to undertake customised tasks, specific to a project or institution/company situation. Modern GISs have charting and visualisation capabilities that extend far beyond those of many hydrographic software packages. GIS provides a scalable solution for the size of the particular data sets, number of uses, location (local PC, intranet, internet), complexity, with different GIS packages and hardware configurations. This includes server and web based GIS, potential for custom development with modern software development strategies such as .NET, multi-user support and other enterprise level functionalities. The number of specialised features of GIS software make it an attractive addition to a hydrographic workflow.

Developing custom GIS applications is one of the most time-consuming and expensive elements of implementing a GIS, and a key task for a successful GIS

(HU, 2004). A GIS planning, designing and development method to reduce time while allowing many iterations of software to be built is present in HU (2004) and the flexible method is appropriate when software requirements and specifications documents need to be altered throughout the development cycle. HU's (2004) work provides useful insight for planning a production GIS application that extended from the proof of concept project presented here.

CONCLUSIONS

Early attempts during this research to use multibeam data sets on a single computer failed to meet expectations of performance, scale of visualisation and analysis. Thus, a multiple-computer method has been researched and employed here to overcome many of the limitations initially observed. The data acquisition system consists of multibeam computers and therefore it is logical to distribute the workload between multiple computers. To address the databasing of hydrographic information this research prototypes a GIS based approach using servers and client computers, custom GIS applications, DBMS, and off-the-shelf software to create a hydrographic data management system.

The topic of hydrographic data management is too broad to be covered in one research article. Thus this ArcGIS enterprise approach is not considered the only solution to the problem, but has numerous advantages over the file based methods previously used by the CMG. The method overcomes many of the data management problems associated with the datasets by showing geographically where data is located, and storing the data in a manner where it can be readily accessed. The GIS system prototyped enables access to the hydrographic information, not just metadata. The method can automate the management and metadata capture for MBES soundings to improve data integrity, and make the process more efficient. In the year 2000 typical hydrographic datasets being dealt with by the CMG were in the 10s of thousands to the low 100 thousands. Now typical soundings data sets for the CMG are in 10s of millions, sometimes 100s of millions, showing significant advances enabled through using the GIS approach presented here. Future research should develop the ability to store billions of points, as well as internet distribution of hydrographic data products.

The reason for using a ArcSDE/DBMS method rather than file-based geodatabases was to design a GIS that could fit in within a larger GIS, completely

scalable for future unknown uses. A file-based method would suit many hydrographic users, but the use of the DBMS should ultimately be faster and more powerful, at the expense of complexity, computer hardware and software licenses. The appropriate GIS design will depend on the resources available to develop the system and purchase computer hardware and GIS software.

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Chapter 6 - BASELINE BATHYMETRIC DATA COLLECTION FOR MONITORING OF BAR, RIP AND SALIENT RESPONSE TO AN ARTIFICIAL SURFING REEF - MOUNT MAUNGANUI, NEW ZEALAND

PREFACE

The previous chapters have provided a background to the existing surfing research, the impacts coastal development has had on surfing, and proposed methods for incorporating surfing into coastal management and engineering. Bathymetric data is key to successfully managing issues around surfing breaks, and a shallow water charting method has been presented, including a GIS geodatabasing method for managing hydrographic information. Thus the research problem and techniques have been developed, and are applied in this chapter to a real-world surfing break monitoring situation.

Baseline data was identified in Chapter 3 as important for managing surfing amenities, and various environmental data types were identified (Table 3-7 and Table 9-2). Specifically, this chapter applies the baseline data idea to the monitoring of an artificial surfing reef (ASR). Before the reef was constructed, a 2 km by 2 km survey (including the foreshore) was undertaken to provide for the first time a detailed digital terrain model of a beach shape before an ASR construction. Eight subsequent surveys analysed in Chapter 8 track the bathymetric changes relative to the baseline. The technique is an example of a surfing break monitoring method that can be applied when other coastal engineering activities occur near surfing breaks. The technique could also be applied during environmental impact assessment studies around surfing breaks.

The chapter contributes to the following aims of the thesis.

4. *to develop improved methods for charting surfing breaks, including management of environmental data.*
5. *to present methods and results of pre-construction baseline bathymetric data collection around a surfing break as an example of a modern surfing break Environmental Impact Assessment (EIA) requirement.*

The editorial and supervisory role of HEALY during the development of this paper was very important and worthy of co-authorship. The paper has been peer-reviewed and published. The citation is:

SCARFE, B.E., and HEALY, T.R., 2005. Baseline Bathymetric Data Collection for Monitoring of Bar, Rip and Salient Response to an Artificial Surfing Reef - Mount Maunganui, New Zealand. *In:* TOWNSEND, M. and WALKER, D. (eds.), *Proceedings for the 2005 Coasts and Ports Australasian Conference* (Adelaide, South Australia), 20-23 September 2005, pp. 459-464.

ABSTRACT

A multipurpose artificial surfing reef (ASR) at Mount Maunganui, New Zealand, is being constructed for surfing and research purposes. The reef can potentially create a salient in its lee, provide recreational and economic benefits as well as ecologically enhancing the area by creating a more complex and stable habitat that the present sandy beach. It is located 300 m offshore of the beach between the 3 and 4.5 m contours (LAT) and is predicted to provide 50-90 m long surfing rides for surfers. This paper outlines a pre-construction bathymetric monitoring program that will serve as a baseline dataset of the nearshore beach bathymetry. The dataset will be valuable for post-construction analysis of the sub-tidal beach response to the reef. The monitoring consists of multibeam hydrographic surveys with land-based foreshore mapping and oblique photos to show wave focusing and bar formations. RTK GPS measurements of tide and foreshore topography are corrected with a precise geoid-ellipsoid incline plane model to yield optimum accuracy. The natural evolution of the bar formations and those induced by the reef construction can be studied using the technique. It is shown how the location of surfer rides can be related to the sand bar and rips to better understand the relationship between bathymetric features, waves and recreational surfers.

INTRODUCTION

A multipurpose artificial surfing reef (ASR) at Tay Street, Mount Maunganui, New Zealand (Figure 6.1) is being constructed for coastal protection, amenity and biological enhancement (MEAD *et al.*, 1998; MEAD and BLACK, 1999; BLACK and MEAD, *in press*[6]). The location is one of the most popular beaches in New Zealand and surfing makes up a significant component of the beach recreational usage. However, "world-class" waves that challenge top surfers (HUTT *et al.* 2001; BLACK and MEAD, 2001a) rarely break around the Tay Street area and this is the main motivation for the reef development.
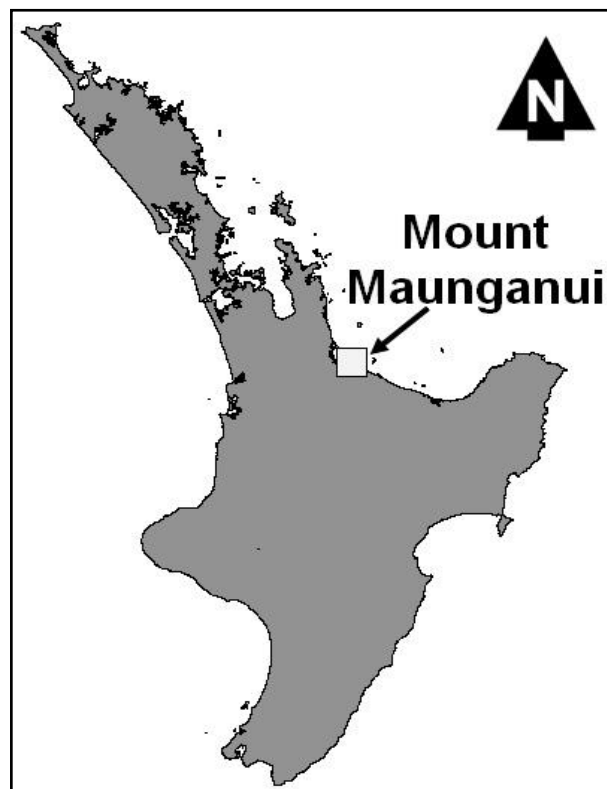
Figure 6.1. Location of Mount Maunganui on New Zealand's North Island.

A well-designed ASR can potentially widen the beach, provide recreational and economic benefits as well as enhancing the ecology in the area (WALKER, 1974; SCARFE, 1999 and 2002; BLACK, 2001a and b; BLACK and MEAD, 2001 and 2003; MEAD, 2001). The beach is widened by modification of wave attenuation and wave induced currents. The recreational amenity is enhanced by improving waves for surfing, bodyboarding and wind surfing as well creating sheltered swimming

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[6] Paper submitted to the 4th Surfing Reef Symposium, Manhattan Beach, Calfornia. The proceedings are yet to be published.

in the lee. The ecology is enhanced by creating a more complex and stable habitat and this also improves diving and snorkelling in the area.

Although a salient response is expected from offshore obstacles (ANDREWS, 1997; BLACK and ANDREWS, 2001; BLACK, 2003), this is a secondary objective of the reef as the location is in shoreline equilibrium and does not suffer from chronic erosion. The reef is located 300 m offshore of the beach between the 3 and 4.5 m contours (LAT; Port of Tauranga Datum) and is a "Double-Sided Multi-Level reef in the Delta Reef category," or A-Frame (BLACK and MEAD, *in press*). The reef will provide a minimum 50 m tubing left and right hand ride for two surfers at a time and has a skill level rating of top amateur surfers (Figure 2.5; rank 6-7; BLACK and MEAD, *in press*).

Monitoring the various aspects of an ASR project such as bathymetric response, surfing amenity, ecological changes, wave and current patterns around the reef, as well as social and economic impacts, is important for identifying positive and negative outcomes of the development, as well as indicating potential design improvements for future ASR projects. BANCROFT (1999), PATTIARATCHI (2002), BORRERO (2002), JACKSON *et al.* (2002), BORRERO and NELSEN (2003) all have undertaken various types of monitoring, and this paper outlines a pre-construction bathymetric monitoring program that will serve as a baseline dataset of the beach shape and dynamics for the Mount Maunganui ASR. The dataset will be valuable for post-construction analysis of the beach response to the reef. It is important to quantify the morphodynamics of micro-scale bathymetric features (SCARFE *et al.*, 2003) before the reef is built, so that the impacts of the reef on the beach morphology can be quantified.

Here the configuration of surfing break components (MEAD and BLACK, 2001a and 2001b) is identified from bathymetric data. Surfing break component analysis is a key step in understanding a surfing break and should be one of the first steps in any surfing break study. With the addition of peel angle measurements or predictions (WALKER, 1974; HUTT *et al.*, 2001; SCARFE *et al.*, 2003) and break intensity calculations (MEAD and BLACK, 2001c), a surfing break can be deconstructed to understand the processes that create the surfable waves.

This paper also attempts to approximate magnitude and variability of the bar-rip spacing for the survey period. The location of popular surfing spots are related to

the bar-rip formations as well as offshore features. It is shown that the offshore features are the reason why surfers frequent this 500 m stretch of beach. The methods presented in this paper can be used as a base to develop a standardised method for bathymetric monitoring of beach response to ASRs.

OBJECTIVES OF RESEARCH

The main objective of this research is to:

> *Identify bathymetry and topographic foreshore features that will be affected by the ASR construction and to understand the temporal variability of the features before construction and how the features relate to surfing conditions.*

The secondary objective of this research is to:

> *.. begin development of standardised methods to monitor the effects of ASRs on bathymetry and foreshore topography as well as for surfing break charting.*

SURVEY TECHNIQUES

There are many types of information that can be used to study surfing breaks including, but not limited to, bathymetric data, wave climate information, aerial photographs, oblique photos, video footage, wind data, sediment transport patterns, side scan imagery and sub-bottom profile transects (*see* Table 3-7). Within each field many different technologies can be used and they are all of varying usefulness. For hydrography, techniques include multibeam, single beam, LIDAR, beach profiles, RTK GPS or conventional survey methods for foreshore topography, aerial photographs for shoreline position, video base techniques and low-cost sounder/GPS systems.

Bathymetric data is required for bathymetric component analysis, wave hindcasting, refraction modelling, peel angle and breaker intensity calculations, artificial surfing reef baseline studies and construction monitoring, as well as for surfing bar and rip studies. Different surveying methods and spatial distribution of soundings are suitable for investigating different aspects as surfing breaks, and at varying scales (macro-meso-micro; SCARFE *et al.*, 2003). Navigational charts are useful for understanding offshore wave focusing and sheltering at a macro scale

for hindcasting the number of surfable days and developing reef design wave criteria. However the density of data is usually too sparse to understand the micro, and sometimes the meso-scale behaviour. Often, existing hydrographic data collected for another purpose (e.g. beach erosion study) can be useful for analysis at a meso-scale. It is rare though to find dense enough data for analysis at a micro-scale, especially in the surf zone, and dense data needs to be collected specifically for the purpose. Micro-scale analysis is needed for investigating of wave sections, which allow for interesting and challenging surfing rides (*see* WALKER 1974; DALLY, 1989; MEAD and BLACK, 2001a, b and c; MOORES, 2001; SCARFE *et al.*, 2003). HUTT (1997), SCARFE (1999 and 2002) and MEAD and BLACK (2001a) and SCARFE *et al.* (2002) all provide a discussion of survey methods for surfing breaks and are useful references for some of the issues that need to be considered.

The survey technique used here for all water-based measurements are a Simrad EM3000 multibeam sounder (using Triton Imaging Inc. processing and acquisition software), a TSS Mahrs motion sensor and gyro, and Trimble MS750 RTK GPS tide corrections (using Trimble HYDROpro). The integrity of the data is compared with concurrent single beam soundings and existing hydrographic data. The foreshore mapping also utilised RTK GPS technology but was backpack mounted. All RTK GPS heights were converted using an accurately calibrated ellipsoid-geoid incline plane model, discussed in more detail below.

Ellipsoid-Geoid Incline Plane Model

RTK GPS measures 3D positions relative to the WGS84 ellipsoid (FEATHERSTONE and STEWART 2001; PARKER, 2002), which roughly represents the shape of the earth. However, for most applications that use GPS heights (*such as* topographic surveys and RTK GPS tide measurements), the relationship between the WGS84 ellipsoid and the local geoid is required (e.g. EEG, 2004). For the survey area in this study, the separation between the two surfaces ranges from 30.8 m to 31.0 m (Figure 6.2). All RTK GPS measurements for this study have been corrected using an incline plane model created with 27 control marks surveyed with orthometric and WGS84 ellipsoid heights. A high confidence can be had in the model since the average residual error of modelled heights was 0.03 m. The model had an incline slope of 0.006 m per kilometre and can be seen in Figure 6.2.
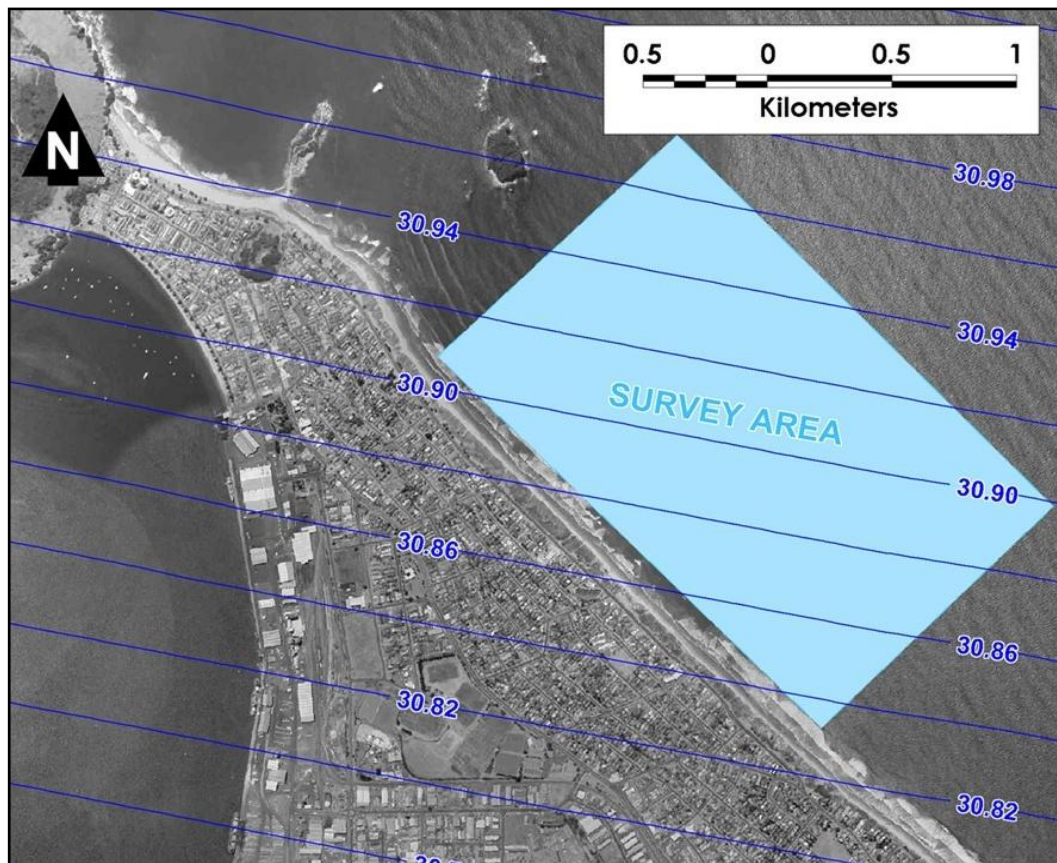
Figure 6.2. Incline plane geoid-ellipsoid over Mount Maunganui Beaches.

SURFING WAVES AND BATHYMETRY AROUND ASR SITE.

The beach around the ASR shows significant wave focusing (Figure 6.3). Although Figure 6.3 suggests that an offshore bar is breaking waves further out to sea, the survey (Figure 6.4) and the analysis of the MEAD and BLACK (2001a and b) surfing break components does not show a sand bar of this scale. Instead a 400 x 400 m focus component offshore in 13-18 m water, slightly northeast of the reef site can be seen. This type of feature, as described in MEAD and BLACK (2001a), converges wave orthogonals to form a peak in wave height and subsequent loss of wave height on either side of the peak. Further offshore, islands shelter wave energy also contributing to the variation in surf zone width (*see* Chapters 2, 3, and 8). Although calibrated numerical refraction analysis is required to validate the theory[7], the primary mechanism for this wider surf zone is considered to be wave focusing and sheltering.

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[7] Refraction modelling after publication of this paper (undertaken in Chapters 2, 3, 7, 8 and Appendix Two) suggest that this focus (13-18 m deep) plays a much smaller role in wave focusing than the offshore features deeper than 20 m, and sheltering/focusing effects of the offshore islands.

Figure 6.3. Oblique image of approximate ASR site showing focused wave heights and a wider surf zone.

Wave focusing for surfing has already received attention in the literature (BEAMSLEY and BLACK, 2003; MEAD *et al.*, 2003) and is one of the two mechanisms identified by SCARFE *et al.* (2003) that creates peeling waves. The other mechanism is bathymetric contours aligned at an angle to the wave crest. It is a combination of these two processes that makes good surfing waves. The absence of significant shallow nearshore features to cause this second process (rhythmic sandbars and deep troughs) is the reason high skill level waves are rare at Tay Street.

Observations of surfer locations at the time of eh surveys showed surfers prefer to catch waves around the most prominent bar-rip feature along the 2 km study area. This feature can be seen in Figure 6.5 with the rip depth and bar crest height being 3 m and 1.5 m (Port of Tauranga Datum) respectively. It is possible that the feature is likely to be controlled by wave focusing over the offshore feature, which creates wave driven currents and more prominent rips than the adjacent section of beach.
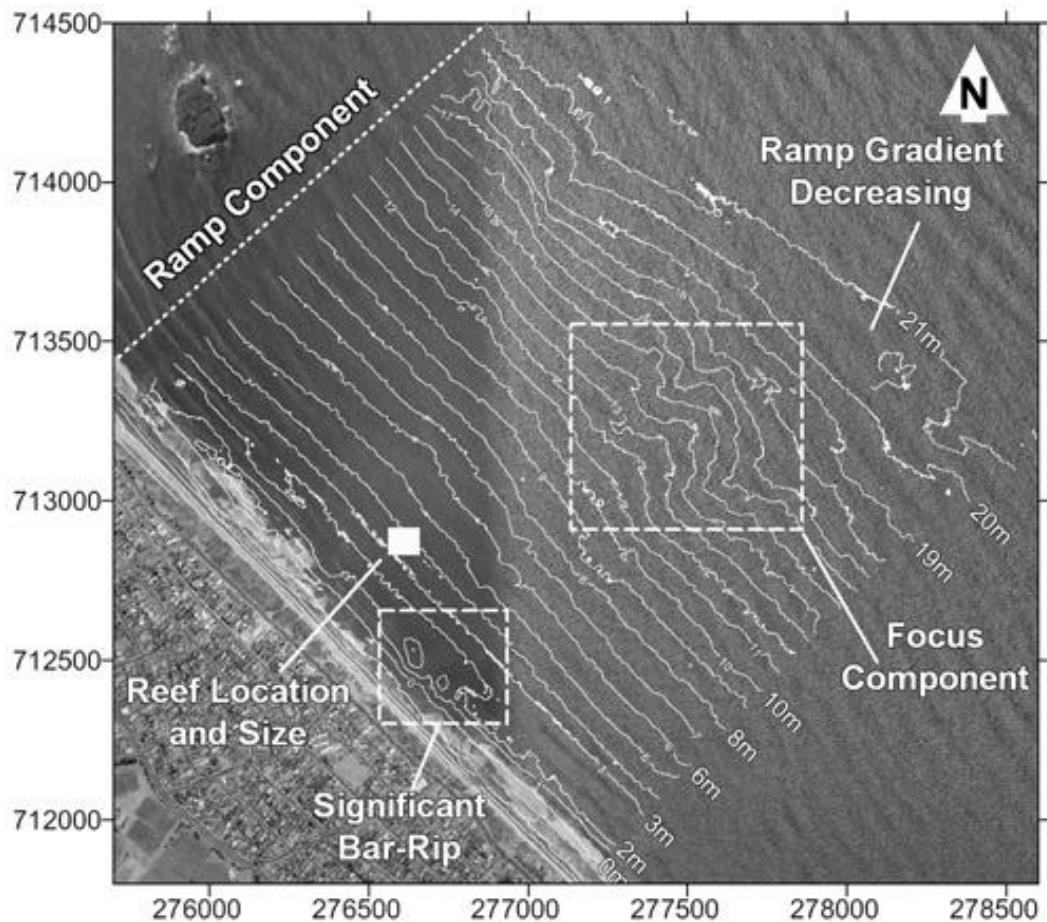
Figure 6.4. Multibeam and foreshore RTK GPS image of 2km x 2km survey (Port of Tauranga Datum = Chart Datum). The ASR Location is shown relative to meso-scale surfing break components.

The more prominent bar/rip features will create surfing rides by allowing more surfable peel angles and increased breaker intensities because of the more complicated relief. This is the first known publication of detailed surf zone imaging being related to the location of surfing rides. It is a research area that if developed will help show the magnitude of sea floor relief required for a good surfing break. It can be assumed that the relief shown in Figure 6.5, although creating average surfing waves, is not prominent enough to create a consistent take off and wave path, and surfzone hydrodynamics suitable for a high quality beach. The waves breaking here are described as peaky, with each wave breaking with varying character and in a different location. This suggests the bars play a smaller role than the offshore transformations, and wave peakiness, in creating the surfing waves. A successful surfing outcome of the ASR will be to provide a far more stable take off zone and predicable wave path, with increased breaking intensity.
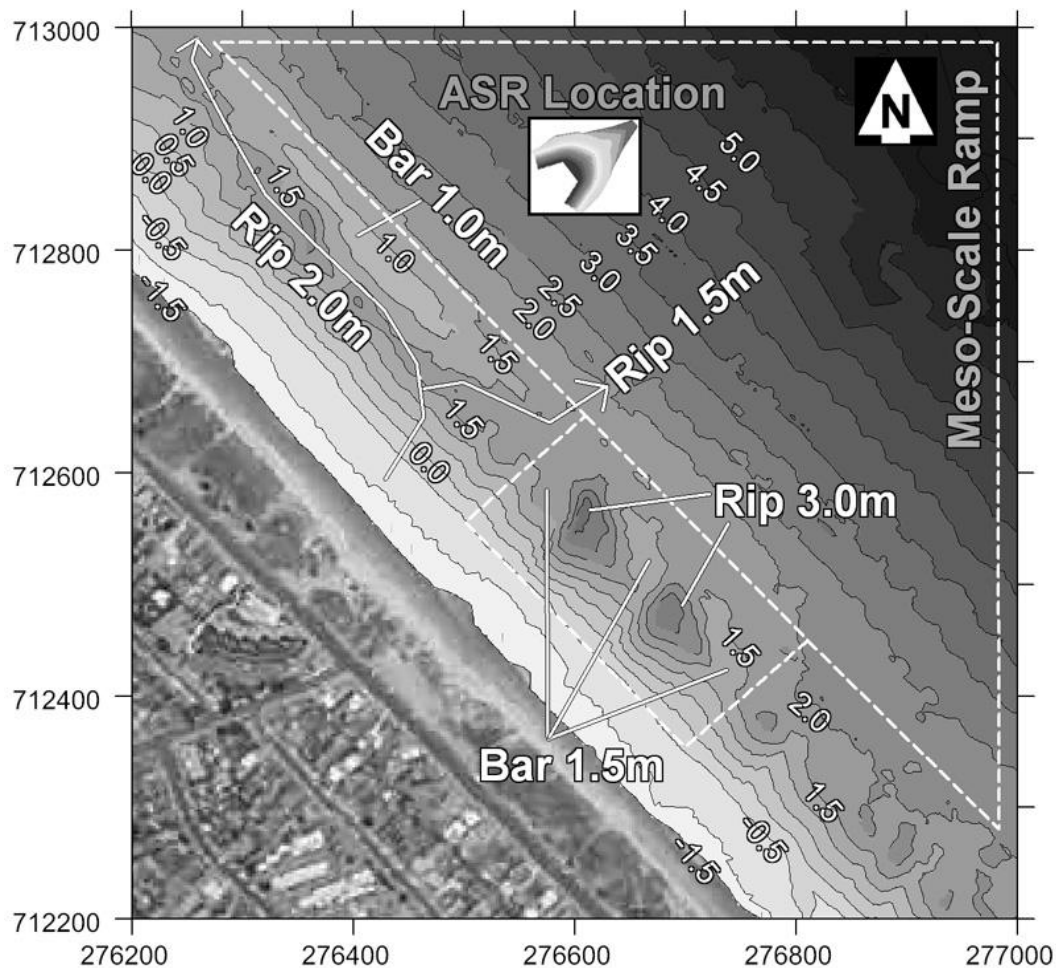
Figure 6.5. Limits of meso-scale offshore ramp component and location of bar and rips with crest and trough depths.

To understand the magnitude of variability in these surf zone features a further survey was undertaken (Figure 6.6). The main surfing bar and rip have remained very similar in shape but have migrated southeast. If the rip and bar are controlled by the offshore focus it is possible that this bar and rip will remain similar in character, but oscillate up and down the beach 100-200 m depending on the recent wave directions. Ongoing monitoring is planned to test the hypothesis and determine any impacts of the ASR on this feature[8].

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[8] Monitoring is presented in Chapter 8, but the reef has artificially changed the surf zone morphology and it was not possible to determine any further variability in the natural bars and rips.
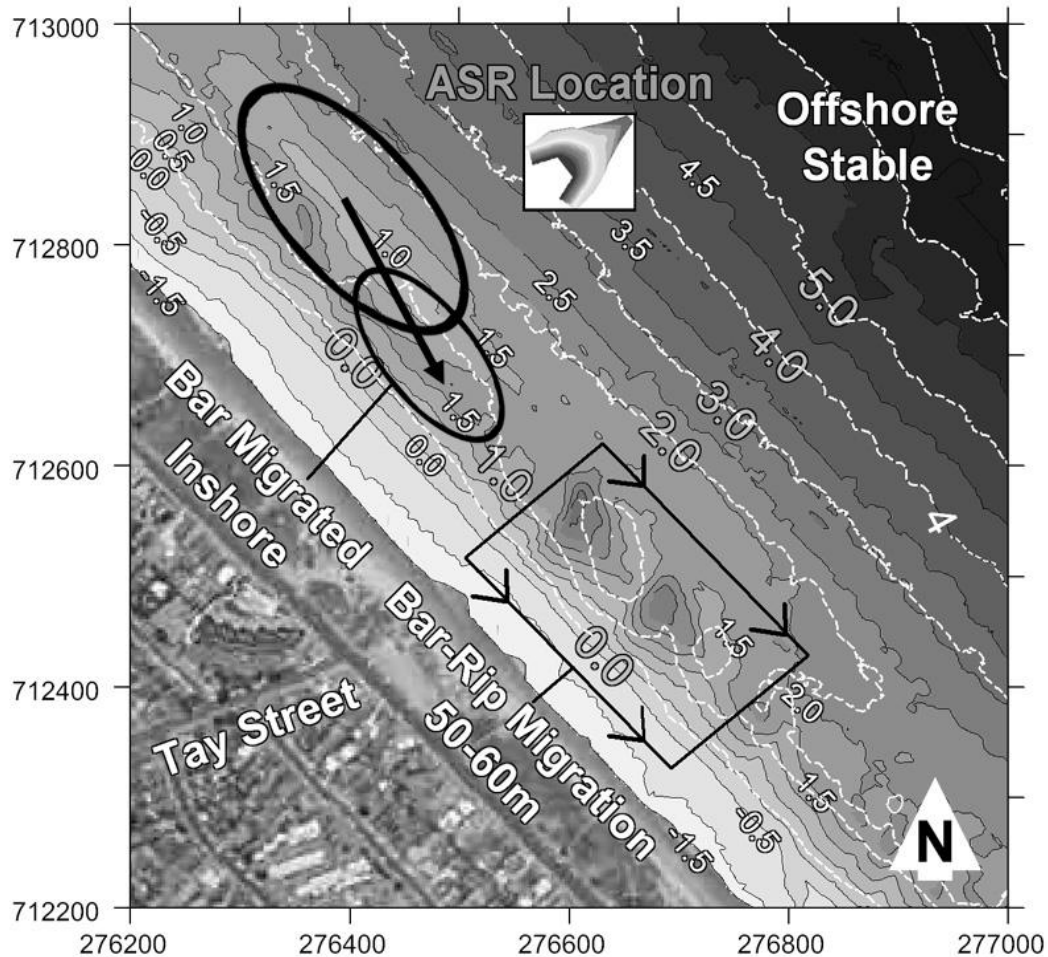
Figure 6.6. Migration of sand bars between August and October 2004.

Breaker Intensity

Breaker intensity (B_I) defines how a powerful a wave is when it breaks and this is important for determining the skill level required to surf a wave (HUTT, 1997; HUTT *et al.*, 2001 and BLACK and MEAD, *in press*) as well as the types of surfing manoeuvres that can be performed (SCARFE, 2002). Typical breaker intensities (B_I) at Tay Street were calculated using the vortex ratio method of MEAD and BLACK (2001c) because it is more specific to surfing waves than the Iribarren number. The method is based on the orthogonal seabed gradient and predicts the shape of a barrelling wave.

Analysis of the survey data showed that there were three gradients in a typical beach profile around the reef site (Figure 6.7). Applying the formular for the breaking intensity (B_I) of the offshore, surf zone and beach face were 5.9, 10.8 and 2.7 respectively. The MEAD and BLACK (2001c) scale only reaches 3.1 so it is clear that most waves at Tay Street are very gently spilling and not as well suited

to shortboarders. Although many shortboarders use the surfing break, there are also a large number of longboard surfers at the beach. The B_I value of 5.9 is expected to generally describe the take off wave type for most surfing conditions. Many surfing waves break with higher intensity at take off and this helps surfers to catch the wave. Figure 6.7 shows that through the surf zone the B_I decreases significantly, explaining why barrel rides are not often found at the beach. When barrels are ridden it is usually as a wave links with the steeper beach face at the end of a surfing ride, or when winds are directed offshore, or the steeper side of a through. This B_I of 2.7 is described as medium/high by MEAD and BLACK (2001c) and similar to Bells Beach, Australia, or Bingin, Bali. Because the steep shoreface is only in shallow water (< 2 m at low tide), even at high tide (~ 3.5 m), the size of barrelling waves is limited. Using the breaking criteria of 0.78, the maximum breaking wave height at high tide is around 2.5 m. It can be theorised that the ideal barrel conditions at high tide with H_b = 1.5-2.5 m. When larger swells break at Tay Street they break further out where the breaking intensity is lower.
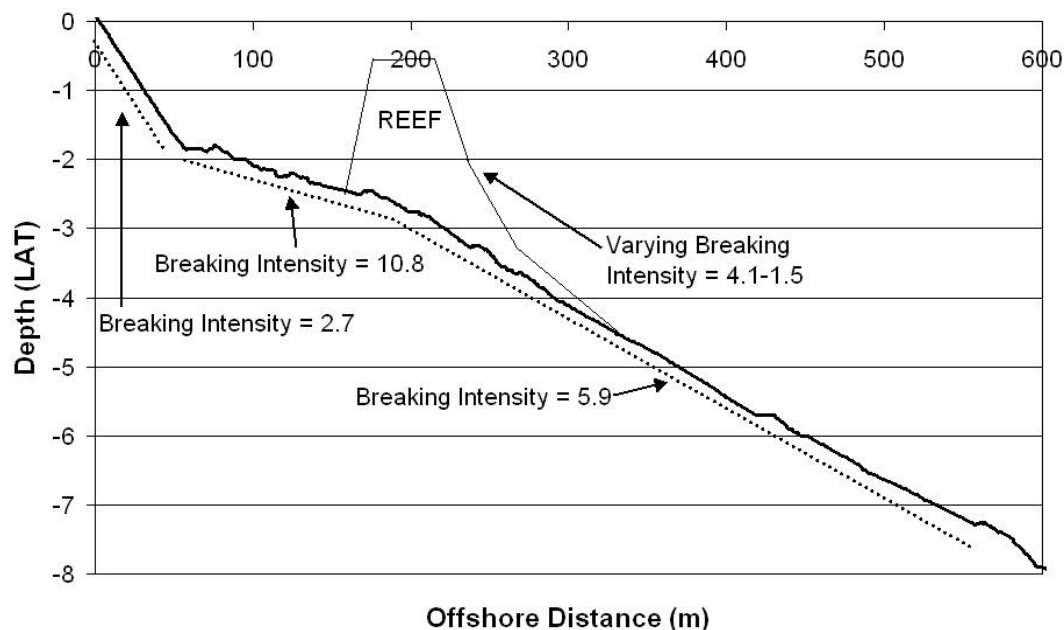
Figure 6.7. August 2004 profile at Tay Street with wave breaking intensities and approximate orthogonal reef profile.

CONCLUSIONS

This paper has proposed a bathymetric method for collecting bathymetry as part of monitoring and ASR construction. An RTK GPS and mulitbeam eachosoundings system is used to collect a 2 km by 2 km baseline datasets, with subsequent charting of the surfzone 2 months later. Although initially the area was

thought to be a reasonably simple planar beach system, bathymetric component analysis shows that offshore wave focusing may control the formation of a popular surfing bar and rip formation. The shape and location of the bar and rip are expected to change depending on the preceding wave events, although the features create surfing waves they are not considered to protrude enough to create consistent high quality surfing waves. The impacts of the reef on the surfing break component have not been investigated. A positive effect would be further stabilisation of the bar and rip and perhaps deepening of the rips surrounding the bar to create more consistent surfing rides.

The breaker intensities of waves at Tay Street are shown here to be too low for high skill level waves, and peel angles are variable because the wave breaking location is not consistent. It is concluded that the types of surfing waves that break at Tay Street are beginner to intermediate with the skill level required increasing with wave height. Personal observation combined with breaker intensity calculations are used to draw this conclusion. The factors that limit the breaking intensity and consistency of wave breaking location are identified, and thus a major rationale for the ASR here is to create a consistently high intensity surfing break where currently there is not one.

Other aspects of ASR design, monitoring and surfing science research that need more standardized methods and research into study methodologies are included in Table 6.1.

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Table 6-1. Aspects of ASR design, monitoring and surfing science research that requires further analysis, particularly in relation undertaking baseline studies[9].

Design or Monitoring Aspect	Research Area
Salient formation and fringe erosion (at the ends of the salient);	Shoreline response/morphology
Bar and rip morphology;	Morphology
Sediment transport around surfing breaks.	Morphology
Sand bag settlement;	Engineering
Tracking wave paths;	Surfing Science
Wave-wind hindacsting for surfing;	Surfing Science
Estimation of number of surfable days;	Surfing Science
Peel angle measurement/prediction calculations;	Surfing Science
Breaking intensity calculations; and	Surfing Science
Cost/benefit studies;	Sociology/Economics
Surfer number/reef usage studies;	Sociology

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[9] This table has been created based on a list published in the original 2005 paper. The information was converted to a table based on the advice of one of the thesis examiners.

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Chapter 7 – OCEANOGRAPHIC CONDITIONS OFFSHORE OF THE ARTIFICIAL SURFING REEF AT MOUNT MAUNGANUI, NEW ZEALAND

INTRODUCTION

To include surfing breaks in ICZM, SCARFE *et al.* (Chapter 3) recommends studying surfing and oceanographic aspects of surfing breaks (Table 3-6) using various environmental information (Table 3-7). This assists in providing transparency about coastal processes and impacts of various coastal activities (Table 3-5). As an example of such a study this chapter analyses the oceanographic conditions around the Mount Maunganui ASR during surfing and storm events. It presents empirical and hindcast model predictions of wave, wind and tide parameters during these events. The chapter contributes to the overall understanding of the oceanographic conditions around the ASR and enables wave refraction model boundary conditions to be created. More specifically, this chapter addresses the following thesis objective outlined in Chapter 1:

> 7. *to monitor the beach and wave response to an artificial surfing reef using techniques identified and developed in this thesis.*

METHODOLOGY

The monitoring of the Mount Maunganui ASR reported here was undertaken during the period of May 2004 to December 2007 (Chapters 6-8). Data collection and collation occurred around the reef site, before and during construction, and included wave, tide, wind, bathymetry, sidescan, oblique and aerial photography. Due to construction and funding issues, the reef was still only 70 % complete by the end of the study period, but the analysis in these chapters nonetheless provides an insight into how the construction has modified waves and the beach.

The specific tasks undertaken for this oceanographic portion of the study, presented in this chapter are the analysis of:

1. published oceanographic information including wave climate, and storm surges;
2. hindcast data for creating wave model boundaries and investigating long term wave climate;

3. InterOcean S4 deployment near the ASR to validate the hindcast, provide measured wave information at the site, and for model calibration;

4. Port of Tauranga wave and tide data for wave model calibration and creation of boundary conditions; and

5. Environment Bay of Plenty (regional council) wave data for wave model boundary calculation and calibration.

The sources of oceanographic data utilised in this study are shown in Figure 7.1, Figure 7.2 and Table 7-1. Two wave instruments collected data for the majority of the study period (A_BEACON and EBOP), with some gaps during maintenance of the instrumentation. Although complete records do exist, only specific date ranges were requested for this research. The EBOP buoy was deployed by Environment Bay of Plenty in 61 m depth, 13 km off Pukehina Beach. The buoy monitors the ocean's current and waves for five years to provide data on the dynamics of the Bay of Plenty's offshore environment (www.ebop.govt.nz). The A_BEACON wave sensor (14 m depth) belongs to the Port of Tauranga and is a long term non-directional sensor that provides oceanographic information (H_{sig}, H_{max}, T_{peak} ,T_{zero}, H_{max}, Tide) pertinent to the port's operations. Concurrent to this study, research was being undertaken at the Mount Maunganui beaches (SPIERS 2005), and three InterOcean S4 current meters were deployed to be of use for both studies. The InterOcean S4 data was processed into summary statistics by SPIERS (2005). National Institute of Water and Atmospheric Research (NIWA) wind data from Tauranga Airport (site = AIRPORT), 3 km to the south of the reef was obtained. The airport location is expected to have similar wind conditions to the reef site as no major topographic features exist to significantly modify the wind climate, although validation was not undertaken.

The analysis of measured surfing waves has been previously reported (e.g. HUTT, 1997; SAYCE, 1997; MOORES, 2002; SCARFE, 2002; MACK, 2003; BLACK *et al.,* 2004; MEAD *et al.,* 2004), but has not been the sole focus of any publication. Most of the previous research on surfing waves present time averaged wave statistics such as peak and mean directions, or significant wave height. MACK (2003) has analysed time series pressure transducer measurements around the El Segundo (California) ASR to empirically investigate which waves in a set of waves are ridden by surfers. While this type of analysis would also be useful around the

Mount Maunganui ASR, the main focus of this study is to understand the observed beach morphology (presented in SCARFE *et al.,* Chapter 8), and to create boundary conditions for hydrodynamic modelling. Therefore, only time averaged conditions are presented, and this includes determining wave height, period, direction and tide levels. The relationship between significant wave height and breaking wave height is left for future research.

Wave modelling is a critical tool in understanding the effect of an ASR on surfing wave quality and beach morphology. Thus the wave data discussed in this chapter is important calibration data for the two model grids shown in Figure 7.3. The larger scale modelling is used to transform the directional EBOP data to the nearshore model grid and investigate island sheltering and wave focusing. The S4_SILTDUMP site is used for calibration of the 60 m model grid and the modelled waves are driven from the EBOP location. The S4_SILTDUMP site is used to drive the 3 m model grid, and utilises S4_BCDUMP as a calibration point. More information on the WBEND model and calibration is provided in Appendix Two.
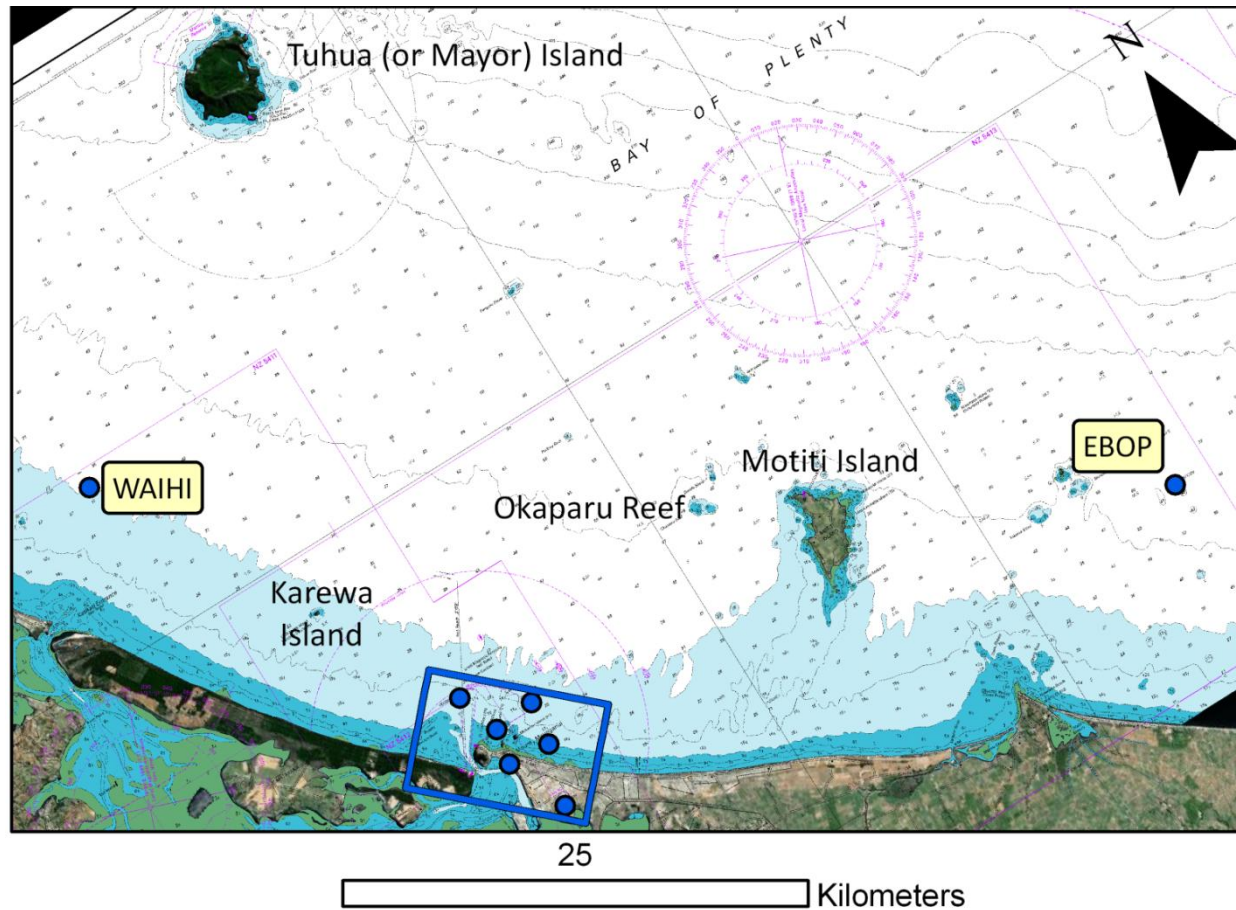
Figure 7.1. Location of oceanographic data discussed in text (blue circles) with coverage of Figure 7.2 depicted by the blue square. Navigational chart adapted from Land Information New Zealand chart NZ541. Background satellite imagery from Environmental Systems Research Institute (ESRI) ArcIMS service.
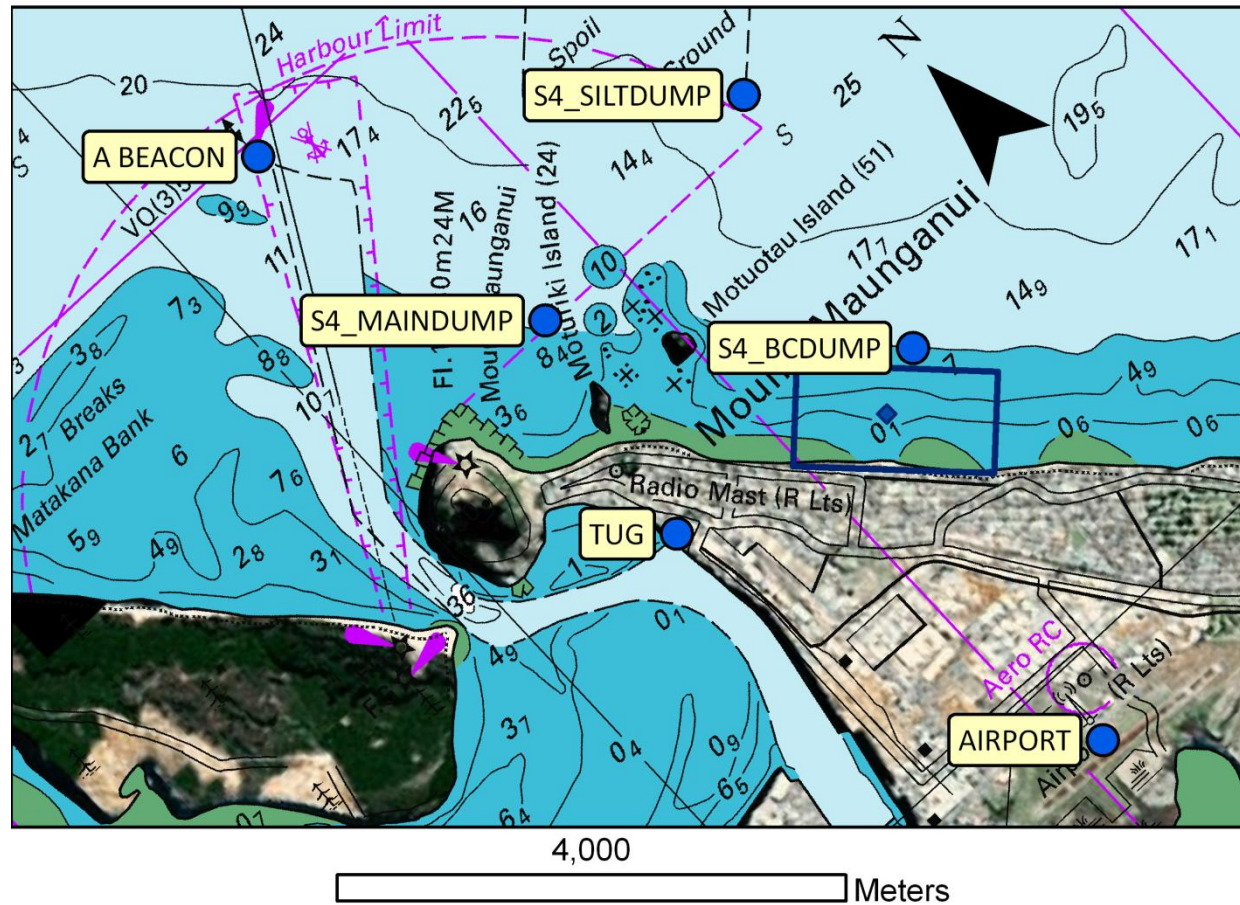
Figure 7.2. Location of oceanographic data discussed in text (blue circles) near the ASR study site (blue square by instrument S4_BCDUMP). Navigational chart adapted from Land Information New Zealand chart NZ541. Background satellite imagery from Environmental Systems Research Institute (ESRI) ArcIMS service. Note that S4_SILTDUMP and HIND_SILTDUMP site are at the same location.

Table 7-1. Approximate location, depths and dates of wave data referred to in the text.

NZMG_E	NZMG_N	NAME	DATA_TYPE	DATA_SOURCE	START_DATE	FINISH_DATE	DEPTH (Chart Datum)
2829021	6383192	EBOP	MEASURED WAVE	Environment of Plenty	22/09/2003	20/02/2007	-61.0
2793305	6390465	S4_BCDUMP	MEASURED WAVE	SPIERS (2005)	21/09/2005	27/10/2005	-9.0
2791393	6392622	S4_MAINDUMP	MEASURED WAVE	SPIERS (2005)	21/09/2005	27/10/2005	-11.0
2793781	6392822	S4_SILTDUMP	MEASURED WAVE	SPIERS (2005)	21/09/2005	27/10/2005	-24.5
2793781	6392822	HIND_SILTDUMP	MODELLED WAVE	GORMAN *et al.* (2003a and b)	01/01/1979	31/03/2007	-24.5
2780544	6415706	WAIHI	MEASURED WAVE	MACKEY *et al.* (1995)	N/A	N/A	-30.0
2790730	6395177	A_BEACON	MEASURED WAVE (NON-DIRECTIONAL)	Port of Tauranga	Only specific events		-14.0
2790950	6390740	TUG	MEASURED TIDE	Port of Tauranga	Only specific events		N/A
2792166	6387218	AIRPORT	MEASURED WIND	NIWA	31/05/1990	31/12/2007	N/A
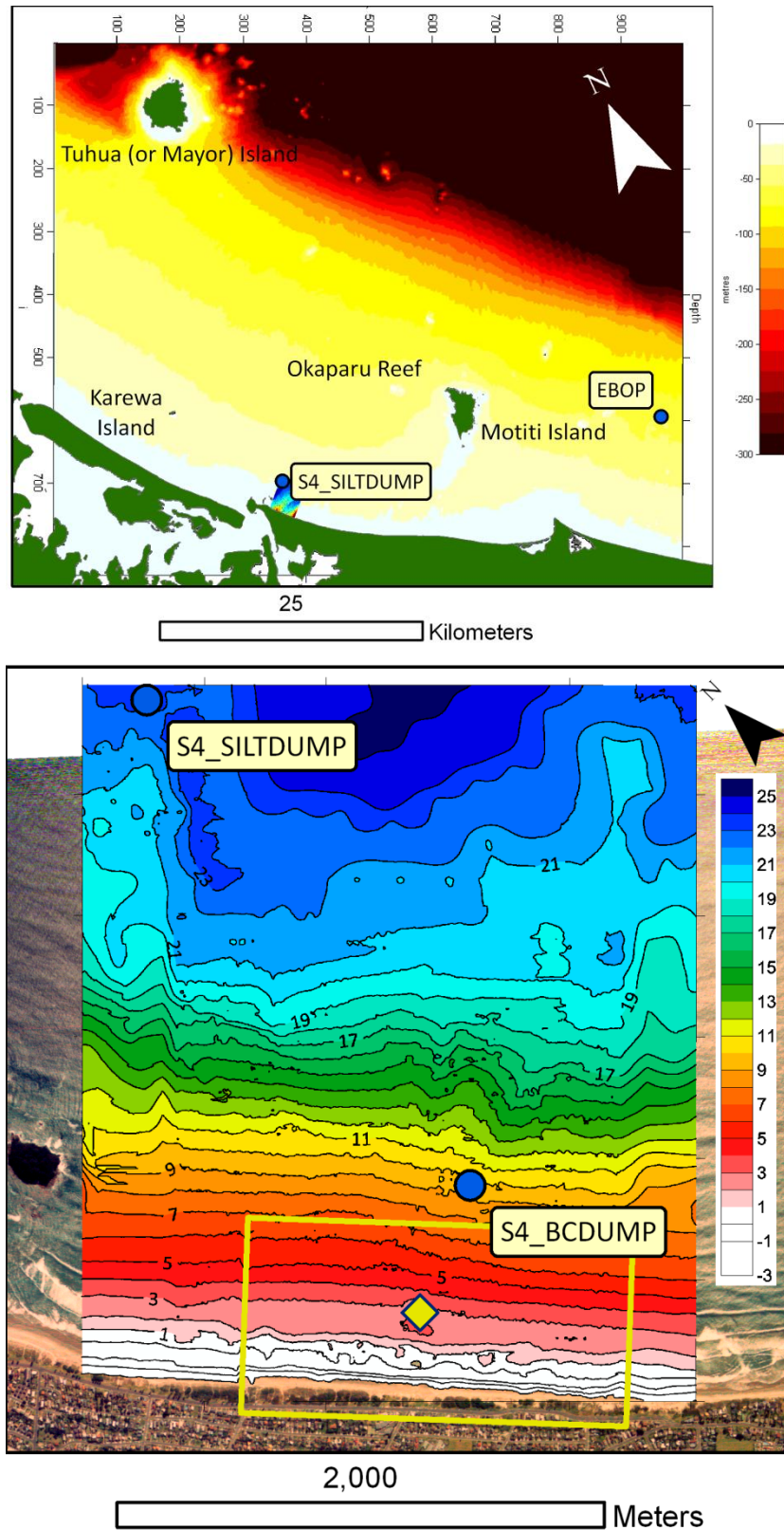
Figure 7.3. Coverage of large scale (60 m cell; top) and small scale (3 m cell; bottom) WBEND monochromatic wave refraction model grids and location of wave boundaries (EBOP=top; S4_SILTDUMP=bottom) and calibration data (S4_SILTDUMP=top; S4_BCDUMP=bottom). The yellow rectangle (bottom) represents the morphology study site (Chapter 8) and the yellow diamond indicates the location of the ASR.

WAVE CLIMATE LITERATURE REVIEW

To supplement the analysis of the oceanographic data, a literature review on the evolution of wave climate analysis in the Bay of Plenty region in the last 30 years follows. Although the review is not exhaustive, the wave climate is well described and the references provided will direct readers to further literature on the topic.

The first and formative study of the New Zealand wave climate was undertaken by PICKRILL and MITCHELL (1979) based on measured wave data around New Zealand. The study summarises the macro-scale wave conditions around the New Zealand coast for the first time. The longest wave record available to PICKRILL and MITCHELL (1979) was only 17 months and the sites were sporadic in their spread around the coast, often negatively influenced by nearshore bathymetric affects. The research still successfully begins to place boundaries on the character and variations in wave climate around the New Zealand coast.

The application of numerical wave modelling to New Zealand waters (e.g. LAING, 1983, 1990 and 1993; GORMAN *et al.,*2003a and b; GORMAN, 2005; BEAMSLEY *et al.*, 2007) and satellite based observations (e.g. LAING, 2000) in recent years means that the New Zealand wave climate is now much better understood at both a finer spatial and temporal scale. Now accurate deepwater as well as nearshore wave statistics are available, including extreme wave event calculations (STEPHENS and GORMAN, 2006), which are important for coastal management and engineering. Studies specific to the Mount Maunganui beaches are reviewed in SPIERS (2005), with possibly the first study presented in DAVIE-COLLEY and HEALY (1978).

PICKRILL and MITCHELL (1979) summarise that southwesterly swell created by the westerly wind flow in the mid latitudes of the southern hemisphere dominate wave generation and the direction of wave travel south of New Zealand. The Bay of Plenty coast is said to be a lee shoreline of the dominant wave conditions. Significant northerly to easterly swell events still occur in the Bay of Plenty and are generated by tropical cyclones passing north of New Zealand, blocking anticyclones, and from depressions moving down from the northwest (PICKRILL and MITCHELL, 1979). Consequently, the Mount Maungaui wave climate is smaller than that found in most New Zealand waters, with swells from the north or the east (<1 m H_{sig}, 9-12 s period) dominating the wave climate (MEAD and

BLACK, 1999). Long period swells with large wave heights (1-5 m) occur less frequently and originate from these distant wave sources.

Data from a 3 year wave deployment in 34 m (WAIHI; Figure 7.1), directly in the lee of Mayor Island, showed the effects of wave transformations caused by local winds and sheltering behind the Coromandel Peninsula and East Cape (MACKEY *et al.* 1995). Wave focusing and sheltering is evident (SCARFE *et al.,* Chapters 2 and 3) and can be seen in the large scale SWAN hydrodynamic modelling of a storm event presented in Figure 7.4. Although the MACKEY *et al.* (1995) study is useful for analysis of waves at the ASR location, at times significant differences will occur between the sites. An interesting finding by MACKEY *et al.* (1995), which will be applicable for the waves at both sites, is that the wave steepness measured suggests that many of the measured waves were wind forced and generated close to the measurement site. In summary, MACKEY *et al.* (1995) found that:

- significant wave heights were less than 1 m 70 % of the time, with a mean H_{sig} of 0.80 m and max of 4.30 m;
- there is some evidence of higher wave energy in winter;
- calculations of longshore wave energy flux suggests that the direction of littoral drift changes frequently;
- the Southern Oscillation Index (SIO) plays an important role in the BOP wave climate; and
- data was measured during El Nino conditions when fewer storms occur.
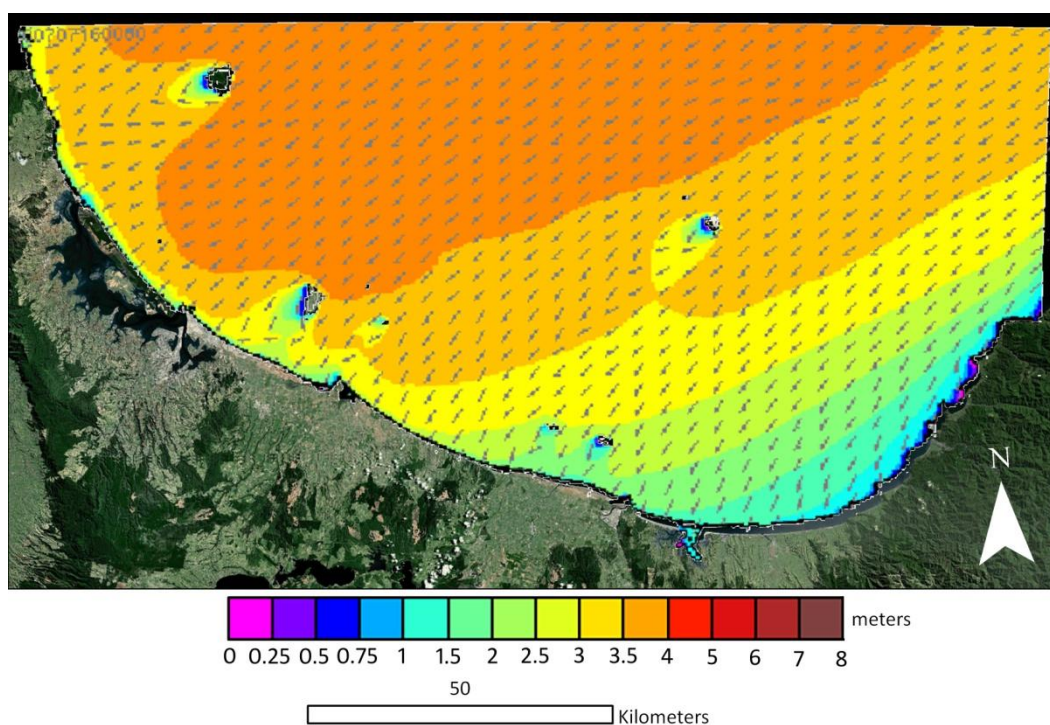
Figure 7.4. SWAN modelling of offshore wave heights during storm on 16 July 2007. Adapted from image by www.swellmap.com (MetOcean Solutions Ltd, New Zealand). Background satellite imagery from Environmental Systems Research Institute (ESRI) ArcIMS service.

After analysing wave data at Mount Maunganui and by reviewing DE LANGE (1991), SPIERS (2005) concluded that swell events generally lasted less than 36 hours and occurred approximately every 5 days. HEALY (1980) earlier reported storm frequency at Waihi Beach (April 1974 to May 1975) and calculated that there were 17 storms lasting more than one day at Waihi Beach, making an average of 1.3 storms per month. This is less than the estimate by SPIERS (2005), possibly because of differing definitions of what constitutes a swell event. SPIERS (2005) agrees with DE LANGE (1991) that the typical wave conditions are "persistent long period swell with a local sea superimposed". SPIERS (2005) also found swell events to be typified by a fairly rapid rise in wave height up to the peak, which steadily abates.

BLACK and MEAD (2007) note that the wave climate exhibits rapid variations, and this complicates the ASR design process when compared to a ASR location such as Cable Stations where waves come from a 10° wave window (PATTIARATCHI, 2007). BLACK and MEAD (2007) found that the wave climate varies between calm and short term swells (1-5 days), and that the wave direction rotates as the source of the swell passes New Zealand. They conclude that the beaches are in a constant

state of adjustment because of varied wave character and direction. A probability analysis of different wave events was published in RENNIE *et al.* (1998).

DE LANGE and GIBB (2000) analysed nearly 40 years of storm surge measurements at Tauranga. Storm surge events were defined as occasions when the residual level between the predicted high tide level and recorded water level exceeded 10 cm (DE LANGE and GIBB, 2000; p. 419). Storm surge was found to vary in magnitude and frequency with a noticeable shift in character after 1976 attributed to the reversal of the Inter-decadal Pacific Oscillation (IPO). The SIO was also found to effect storm surge with La Nińa events creating more storm surge events. Slightly larger winter storm surges were observed and storm surge was found to be generally 0.20-0.30 m but could reach 0.6 m.

WAVE HINDCAST ANALYSIS

To understand the wave climate offshore of the ASR, wave hindcast data (GORMAN *et al.,* 2003a and b; GORMAN, 2005) has been analysed for the HIND_SILTDUMP site. The hindcast provides wave information at 3 hourly intervals and was analysed using MATLAB® routines (provided by GORMAN, *pers. comm.*) that output monthly, annual, yearly or combined statistics for the hindcast period. Figure 7.5 shows the probability of wave directions and significant heights over the hindcast period. The majority of waves approach from around 45°, near perpendicular to the beach (mean=47.1° σ=24.6° coast = 132°). When storms occur they are more likely to be from the north to northeast, driving net longshore currents, and sediment transport to the southeast. Geomorphic indicators of longshore transport (HEALY, 2007) to the southeast, appear around the ASR and are shown in SCARFE *et al.* (Chapter 8) to support this theory.
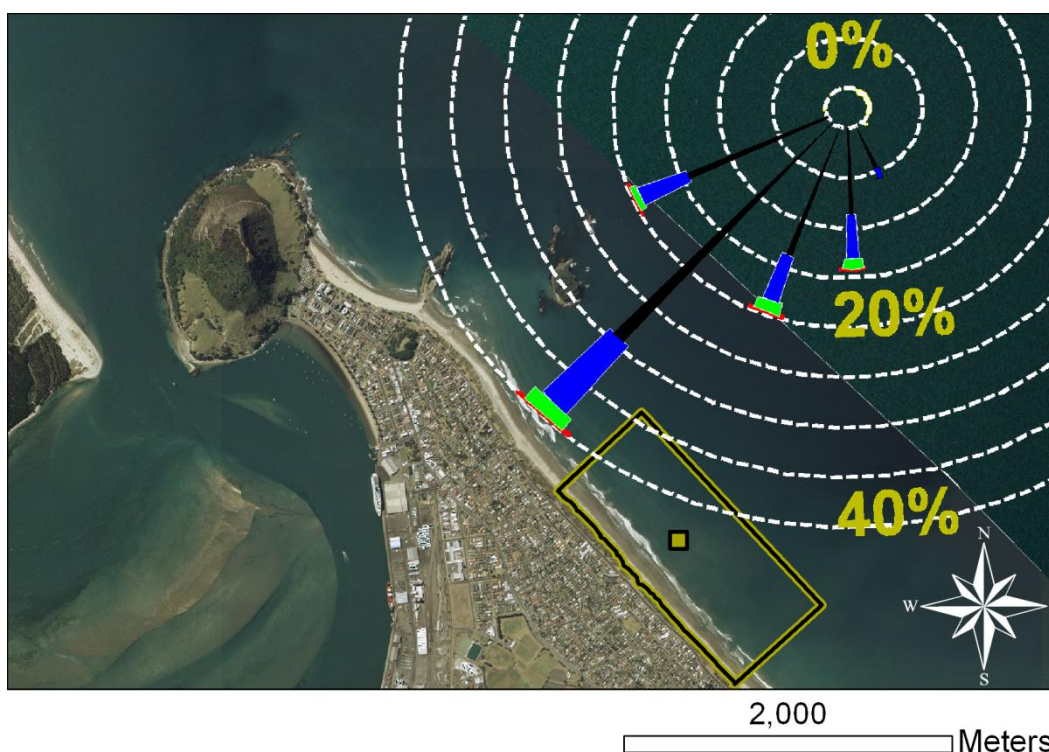
Figure 7.5. Mean wave direction and significant wave height from hindcast data for HIND_SILTDUMP site. Black (0-1 m), blue (1-2 m), green (2-4 m) and red (4.0-infinity m). The ASR study site (shore parallel rectangle) and reefs the (yellow square) cover 1.6 km of the beach from the dune line to 10 m depth contour.

Validation of the hindcast by comparison to measurements (HIND_SILTDUMP vs S4_SILTDUMP; Figure 7.6) shows strong similarities between datasets. Shallow water bathymetry was not included in the hindcast, accounting for some of the variation, especially in wave directions. The hindcast covers the entire New Zealand coast and therefore is not necessarily optimised for this location, but still reasonably well represents measurements for the purpose of this thesis. The A_BEACON and EBOP measurements are very similar to the S4_SILTDUMP measurement site, even though they are in different locations. Thus the longer term A_BEACON and EBOP buoys, plus the hindcast, are considered extremely useful for wave studies around the reef site.
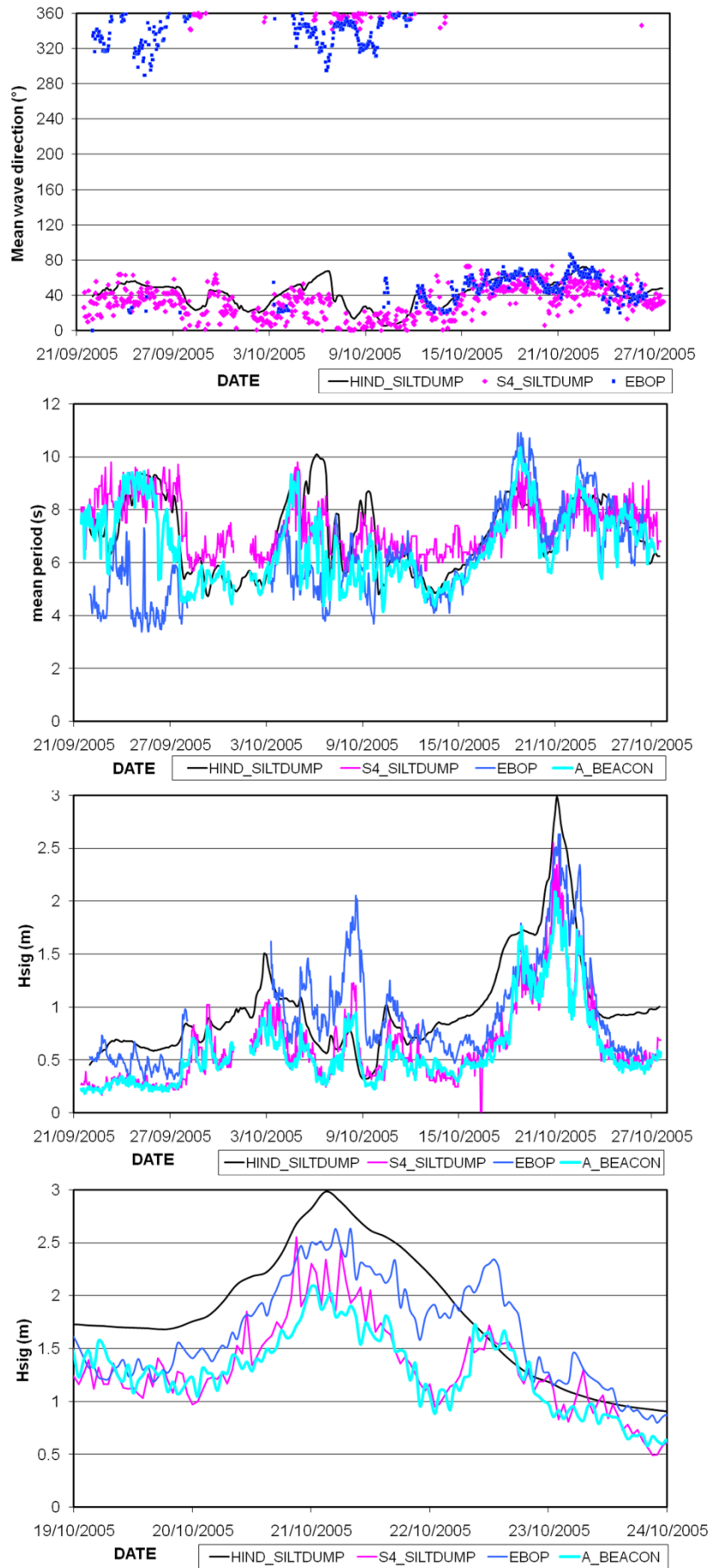
Figure 7.6. Comparison of EBOP, HIND_SILTDUMP, S4_SILTDUMP and A_BEACON wave datasets showing reasonable agreement between wave hindcast and nearby measurements.

DAVIES-COLLEY and HEALY (1978) found that calm conditions (waves less than 15 cm H_{sig}) occur 11 % of the time and 60 % are smaller than 1.0 m. Further research by SPIERS (2005) found waves below 1.0 m occur between 60 and 80 % of the time with waves above 2 m occurring 3 to 5 % of the time. The hindcast showed that H_{sig} is below 1.0 m 65 % of the time, which is at the lower end of estimate by SPIERS (2005). Thus DAVIES-COLLEY and HEALY (1978) estimate of percentage of waves below 1 m is accurate despite being collected using visual techniques. Calm conditions from the hindcast was only 1.1 %, significantly less than DAVIES-COLLEY and HEALY's (1978) estimate. SPIERS (2005) estimate of storm conditions (> 2 m) compares well with the hindcast estimate of 5.7 %. Waves with a height commonly suitable for surfing at the Mount Maunganui beaches (1-3 m; H_{sig}) were found to occur 36.4 % of the time. Tide, wind, and wave direction also need to be suitable so the percentage of time surfable waves are present is likely to be significantly less. Although large storm events occur, significant wave heights over 3 m only happen 1.0 % of the time.

Citing various sources, SPIERS (2005) found published mean H_{sig} wave heights between 0.41 m to 1.50 m and concluded the true value to be around 0.80 m, which matches reasonably well the mean H_{sig} of 0.95 m calculated from the hindcast. SPIERS (2005) cites some disagreement between the average significant wave period between researchers, with two researchers calculating 6 seconds while three researchers estimate around 8.5 seconds. The average mean period from the hindcast is 6.3 seconds, significantly lower than the mean period during the study period of 7.5 seconds, showing variations in the wave climate over time, probably influenced by long term weather patterns such as the Southern Oscillation Index (SIO).

Analysis of Longshore and Onshore Energy Flux

Sediment transport occurs in both longshore and cross-shore directions. The longshore sediment transport rate is commonly correlated to the longshore component of wave energy flux or power (ROSATI *et al.,* 2002). The cross-shore energy flux is often considered separately (DEAN *et al.,* 2002) and is an indicator of the sediment transport induced by waves along a two-dimensional profile. Additionally, sediment transport by wind is also an important component in coastal sediment transport (HSU and WEGGEL, 2002), but at Mount Maunganui wind forced upwelling (offshore winds; e.g. El Nino) and downwelling (onshore

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winds; e.g. La Nina) from wind forcing is likely to move more sediment than aeolian sediment transport.

The hindcast datasets provide total energy flux, longshore flux and onshore flux estimates, shedding some light on macro-scale wave induced sediment transport. The character of the longshore and onshore energy flux for different significant wave heights, periods and directions is shown in Figure 7.7 and Figure 7.8. There is a limit to the size of the longshore transport for a particular wave height, consequently the largest longshore transport is likely to occur when waves are larger than 2 m. However, longshore flux can be small even during large wave heights when waves approach perpendicular to the coast. The height and direction graphs in Figure 7.7 are reasonably symmetrical for flux to the southeast and northwest, whereas the period graph exhibits some asymmetry caused by the different character of swells from different directions.

Figure 7.9 shows the relationship between mean wave direction and various wave parameters. There is no clear relationship between the heights of storm waves (from 350-90°) and wave direction. The directional spread of storm waves is limited by the East Cape and the Coromandel Peninsula. The hindcast predicts small waves to occur outside of this directional window and they can occur at acute angles to the beach, created by local winds with H_{sig} under 1.00 m. The spectral width and mean periods also exhibit filtering of waves outside of a 350-90° window, but show some variation in character between the northerly and easterly storm sources. This is indicated by the easterly storms having larger maximum periods than the northerly storms, and the spectral width potentially being wider for easterly sources.
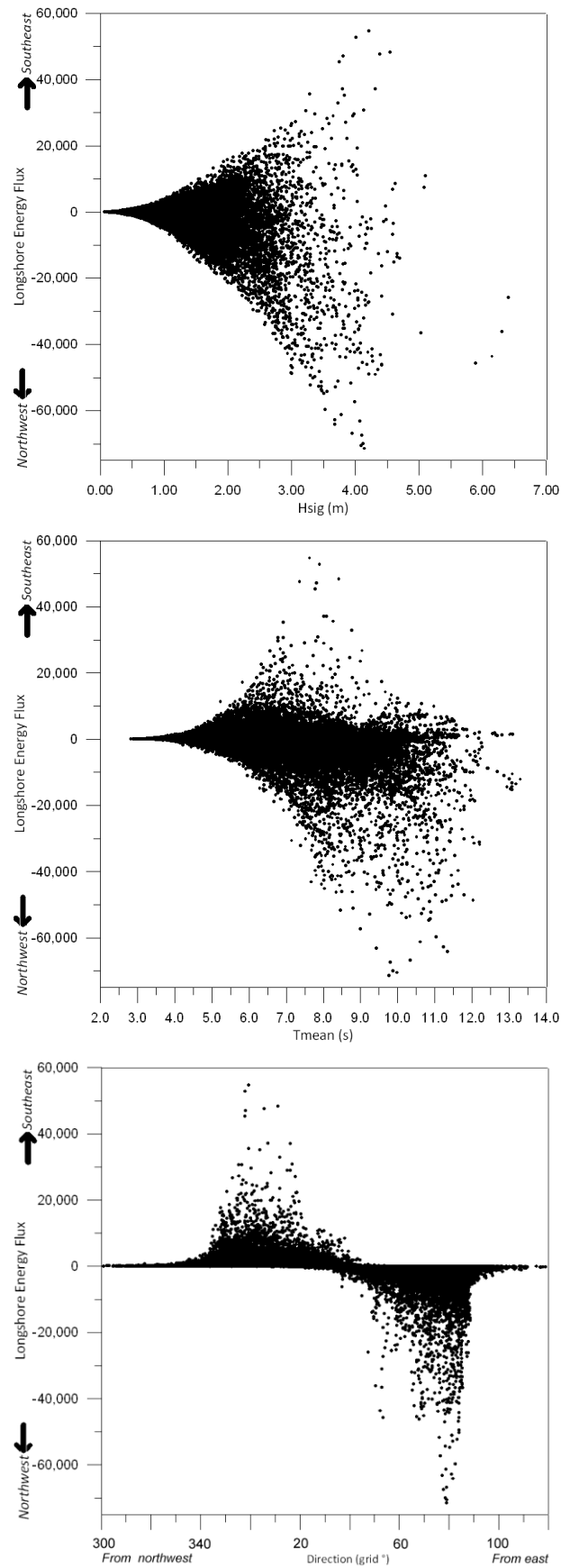
Figure 7.7. Relationship between longshore energy flux (W/m) and significant wave height (top), mean wave period (middle) and mean wave direction (bottom) from hindcast data between 1979 and 2007.
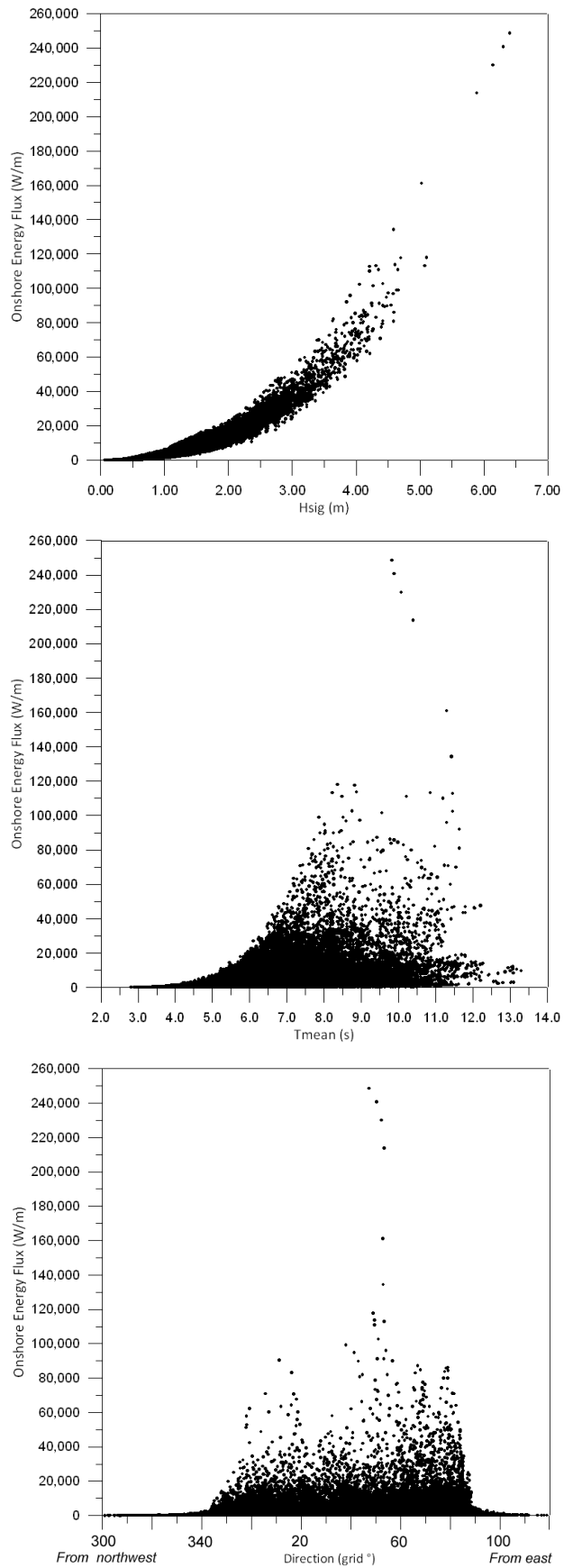
Figure 7.8. Relationship between onshore energy flux (W/m) and significant wave height (top), mean wave period (middle) and mean wave direction (bottom) from hindcast data between 1979 and 2007.
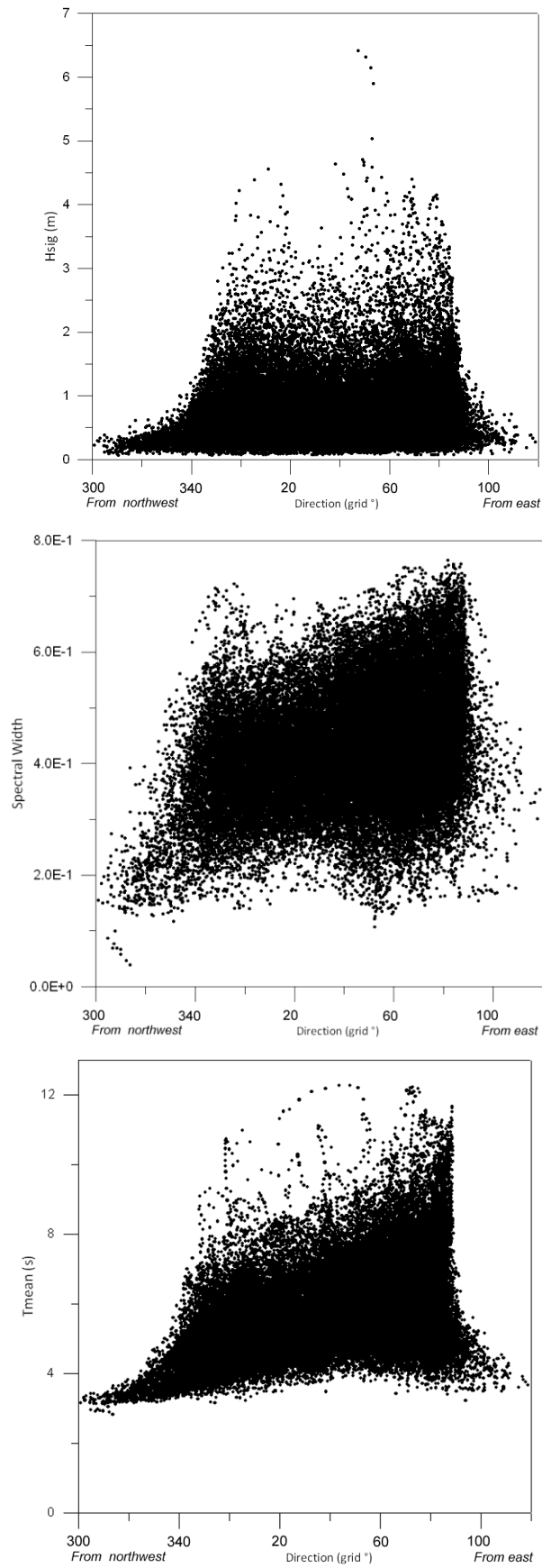
Figure 7.9. Relationship between mean wave direction and significant wave height (top), spectral width (middle) and mean wave period (bottom) from hindcast data between 1979 and 2007.

WAVE MEASUREMENT ANALYSIS

The three InterOcean S4 current and wave instruments collected pressure and currents relative to New Zealand Standard Time (NZST) and sampled at 2 Hz for 18 minutes per hour. Weighted aluminium tripod frames were used for mountings and the current meters were 1 m above the seabed. The measured data allowed the hindcast to be validated (Figure 7.6), wave conditions during surfing and storm events to be analysed (Table 7.2), and hydrodynamic models to be calibrated (Appendix Two). Of particular interest in this section is the relationship between the wave heights at the S4_SILTDUMP site to the EBOP and A_BEACON buoys.
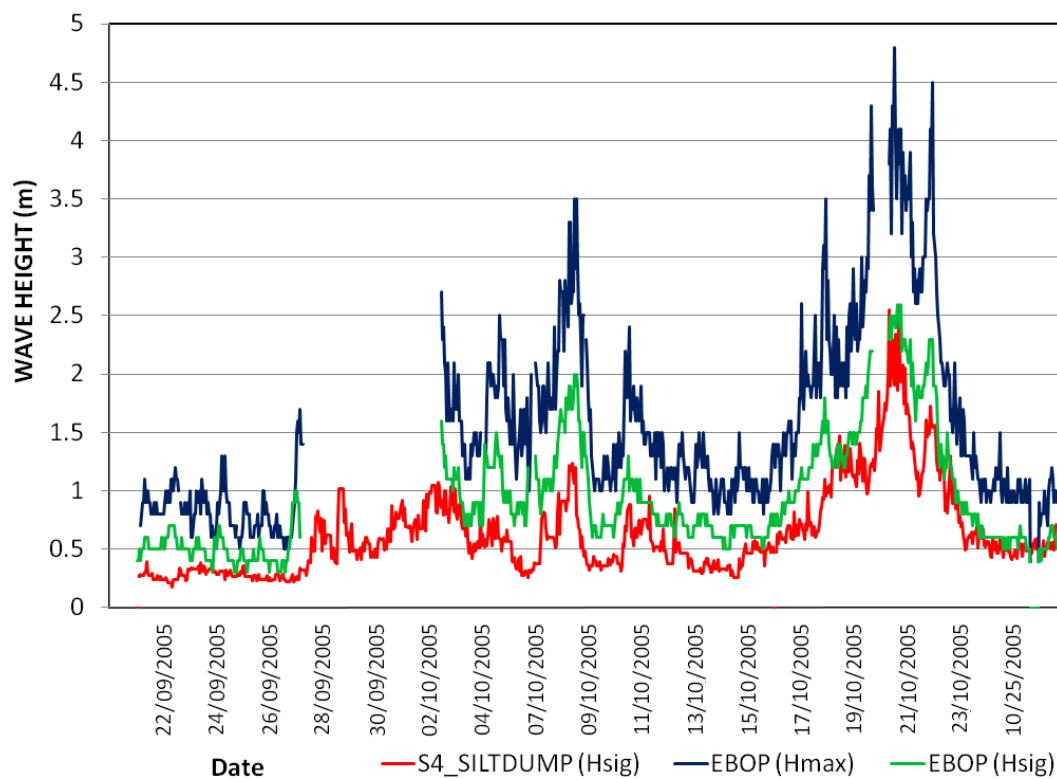
Figure 7.10. Comparison of measured EBOP buoy (61 m) and S4_SILTDUMP (24 m) significant wave heights. Note that the EBOP sensor has some holidays in the data during maintenance works.

A comparison of significant wave heights at the EBOP offshore buoy and the S4_SILTDUMP (Figure 7.10) shows that the locations are subject to very similar patterns, although the EBOP measured wave heights are consistently larger, and there is expected to be some differences caused by local winds. Since waves arrive in a spectrum of different wave heights, period, and directions, it is difficult to come up with single figures to describe the character of a surfing swell. HUTT (1997) suggests using $H_{1/10}$ as surfers usually ride the largest waves in a set. Thus

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the H_{max} measurement at the EBOP, which is at times twice H_{sig} at S4_SILTDUMP, might be close to a realistic estimate of the maximum surfing wave ridden within an hour sampling period at the S4_SILTDUMP site.

Analysis of the relationship between the one month record (S4_SILTDUMP) and the EBOP and A_BEACON has been undertaken to provide simple, empirical relationships between the measurement sites. Although often the relationship between oceanographic parameters is complex, Figure 7.11 and Figure 7.12 exhibit a near linear fit for the measured wave heights. Significant wave heights at A_BEACON wave heights are slightly smaller (93%) than at the S4_SILTDUMP site for the measured wave events. Regression between the EBOP and S4_SILTDUMP sites further proves that the deeper and more exposed site (EBOP) has a larger ambient wave climate. The distributions of the results is more scattered than for Figure 7.11 as there is 36.5 km between the Figure 7.12 sites, and only 3.8 km for the Figure 7.11 sites. Figure 7.13 shows the relationship between wave height measurements at the S4_SILTDUMP and S4_BCDUMP sites further has an even stronger agreement and suggests that waves decrease in height by 86 % from 24.5 m to 9 m depths offshore of the ASR.

Since the hindcast shows that waves come from a wide range of directions and wave measurements can be over 5 m (e.g. 11 July 2007 – 5.80 m H_{sig} and 11.21 m H_{max}; A_BEACON measurement), further validation with longer term records would be needed to confirm the validity of these initial calculations. Still the linear nature of the distribution adds confidence to the estimate. These empirical relationships are applied to the 60 m model grid wave height boundary to estimate conditions at the 3 m model grid boundary, adding redundancy to the wave boundary calculations. This is addressed further in the discussion section.
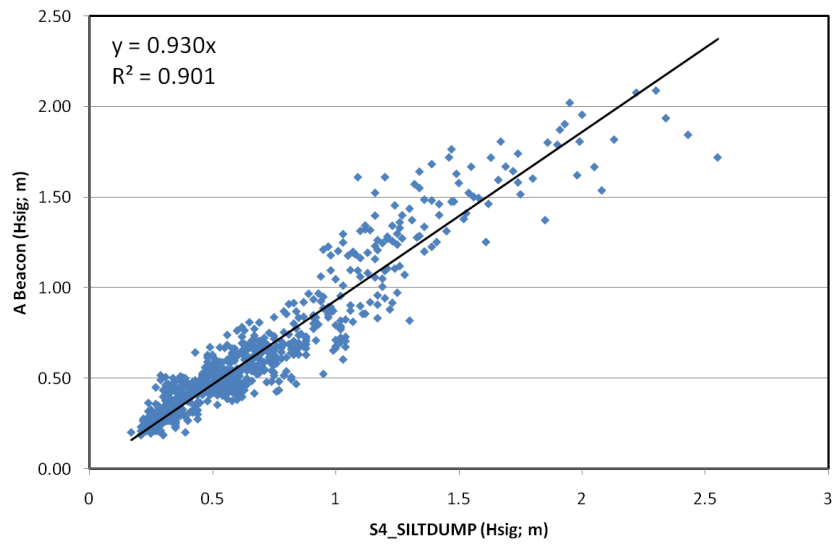
Figure 7.11. Relationship between the measured significant wave height at S4_SILTDUMP and A_BEACON showing larger waves at the 3 m model grid boundary (S4_SILTDUMP).
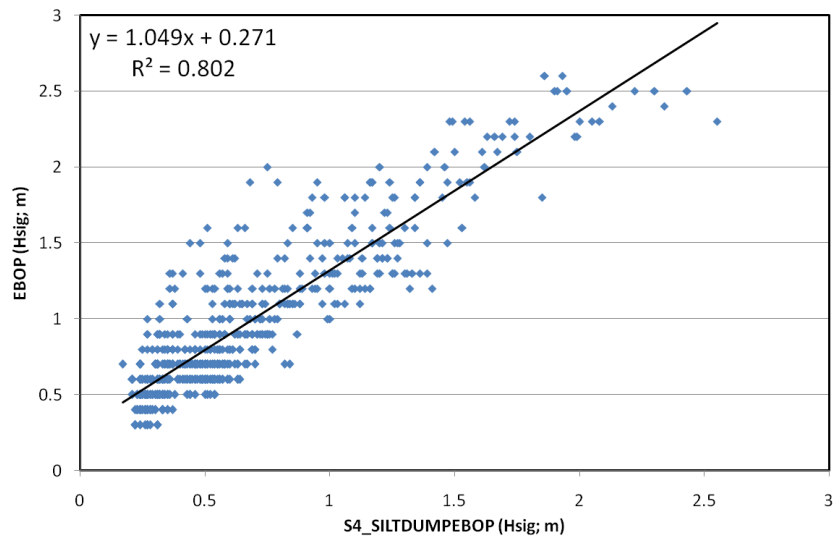
Figure 7.12. Regression between the measured significant wave height S4_SILTDUMP and EBOP showing larger waves at the 60 m model grid boundary (EBOP) than the 3 m model grid boundary (S4_SILTDUMP).
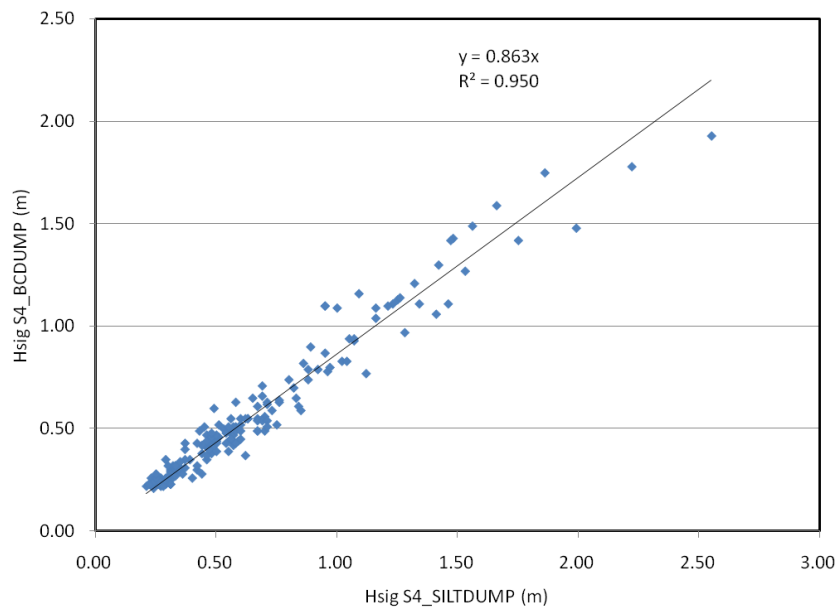
Figure 7.13. Regression between the measured significant wave height S4_SILTDUMP and S4_BCDUMP showing a reduction in wave height from the 24.5 m to the 9 m deep site.

Modelling of wave directions using monochromatic wave models, as utilised in SCARFE *et al.* (Chapter 2, 3 and 8), is difficult to undertake accurately over large areas. Differences can be observed during model calibrations depending on the swell spectral width, whether mean or peak wave directions are used, and localised wind patterns. To increase the confidence in the modelled directions, and the boundary predictions of the 3 m model grid, an empirical analysis of the relationships between the EBOP and S4_SILTDUMP and S4_BCDUMP direction measurements is presented in Figure 7.14 and Figure 7.15. The analysis helps to understand the wave angle behavior between the EBOP site and near the ASR.

The relationship between the EBOP and S4_SILTDUMP wave directions, and the EBOP and S4_BCDUMP wave directions (Figure 7.14) shows significant scattering and a poor linear relationship ($R^2 = 0.2588$ and 0.2418). However, the figure does confirm that waves at the inshore sites (S4_SILTDUMP and S4_BCDUMP) approach from more easterly directions, which are closer to the dominant wave angle at these sites (~45°, perpendicular to the coast). This can be explained by Figure 7.15 which shows the relationship between the EBOP site and the difference between S4_SILTDUMP and EBOP sites (=S4_SILTDUMP − EBOP) as well as between the S4_BCDUMP and EBOP sites (=S4_BCDUMP − EBOP). These figures represent the degree of wave refraction as waves approach from different directions. The least wave refraction occurs when waves approach with the wave crests aligned to within 20° the coastline (coast = 132°). This

generally arises when wave directions approach from 20-60°. It is clear that the most wave refraction happens when north to northwesterly waves at EBOP occur (waves from 300-360°) and these waves are generated from local winds as the Coromandel Peninsular blocks swell waves from these directions. During these conditions the behaviour of wave induced sediment transport and beach morphology is expected to be different than for longer period swells generated at distant sources, which refract less as they approach the Mount Maungaui coast.
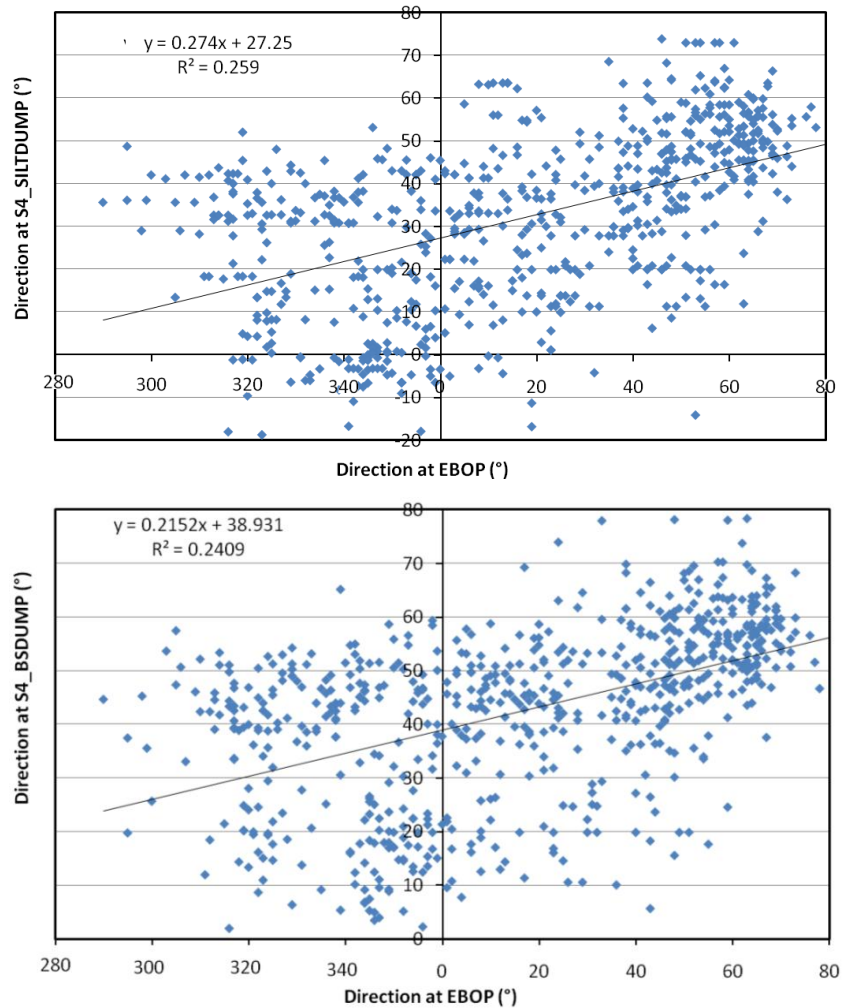
Figure 7.14. Measured wave direction at EBOP and S4_SILTDUMP sites (top) and EBOP and S4_BCDUMP sites (bottom) showing high spread in the data, but a general increase in angles at the S4_SILTDUMP and S4_BCDUMP site due to waves becoming aligned with the 132° coast.

$$y = -0.6613x + 26.267$$
$$R^2 = 0.5869$$

$$y = -0.7848x + 38.931$$
$$R^2 = 0.808$$
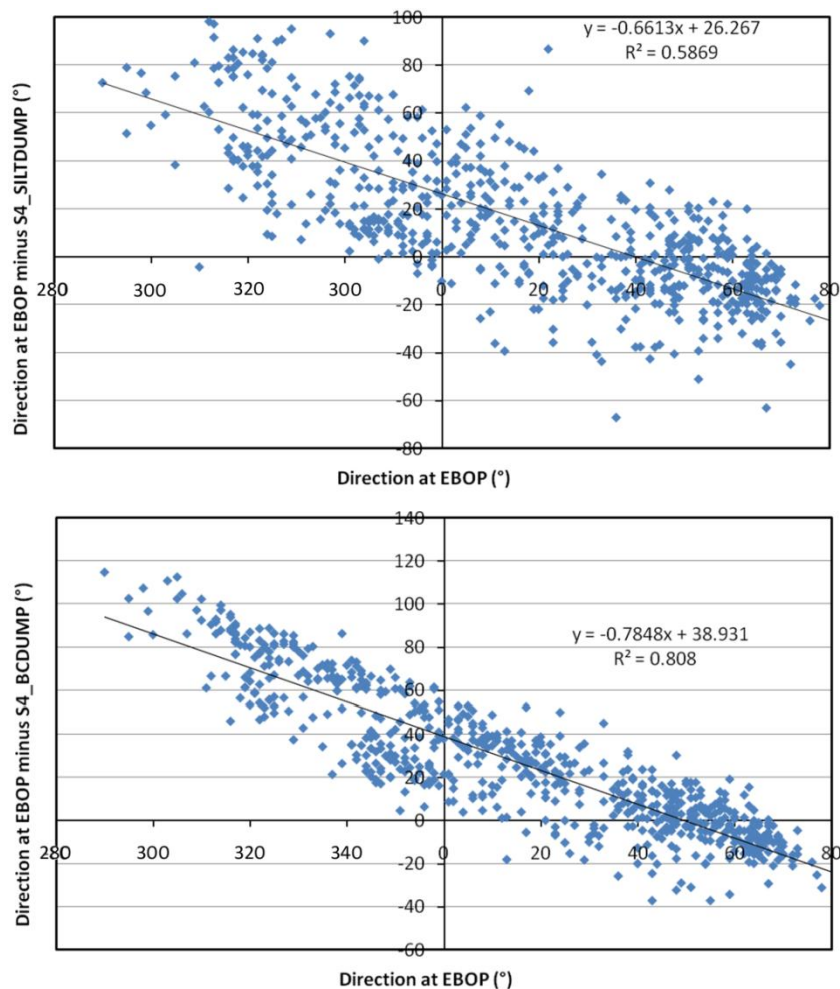
Figure 7.15. Measured wave direction at EBOP site versus S4_SILTDUMP minus EBOP sites (top) and EBOP site versus S4_BCDUMP minus EBOP sites (bottom). The graphs show the degree of refraction as waves approach from different directions. On the y-axis, positive wave directions are when wave directions have refracted clockwise (more easterly direction) and negative angles when directions have refracted anti-clockwise (more northerly direction.

DISCUSSION

Oceanographic data in the vicinity of the Mount Maunganui ASR has been collated and analysed. Now that a reasonable understanding of the wave conditions has been presented, various surfing wave events and recent and historical storm events are identified to provide boundary conditions for numerical modelling in this thesis, and for future research in the area. The surfing waves are modelled to understand the wave patterns during surfing wave events. The storm waves are modelled to understand surf zone processes and wave forces that drive beach morphology. The surfing wave events were identified during site visits, from personal communications with other surfers, as well as publicised dates when good surfing conditions have occurred on the reef. This includes reports,

photos and video presented on the ASR developers' website (www.mountreef.co.nz), as well as a New Zealand surfing website (www.surf2surf.com). The storm wave events range from small locally generated swells that occur frequently, to larger storms which occur several times per year, plus historic cyclones that have caused significant erosion along the Bay of Plenty coast.

For the dates and times of the surfing and storm events identified, a boundary condition that includes significant wave height, direction, period and tide level has been created for the 60 m model grid boundary, EBOP. These oceanographic conditions are presented in Table 7.2 along with estimates of the wave condition at the 3 m boundary (S4_SILTDUMP). Wave periods for the S4_SILTDUMP boundary conditions was taken from the HIND_SILTDUMP hindcast datasets as the validation of the hindcast period (Figure 7.6) is very good. Although period is conserved during wave refraction, differences in local winds between the EBOP site and the Mount Maunganui beaches mean that it is likely that the hindcast prediction of period is more accurate at the 3 m model boundary than the remote measurement at the EBOP site.

Table 7.2. WBEND wave model boundary conditions for 60 m and 3m model grids. Surf and storm swell events are shown with a brief description of wave conditions.

EVENT	DATE	TIDE MOT (m)	TIDE POT (m)	SOURCE	NOTES	SURFABLE WAVES	HSIG EBOP (m)	PERIOD EBOP (s)	DIR GRIDNORTH (°)	HSIG CALC (m)	DIR GRIDNORTH CALC (°)	PERIOD HINDCAST (s)
1	6/02/1990 10:45	-0.33	0.63	Scanned aerial photograph	Outside of model grid rotation	UNKNOWN	1.22	8.4	38.0	1.06	39.0	8.2
2	30/12/1996 03:00	0.84	1.80	Pickett (2004)	Cyclone Fergus	UNKNOWN	5.07	8.2	43.0	4.44	44.2	8.3
3	30/12/1996 03:00	0.84	1.80	Pickett (2004)	Cyclone Fergus	UNKNOWN	5.07	11.2	43.0	4.44	44.2	8.3
4	11/01/1997 12:00	1.28	2.24	Pickett (2004)	Cyclone Drena	UNKNOWN	3.77	6.9	17.0	3.27	19.2	6.7
5	11/01/1997 12:00	1.28	2.24	Pickett (2004)	Cyclone Drena	UNKNOWN	3.77	9.2	17.0	3.63	19.2	6.7
6	11/03/1997 12:00	1.34	2.30	Pickett (2004)	Cyclone Gavin	UNKNOWN	3.50	8.2	80.0	3.07	71.3	8.5
7	11/03/1997 12:00	1.34	2.30	Pickett (2004)	Cyclone Gavin	UNKNOWN	3.50	12.3	80.0	3.07	71.3	8.5
8	21/07/2004 11:30	0.25	1.21	Site visit and photographs	Good surfing swell, tide too full	YES	1.27	5.3	23.8	1.09	26.1	7.5
9	21/07/2004 13:30	-0.40	0.56	Site visit and photographs	Good surfing swell, tide too full	YES	1.20	5.7	20.4	1.00	24.3	7.7
10	11/08/2004 16:00	0.45	1.41	Site visit and photographs	Very small surfing waves on main beach, wave breaking at 30-40° angle to the beach	YES	1.54	4.6	344.2	1.00	-10.3	7.3
11	2/09/2004 14:45	-0.84	0.12	Site visit and photographs	Small surfing waves and strong wave focusing along coast	YES	1.49	7.2	0.0	1.14	10.2	6.4
12	5/10/2004 12:15	0.69	1.65	Site visit and photographs	Surfing at main beach and messy waves along coast - offshore winds	YES	2.36	5.9	9.7	1.56	15.8	7.8
13	1/01/2005 13:50	0.25	1.21	Site visit and photographs	Good waves and surfing at Main Beach, messy along coast	YES	1.46	5.0	2.7	1.31	21.5	8.1
14	22/10/2005 12:00	0.63	1.59	S4 wave deployment	Good swell with offshore winds	YES	2.30	7.0	59.9	1.76	71.2	7.5
15	30/11/2005 9:15	0.00	0.96	Site visit and photographs	Waves breaking on offshore bar	YES	1.30	6.7	61.9	1.26	64.7	8.2
16	17/12/2005 8:45	0.80	1.76	www.mountreef.co.nz	first waves on the reef, heavy small barrelling waves	YES	2.01	7.5	39.4	1.96	20.9	6.6
17	17/12/2005 14:53	-0.61	0.35	www.mountreef.co.nz	first waves on the reef, heavy small barrelling waves	YES	1.95	7.7	39.0	1.88	20.9	7.3
18	19/12/2005 7:13	0.00	0.96	www.surf2surf.com	waves only broke on larger sets mid outgoing tide - mean period 6.3 s - peak 12.3 s	YES	1.60	7.0	27.8	1.54	14.8	6.5

Table 7.2. continued.

EVENT	DATE	TIDE MOT (m)	TIDE POT (m)	SOURCE	NOTES	SURFABLE WAVES	60 M EBOOP BOUNDARY			3 M S4_SILTDUMP BOUNDARY		
							HSIG EBOP (m)	PERIOD EBOP (s)	DIR GRIDNORTH (°)	HSIG CALC (m)	DIR GRIDNORTH CALC (°)	PERIOD HINDCAST (s)
19	5/01/2006 17:00	-0.93	0.03	Site visit and photographs	Small surfable waves at a extremely low tide, surfers riding waves to the north and south of reef, significant rip heads and small transverse bars welding to shoreline	YES	0.90	4.9	0.0	0.76	16.0	8.8
20	3/02/2006 17:15	-1.00	-0.04	Site visit and photographs	Malibu surfing waves focusing to the north and south of reef and breaking on offshore bar - lull in area around reef	YES	1.40	6.9	27.0	1.25	34.5	7.0
21	19/02/2006 11:48	0.69	1.65	www.wannasurf.com	Good surfing conditions on Bay of Plenty and Coromandel coast	YES	1.70	8.6	65.9	1.70	70.6	9.2
22	8/03/2006 8:19	-0.59	0.37	www.mountreef.co.nz	first decent surfing conditions on reef	YES	3.20	8.7	349.0	2.39	11.1	8.4
23	8/03/2006 11:19	0.00	0.96	www.surf2surf.com	first decent surfing conditions on reef	YES	2.50	7.9	1.0	1.65	17.3	8.4
24	8/03/2006 14:23	0.63	1.59	www.mountreef.co.nz	first decent surfing conditions on reef	YES	2.40	6.8	1.9	1.63	16.2	8.5
25	15/03/2006 8:06	0.68	1.64	www.mountreef.co.nz	Offshore winds and waves breaking on reef but are too intense to surf	NO	2.60	8.4	59.0	2.35	62.9	9.1
26	15/03/2006 14:21	-0.62	0.34	www.mountreef.co.nz	Offshore winds and waves breaking on reef but are too intense to surf	NO	2.10	8.8	59.0	2.00	62.8	9.1
27	3/10/2006 9:14	-0.68	0.28	www.mountreef.co.nz	Messy bodyboarding waves breaking on reef	YES	1.20	7.7	43.0	1.30	50.0	7.8
28	3/10/2006 15:40	0.68	1.64	www.mountreef.co.nz	Messy bodyboarding waves breaking on reef	YES	1.20	8.2	52.0	1.28	55.6	8.3
29	4/10/2006 8:30	-0.46	0.50	www.mountreef.co.nz and personal communications	Some of the best surfing conditions on reef to date, supported with video	YES	1.43	8.7	42.0	1.26	53.7	9.0
30	4/10/2006 10:16	-0.71	0.25	www.mountreef.co.nz	Some of the best surfing conditions on reef to date, supported with video	YES	1.55	9.3	44.0	1.33	54.6	9.0
31	4/10/2006 16:45	0.71	1.67	Personal communications	Good high tide surfing waves on offshore bar and very close to shore, but not of reef	YES	1.55	9.0	45.0	1.30	57.3	8.9
32	5/10/2006 11:18	-0.76	0.20	www.surf2surf.com and www.mountreef.co.nz	Websites stated surfing on reef for much of the day	YES	1.30	6.6	86.0	1.01	68.8	9.1
33	5/10/2006 17:39	0.81	1.77	www.surf2surf.com and www.mountreef.co.nz	Websites stated surfing on reef for much of the day	YES	1.00	5.7	95.0	0.81	69.4	9.0

Table 7.2. continued.

EVENT	DATE	TIDE MOT (m)	TIDE POT (m)	SOURCE	NOTES	SURFABLE WAVES	60 M EBOOP BOUNDARY			3 M S4_SILTDUMP BOUNDARY		
							HSIG EBOP (m)	PERIOD EBOP (s)	DIR GRIDNORTH (°)	HSIG CALC (m)	DIR GRIDNORTH CALC (°)	PERIOD HINDCAST (s)
34	21/12/2006 11:54	-0.27	0.69	Site visit and photographs	Surfers riding close out waves on bars in reef lee - poor surf, waves only just breaking and crumbling on reef – Calibration for breaking criteria	YES	0.90	4.3	344.0	0.78	-1.4	9.0
35	11/01/2007 11:30	0.45	1.41	Personal communications	Surfable waves but not breaking on reef	YES	1.10	5.8	23.0	1.11	31.1	6.5
36	15/01/2007 9:13	-0.39	0.57	www.mountreef.co.nz	Some of the best surfing conditions on reef to date, supported with video	YES	1.50	6.8	40.0	1.40	44.1	7.4
37	15/01/2007 15:13	0.39	1.35	www.mountreef.co.nz	Some of the best surfing conditions on reef to date, supported with video	YES	1.50	6.6	40.0	1.39	44.3	7.5
38	16/01/2007 9:03	0.76	1.72	www.surf2surf.com	small barrelling waves on reef, rights better for surfing, body boarders on left - video	YES	1.30	6.0	45.9	1.23	46.2	7.9
39	16/01/2007 15:15	-0.59	0.37	www.surf2surf.com	small barrelling waves on reef, rights better for surfing, body boarders on left - video	YES	1.40	6.3	46.9	1.28	47.2	8.0
40	10/07/2007 16:35	-0.67	0.29	Site visit and photographs	Extreme easterly swell and wind, stormy swell increasing in size	NO	3.80	8.0	28.0	3.57	30.3	8.0
41	11/07/2007 12:00	0.11	1.07	Site visit and photographs	Peak of large storm showing waves breaking hundreds of metres out to see	NO	4.60	10.5	37.0	4.15	40.0	10.5
42	24/11/2007 4:00:00 p.m.	0	0.96	Site visit and photographs	Good clean surfing waves along Mount Maunganui coast	YES	2.00	8.0	19.9	1.62	23.9	8.0
43	24/11/2007 7:00:00 p.m.	0.89	1.85	Site visit and photographs	Good clean surfing waves along Mount Maunganui coast	YES	2.00	8.5	9.9	1.56	17.8	8.5
44	25/11/2007 7:40:00 a.m.	0.97	1.93	Site visit and photographs	Good clean surfing waves along Mount Maunganui coast	YES	1.40	8.3	24.9	1.14	27.7	8.3
45	25/11/2007 1:46:00 p.m.	-0.82	0.14	Site visit and photographs	Good clean surfing waves along Mount Maunganui coast	YES	1.20	9.0	32.9	0.98	35.6	9.0

Significant wave heights at the 3m boundary were calculated by averaging the 60 m model grid prediction, an empirical estimate from Figure 7.11 and Figure 7.12, and the hindcast prediction to give a robust estimate of the true wave height. Although variation between estimates can be seen (0.25-1.0 m) in Figure 7.16, the method used adds redundancy to the height boundary. For wave directions, the value at the boundary was calculated by averaging the hindcast estimate and the 60 m model prediction. Where directional discrepancies larger than 40° existed the hindcast rejected as it was assumed less accurate than the measurement that was transformed from the EBOP site with the 60 m grid.
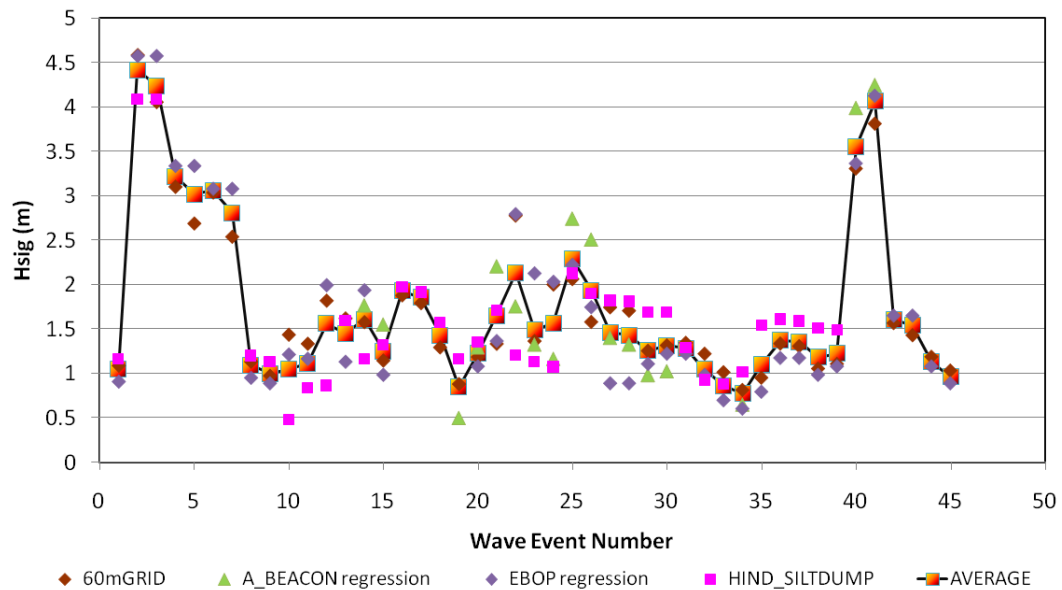
Figure 7.16. Estimation of significant wave height for 3 m model grid boundary (S4_SILTDUMP) based on averaging various wave height estimates.

Where large variations exist the modelling output needs to be analysed with care. The model calibration process showed that the model performance degrades for northerly swell sources, which accounts for some of the variation. Considering a swell is comprised of a swell spectrum that is not accounted for in the WBEND model, the variation is considered acceptable for the monochromatic modelling undertaken in this thesis. More robust modelling would require more complex and computationally expensive techniques, which is to develop a general understanding of refraction patterns.

Analysis of the 45 wave conditions has shown some patterns in the performance of the ASR for surfing. The few publicised occasions when good waves have occurred on the ASR (from personal communications or internet based video and

photo evidence) have occurred when the wave conditions have been from a small range of conditions. The best conditions have occurred when the wave direction approached from an angle perpendicular to the beach (40-50°), in between the two major offshore islands. Under these conditions waves will be aligned best with the two arms of the reef to cause wave breaking most suitable for surfing, and the swell can pass between the two major offshore islands without the wave crest being disrupted.

CONCLUSIONS

This chapter has outlined in broad terms the oceanographic conditions around the ASR site. Literature on wave climate in the area has been identified, demonstrating the evolution of wave climate research at the Mount Maunganui beaches. The coastline is in the lee of the prevailing wave conditions of New Zealand, but still experiences significant and regular swells, contrasted by periods of calm seas.

To extend the knowledge on the wave climate in the area, nearly 30 years worth of hindcast data is validated and analysed. The analysis shows the average significant wave height is 0.95 m, with storm waves (>2 m) occurring 4.6 % of the time. Although the literature shows variations in mean period estimates, the hindcast suggests a value of 6.3 seconds, with long term variations influenced by SIO. Typically the wave conditions are small (65 % < 1 m), and waves over 3 m occur only 1.0 % of the time. Wave heights suitable for surfing occur 36.4 % of the time, although tide, wind and direction needs to be suitable also making the true estimate of the time waves are surfable significantly less.

Wave energy flux from the hindcast is analysed as an indicator of sediment transport to shed light on the observed morphology in SCARFE *et al.* (Chapter 8). Onshore energy flux comprises the majority of wave energy, and longshore flux is shown to vary in direction and magnitude depending on the wave direction and size. However, the net flux is to the south east, consistent with the geomorphic indicators presented in SCARFE *et al.* (Chapter 8). Even during large swells (> 3 m) the net longshore energy flux can be low when waves approach perpendicular to the beach.

Various surfing and storm events are tabulated to be used as WBEND wave model boundary conditions. These events include small and large swells that often have photographic or video evidence to further describe the character of the swell. Surfing events identified during site visits and from other information sources rarely had surfable waves on the reef.

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Chapter 8 – Detailed Monitoring of the Morphodynamic Response of a Beach to an Artificial Surfing Reef at Mount Maunganui, New Zealand

PREFACE

It is unlikely that coastal engineering around surfing breaks will cease in the near future. So in order for coastal engineering to sustainably continue nearby surfing breaks, it is important that techniques are developed that achieve the primary objectives (e.g. mitigate beach erosion or improve vessel navigation) as well as secondary objectives such as surfing enhancement or protection. It has been proposed during this thesis, and in many publications identified in Table 2-1, that the ASR concept can achieve this goal.

In order to empirically test the beach response to an ASR, this chapter presents monitoring and modelling of the Mount Maunganui ASR. The chapter evaluates the ASR performance and provides an example of a valuable morphological monitoring method, for ASRs, and surfing breaks in general. Although the reef was not completed at the summation of this research, and the coastal protection and surfing benefits only minor, from a research stance the monitoring program has provided valuable empirical information about the beach response to the reef. This type of research is invaluable for inclusion of surfing into coastal management and engineering.

This chapter has been submitted to the peer reviewed journal, Coastal Engineering, and contributes to the following aims outlined in chapter one.

3. *to identify the range of physical effects coastal engineering activities can have on different types of surfing breaks, and to propose methods to manage the oceanographic aspects of surfing breaks.*

6. *to demonstrate the potential of Geographic Information Systems (GIS) overlay, geoprocessing and geodatabase techniques to store and analyse information for management of surfing amenity.*

7. *to monitor the beach and wave response of a beach to an artificial surfing reef using techniques identified and developed in this thesis.*

This paper has been through many revisions, and HEALY and RENNIE have helped identify the strengths of the research in order to identify the most appropriate way to focus the paper into a publishable form. The editorial and supervisory nature of this input qualifies them for co-authorship, as does the technical and fieldwork contributions of IMMENGA. The current citation for the paper is:

> SCARFE, B.E., HEALY, T.R., RENNIE, H.G., and IMMENGA, D.K.H., *in press*. Detailed Monitoring of the Morphodynamic Response of a Beach to an Artificial Surfing Reef at Mount Maunganui, New Zealand. Submitted to *Coastal Engineering,* 25 March 2008.

ABSTRACT

The artificial surfing reef concept is a method to incorporate surfing into coastal management. An empirical study presented here shows the morphological response of a beach to a constructed reef. Monitoring consists of nine multibeam echo sounding and RTK GPS foreshore surveys showing the reefs effect on the beach-state. Although no salient was observed, a groin effect on the offshore bar and development of nearshore rhythmic features has occurred. A scour hole 3.1 times the surface area of the reef has been created, having a significant effect on surf zone hydrodynamics and morphological coupling.

ADDITIONAL INDEX WORDS: beach mapping, beach-state, coastal erosion, groin effect, innovative coastal engineering, intermediate beach, morphodynamics, multibeam echo sounding, rip cells, rip formations, salient, surf zone mapping, surf zone morphology.

INTRODUCTION

It is increasingly being recognized that innovative coastal engineering is required to satisfy a parties in a mixed-use coastal space. This can be achieved by mimicking naturally occurring processes, and SCARFE *et al.* (Chapter 3) demonstrate the need to include recreational surfing in coastal engineering. They note that technologies such as artificial surfing reefs (ASR) are a potential method to incorporate surfing in Integrated Coastal Zone Management (ICZM). ASRs can potentially overcome some problems with many coastal engineering practices including negative down drift impacts, compromise of aesthetic values, changes to environmental laws and negative public reaction to rocks on beaches (MEAD and BLACK, 1999). Yet little research exists on monitoring such structures as the literature is primarily focused on their design (SCARFE *et al.*, Chapter 2). Research in this area is important for the emerging global coastal issue of surfing and coastal management (*see* LAZAROW *et al.*, 2007; NELSEN *et al.*, 2007; SCARFE, 2008).

Although Ranasinghe and TURNER (2006) question the success of attempts in the last 20 years to build submerged structures to control erosion, the theoretical reef literature (BLACK, 2001a, b and 2003; BLACK and MEAD, 2001; MEAD, 2001) provides convincing arguments for the ASR concept. Analysis of the shoreline response to ASRs using physical and numerical modelling (TURNER *et al.,* 2001; BLACK, 2003; RANASINGHE *et al.*, 2006; BLACK and MEAD, 2007) suggests that it is not the coastal engineering concept, but the implementation of the concept that is still to be proven. The U.S.A.C.E. have adopted an ASR for Ventura, California as their Section 227 innovative and non-traditional erosion control project (MEAD *et al.*, 2004), further highlighting the potential of such reefs. Inclusion of multiple design objectives has seen ASRs also referred to as multi-purpose reefs (MEAD and BLACK, 1999) or multifunctional artificial surfing reefs (RANASINGHE and TURNER, 2006; RANASINGHE *et al.*, 2006).

ASRs provide a flexible solution as there are many design parameters that can be modified to control wave breaking, currents and sedimentary patterns (BLACK, 2001a). However, ASRs need to be prototyped and monitored for widespread acceptance of the concept. The engineering method is still in its infancy and worldwide only five reefs have been attempted in the following locations:

- El Segundo, California, U.S.A (MOFFAT and NICHOL ENGINEERS, 1989; BORRERO, 2002; BORRERO and NELSEN, 2003; MACK, 2003);

- Cable Station, Western Australia, Australia (BANCROFT, 1999; PATTIARATCHI, 2000, 2002 and 2007);

- Narrowneck, Gold Coast, Australia (BLACK, 1998 and 1999; BLACK *et al*., 1998; HUTT *et al*., 1998 and 1999; AARNINFKOF *et al*., 2003; TURNER, 2006; JACKSON *et al.*, 2002 and 2007);

- Tay Street, Mount Maunganui, New Zealand (MEAD *et al*., 1998 and 2007; MEAD and BLACK, 1999; RENNIE *et al.*, 1998; RENNIE and MAKGILL, 2003; SCARFE and HEALY, Chapter 6; BLACK and MEAD, 2007); and

- Opunake, New Zealand (BLACK *et al.*, 2004).

The Mount Maunganui reef (Figure 8.1 and Figure 8.2) is the focus of this paper and the project benefits from the combined experiences of the previous reefs. The design and construction methods used (described in MEAD *et al.*, 2007) are significantly more robust than earlier reef projects. This study analyses the short term beach morphology around the constructed ASR to achieve the following objective:

- to monitor an artificial surfing reef construction and nearby surf zone morphology using repetitive multibeam echo sounding (MBES) surveys.

The reef was 70 % complete at the end of this study and the study methods consists of:

  (i)   nine highly accurate and dense bathymetric surveys using multibeam echo sounding (MBES) and RTK GPS topographic surveying;

 (ii)   modelling of wave transformations offshore and around the reef site; and

(iii)   analysis of the morphological changes.
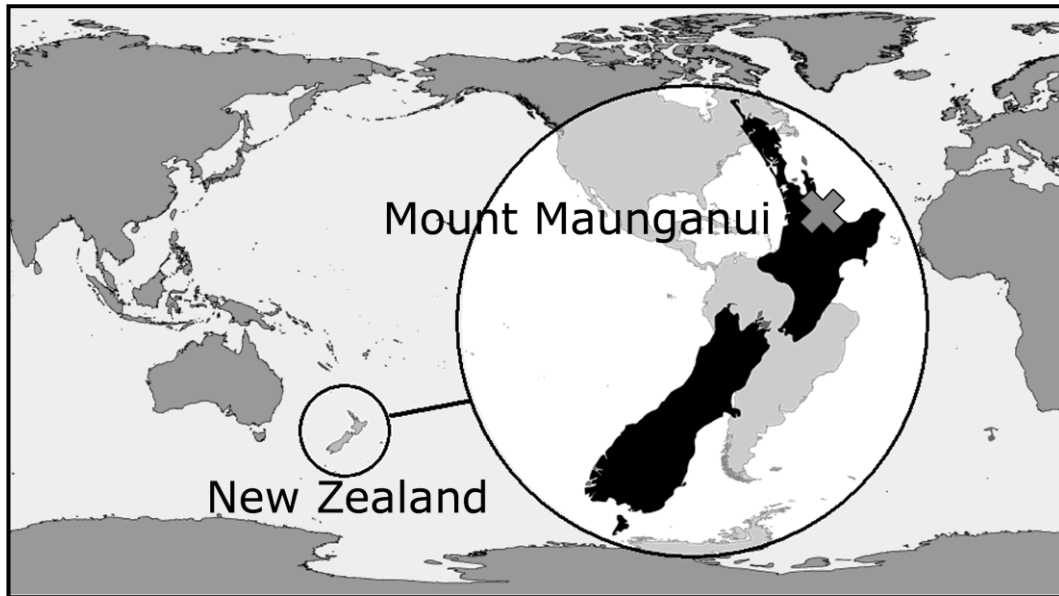
Figure 8.1. Location of study site at Mount Maunganui, New Zealand.
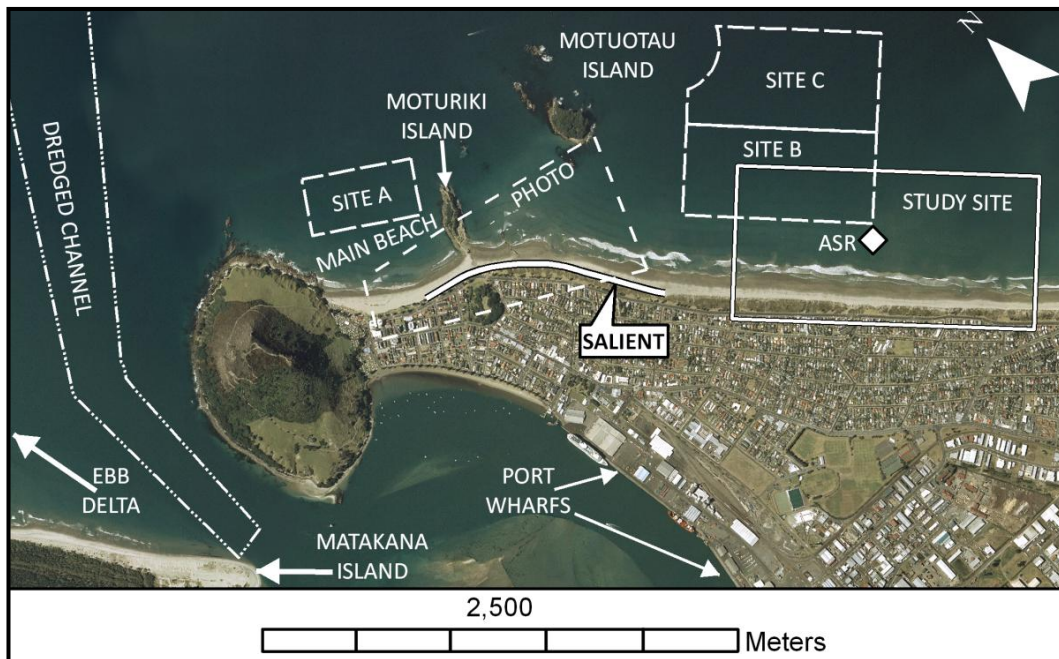
Figure 8.2. Features of interest at the Mount Maunganui beaches. The ASR study site (shore parallel rectangle) covers 1.6 km of the beach from the dune line to 10 m depth contour. Identified features are the Port of Tauranga dredging disposal sites (A, B and C), location of ebb delta surfing break at Matakana Island and coverage of photograph in Figure 8.4. Background aerial photography by Terralink International Limited.

METHODOLOGY

This study begins with a description of the study site including an overview of the wave climate and shoreline morphology. Next, the beach-state (WRIGHT and SHORT, 1984; SHORT, 1999a) and beach reflectivity are discussed relative to the observed morphology. SHORT and MASSELINK (1999) found that interruptions to

natural circulation, such as caused by the ASR construction, lead to stronger rips, topographically controlled rips and crenulated sedimentary features and this study shows that the beach has clearly been modified since the reef construction. Although no current measurements have been undertaken, topographic controls on rip formations such as the troughs and eroded sedimentary features in the surf zone are discussed. Monitoring of these features is important for surfing, swimming safety, surf zone hydrodynamics and identifying sediment transport pathways. To address the issue of shoreline response, the near shore is studied to identify any salient or erosion. GIS methods are utilized throughout the study including 2D and 3D analysis of erosion and accretion, and selected cut and fill charts are presented to show the migration of sedimentary features.

Numerous (> 40) site visits to the ASR were made to chart the beach, view and photograph wave patterns and focusing and this study reports on the findings. During the study SCARFE and HEALY (Chapter 6) collected a baseline bathymetric dataset (August 2004) covering a 2 km x 2 km area from the dune line to the 21 m contour. The dataset was collected using MBES and backpack mounted RTK GPS to map the foreshore. The use of MBES has many advantages over singlebeam echo sounding (SBES) systems, as discussed in MCRAE (2007) and SCARFE *et al.* (Chapter 4), primarily due to the increased coverage of the seafloor at a faster rate, and addition of backscatter imagery of seabed type. An overview of MBES for shallow water charting is discussed by HUGHES-CLARKE *et al.* (1996) and EEG (1999), and future trends by MAYER (2006). The specific charting process used here is described in SCARFE *et al.* (Chapter 4 and 5).

Subsequent to the baseline survey, a series of eight further surveys of the surf zone, offshore bar, beach and reef structure have been undertaken (Table 8-1) within the study site depicted in Figure 8.2. The data collected in this study is used to create digital terrain models (DTM) of the beach using a terrain GIS format discussed in ESRI (2006). The ArcGIS software is used for the majority of the analysis and geodatabasing undertaken in this research.

Table 8-1. Dates of hydrographic surveys and stage of reef construction.

Survey Date	Percentage of Reef Complete
19/08/2004	0 %
28/10/2004	0 %
26/04/2005	0 %
08/09/2005	0 %
17/11/2005	10 %
20/04/2006	25 %
15/08/2006	25 %
23/01/2007	70 %
15/05/2007	70 %

The initial objective of the bathymetric monitoring was to monitor shoreline response (salient/erosion) and to image the reef construction, thus not all surveys covered the entire study area. The early surveys were carried out concurrently with data collection for SPIERS (2005) and at times much larger survey coverage was obtained. August 2004, November 2005 and January 2007 provided the best survey coverage. On occasions other survey work (e.g. spoil dump grounds or harbour channels) was being undertaken during the same weather/time window and complete coverage of the study area was not always achieved. Equipment and daylight issues further reduced the ability to completely cover the survey area.

Although the area experiences a lot of calm periods, small swells in the shallow surf zone still shoal and break. Surf beat was present in the RTK GPS water level record (SCARFE *et al.*, Chapter 4), even when waves were small. Therefore depending on the swell size the distance inshore that could be surveyed varied. Generally it was not possible to survey between the -1.0 m and -2.0 m (MSL, Moturiki Vertical Datum 1953) depth contours except during spring tides with minimal swell. A different surveying technology (e.g. wetbike/jetski based system) would have been needed to map the shallows. Full coverage maps are included in Appendix Three.

An additional complication that happened between the April and September 2005 surveys was that the ASR location was moved around 220 m southward, and 60 m inshore as part of the detailed reef design process. Therefore the earlier surveys focused on an area further to the north and this is apparent in the survey coverage

from August 2004 to April 2005. Despite these constrictions, the survey datasets still clearly show the evolution of the beach and reef structure.

Citing various sources, BLACK and MEAD (2007) identify four mechanisms that can contribute to the creation of a salient by an ASR. They are:

1. wave sheltering;
2. wave rotation;
3. reduction of wave setup in the lee of a reef due to wave breaking; and
4. counter-rotating current vortices in the reef lee that direct sediment to the salient location.

To demonstrate the impact of the reef structure on these first two mechanisms refraction model results are presented. The model WBEND (BLACK and ROSENBERG, 1992; BLACK, 1997 and 2000) from the 3DD Suite of models is used to calculate the average conditions over the study site. The model calibration is presented in Appendix Two. The 3DD Suite model support tools were used to bin the 3464, 3 hourly, hindcast predictions into 86 wave events with associated probabilities. The binned data covered from the first survey after reef construction began to when the hindcast data ran out (between November 2005 to January 2007 surveys). WBEND was used to simulate the 86 wave events and the events were averaged based on the probability of occurrence, yielding estimates of the average significant wave height and angle conditions. The model extends 2.5 km offshore of the reef site to depths of 27 m allowing near shore features that control focusing to be accounted for. SCARFE *et al.* (Chapter 2 and 3) show the importance of offshore island effects at Mount Maunganui and these will have largely been compensated for by the hindcast modelling, which is described in GORMAN *et al.* (2003a and b) and GORMAN (2005). Sea levels and currents cannot be predicted using this particular model and thus the reduction of wave setup and presence of current vortices cannot be analyzed in this study. However, they are identified here however as important processes for future research.

SITE OVERVIEW

The Mount Maunganui reef is located 3.6 km from the southeastern entrance of Tauranga harbour, which is also the main navigation channel for the Port of Tauranga. The site is characterized by an open coast backed with a sandy beach, dunes and a gently sloping seabed gradient (BLACK *et al.*, 1998). This forms

surfing waves with low wave breaking intensities (spilling) that were calculated to be between 6 and 11 by SCARFE and HEALY (Chapter 6). Wave breaking intensity has been empirically derived by MEAD and BLACK (2001) and relates to the shape of a breaking surfing wave. Lower breaking intensities (plunging waves) will occur when waves break on transient sand bars with steeper profiles, such as the side of a rip, or on a steep beach face. Offshore winds will also lower breaking intensities and increase the chance of plunging waves, which are desired by surfers with higher skill levels (FEDDERSEN and VERON, 2005; SCARFE *et al.*, Chapter 2).

The Mount Maunganui beaches are part of a wave exposed open sediment sandy beach system (HUME and HERDENDORF 1992) and lie in the middle of a 65 km littoral cell extending from Waihi Beach to Okurei (Town) Point. HEALY (1980) found the net littoral drift to be 70-80,000 m^3/yr to the southeast, and subsequent research has supported the direction and magnitude estimate (SPIERS, 2005 = 50-100,000 m^3/yr; RENNIE *et al.*, 1998 = 68-77,000 m^3/yr). JACKSON *et al.* (2007) quoted a unidirectional transport of 500,000m^3/year at the Narrowneck ASR making the magnitude of sediment movement much smaller at Mount Maungaui. SCARFE (2008) shows that the magnitude of longshore wave flux, which infers sediment transport magnitude and direction, is dependent on wave angle with a small flux predicted for swells approaching perpendicular to the coast (~ from 45°).

Immediately offshore and to the north of the ASR are the Port B and C dredge disposal grounds that help supply the beach with extra sandy sediment. The deepening of the harbour entrance channel by dredging and the orientation of the channel was suggested by SPIERS (2005) to trap sediment in the channel, leading to a reduction of sediment supply to the beaches to the southeast. The reduction in sediment supply was partially offset by the continued nourishment with dredge spoil (SPIERS, 2005; SPIERS and HEALY, 2007a).

Surveys from August 2004 (baseline; SCARFE and HEALY, Chapter 6) and January 2007 are presented in Figure 8.3. An immediate observation that can be made is that the beach to the northwest of the reef was wider than to the southeast, even before the ASR construction. This is possibly due to the dumping of the artificial nourishment or other process that cannot be resolved in this study.
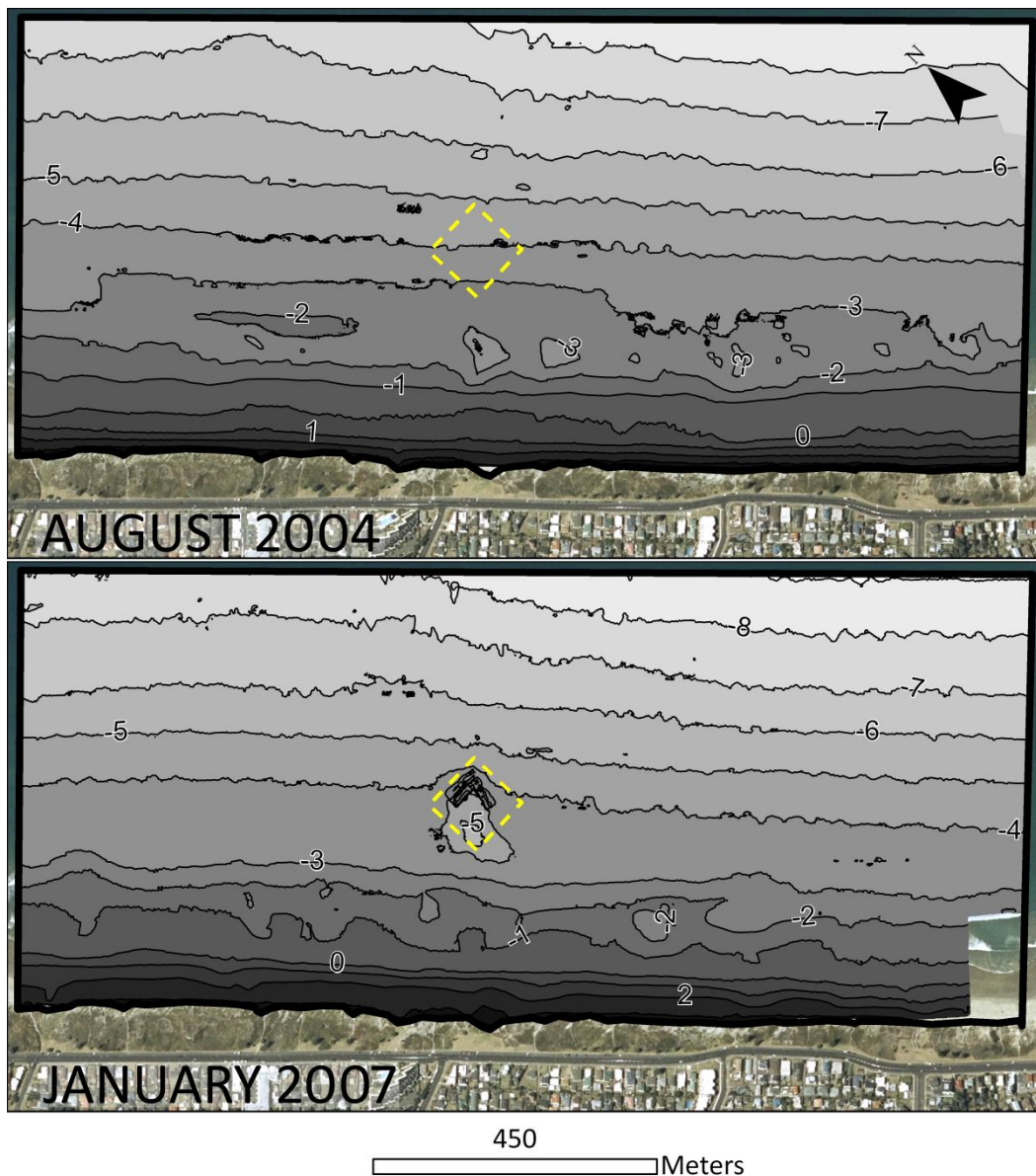
Figure 8.3. Bathymetry of study site and reef location (diamond). Datum is mean sea level (Moturiki Vertical Datum 1953).

Immediately to the northwest of the reef site the shoreline shows irregularities caused by reefs and islands (Figure 8.2 and Figure 8.4). In fact, nearby the ASR the beaches naturally form similar features to those that result from coastal engineering structures including groin effects, salient and tombolo formations. A fully formed tombolo has developed in the lee of the shore perpendicular structure, Moturiki Island, and blocks some littoral sediment from passing southeast. Further south, Motuotau Island and the surrounding reefs modify wave, sea level and current patterns to cause a salient to develop in the lee. Inshore of Motuotau Island a small natural groin structure can be seen to cause accretion (updrift) and erosion (downdrift) of the shoreline. BLACK and ANDREWS (2001a) present the geometric measurement parameters for a salient and the combined

effect of these structures has caused the shoreline to protrude around 160 m (Y_{off} parameter), with the salient width being around 1 km wide (D_{tot} parameter). The salient structure's centre is 1.7 km from the reef site and it could be argued that the development of a salient in the lee of the ASR could create a visual point of interest of similar character to the natural shoreline. The salient is generally what BLACK and ANDREWS (2001a) term a Type D_2 multiple offshore obstacle salient, but with smaller features further contributing to the salient size and stability.
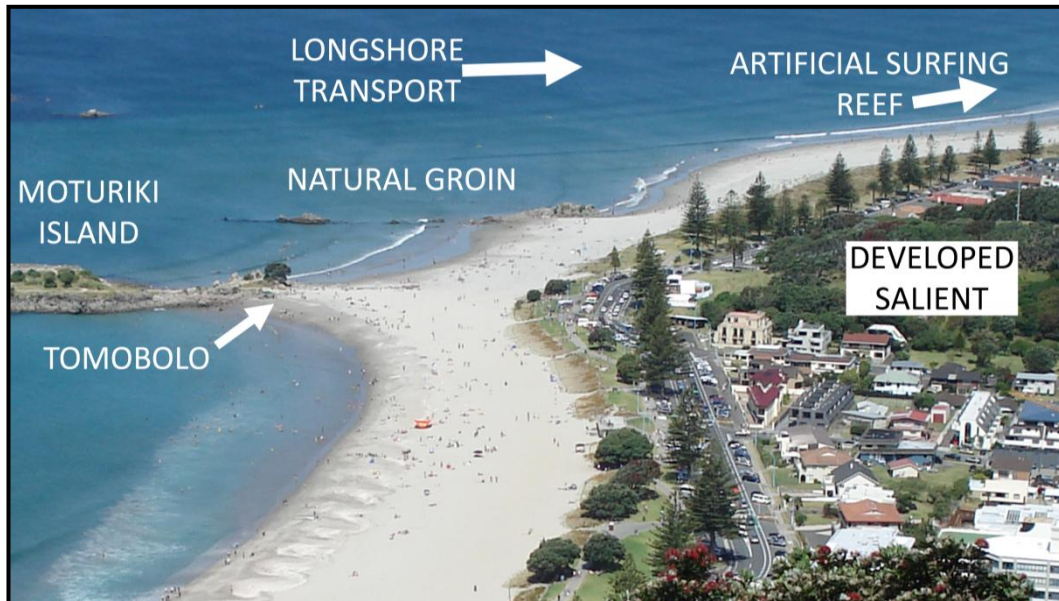
Figure 8.4. Examples of natural reef and island control structures creating a salient, tombolo and groin effects at Mount Maunganui.

The wave climate at Mount Maunganui has been studied by numerous researchers, with recent reviews and analysis provided in SPIERS (2005) and SCARFE (2008). The study by SCARFE (2008) provides the oceanographic background for this present study including analysis and validation of a 28 year, 3-hourly hindcast. The hindcast is in 24.5 m water depth offshore the reef site and analysis shows that the mean significant wave height is 0.95 m with an average mean period of 6.3 seconds. The date range when the average wave conditions were numerically modelled however has had a slightly average higher wave climate (H_{sig} = 1.15 m). Storm waves (H_{sig} > 2 m) occur 4.6 % of the time, yet larger storms (H_{sig} > 3 m) occur rarely (1.2 %). Significant wave heights below 1 m occur 63 % of time and the best surfable wave heights (H_{sig} = 1-3 m) are prevalent (36.4 %). However, the probability of the wave direction, tide, wind and beach morphology being suitable for surfing means that good surfing waves occur

a lot less, especially since waves in 24 m can approach from a wide range of directions (mean=47.1° σ=24.6° coast = 132°; SCARFE, 2008).

During storm events the wave spectrum consists of a long period swell with a local sea superimposed (DE LANGE, 1991; SPIERS, 2005) and typically last 1-5 days (BLACK and MEAD, 2007). These swells rapidly rise in height and then steadily abate (SPIERS, 2005). Storm surge associated with these swells are typically 0.20-0.30 m, but can reach 0.60 m (DE LANGE and GIBB, 2000), exposing waves to morphological features in the shoreline that are not always prone to wave processes.

EROSION-ACCRETION ANALYSIS

Analysis of the erosion/accretion between each survey was undertaken using various 2D and 3D GIS techniques and a summary is presented here. Between August 2004 and October 2004 the offshore bar northwest of the reef, identified by SCARFE and HEALY (Chapter 6), had moved shoreward, filling in the area between the -1 and -2 m contours. A trough/rip identified in the August survey south of the reef moved to the southeast with the littoral drift during this period (SCARFE and HEALY, Chapter 6). At this time the August rip feature began to turn into a shore parallel trough, presumably associated with the longshore currents. By April 2005 a longshore bar had began to form over the study site with an increasingly prominent longshore trough. The offshore bar crest moved approximately 100 m offshore making the reef construction site shallower. This demonstrates variability in the reef construction site that needs to be accounted for during an ASR design process. During this time the intertidal beach accreted and it appears that some of the longshore bar material has migrated onto the beach.

Sometime before the November 2005 survey the reef began construction and the offshore bar began to migrate inshore, deepening the area around the construction site. The next survey in April 2006 showed continued erosion of the offshore bar at depths around the reef site as sediment from the bar continued to migrate shoreward. By the August 2006 survey the offshore bar sediment had moved into the shallow surf zone and the uniform longshore structure was broken into rhythmic bars and rips in the shallow surf zone (-1 to -3 m, MSL; Figure 8.9). Another prominent offshore bar formed in line with the reef with an equally prominent trough formation immediately in the lee of the reef. By the January

2007 survey, the offshore profile had become more linear as the offshore bar moved shoreward and reduced in prominence. During this time the depth of the structure footing was at its greatest, which was likely to be favourable for the surfing event identified by SCARFE (2008) on 15 January 2007. The rhythmic bars and rips welded to the shoreline by this time, injecting sediment into the intertidal and dry beach making the beach profile near its maximum during the study. By the May 2007 survey the offshore profile was almost completely linear, with a small depression evident from the longshore trough, which was always present during the surveys at some scale. Overall since the baseline survey the entire study area above -2.5 m (MSL) has accreted, and below this level the offshore profile has eroded. These changes are expected to be natural fluctuations in the beach profile, rather than directly attributed to the reef.

The selected erosion/accretion charts (Figure 8.5) show changes in the offshore bar, surf zone and beach. Generally it can be seen that the reef has caused an interruption to the normal onshore/offshore migration of sediment shown in the middle and bottom charts. It is not considered a coincidence that these charts show a difference in erosion/accretion patterns updrift and downdrift of the reef. The analysis showed that the reef is causing a submerged groin effect on the offshore bar. SHORT and MASSELINK (1999) identify that groins cause the creation of rips and shift the beach-state to include more cellular circulation. Thus any groin effect, also studied by TURNER (2006), is an important design and monitoring consideration. Here the offshore bar has trapped sediment updrift with bar raised approximately 0.25 m in line with the reef, and lowered 0.25 m downdrift, since the baseline study. Thus although a seemingly small change, the accurate measurement techniques give confidence that this process is occurring and the groin affect could be more significant at another location or for a larger structure. The offshore bar immediately updrift of the reef is 32 m further offshore compared to the bar downdrift of the reef, further showing the groin effect. Thus at the time of the last survey in May 2007, the volume of sand stored in the updrift offshore bar is significantly more than in the downdrift bar. The long term affect of this on the shoreline stability downdrift is unknown. It can be said with confidence that the groin effect inhibits longshore transport on the offshore bar crest and controls longshore currents shoreward of the reef. However, it cannot be resolved whether the extra accretion on the intertidal beach updrift of the reef

compared to downdrift is caused by the groin effect of the reef structure, the onshore migration of dumped sandy dredged material, or other processes.

The survey data show that the study site generally has one offshore bar that can vary in distance offshore, crest depth, become linear, and can have a terrace structure when the longshore trough is not prominent and the longshore bar is in an eroded state. BLACK and MEAD (2007) comment that the most prominent bar and trough will form when waves approach perpendicular to the coast. The longshore bar and trough was found to consistently cover the entire study site before and after the reef construction. The depth limit to the offshore bar variations can be estimated by depth of closure and PICKETT (2004) calculated this using a variety of methods, concluding it to be 5 m at Tay Street. However, profile analysis undertaken here suggests that the limits of sediment movement are closer to 6 m. Therefore, from a coastal engineering perspective, there will be an advantage in building a reef on the more stable beach beyond the depth of closure.
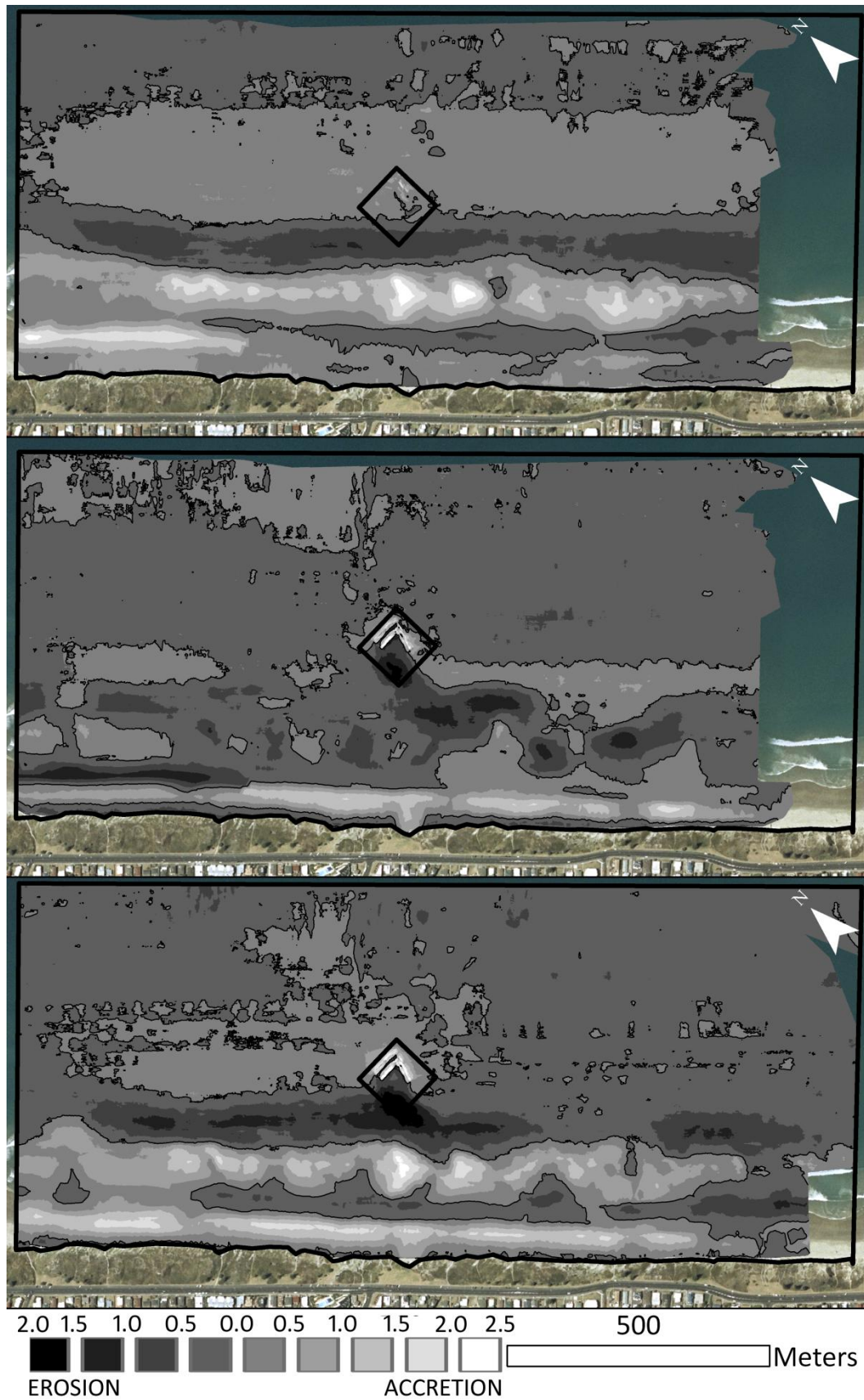
Figure 8.5. Erosion and accretion charts between surveys of the study site. Colour scale in meters and contour delineates the boundary between erosion and accretion. August 2004 to November 2005 (top), November 2005 to January 2007 (middle) and August 2004 to January 2007 (bottom).

BEACH-STATE AND SHORELINE MORPHOLOGY

Breakwaters interact with the hydrodynamic and sediment transport processes in a very complex manner regardless of their dimension, degree of submergence, or location relative to the coastline, resulting in a change in coastal morphology (ZYSERMAN and JOHNSON, 2002). SHORT and MASSELINK (1999) identified that headlands, rocks, reefs and structures will impact a beach by influencing wave refraction and attenuation, and by limiting the development of longshore rip currents and rip feeder currents (SHORT and MASSELINK, 1999). Thus the ASR can be expected to influence morphology not only at the immediate construction site but also neighbouring surf zone, intertidal beach, and updrift and downdrift beaches. The research presented here empirically identifies the types of morphological effects that have occurred.

An important piece of research when studying the effect of an ASR on a beach is the WRIGHT and SHORT (1984) three-dimensional beach-state models. Surf zone hydrodynamics drive morphology and cause transitions between beach-states. After the hydrodynamics have become expressed in the surf zone morphology, the bathymetry further controls the hydrodynamics to reinforce and extenuate the dynamics, and this is termed morphodynamic coupling (SHORT, 1999b). Thus by changing surf zone hydrodynamics the ASR has modified the natural morphodynamic coupling and beach-state. The fundamental beach-state research is based on micro-tidal beaches, such as along the Mount Maunganui coast. Tides also play a role in beach morphology by modulating the surf zone water level causing the morphodynamic zones to shift position periodically, generating tidal currents and modifying the groundwater table (MASSELINK and TURNER, 1999). However, the impact of the ASR on tidal currents is not considered here.

The dimensionless fall velocity (Ω = Dean's parameter) is used to indicate whether a dissipative ($\Omega > 6$), intermediate ($2 < \Omega < 6$) or reflective ($\Omega < 1$) beach will form (SHORT, 1999a). It is calculated here to broadly categorize the type of beach where the reef is constructed using the method of GOURLAY (1968) which is:

$$\Omega = H_b/W_sT$$

where H_b is wave height, W_s is sediment fall velocity and T is wave period. Ω has been calculated using wave information preceding each survey (Table 8-2). Mean

H_b and T were calculated for two week, one month and two month periods before each survey to see how wave sampling period affected the results. PICKETT (2004) found the sediment size at the study site to be medium sand (0.29 mm) and W_s to be 0.038 ms^{-1}. Using 28 sampling site SPIERS (2005) found the grain size to be between 0.16 and 0.23 mm, suggesting slightly finer sediment than PICKETT (2004). BLACK and MEAD (2007) found W_s to be 0.02 ms^{-1}, but without any information on the calculation method, the value from PICKET (2004) has been used.

Table 8-2. Calculation of dimensionless fall velocity (Ω) proceeding each survey as an indicator of the beach reflectivity. Wave height and period were calculated using an average of wave heights and periods for preceding two weeks, one month and two months.

Survey Date	Dimensionless fall velocity (Ω)			Average Height (H_{sig}; m)			Average Period (T_{mean}; s)		
	2 Week	1 Month	2 Month	2 Week	1 Month	2 Month	2 Week	1 Month	2 Month
19/08/2004	3.1	3.5	4.0	0.90	0.94	1.10	7.6	7.1	7.3
28/10/2004	3.0	3.5	3.4	0.82	0.93	0.91	7.1	7.0	7.1
26/04/2005	3.2	3.7	3.9	1.12	1.08	1.16	9.2	7.7	7.8
8/09/2005	4.3	4.5	4.1	1.15	1.23	1.13	7.0	7.1	7.3
17/11/2005	3.3	4.0	3.6	0.92	1.13	0.96	7.4	7.4	7.1
20/04/2006	3.5	4.2	3.8	0.90	1.12	1.13	6.8	7.0	7.7
15/08/2006	4.3	4.5	4.4	1.13	1.26	1.26	6.9	7.3	7.6
23/01/2007	4.8	3.9	3.5	1.41	1.23	1.07	7.7	8.2	8.1

Although wave sampling period induced some variation, only intermediate beach-states (fine to medium sand, moderate to high waves) are predicted in Table 8-2, and such beaches are dominated by cellular rip circulation (SHORT, 1999b). It is not possible to determine the beach-state solely using this method as antecedent beach-state (not included in the calculation of Ω) is a critical factor in how beach-state will evolve overtime (SHORT, 1999b). Techniques such as sight visits, time averaged photography, beach profiles, three-dimensional visualization and contours analysis will allow more robust identification of beach-state, including longshore variations. Encouragingly though, previous research around the study site (PICKETT, 2004; BLACK and MEAD, 2007) also identified intermediate beach-states, which included transverse bar and rip, rhythmic bar and beach and longshore bar and trough.

The surf zone where the ASR is constructed is the most variable part of a beach (SHORT, 1999c) and comprises a complex mixture of wave and currents processes that operate over a range of frequencies including incident waves, infragravity and far-infragravity waves and mean currents (AAGAARD and MASSELINK, 1999). The wave induced processes that occur during storms and drive surf zone processes are covered in detail in works such as KOMAR (1998) and SHORT (1999a). In a discussion by AAGAARD and MASSELINK (1999) on surf zone processes, three types of surf zone currents were identified:

1. bed return currents (undertow);
2. rip currents (cell circulation); and
3. longshore currents.

At the reef site the influence of each of these currents on morphology and shoreline stability is not known. A discussion is included here as a background to future research on the currents and morphology around ASRs. Generally the maximum bed return currents on barred beaches occurs slightly landward of the bar crest (AAGAARD and MASSELINK, 1999) and will also be influenced by winds due to upwelling and downwelling. Rip cell circulation is driven by longshore gradients in water level set-up, or radiation stress, and further modified by wave focusing (AAGAARD and MASSELINK, 1999). Rip currents are important sediment transport pathways because strong rip currents entrain and transport sediment, and bathymetric features such as the ASR will control rip development (AAGAARD and MASSELINK, 1999). Longshore currents are continuous shore-parallel flows within the surf zone and can be driven by incident waves, winds and tides (AAGAARD and MASSELINK, 1999), and compress in the lee of an ASR (BLACK, 2003).

The beaches around Mount Maunganui are generally long and sandy, with evidence of shoreline irregularities caused by offshore wave focusing and shadowing behind islands. Thus rip cell circulation driven by wave height gradients (focusing) is an important consideration in a morphology study. Wave focusing controls shoreline position (HEALY, 1987; STEPHENS *et al.*, 1997) and has impacts on inshore surfing conditions (BEAMSLEY and BLACK, 2003; MEAD *et al.*, 2003; SCARFE *et al.*, Chapter 2 and 3). Focusing at Mount Maunganui (SPIERS, 2005; SPIERS and HEALY, 2007b; SCARFE *et al.*, Chapter 2 and 3) can be

considerable and oblique photography of an extreme case is presented in Figure 8.6 at the peak of a nearly 5 m (H_{sig}) storm event. Waves focus over the ebb delta and also break on the sandbar feature, which protrudes approximately 4.3 km from the shoreline. However, the wave focusing patterns around the reef site are created solely by offshore transformations as the beaches lack significant protruding delta feature in depths under 20 m. SCARFE *et al.* (Chapter 4) identified "rippled scour depressions" or "sorted bedforms" from MBES backscatter imagery immediately offshore the ASR as evidence of wave focusing. These features are also identified at a larger scale by SPIERS and HEALY (2007b) using side scan sonar.

Figure 8.6. Photographs of wave patterns during the peak of a storm from 10-12 July 2007 (SCARFE, 2008 wave event 41; H_{sig} = 4.60 m, H_{max} = 8.50 m T_{mean} = 10.5, DIR_{mean} = from 40.0°). Extreme wave focusing over Tauranga harbour's ebb tidal delta (top) and at the beaches around the study site (bottom) can be seen and the wave height gradients will influence surf zone hydrodynamics. Wave focusing around the reef site is highlighted with the line and the surf zone in excess of 500 m in places, breaking well offshore of the reef.

Bathymetric controls at a beach, such as the one created by the ASR, can cause three impacts:

1. lower wave heights;
2. change wave direction; and
3. interrupt normal surf zone circulation (SHORT and MASSELINK, 1999).

The constructed ASR causes all of these impacts and they are related to the four salient forming mechanisms mentioned earlier that were identified by BLACK and MEAD (2007). TURNER *et al.* (2001) note that during physical modelling of the Narrowneck surfing reef that the reef became increasingly transparent for longer wave periods and increasing wave heights. The 79 m wide reef (67 m in offshore distance) is a small feature in a wide surf zone like in Figure 8.6. Although the photography cannot distinguish effects of the reef, refraction modelling (Figure 8.7) clearly shows the reef dissipating wave energy and rotating waves (5-10°). The waves have broken offshore of the model area presented here and thus the model results presented are estimating wave attenuation in the surf zone after breaking. When conditions are averaged overtime (Figure 8.8) the impact on heights is less than for the storm event (Figure 8.7), but wave angles are rotated more in the lee for the average conditions. The impact of lowering wave heights caused by a structure is identified by SHORT and MASSELINK (1999) as creating a more reflective beach and the increase in bar and rip prominence discussed in this paper is empirical evidence of this occurring.

Figure 8.7. Bathymetry (top; MSL) and WBEND wave height (mid; H_{sig} meters) and wave angle (bottom; grid north) predictions during July 2007 storm (SCARFE, 2008 wave event 41).
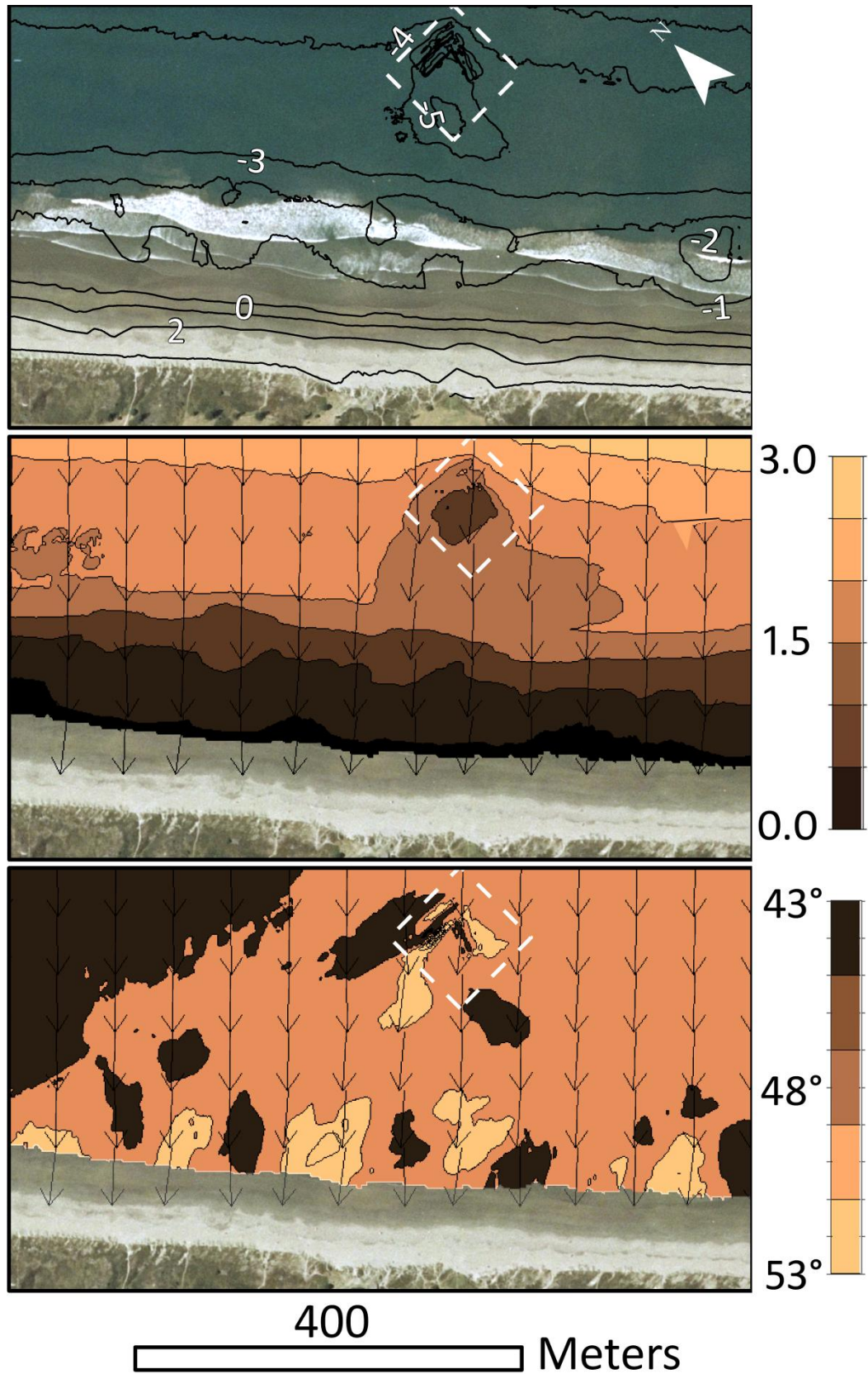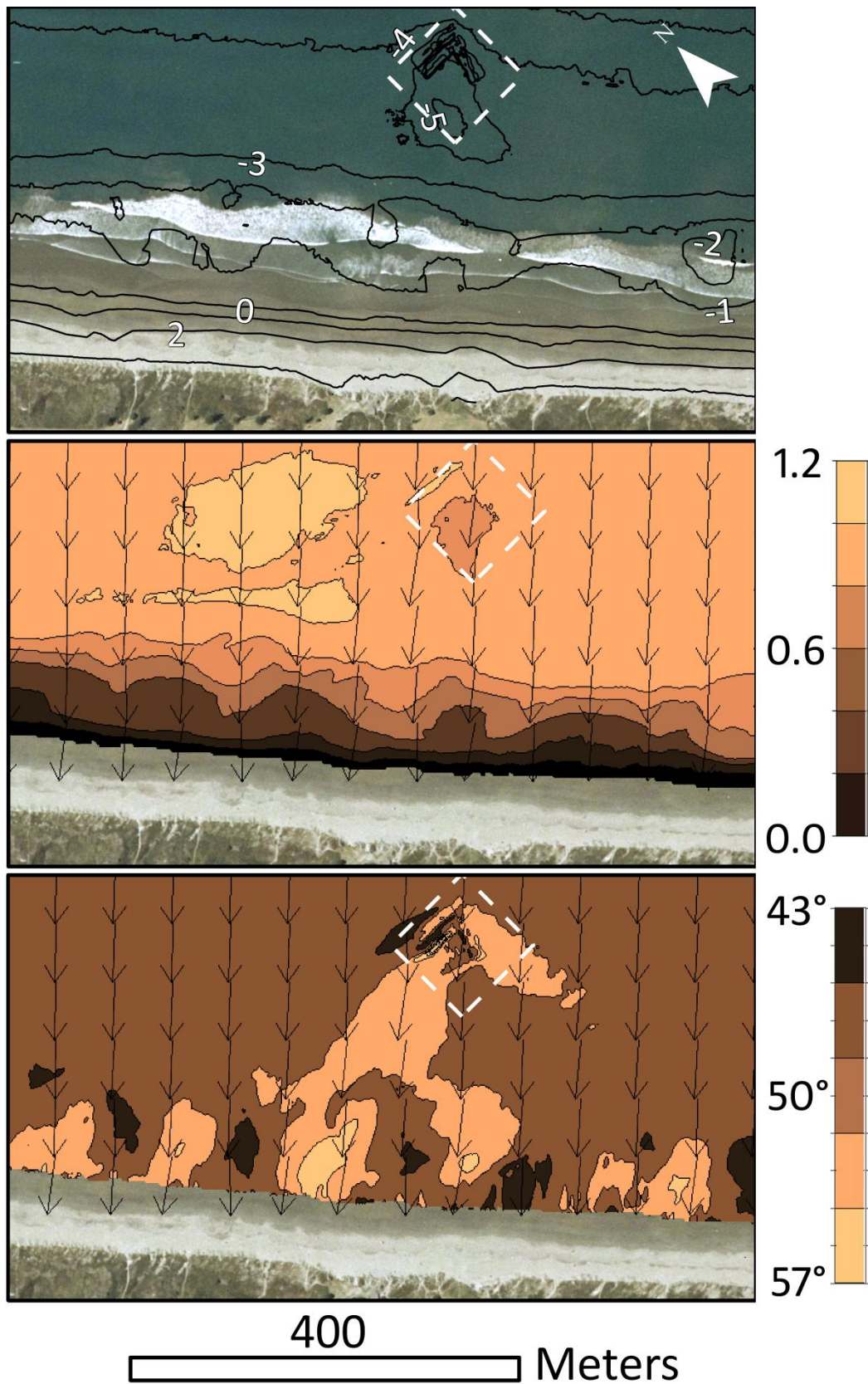
Figure 8.8. Bathymetry (top; MSL) and WBEND wave height (mid; H_{sig} meters) and wave angle (bottom; grid north) predictions for probability estimate of net wave conditions since reef construction (November 2005 to January 2007) based on a weighted average model output.

The results of modelling the average wave conditions show that the wave height on the offshore bar just northwest of the reef has a slightly larger wave height than to the southeast (Figure 8.8). The difference is 0.05-0.07 m and is caused by offshore focusing in depths less than 27 m. Although small on average, this can be significant during larger swells and is dependent on wave direction. The gradient was approximately 0.5 m in 7 m depths offshore of the reef for the wave event in Figure 8.7. Spatial changes in beach-state along or between beaches is driven by changes in modal wave height (SHORT, 1999b) and because the average wave condition modelling predicts longshore gradients in wave height and direction, this partially explains the difference between beach morphology either side of the reef. Differences in sediment supply and longshore infragravity waves could also contribute to the observed changes.

The theory of salient formation in the lee of ASRs has been discussed in the literature (BLACK and ANDREWS, 2001a and b; TURNER *et al.*, 2001; BLACK, 2003; RANASINGHE and TURNER, 2006; RANASINGHE *et al.*, 2006). BLACK and MEAD (2007) and RANASINGHE *et al.* (2006) show that the distance an ASR is offshore is a critical consideration as to whether the reef causes the beach to erode, form a salient or has no impact on shoreline stability. In an empirical study of the shoreline around natural reefs and islands, BLACK and ANDREWS (2001a) show that the ratio (B/S) between the offshore obstruction width (B) and the distance between undisturbed shoreline and the offshore feature (S) is important in determining shoreline response. This ratio was applied by BLACK and MEAD (2007) to the Mount Maunganui reef when only one reef arm was constructed. A value of 0.125 was calculated indicating that no salient would form. The reef now has a larger footprint (70 % complete) and new calculations are presented here (Table 8-3). The constructed value of B is 79 m and S was measured for a variety of positions. Since the constructed reef has a cross-shore distance of 67 m, the offshore position was made for the inshore and offshore tip of the reef when estimating S. For the inshore measurement of S, low water, mean sea level and high tide positions were all included. Although B/S was found to vary slightly with measurement location, a salient is not predicted because a value of greater than 0.5 is required for salient formation.

Table 8-3. Calculation of the ratio (B/S) between the offshore obstruction width (B) and the distance between undisturbed shoreline and the offshore feature (S) for a variety of measurement positions.

Offshore Distance (S; m)	Inshore Measurement Location	Offshore Measurement Location	B/S
220	Low water	Inshore reef edge	0.36
257	MSL	Inshore reef edge	0.31
205	High water	Inshore reef edge	0.39
287	Low water	Offshore reef edge	0.29
324	MSL	Offshore reef edge	0.24
272	High water	Offshore reef edge	0.31

BLACK and MEAD (2007) predict transient salients to occur depending on prevailing wave conditions, they identified that a small salient occurs in the reef lee during their 3rd and 4th surveys of 50 m and 25 m respectively. Using imagery from GoogleEarth^{TM} they identified what they term "double-horned salients". It is not clear where the measurements of salient width were made and no convention such as low tide, MSL or high tide level was discussed. The salient is expected to be more prominent in the lower water area than the high tide making the measurement location an important detail.

In contrast, during this research we visualized the surf zone bathymetry using various techniques and it appears that the "double horned salients" are actually a series of shoreward moving "slugs" of sediment from the offshore bar that eventually weld to the beach. The bar is broken into a series of rhythmic bars and rips, which were at their largest in January 2007 and were still merging into the intertidal beach by May 2007. The rips are spaced at 100-300 m alongshore, having a cross-shore distance of 100-150 m. They are present between the -0.5 and -3 m contour (MSL) and have formed within an area 600 m either side of the reef (Figure 8.9) and tend towards small welded traverse bars. They are identified in their longshore broken form in Figure 8.9, and are beginning to weld to the beach in the shallows of the surf zone. It is unknown if the features are created by the non-linear wave-wave interaction that form proto salients (TURNER *et al.*, 2001), or from standing infragravity waves as per AAGAARD and MASSELINK (1999). Longshore currents will also have some effect on their formations.
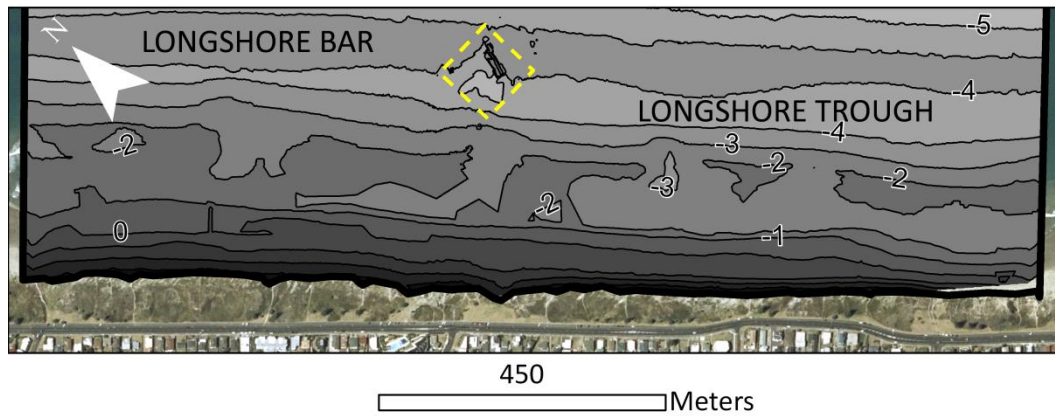
Figure 8.9. August 2006 bathymetry showing a new longshore bar (-4 m MSL) and trough forming that covers the study site. The offshore bar that formed in April 2005 has migrated into the surf zone and broken into rhythmic bars and rips (-1 to -2 m). Generally there is a trough in the lee of this broken bar, but the features are beginning to weld to the shoreline.

Analysis of the low tide shoreline contour (Figure 8.10) before construction and after 70 % of the reef was finished also does not reveal a persistent salient. It is clear when comparing the average preconstruction to post construction shorelines (Figure 8.10 bottom) that the shoreline is undulating around the mean preconstruction shoreline, rather than a salient accreting above the mean position. If there is a signal frequency in shoreline irregularities that are associated with the bars and rips, it has become higher. At low tide (approximately -1 m MSL) the shoreline variation of these welded bars (variation in low tide contour) is 30-50 m. High confidence can be had in the contour position due to the survey method employed. It was also clear while collecting data with the RTK GPS that the shoreline became more undulating once the reef was in place, and photographic evidence can be seen in Figure 8.11. Such eroded features are often linked with a shore parallel ridge and runnel in the intertidal area that drains and floods during different stages of the tide. Therefore they are morphological controls for rip formation, which evolve overtime through morphological coupling.
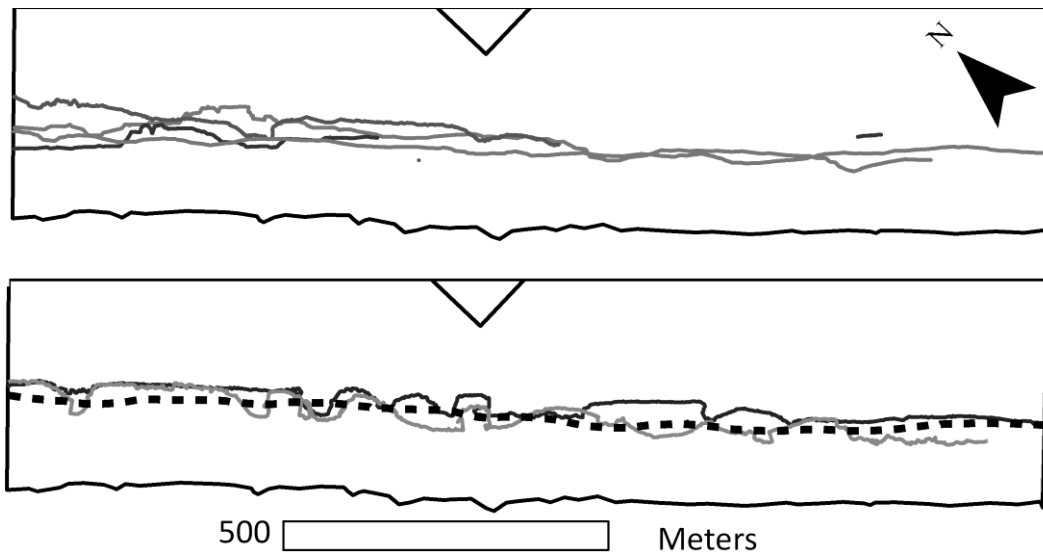
Figure 8.10. Lowest astronomical tide contours before reef construction (top) and after reef was 70 % complete (bottom) showing more prominent undulations in post construction shoreline, which are linked to rhythmic bar and rip features. The jagged line at the bottom of each figure is the dune line. The half diamond is the inshore part of the reef construction site and the left and right boundaries are the edges of the study site. The dashed line in the bottom image is the average pre-construction shoreline position.
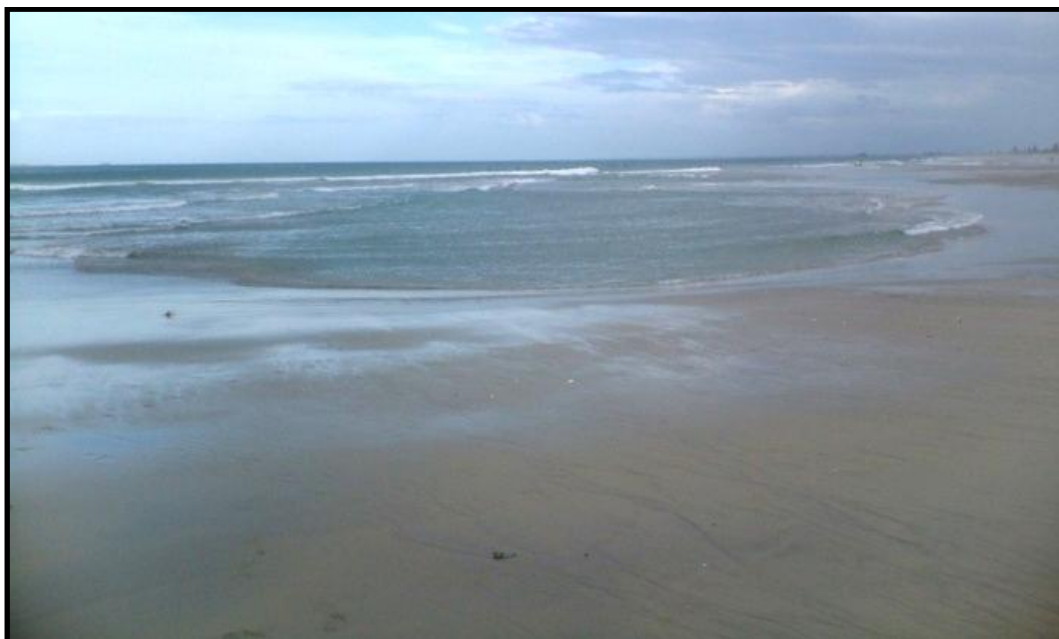
Figure 8.11. Example of a rip eroded in the shoreline immediately southeast of reef. The eroded features as well as accreted bars have appeared rhythmically around the reef site since construction. Development of such features is important to understand for beach safety reasons.

In the surf zone breaking gravity waves decrease in energy and unbroken infragravity energy increases (SHORT, 1999c), and this process may be influencing the observed morphology. Standing infragravity waves provide a simple and quantitative theoretical explanation of many morphological features, including rip

currents, crescentic bars, multiple longshore bars and welded sand bars (AAGAARD and MASSELINK, 1999). Thus a change in the character, frequency and location of bars and troughs infers a change in infragravity wave energy patterns in the surf zone, such as the feature observed since the reef was installed. Nearshore bars are the main expression of hydrodynamic and sediment transport gradients and form as a results of sediment convergence and in areas of sediment divergence troughs form (AAGAARD and MASSELINK, 1999). Therefore the reef has changed the sediment convergence and divergence patterns.

BLACK and MEAD'S (2007) modelling when only one arm of the reef was installed predicts what they call "reef bar" formations, attributed to perturbation of waves and currents. They stress that there are two main bars but the measurement clearly shows 6-8 bar features along about 1.2 km of beach. Tracking of the migration of the features showed that the reef bars are actually the shoreward moving longshore bar broken in the surf zone into rhythmic bars and rips. It is possible that when the features are most distinctive in form they will tend towards the transverse bar and rip beach-state. It has taken at least 25 months from the time of the longshore bar formation (April 2005) to when the rhythmic structures began to smooth in the -0.5 m to -1.5 m contours (May 2007). The migration of a broken longshore bar and conversion to rhythmic bars and troughs can be seen in Figure 8.12. Thus BLACK and MEAD'S (2007) model maybe representing the mechanism for the observed bar formations, but perhaps is exaggerating the actual size and under predicting the frequency of the sedimentary features. Thismay have been caused by the small spatial coverage provide by the sediment transport model grid. A discussion of the relationship between the longshore bars and any "reef bars" is considered an important research area for salient formation.
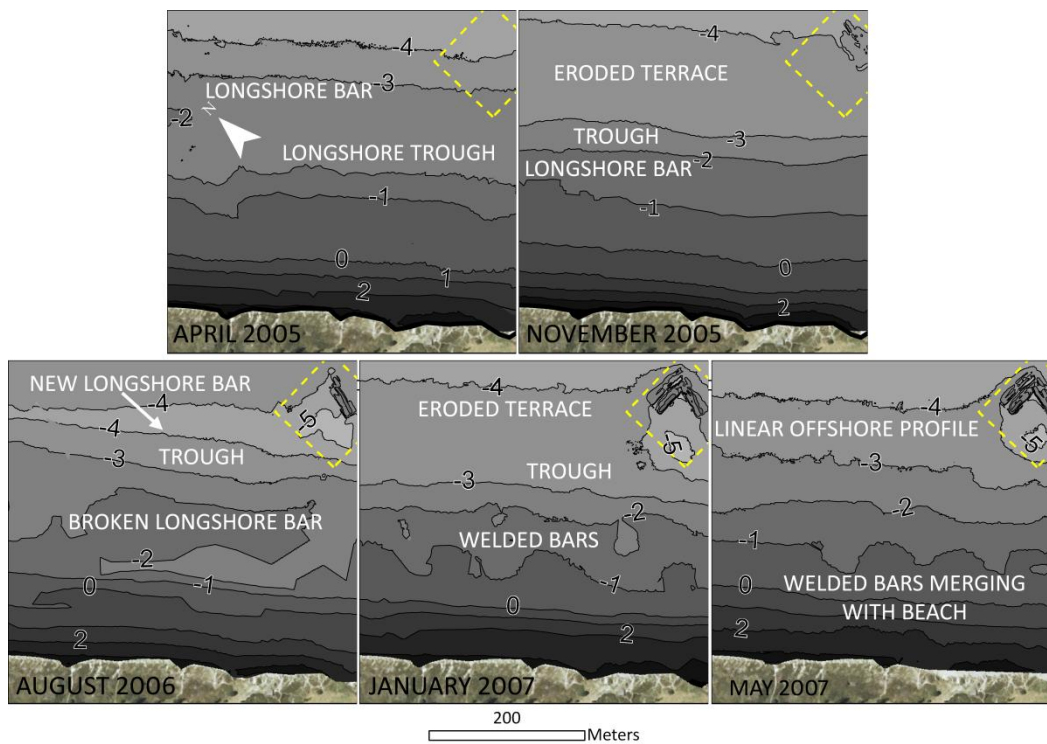
Figure 8.12. Beach contours and location of sedimentary features. The broken longshore features identified in Figure 8.9 began as a longshore bar and trough formation (April 2005) and migrated shoreward leaving an eroded terrace and a less prominent trough (November 2005). A new longshore bar formed on the terrace and the shoreward migrating bar broke into rhythmic bars and rips (August 2006), possibly due to more infragravity energy in the shallow surfzone. Once the rhythmic bars welded the beach (January 2007) they began to dissipate in structure (May 2007). Aerial photography of beach dunes from 2002 (source Terralink International Limited).

Eroded troughs (Figure 8.13) are important to the circulation of currents, and hence morphology, and are an expression of surf zone hydrodynamics. Three important eroded features were observed:

1. rhythmic troughs in -0.5 m to -3.0 m depths (MSL);
2. a longshore trough in -3.0 m to -4.0 m depths (MSL); and
3. a scour hole in the reef lee, eroded to -4.0 m to -5.0 m depths (MSL).

The rhythmic troughs are expected to drive nearshore rip circulation, and link with intertidal runnels as discussed earlier. Wave rotation inshore on welded reef bars (Figure 8.7 and Figure 8.8) will be a process that will cause the bars to continue to evolve and will be important to swash processes including wave run-up behaviour. The convergence and divergence of waves may further encourage sea level gradients which in turn can drive circulation. The longshore trough present throughout the study period will be a topographic control on longshore currents, engraved in the surf zone by preceding longshore currents.

The scour hole is likely to be formed by strong wave induced currents over the reef, and such currents were predicted to occur by BLACK (2003), VAN ETTINGER (2005) and RANASINGHE *et al.* (2006). However, measurement of scour hole development in the lee of an ASR has not been found in previous literature. The reef acts as a control point for this formation and this theory is support by the erosion/accretion plots presented in RANASINGHE *et al.* (2006), which show erosion immediately shoreward of an ASR for both erosive and accretive reef positions. BLACK and MEAD (2007) also predict the scour hole formation. Water level setup in-between the reef structure and the shoreline (BLACK, 2003; RANASINGHE *et al.*, 2006) will further influence the scour hole morphology.
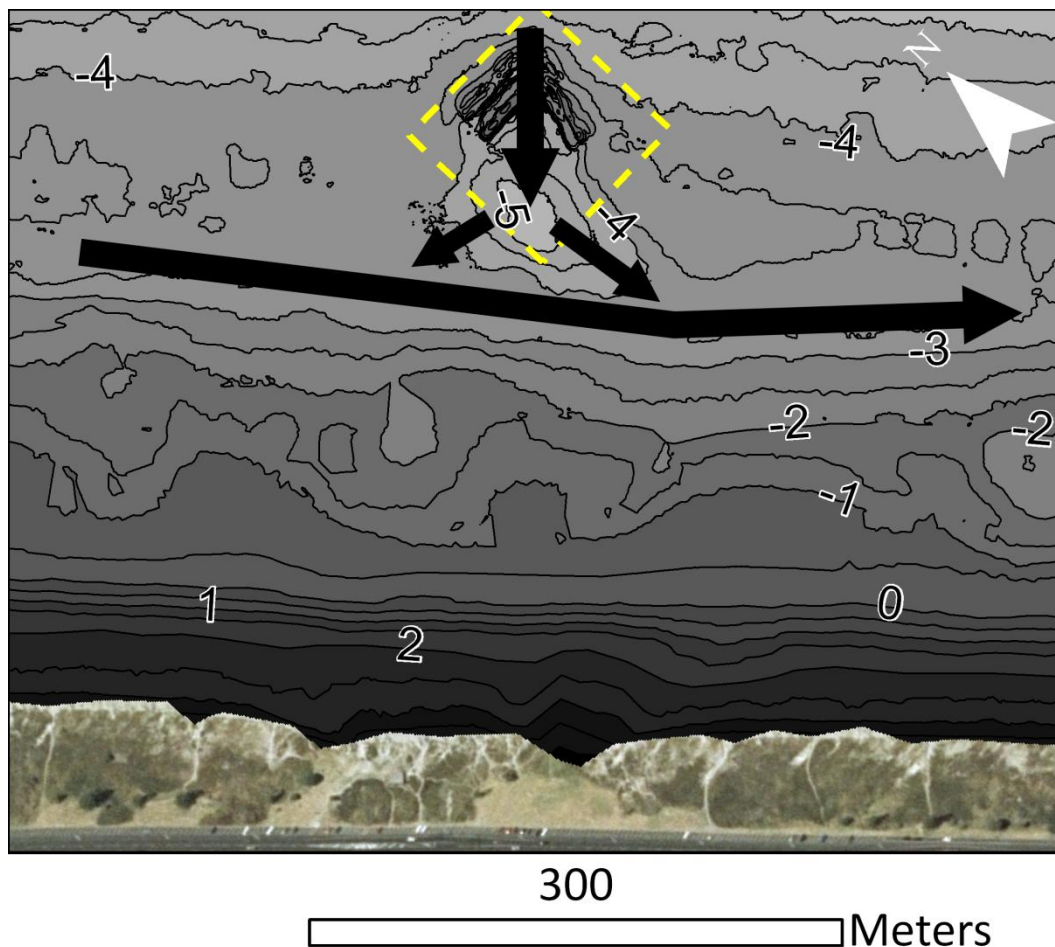
Figure 8.13. Eroded troughs around the ASR with probable current patterns derived from morphology. Wave driven currents over the reef join with the longshore currents that focus in the longshore trough. The rhythmic features (-0.5 to -2 m MSL) will further drive cellular rip circulation and swash zone patterns. Aerial photography of beach dunes from 2002 (source Terralink International Limited).

Longshore currents compressed between the reef and shore (*see* BLACK, 2003; BLACK and MEAD, 2007), and focused in the trough inshore of the longshore bar

during swell events, will modify the scour hole formation somewhat, and this is evident in the morphology. The currents over the reef diverge when meeting the longshore trough, and this is expressed through channels eroded between the scour hole and the longshore trough. The net longshore currents to the southeast have superimposed an asymmetry in the feature and the channel joining the scour hole and trough is more prominent to the southeast. This is a geomorphic indicator of littoral drift as discussed by HEALY (2007) and could be similar to the oblique erosive case modelled by RANASINGHE *et al.* (2006), where currents diverge in the lee of a reef, although in this case the longshore currents impacts behaviour, and shoreline shoreline erosion is not observed.

Although the concept of wave rotation for coastal protection presented by MEAD and BLACK (2001) makes theoretical sense, the wave refraction over the scour hole is much more significant than over the reef for the average conditions (Figure 8.8). The shape of the scour hole causes wave divergence in the lee of the reef, modifying longshore currents. This is not surprising given that the scour hole's surface area (7 500 m²) is 3.1 times larger than the reef (2 400 m²). The scour hole is 1.75 m deeper than the ambient seabed, whereas the maximum relief created by the reef structure peaks at 2.5 m (crest height = -1.25 MSL), but is generally only 1.5 m (-2.5 m MSL). Thus understanding the potential scour hole that will be eroded in the reef lee is critical as this scour hole feature potentially can have as much, or more, of an effect on surf zone hydrodynamic than the reef structure, as well as driving morphodynamic coupling.

One concept that the reef has proven in this study is that the submerged reef can have an affect an order of magnitude larger than the reef size. Thus designing a reef to control offshore bars, longshore currents, rip/bar formations, beach-state and wave transformations for surfing and coastal protection could be an evolution of the ASR concept. Breaking waves on the reef structure itself might not be the method through which surfing is improved, but rather of modifying the beach in general to improve sand bars for surfing and achieve other objectives such as coastal protection. Thus a broader scale definition of such techniques is termed here as 'multipurpose sediment controlling structures', where artificial surfing reefs would be a subset of this larger family of engineering techniques.

DISCUSSION

There are no absolute rules, or generic solutions that can be applied to coastal erosion problems because of the dynamic and diverse character of shorelines (MORANG, 2006). TAJZIEHCHI and COX (2005) commented that submerged breakwaters/reefs are increasingly being used to manage coastal erosion, but the knowledge on the structures impacts on wave transmission, currents, sediment processes and shoreline response is still only developing. The resource consent application to build the reef (RENNIE *et al.*, 1998) states that the reef was being built to research coastal protection, amenity enhancement (surfing, diving, fishing and beach recreation), biological enhancement and social and economic impacts of the reef. This research contributes to that goal and is important due to the significant gap in the literature on ASR monitoring identified by SCARFE *et al.* (Chapter 2).

Although various studies have monitored ASRs (e.g. BANCROFT, 1999; BORRERO, 2002; BORRERO and NELSEN, 2003; MACK, 2003; BLACK and MEAD, 2007; JACKSON *et al.*, 2007; PATTIARATCHI, 2007), results of detailed oceanographic research including charting bathymetry, measuring oceanographic conditions, and retrospective wave and sediment modelling have not be widely published. This sentiment is echoed by HENRIQUEZ (2005) when referring to the Narrowneck reef (Gold Coast, Australia), which is perhaps the most well funded reef construction to date. Detailed analysis of morphodynamics, constructed reef shape, reef settlement, wave, sediment and current modelling and measurements and "surfability" improvements are required. Detailed oceanographic studies are commonplace for surfing and ASR design studies (e.g. BLACK, 1999; MEAD, 2003; VAN ETTINGER, 2005; MEAD and BLACK, 2005; MEAD *et al.*, 2004a, b and 2007; MOCKE *et al.*, 2003), but have not been widely practiced after reef construction (SCARFE *et al.*, Chapter 2). It appears that to date the *a priori* estimate of reef shape and surrounding processes has not been compared with the *a posteriori* result. The opportunity to derive maximum benefit from a reef project comes from such *a posteriori* analysis. Of course this type of analysis does increase the total project cost, but without the data questions about the effectiveness and impacts of ASRs remain.

In a generic discussion of monitoring coastal structures, HUGHES (2006) highlighted that monitoring is required to assure continued acceptable project performance. Additionally HUGHES (2006) discussed that monitoring during and after construction is required to identify a project's success and failures, to manage environmental effects, and in the case of a new engineering concept like the ASR, to further develop the technology in different coastal environments. The research presented here has contributed empirical information on ASRs and morphology, and provided a methodology to monitor the beach response to such a structure.

BLACK and MEAD (2007) is the only paper to publish retrospective morphological modelling or a series of beach surveys. Considering the primary function of an ASR is to control the coastal processes by modifying the surf zone bathymetry, bathymetric measurements over time and morphology modelling are considered extremely important. Neither of the main monitoring publications for the Narrowneck (JACKSON *et al*., 2007), or Cable Stations (PATTIARATCHI, 2007) ASRs, published bathymetry or an oceanographic analysis of how the new bathymetry transforms waves to improve surfing or modifies surf zone hydrodynamics. Both PATTIARATCHI (2007) and JACKSON *et al*. (2007) calculate the number of days waves break on the reef, however this is a limited measure of "surfability". ASR "surfability" monitoring methods employed by BORRERO (2002), BORRERO and NELSEN (2003) and MACK (2003) are considered more robust methods. HUTT (1997), MOORES (2001) and SCARFE (2002) also provide scientific methods for measuring "surfability". The monitoring by JACKSON *et al*. (2007) includes ARGUS video imaging, hydrographic surveys, photography, surf observations, GPS surfing track plots, structural performance, ecological surveys, beach protections, and "surfability", but the paper does not provide much scientific evidence about the actual performance. Analysis is mostly limited to discussions of experiences rather than scientific experiments. JACKSON *et al*. (2007) does however provide an interesting method to measure the path of surfed waves. However, without publishing the bathymetry relative to the surfer paths the results are of very limited value to readers.

Although previous monitoring studies do not reveal much about the oceanographic impacts of the structure, each reef monitoring study to date has contributed to the knowledge on the subject. There is considerable scope for

further monitoring research and morphological research should continue to investigate changes in beach-state around ASRs. From an oceanographic perspective, this should be undertaken with two aims, firstly changes in morphology for shoreline stability and secondly changes in beach-state for recreational amenities (e.g. surfing and swimming safety). Of particular interest would be a study that used time averaged images (e.g. HOLMAN *et al.*, 1993; AARNINFKOF *et al.*, 2003; TURNER *et al.*, 2006), more detailed modelling including currents, sea levels, non-linear wave propagation and morphology (e.g. KENNEDY and CHEN, 2000; SYMONDS and BLACK, 2001; KARAMBAS and KOUTITES, 2002; BLACK, 2003; PHILLIPS *et al.*, 2003; CHEN *et al.,* 2004; CACERES *et al.*, 2005; VAN ETTINGER, 2005; RANASINGHE *et al.*, 2006; POORT, 2007) and tracking of surfers over the reef and nearby sand bars (MOORES, 2001; SCARFE, 2002; JACKSON *et al.*, 2007). From a shoreline stability perspective, the odd-even mode method of TURNER (2006) is a robust means of distinguishing "natural" shoreline behaviour from engineering impacts, and could be applied to low, mid and high tide contour datasets collected here.

The size of the study area used in this study is considered adequate to resolve the reef, surf zone and shoreline morphology. However, to understand downdrift effects and the movement of sediment along the coast a study area of a much larger scale is recommended (>4000 m longshore). Longer term monitoring is also required to determine if the next offshore bar will go through the same series of processes as mapped here. The exact mechanisms for creating the rhythmical features is not measured with any instrumentation, only inferred from surf zone and ASR literature. Future research could include measurements of waves (gravity and infragravity), currents and suspended sediments in the surf zone. Measurements should be supplemented with hydrodynamic modelling.

CONCLUSIONS

This study presents results and a method for monitoring ASR and other submerged structures, and sesults of an attempt to incorporate surfing into coastal engineering and management. The MBES data has provided valuable empirical information as to how a beach and waves respond to an ASR, which is not possible to collect using SBES. This type of monitoring has not previously been undertaken for ASR projects. The main findings of the research are:

- the reef is inhibiting sediment transport on the offshore bar crest, creating a submerged groin affect;

- the beach has an intermediate beach-state that has become more reflective and rhythmic, which is attributed to the reef construction's impact on surf zone hydrodynamics;

- the reef has formed a scour hole 3.1 times the size of the reef that links with an existing longshore trough;

- refraction modelling shows the reef is attenuating waves but the scour hole in the lee of the reef rotates waves more than the reef structure;

- no salient has formed;

- sediment from the shore parallel longshore bar migrates shoreward supplying sediment to form the rhythmic bars and rips;

- future research around ASRs should monitor the reef's impact on the beach system over a longer length of the coast; and

- future reefs may benefit from being built beyond the depth of close where sediment mobility is less, and salient response is more likely.

The observed shoreline structures, reasonably symmetrical around the reef, suggest possible changes of infragravity energy patterns, non-linear wave-wave interactions, energy dissipation through wave breaking, radian stress, wave height gradients in the reef lee and water levels setups caused by the reef. Since the beach is broadly classified as an open coast beach system, without significant nearby reefs or headlands the amount of reflected infragravity wave energy is limited. For such open coasts, wave height gradients will form a significant driver for hydrodynamics (SHORT, 1999a).

Before the reef was constructed the intermediate beach within the study area was generally described as having a longshore bar and trough formation broken up by periodic rips tending to a rhythmic bar and rip beach-state. Throughout this study a longshore bar formed and migrated shoreward and then broke up rhythmically in the shallows of the surf zone (-0.5 to -3 m MSL), eventually welding to the intertidal beach. Although the welded bars were at times transverse in nature, they did not form into large cuspate formation as seen on the cover image of SHORT (1999a).

The ASR's impact on natural rip and bar formation is considered significant and needs to be addressed during reef design. Because the small structure has had an impact over a much larger area of the beach, an alternative coastal engineering concept is identified, which does not cause wave breaking for surfing, but aims to control beach morphology for coastal protection and surfing. There is a large scope for future research on such technology (e.g. RANASINGHE and TURNER, 2006) and are described here as "multipurpose submerged sediment controlling structures".

The biggest advances in reef design to date have come from actual artificial reef projects with each reef being significantly different in size, construction and design as knowledge on the subject grows. Through the construction of reefs, theories about the shape and manner in which reefs should be built can be tested. Thus it is critical that any reef projects are well planned and monitored with a significant research component. It is through transparent analysis of reef projects that the concept will evolve most efficiently. The interest in the technology will diminish if people are consistently told about how well a reef development will perform, only to be let down by the actual results.

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Chapter 9 – MAJOR RESEARCH FINDINGS AND CONCLUSIONS

INTRODUCTION

Although modern coastal science and engineering methods attempt to achieve long term sustainability, the damage caused by much of the engineering works of the 20th century is significant to our natural beachscapes, which includes surfing breaks. To address this problem at a practical level, various "non-profit surfing advocate groups" have evolved to protect and enhance the surfing amenities of the world's coastlines (WALTHER, 2007). In order for their advocacy to be successful, problems need to be addressed on several fronts including resource management, political, sociological, economic and coastal science. Although political, social and economic progress has been made (e.g. LAZAROW *et al.*, 2007; NELSEN *et al.*, 2007), prior to this thesis the oceanographic component of surf advocacy was not well articulated in the academic literature.

It is only in recent years that the academic literature has begun to address matters relating to surfing (Figure 2.1). SCARFE *et al.* (Chapter 2) categorises the different area of research-based surfing literature and found that although surfing wave transformations are well described, the majority of the literature is concerned with ASR design. Coastal management issues and surfing are frequently mentioned in the literature, but specific publications on how to include surfing in coastal management are rare. Thus this thesis provides original contributions to this research area. This includes highlighting the importance in coastal management of the oceanographic considerations listed in Table 9-1.

Table 9-1. Oceanographic considerations identified in this research that are important to continue researching if surfing breaks are to be effectively included in coastal management.

Oceanographic Considerations	Research Area
surfing wave parameters (H_B; α; B_I; and S_L)	Oceanographic/surfing science
identifying surfing break components	Geomorphic/surfing science
affect of wind on surfing wave transformations	Oceanographic/surfing science
the relationship between surfer skill level, surfing manoeuvres and surfing wave parameters	Oceanographic/surfing science
impacts of current patterns on the formation and "surfability" of a surfing break	Oceanographic/surfing science
the geomorphic category of a surfing break (headland or point break, beach break, river/estuary entrance bar, reef break, ledge break)	Geomorphic/surfing science
offshore wave transformations important for surfing	Oceanographic/surfing science
beach-state and morphology around surfing breaks	Geomorphic/surfing science
non-linear wave-wave interactions and infragravity wave energy around surfing breaks	Oceanographic/surfing science

SURFING AND ICZM

Coastal management involves trying to satisfy the needs of various interest groups based on sound rationale and strategic processes, and to maintain sustainability. ICZM is commonly held as the desirable method of achieving this aim, but has not been discussed previously in a surfing context. SCARFE *et al.* (Chapter 3) provides evidence of positive and negative impacts to surfing breaks from coastal engineering when ICZM practices have not been followed. Without proper consideration in ICZM, surfing breaks will continue to be altered by coastal development.

Utilising the principles discussed in SCARFE *et al.* (Chapter 3), accompanied by detailed oceanographic studies, will assist in adding transparency to decision making around surfing breaks. Included in the recommendations is the use of multipurpose coastal engineering methods, such as artificial surfing reefs and other "multipurpose sediment controlling structure". Such technologies can potentially provide multiple benefits to multiple user-groups and rely on modifying holistically various physical processes including surf zone hydrodynamics, sediment transport pathways and sedimentary control points. The inclusion of multiple design variables allows outcomes to be much more sophisticated, but such technology is still experimental. Thus although significant

theoretical research exists, more attention needs to be given to evaluating the performance of constructed reefs.

The increased awareness in New Zealand over recent years of the engineering impacts to surfing breaks has resulted in the inclusion of a specific policy on surf break protection in the draft New Zealand Coastal Policy Statement (DEPARTMENT OF CONSERVATION, 2008). The policy states that 'protection from inappropriate use and development' is required and this is the first time surfing has been specifically included in New Zealand's resource management framework. The policy is a significant driver towards integrating surfing into coastal management and a model to further evaluate in future research [10]. However, the policy only currently applies to the most iconic surfing breaks, whereas surfers have a variety of skill levels and not all surfers can negotiate riding waves at such locations. For surfers to improve and gain the skill level required to surf the more dangerous or busy surfing locations, they need to go through a progression of surfing breaks, from beginner to advanced. Some beginner surfing breaks might not rate on a national scale of the best surfing breaks, but still are important surfing "nurseries". Future research on ICZM and surfing will need to consider how the protection of important surfing "nurseries" should be included as they eventually supply the iconic spots with surfers. In the same way that a range of biodiversity is protected, a range of surfing breaks for different skill levels, and with a range of geomorphology, should be preserved for future generations. The surfing reserves concept (FARMER and SHORT, 2007) also only addresses the protection of the most iconic surfing breaks further highlighting the need for more research in this area.

Generalised EIA for Development around Surfing Breaks

EIA is identified as a potential method to highlight impacts from coastal activities to surfing breaks as part of ICZM. Although EIAs on surfing have occurred worldwide, NELSEN and HOWD (1996) and MEAD *et al.* (2004) show that they are not always undertaken adequately. SCARFE *et al.* (Chapter 2) found that peer-

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[10] As the policy is currently only in draft form, and open to public submissions, the final wording or decision about its inclusion is not known. The policy could be modified, rejected or included under a broader recreational policy.

reviewed articles discussing EIA are not commonplace in coastal literature. Thus methods for incorporating surfing into EIA processes are not widely known.

To initiate discussion in the literature, coastal activities, oceanographic factors to consider and environmental data types have been tabulated (Tables 3.5-3.7). These tables are further developed here to provide a generalised EIA checklist for activities around surfing breaks. As this thesis is primarily focused on physical processes, the EIA checklist provides various surfing and oceanographic considerations, and but also makes some contribution to potential socio-economic methods to assess the impacts of activities on surfing breaks. Specifically, Table 9-2 relates different surfing and oceanographic factors to data types that can be used during EIA analysis. The generic EIA checklist (Table 9-3) presents considerations for the development of assessment methods during project planning, construction and monitoring phases, and can be adapted and further developed with considerations specific for particular coastal projects.

Table 9-2. Potential oceanographic and surfing factors to consider during an EIA. Numbers represent examples of data types that can potentially be used during impact analysis. The table is derived from Tables 3.6 and 3.7.

Bathymetry [1, 8, 9, 11]	Sediment transport pathways [2, 3, 5, 6, 7, 8, 14, 15]	Surfer skill level [8, 12, 13]	Breaker intensity [2, 7, 8, 9, 10, 12, 13]
Wave climate (inshore and offshore) [1, 2, 3, 7, 8, 9, 10]	Sediment grain sizes within littoral cell [3, 8, 14, 15]	Peel angles [1, 2, 7, 8, 9, 10, 11, 12, 13]	Breaking wave height ratio [2, 6, 7, 10]
Storm surge [6, 8]	Wave and tide induced current patterns [2, 3, 5, 6, 7, 8, 10]	Tidal patterns and long term water level trends [6, 8]	Surfable days per year [6, 7, 8, 10, 12, 13]
Wind patterns [4, 8]	Wave refraction/ diffraction/ Shoaling [1, 2, 3, 6, 7, 8, 9, 10, 11, 12, 13]	Surfer numbers and seasonal variations [8, 12, 13]	Precise location of surfing rides [1, 2, 6, 7, 8, 9, 10, 11, 12, 13]

1. Aerial photos	6. Tidal data
2. Bathymetry data	7. Wave data
3. Side scan images	8. Documents/reports
4. Topographic data (e.g., contours, LIDAR data)	9. Digital Elevation Models (DTM)/Digital Terrain Models
5. Current data	

10. Hydrodynamic modelling of oceanographic conditions
11. Surfing break component schematics
12. Video of surfing waves
13. Oblique photos of surfing waves
14. Sediment grain size data
15. Suspended sediment concentrations
16. Water quality data

Table 9-3. Generalised environmental impact assessment template that can be adapted and applied when potentially harmful activities are undertaken nearby surfing breaks. The suggested activities that require such an environmental impact assessment to be applied are included in Table 3.5.

PROJECT PHASE	TYPE OF IMPACT	ISSUES AND CONSIDERATIONS	TEMPORAL REQUIREMENTS
PLANNING *Develop baseline understanding of issues/processes and predict impacts from proposed activity to each issue/process*	Social/ Economic	• Number of surfers utilising the surfing break, including daily and seasonal variations • Socio-economic conditions • Cultural/demographic conditions • Sociological surfer profile • Surfing break amenities (accessibility/facilities/car parks/toilet/beach access etc)	The study to determine baseline understanding of existing conditions should cover at least one year to allow for seasonal variations to be understood. Depending on the issue that is being considered, longer analysis may need to be undertaken
	Physical	Develop an understanding of surfing and oceanographic considerations identified in Table 9.2 and predict expected impacts of the proposed activity to them	
CONSTRUCTION *Monitor predicted impacts and identify when unpredicted impacts occur*	Social /Economic and Physical	Monitor changes to issues/processes identified during the planning phase, and assess whether the impacts are acceptable, temporary or unacceptable	Monitoring will need to take place for the length of the construction period, with the frequency of monitoring being dependent on the issue/process being monitored
MONITORING *Undertake monitoring of impacts to identify when unpredicted impacts occur*	Social /Economic and Physical	Compare *a priori* predictions with *a posteriori* measurements of impacts and determine implications of the project to the surfing break	Monitoring of impacts should last at least two years to allow new beach equilibriums to be formed. For some projects monitoring will need to be ongoing for the life of the project (e.g. continuous beach nourishment)

SURFING GIS

Coastal management decision-making requires the availability and interpretation of often complex environmental data. However, specific tools can be developed to better understand surfing-related coastal management issues. As demonstrated throughout this thesis, understanding the relationship between the surfing and oceanographic factors identified in SCARFE *et al.* (Chapter 3) can be accomplished via GIS. The technology can be used to manage, visualise, process and interpret spatial and non-spatial data. Also GIS can be utilised during the design and monitoring of multiple-purpose structures and when predicting or monitoring the effects of coastal activity on surfing. Therefore, a pressing need exists to further

develop surfing specific GIS technology within environmental surfing organisations and coastal management authorities. Research undertaken here complements and extends the existing Surfrider Beachscape surfing GIS discussed by NELSEN and RAUSCHER (2002) by incorporating modern oceanographic analysis. Of particular interest in the thesis have been the development of custom geoprocessing software and the geodatabasing of environmental information.

The research demonstrates the potential to incorporate hydrodynamic model output into GIS, exponentially improving data management, visualisation, analysis and distribution when compared with standard modelling visualisation software. This point is iterated by the fact that various DHI models are being now run from within a customised ArcGIS environment. The GIS development method is similar, but much more in depth than the method employed to manage hydrographic data in Chapter 5. For example, DHI's storm and waste water modelling software Mike Urban is run completely from within a heavily customised version of ArcMap (2D mapping software from ArcGIS). This gives users access to the GIS technology and allows data storage in a modern geodatabase format. The integration of modelling software and GIS in the coastal area is also expected to develop in the future, and is an important future research area for surfing and coastal management.

GIS has been used in two ways throughout this research. Firstly, SCARFE *et al.* (Chapter 5) uses GIS in the classical manner where the technological system combines data storage, users, data processing, visualisation, data distribution and computer hardware in an ongoing manner. The second use of GIS has been much more ad hoc where information has been analysed to understand a phenomenon, create a map or figure, or make a three-dimensional visualisation. This ad hoc GIS approach has been used throughout the thesis and often data processing methods and data schemas are designed for single tasks. This is in contrasts to the classical GIS method, which has strictly enforced data schemas and geoprocessing models. Future research should continue to develop these ad hoc analysis methods and implement them into classical GIS once the methods and data schemas are refined. Such research should pay particular attention to the environmental data types identified in Table 3.7.

COASTAL CHARTING

Bathymetry is a key component of a surfing break, and therefore techniques to depict bathymetry are critical for including surfing in coastal management. The use of MBES to image surfing breaks has been evaluated here. Such systems are an array of commercial sensors and processing software, which are often supplemented with custom components and software processes. Overtime sensors, software and surveying workflows are changed to yield improvements in reliability, efficiency and outputs. So although many components of the MBES are commercially available, there is a significant research element to refining the system.

During this thesis many customised tasks have been developed to plan, acquire, process, interpret and publish survey data. This includes research on the best software for specific tasks, as well as highly customised geodatabases, GIS models, GIS scripts, and GIS applications. Although many facets of MBES are commercial products, to optimise the system significant original research contributions have been made. This includes GIS methods to calculate the accuracy of survey datasets.

The use of RTK GPS for measuring water levels during surveying has been developed and demonstrated. This includes the use of incline plane models of the geoid-ellipsoid separation. Although software by Trimble Navigation was used, input has been provided into the development of RTK GPS water level portion of the software. SCARFE *et al.* (Chapter 4) presented detailed methods and results of implementing the technology for the first time. Ten contributing factors between measured tidal records using traditional in situ gauges and RTK GPS are listed in SCARFE *et al.* (Chapter 4) and such a discussion was not previously been found in existing literature.

The speed of data collected using MBES over SBES is discussed in SCARFE *et al.* (Chapter 4) and it was found that the Mount Maunganui surveys were approximately seven times more efficient than the SBES survey of a surfing break by KILPATRICK (2005), with significantly better sea floor coverage. The application of bathymetric LiDAR technology to charting surfing breaks was not found in the literature, and it is expected to further increase the speed of surveying over MBES, but with a reduction in accuracy and spatial density of

measurements. The use of bathymetric LiDAR around surfing breaks enables coverage of sea floor areas coastal area and is an exciting area of potential future research. Such datasets may be collected for different purposes, but can be reinterpreted in a surfing wave context.

ARTIFICIAL SURFING REEF MONITORING

The role of an ASR is to change the bathymetry and it needs to be monitored in detail. Previous ASR projects have not resulted in publication of the resultant bathymetry, let alone a series of MBES surveys such as those collected during this project. From a research perspective the monitoring has been valuable in demonstrating how a beach responds to an ASR. This has been discussed in depth in SCARFE *et al.* (Chapter 8). In summary:

- the reef did not form a salient, but still provides valuable empirical evidence of the impacts to morphology;

- the morphodynamic beach-state was found to be significantly modified and this has the potential to change surfing conditions and swimming safety around the reef; and

- the impacts of the reef on the offshore bar, beach-state, salient response and scour hole development all need to be incorporated into future reef design as the research shows that the reef has caused changes over a large area (at least the size of the 112.5 Ha monitoring area).

The monitoring of the ASR has led to the conclusion in SCARFE *et al.* (Chapter 8) that the ASR concept is encapsulated in the larger family of "multipurpose submerged sediment controlling structures". Since the wave preconditioning function of a surfing break (discussed further in MEAD and BLACK, 2001a and b) is at a scale too large to easily engineer, the idea of using submerged structures to control sediment and hydrodynamics rather than break waves for surfing is considered to have merit. Such structures would not require as accurate construction tolerances as surfing improvement would result from the new morphology and surf zone hydrodynamics created by the submerged structure. The literature on ASR design is primarily focused on the actual reef shape and impacts to wave transformations, but the research in this thesis suggests that the larger scale morphological processes should be the main focus of research into ASR design theory.

Considering the resource consent application for permitting of the reef construction (RENNIE *et al.*, 1998) stated the primary purpose of the reef was for University research, it is difficult to compare the research and public expectation of what constitutes a successful surfing reef. For the purpose of improving knowledge on multipurpose coastal engineering technology, a key tool to achieve integrated coastal zone management, the research presented in this thesis complements that of MEAD *et al.* (2007) and BLACK and MEAD (2007) and makes a significant contribution to knowledge on innovative coastal engineering. However, for the local surfers the benefit of the reef has not been dramatic. The most likely reasons for this is that the reef is not complete, is too small to precondition waves and only can cause wave breaking for surfing during a limited range of conditions.

CONCLUSIONS

Although the initial motivation for this research was to aid the struggle of surfers in protecting their local surfing breaks, as the research developed it became apparent that opposing development around surfing breaks completely, again promotes this single-issue or single sector view point. Therefore there is a need for multipurpose engineering that aims to provide multiple benefits to multiple user-groups. Such technologies rely on modifying various physical processes such as surf zone hydrodynamics, sediment transport pathways and sediment control points. Thus it is advocated that a combination of coastal management techniques and innovative engineering methods be used around surfing breaks to ensure the world's surfing breaks are sustainably managed, and enhanced or created where deemed appropriate. However, in this early stage in the development of surfing engineering technology it is recommended that staged developments be investigated. It is considered critical that such engineering works are approached from a research point of view and that ongoing monitoring of critical environmental and social variables is undertaken (Table 9-2). Only then will surfing developments be able to be adequately considered in ICZM.

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Appendix 1 – DHI Mike 21 NSW Refraction Modelling of Aramoana

This appendix presented all five wave events modelled during the study of Aramoana in Chapter 3. The wave events were identified and bathymetry collected by KILPATRICK (2005), and further information including photographs and descriptions of the wave events are included the research. The oceanographic conditions is republished here. All wave heights are in meters and angles in degrees relative to grid north.

KILPATRICK, D., 2005. *Determining Surfing Break Components at Aramoana Beach, Dunedin.* Dunedin, New Zealand: The University of Otago, Honours dissertation, 68p, + appendices.

Oceanographic Conditions

Event 1 - 18/03/2005 10:21am NZST
> **Tide**: 1.62m above chart datum. At the peak of full tide, beginning to drop.
> **Swell:** From 73° (surfer's ENE swell). Significant wave height: 2.7m. Period: 12.3 s.
> **Wind**: To 240° (surfer's ENE wind). Velocity: 4.5 ms⁻¹

Event 2 - 19/06/2005 4:06pm NZST
> **Tide:** 1.759m above chart datum. Dropping
> **Swell:** From 80° (surfer's ENE swell). Significant wave height: 1.7 m. Period: 12.3 s.
> **Wind**: To 52° 7 (surfer's south-west wind). Velocity: ms⁻¹

Event 3 - 20/07/2005 11:30am NZST
> **Tide**: 1.377m above chart datum. Rising.
> **Swell:** From 111° (surfer's ESE swell). Significant wave height: 3.0 m Period: 12.3 s.
> **Wind**: To 70° (surfer's WSW wind). Velocity: 5.5 ms⁻¹

Event 4 - 10/8/2005   12:34pm NZST
> **Tide**: 0.49m above chart datum. Low-tide.
> **Swell:** From 162° (surfer's SSE swell). Significant wave height: 3.0 m Period: 13.5 s.
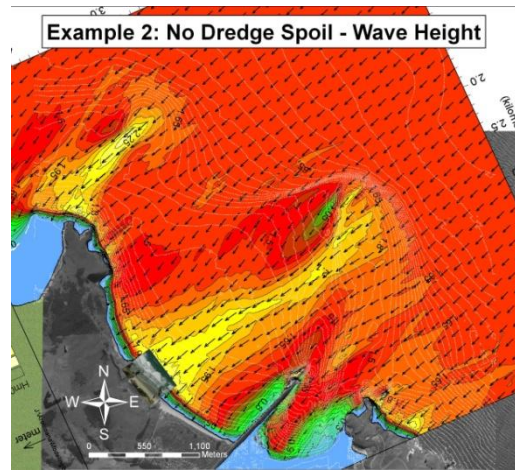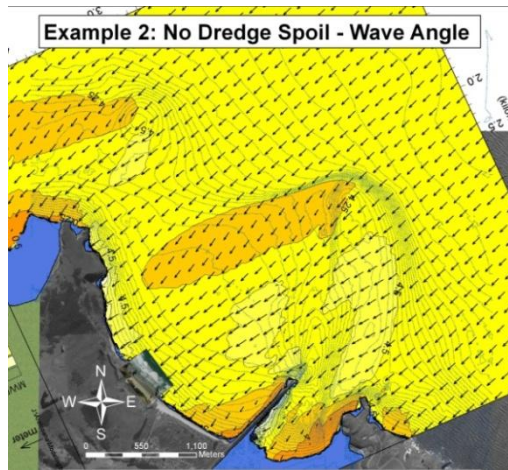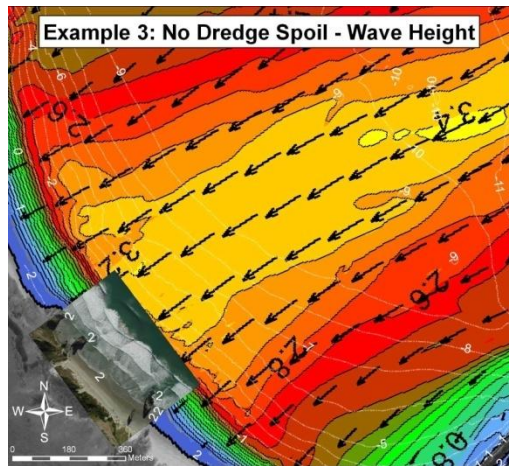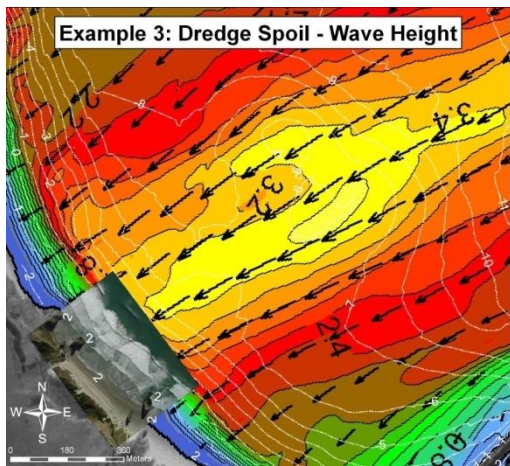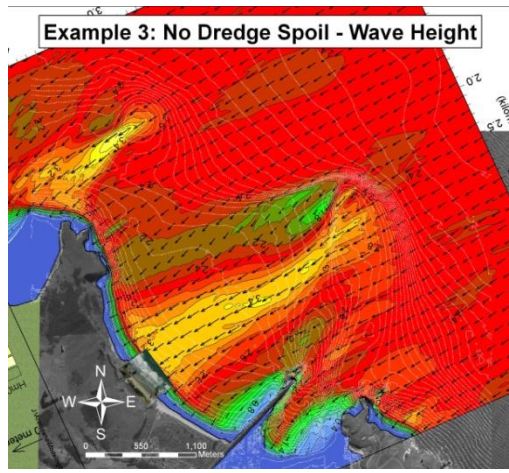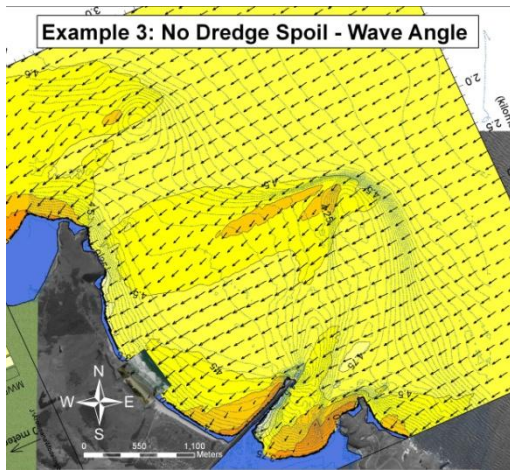> **Wind**: To 52° (surfer's south-west wind). Velocity: 2.5 ms⁻¹

Event 5 - 8/10/2005   11:09am NZST
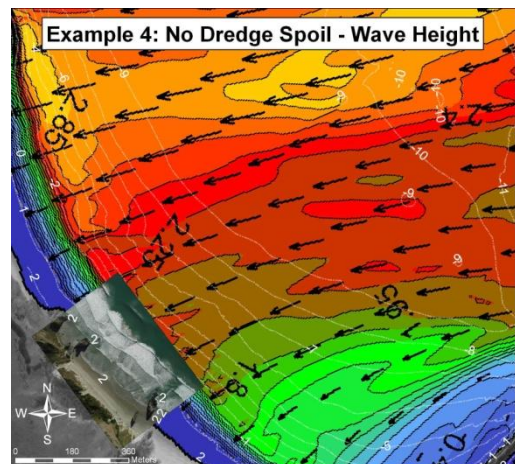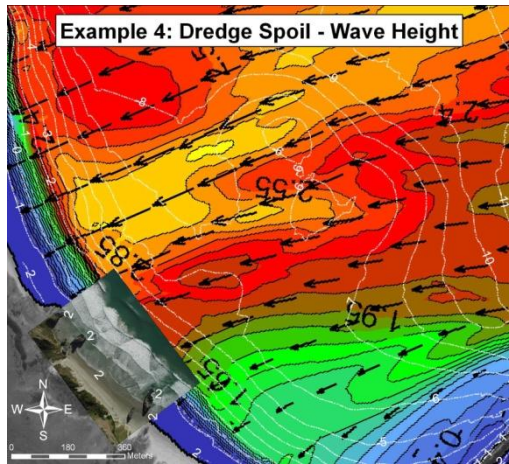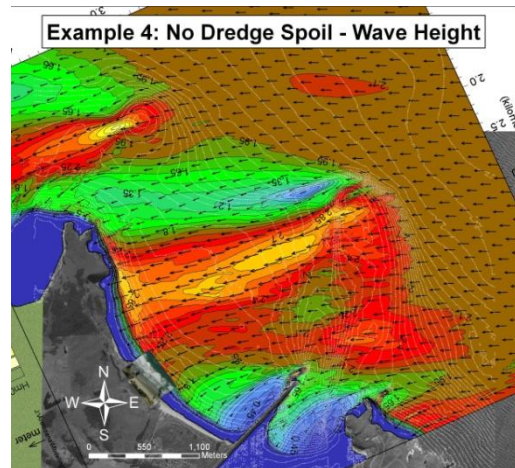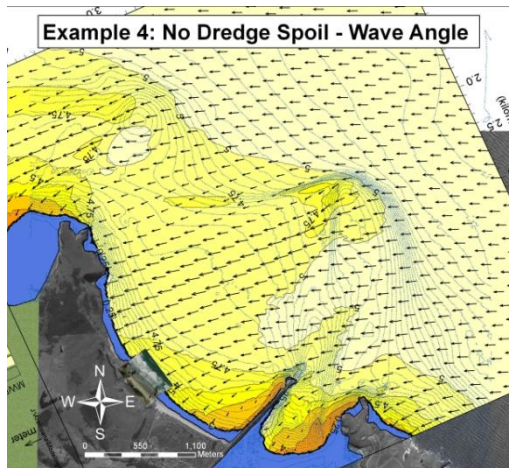> **Tide**: 0.6m above chart datum. Dropping.
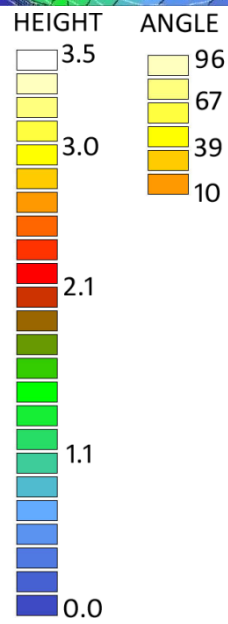> **Swell:** From 176° (surfer's south swell). Significant wave height: 3.3 m. Period: 13.5 s.
> **Wind**: To 357° (surfer's southerly). Velocity: 6.5ms⁻¹

Example 3: No Dredge Spoil - Wave Angle

Example 3: No Dredge Spoil - Wave Height

Example 3: Dredge Spoil - Wave Height

Example 3: No Dredge Spoil - Wave Height

Example 4: No Dredge Spoil - Wave Angle

Example 4: No Dredge Spoil - Wave Height

Example 4: Dredge Spoil - Wave Height

Example 4: No Dredge Spoil - Wave Height

HEIGHT

ANGLE

Example 5: No Dredge Spoil - Wave Angle

Example 5: No Dredge Spoil - Wave Height

Example 5: Dredge Spoil - Wave Height

Example 5: No Dredge Spoil - Wave Height

HEIGHT
3.5
3.0
2.1
1.1
0.0

ANGLE
96
67
39
10

Appendix 2 –Mount Maunganui WBEND Refraction Model Calibration

As with all hydrodynamic modelling, there are caveats with the results and this appendix discusses the model calibration and implication for the interpretation of the output. Still, the modelling at 60 m and 3 m cell size model grids achieved the objectives of the exercise. Namely, to gain understanding of the offshore and nearshore wave processes occurring for a surf and storm events at Mount Maunganui.

The rapid-solution monochromatic and spectral numerical wave refraction model WBEND (BLACK and ROSENBERG, 1992; BLACK, 1997 and 2000), from the 3DD Suite of models, was used for the analysis. The model has been successfully applied to a broad range of projects and simulates refraction and diffraction over complex bathymetric features (MEAD et al., 2004a and b; MEAD and PHILLIPS, 2007). The model has been applied numerous times to surfing wave studies including studies of Raglan, New Zealand (HUTT, 1997; SCARFE, 2002; MEAD and PHILLIPS, 2007), the Mount Maunganui ASR (MEAD et al., 1998 and 2007) and the Oil Piers, California, ASR (MEAD et al., 2004b). The models require waves to pass into the grid from the left hand boundary, requiring rotation of the bathymetry. The model was used with a single cell as the boundary condition allowing a time-series calibration data to force the model for calibration. If the cell is not on the boundary (as in the 60 m grid), the model back-refracts the waves to the boundary before being transformed in a shoreward direction.

60 m WBEND Model Calibration

The 60 m model grid used the EBOP site as the model boundary and three inshore direction and four wave height measurement sites to be used as a calibration points. The location of the various wave instruments can be seen in Chapter 7 (Figure 7.1 and 7.2). One month's wave data at the S4_SILTDUMP site was available and yielded over 700 hourly wave measurements. The output files of the model the version used was limited at 2 GB so not all of the wave measurements and tides measurement could be efficiently used. Every fourth measurement was used and two simulations were required to model the entire period. In all, 178 wave events were simulated and results were obtained in separate files (first

period = 21/9/2005 to 10/11/2005; second period = 10/11/2005 to 27/10/2005). Wave height were below 1 m for the first period and a storm occurred peaking at 2.5 m (Hsig) during the second period.

Figure A shows the measured and modelled wave directions for the three InterOcean S4 current meters. The model has consistently underestimated wave angles, with the best agreement seen for the deepest site at S4_SILTDUMP. The shallower the water, the more important it is to have good bathymetry. It is possible that the New Zealand Navy soundings from the 1960s used for much of the model grid contain inaccuracies, and poor spatial distribution, contributing to some of the bias observed. Any error could be magnified in shallow water.

Another additional source of error may come from the modelling technique itself. The use of a monochromatic wave model does not account for local winds for the wave spectrum meaning that perfect results will be unlikely over such a large area. The model output presented in Chapters 2 and 3 (Figure 2.9 and Figure 3.12) shows extreme gradients due to the islands and bathymetric focusing. However, the spectral wave model image presented in Figure 7.4 shows less prominent focusing. This is to be expected because when a non-monochromatic spectrum exists, wave energy from directions other than the mean direction will leak around the island and focus differently over features. This results in smoother wave height gradient. The wave angle can be seen to hardly change between the measured EBOP boundary condition and the modelled S4 sites, other than the last portion of the S4_BCDUMP direction figure.

Figure B shows the wave height calibration for four locations. One immediately obvious observation that can be made is that the model is over predicting wave heights compared with the measurements. The model predictions are very similar to the EBOP boundary heights and this once again suggests that the monochromatic model has over simplified the wave transformations. The empirical relationships derived in Chapter 7 show that the EBOP site is consistently larger than the sites near Mount Maunganui, however the wave energy appears to be conserved as it is transformed between the sites. In reality, the EBOP site will have larger wave heights because of the contribution of winds out at sea. The nearshore sites are in fetch limited positions for offshore and cross-offshore wind directions, and thus the contributions within the wave spectrum

from local winds will be much smaller than at the EBOP site. For example, during offshore winds the Mount Maunganui sites will only measure swell generated from offshore sources, not by local winds. The offshore wind will also reduce the swell height as it blows against the incoming swell. However, The EBOP site during the same offshore wind has 13 km of fetch to generate wave energy. Not accounting for these processes in the model is the expected reason for the observed differences.

When averaging the errors (Table A) the actual height discrepancy appears acceptable for the purpose of the modelling. It is concluded that any error in the calibration are caused by bathymetric quality and density, failure to model the wave spectrum or local winds. However, within the purpose of this thesis the rapid solution model still provides valuable predictions of the offshore wave transformations for the wave events identified in Table. The quick simulation time allowed many simulations to be run.

Table A. Average error and confidence interval for the four wave height measurement locations.

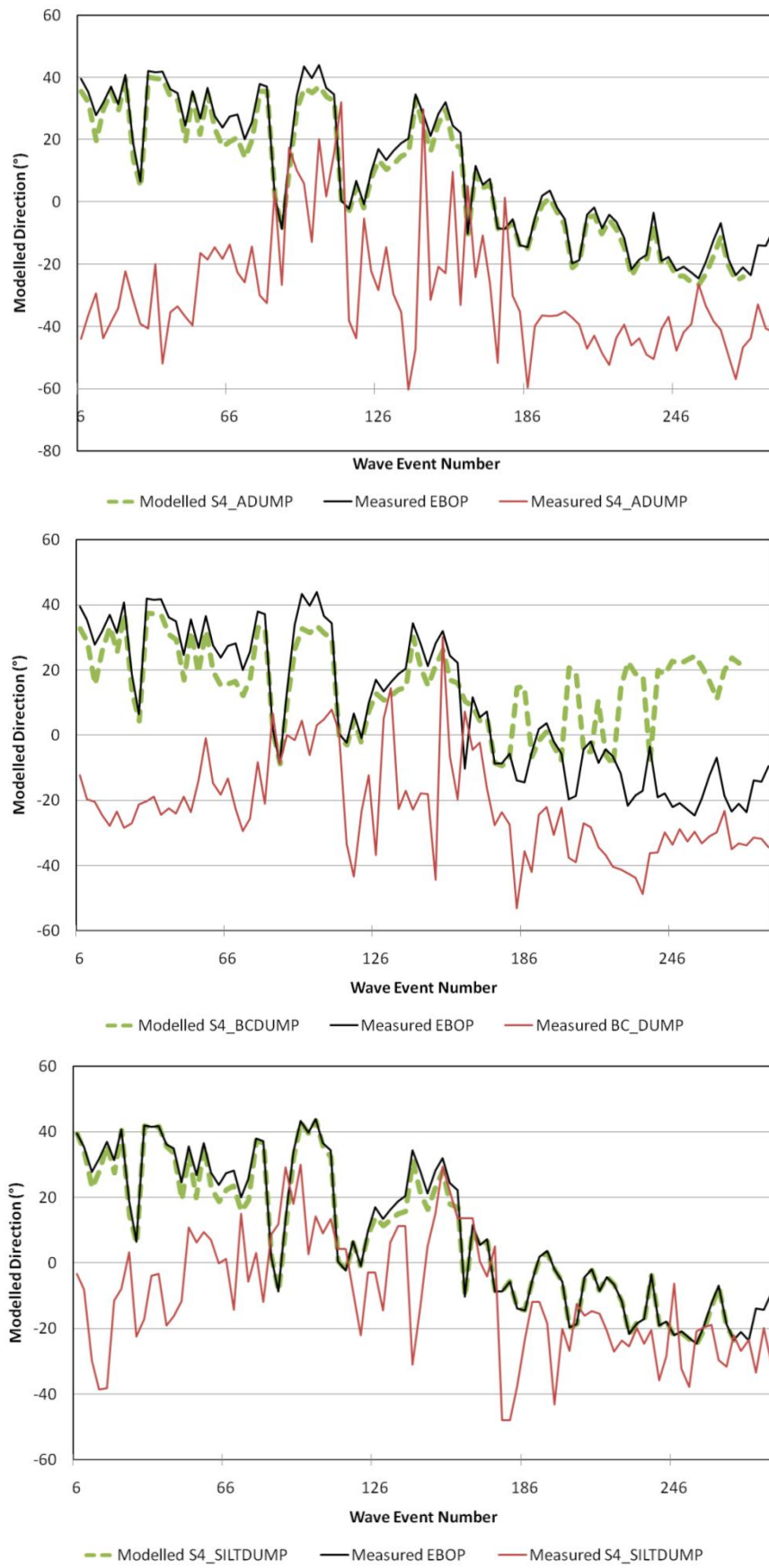|	S4_SILTDUMP error (m)	S4_BCDUMP error (m)	S4_ADUMP error (m)	A BEACON error (m)
average	-0.22	-0.20	-0.20	-0.25
95% CI	0.29	0.29	0.31	0.41

Figure A. Wave angle calibration for S4_ADUMP (top), S4_BCDUMP (middle) and S4_SILTDUMP (bottom).
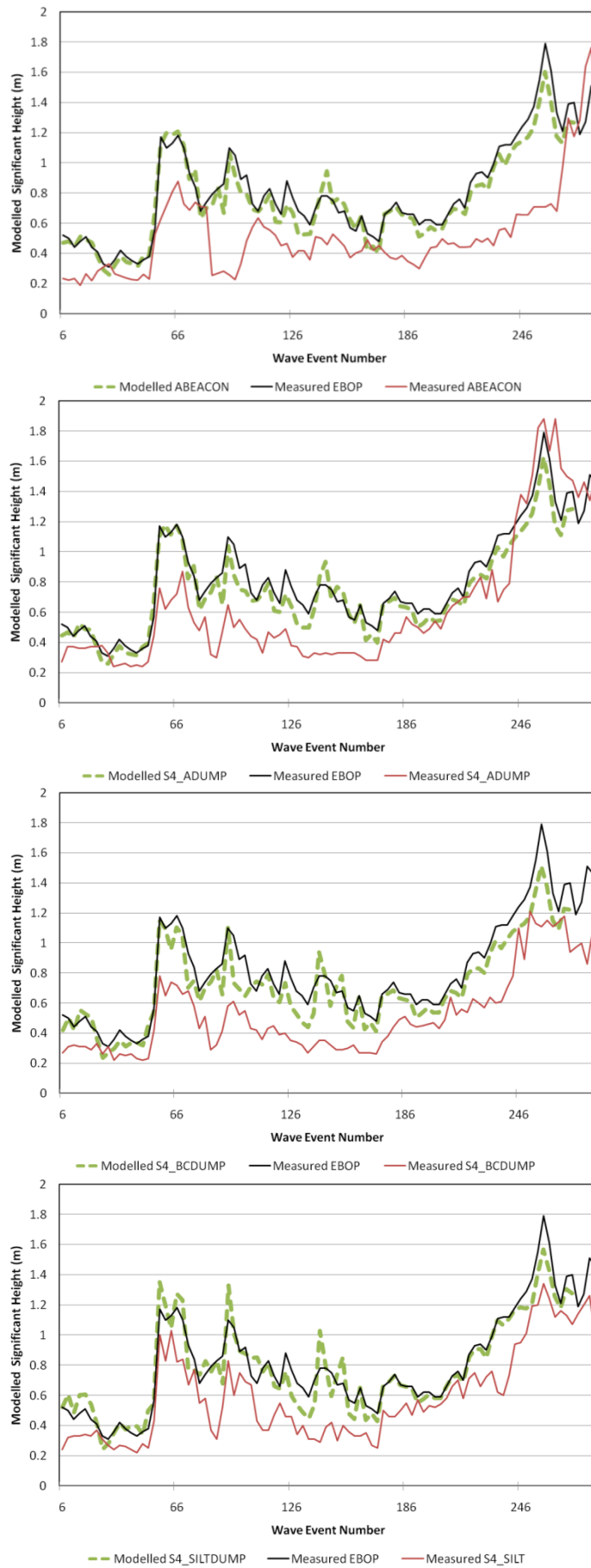
Figure B. Wave height calibration for A BEACON, (top), S4_ADUMP (second to top), S4_BCDUMP (second to bottom) and S4_SILTDUMP (bottom).

3 m WBEND Model Calibration

The S4_SILTDUMP site is used as the model boundary and the S4_BCDUMP site for calibration of the 3 m model grid. The same wave events as for the 60 m grid were used, and the other sensors are outside of this smaller modelling area. The calibration for the 3 m model grid has resulted in much better predictions than for the 60 m grid and the calibration results (Figure C) show close agreement. The jagged nature of the wave directions is attributed to the use of 15 minute sample periods during data collection. If a longer period was used, or the directions smoothed, possibly a closer agreement would have been found. Still the average height error is only -0.06 m (0.18 m 95 confience) giving confidence in the model predictions. The better calibration that the 60 m gird is attributed to:

 (i)   the proximity of the sensors compared with the large grid;
 (ii)   the use of a fine scale grid and more multibeam echo sounding data;
 (iii)   winds being similar between measurement locations; and
 (iv)   similar wave spectrums between measurement locations.
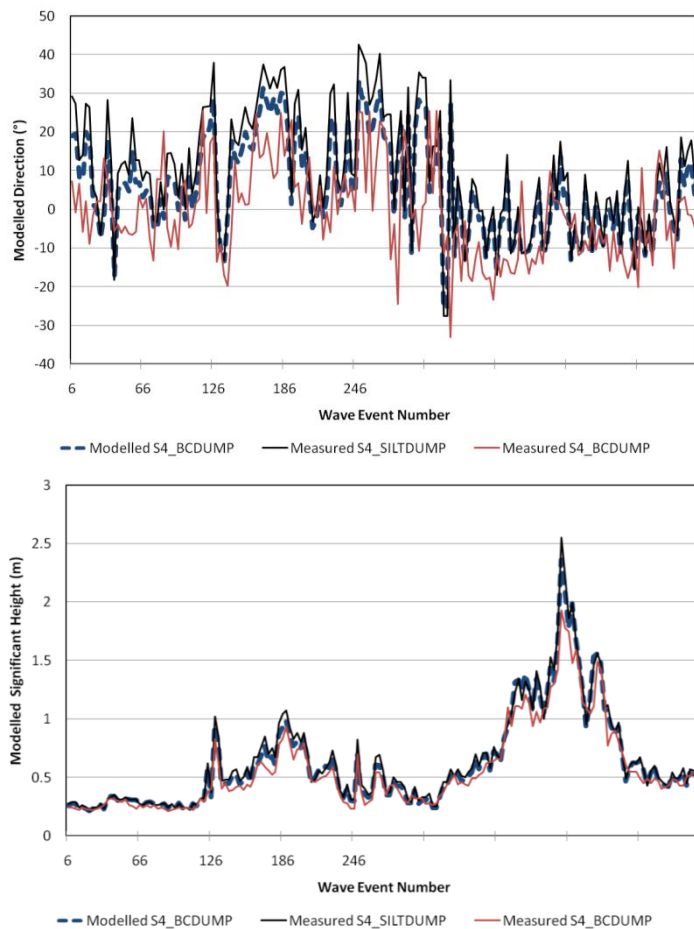

Figure C. Wave angle (top) and height (bottom) calibration for 3 m model grid.

Appendix Three – Survey Coverage for Mount Maunganui Artificial Surfing Reef Surveys

19/08/2004

28/10/2004

26/04/2005

08/09/2005

17/11/2005

20/04/2006

15/08/2006

15/05/2007

23/01/2007