

ASSET MANAGEMENT GROUP

Technical report

ISSN 1174 3085

PORT OF NAPIER

www.portofnapier.biz



HAWKE'S BAY
REGIONAL COUNCIL

Hawke's Bay

Environmental Change,
Shoreline Erosion &
Management Issues

November 2005
AM06/04
HBRC plan No. 3839

Asset Management Group
Technical Report

ISSN 1174 3085

Hawke's Bay

Environmental Change, Shoreline Erosion & Management Issues

Compiled jointly for:

Napier City Council
Port of Napier Ltd
Hawke's Bay Regional Council

Compiled By:

Paul D. Komar, Ph.D.
Consulting Oceanographer
3520 NW Elmwood Drive
Corvallis, Oregon 97330 USA

November 2005

AM 06/04

HBRC Plan Number 3839

Reviewed: _____

Table of Contents

Preface and Acknowledgments

Executive Summary

1	Introduction: The Coast of Hawke's Bay	1-1
2	Tectonics and Earthquakes: Their Roles in the Evolution and Erosion of the Hawke's Bay Shoreline	2-1
2.1	INTRODUCTION	2-1
2.2	THE BIG PICTURE — GLOBAL PLATE TECTONICS	2-1
2.3	THE TECTONICS OF HAWKE'S BAY	2-4
2.4	THE 1931 HAWKE'S BAY EARTHQUAKE	2-13
2.5	SUMMARY AND DISCUSSION	2-20
2.6	REFERENCES	2-21
3	Human Settlement and Impacts on the Environments of Hawke's Bay	3-1
3.1	INTRODUCTION	3-1
3.2	THE ARRIVAL OF THE MAORI AND THE ENVIRONMENTAL CONSEQUENCES	3-2
3.3	EUROPEAN EXPLORATION, SETTLEMENT AND CHANGES IN THE ENVIRONMENT	3-5
3.4	RESEARCH INTO THE CHANGING ENVIRONMENTS OF HAWKE'S BAY	3-15
3.5	SUMMARY AND DISCUSSION	3-21
3.6	REFERENCES	3-22
4	Ocean Processes in Hawke Bay: Waves, Tides and Changing Sea Levels	4-1
4.1	INTRODUCTION	4-1
4.2	PREDICTED AND MEASURED TIDES	4-1
4.3	GLOBAL AND LOCAL CHANGES IN SEA LEVELS	4-5
4.4	THE WAVE CLIMATE OF HAWKE BAY	4-11
4.5	WAVE REFRACTION AND ENERGY LEVELS ALONG THE HAWKE BAY SHORE	4-20
4.6	SURF-ZONE PROCESSES ON THE HAWKE'S BAY BEACHES	4-24
4.7	THE LONGSHORE MOVEMENT OF THE BEACH SEDIMENTS	4-26
4.8	TSUNAMI	4-32
4.9	SUMMARY AND DISCUSSION	4-35
4.10	REFERENCES	4-37
5	The Dynamics of Mixed Sand-and-Gravel Beaches and the Hawke's Bay Monitoring Program	5-1
5.1	INTRODUCTION	5-1
5.2	MIXED SAND-AND-GRAVEL BEACHES: A REVIEW	5-1
5.2.1	The Compositions and Morphologies of Beaches	5-2
5.2.2	Ocean Processes on Mixed Beaches	5-8
5.2.3	The Dynamic Responses of Beaches to Changing Wave Conditions	5-11

5.2.4	The Longshore Transport of Gravel on Mixed Beaches.....	5-16
5.2.5	The Sorting of Sediment Particles on Coarse-Grained Beaches	5-19
5.2.6	Particle Abrasion.....	5-21
5.2.7	The Beach Responses to Long-Term Changes in Relative Sea Level	5-24
5.3	THE BEACHES OF HAWKE'S BAY.....	5-27
5.3.1	Research Investigations of Hawke's Bay Beach Sediments and Morphodynamics	5-27
5.3.2	The Hawke's Bay Beach Monitoring Program	5-34
5.4	SUMMARY AND DISCUSSION	5-40
5.5	REFERENCES	5-43
6	The Coastal Response to the Construction of Moles (Jetties) and Breakwaters: The Hawke's Bay Experience	6-1
6.1	INTRODUCTION	6-1
6.2	THE CONSTRUCTION OF JETTIES AND BREAKWATERS: A REVIEW OF THE COASTAL RESPONSES	6-1
6.3	HARBOUR DEVELOPMENT AT HAWKE'S BAY AND ITS ENVIRONMENTAL CONSEQUENCES: A RE-EXAMINATION	6-11
6.3.1	The Pre-Construction Environmental Conditions	6-14
6.3.2	The Ahuriri Moles.....	6-18
6.3.3	The Port of Napier's Breakwater.....	6-20
6.4	SUMMARY AND DISCUSSION	6-24
6.5	REFERENCES	6-27
7	The Hawke's Bay Littoral Cells: Processes, Erosion Problems and Management Strategies	7-1
7.1	INTRODUCTION	7-1
7.2	THE HAUMOANA LITTORAL CELL	7-2
7.2.1	The Beach Sediment Sources	7-5
7.2.2	The Losses of Beach Sediment.....	7-8
7.2.3	The Budget of Beach Sediments	7-9
7.2.4	The Longshore Transport of the Beach Sediments and Numerical Shoreline-Evolution Models	7-13
7.2.5	Erosion Problems and Management Responses	7-18
7.3	THE BAY VIEW LITTORAL CELL.....	7-25
7.3.1	Sediment Sources and the Budget of Beach Sediments.....	7-27
7.3.2	The Transport and Accumulation of Sand in Hawke's Bay	7-30
7.3.3	The Longshore Transport of Beach Sediment and the Equilibrium Shoreline	7-35
7.3.4	Beach Erosion in the Bay View Littoral Cell and the Sediment Nourishment Program at Westshore	7-40
7.4	MANAGEMENT STRATEGIES	7-51
7.4.1	The Establishment of Hazard Zones	7-51
7.4.2	Shore Protection and Development Strategies	7-56
7.5	SUMMARY AND DISCUSSION	7-60
7.6	REFERENCES	7-63
8	Summary and Discussion: Science and Management of the Hawke's Bay Coast.....	8-1
8.1	INTRODUCTION	8-1
8.2	TECTONICS AND LAND ELEVATION CHANGES	8-2
8.3	NATURAL PROCESSES AND BEACH DYNAMICS	8-3
8.4	HUMAN IMPACTS ON THE ENVIRONMENT	8-6
8.5	HARBOUR DEVELOPMENT AND SHORELINE CHANGES.....	8-8
8.6	MANAGEMENT ISSUES.....	8-11

Preface and Acknowledgments

In the Spring of 2003 I was hired to become the Independent Facilitator for Coastal Issues to work with the Hawke's Bay Regional Council, the Napier City Council, and the Port of Napier Ltd. on issues dealing with investigations of the Hawke's Bay coast and its management. In that role I have interacted closely with the coastal scientists and engineers who have undertaken those investigations, and are currently engaged in additional studies of this coast. I have been asked to prepare this report to provide an overall summary of what is known about the Hawke's Bay coast, including its tectonics and geology, the history of human impacts that have altered its environment, the ocean processes (waves, tides, etc.), the dynamic changes of its beaches in response to those processes, and how that information can be applied to the management of the Hawke's Bay coast. Doing so has been a challenge, as I have had a steep learning curve to familiarize myself about the coast of New Zealand in general, and then to read and absorb the information from a considerable number of reports and publications specifically concerned with the coast of Hawke's Bay.

Perhaps a few words are in order about my background. I was born in the United States, in the State of Michigan, so my first interest in beaches and awareness of erosion problems was derived from time spent as a youngster along the shores of the Great Lakes. Later when I was a student at the University of Michigan and needed a thesis topic for a Masters Degree in Geology, I was determined to undertake a study of the beaches along the shore of Lake Michigan to answer my youthful questions concerning the causes of the erosion I had witnessed. This was a fateful choice, as it later led to my attending the Scripps Institution of Oceanography in California in order to continue my study of beaches, where ultimately I obtained a PhD in Oceanography even though prior to my arrival in California I had only seen the ocean once, when I was 12 years old.

Following a post-doctoral year in Great Britain where I was involved in research at Saint Andrews University in Scotland and at the Wallingford Hydraulics Research Station in England, in 1970 I joined the faculty in Oceanography at Oregon State University in Corvallis, Oregon, and have spent my subsequent career there. The coast of Oregon has served as my laboratory in research spanning 35 years, including investigations of a wide range of topics, many of which again focused on the causes of beach and property erosion. On occasion my research has taken me elsewhere, for example during the 1980s when I worked with Egyptian scientists and engineers in studying the causes of the massive erosion along the shores of the Nile Delta.

In 1998 I retired from the University, but retain an office in Oceanography where I continue my research and work with graduate students, primarily those in the Marine Resource Management Program who have a specific interest in coastal-zone management.

Having become the Independent Facilitator for Coastal Issues on the Hawke's Bay coast is exciting for me as it provides the opportunity to focus on another coast, on its processes, erosion problems and management strategies. I was already somewhat familiar with the New Zealand coast, having spent mini-sabbaticals at Waikato University in 1994 and Canterbury University in 1996, working respectively with Professors Terry Healy and Robert Kirk. Those visits wetted my appetite to learn more about this coast, especially in that while there are similarities to the Oregon coast where I had undertaken most of my research, there are distinct differences that opened horizons for me. This is particularly the case for the coast of Hawke's Bay. Both Hawke's Bay and Oregon have basically the same tectonic settings, with subduction of oceanic plates off their shores, which can result in earthquakes that alter land elevations along their shore; Hawke's Bay had its most significant earthquake in 1931, which raised much of its shore by about 2 metres, while the last major earthquake off the Oregon coast took place on 26 January 1700, at which time most of the coast immediately dropped down by 1 to 2 metres. The main difference between the two coasts is that the Oregon beaches are primarily composed of sand, whereas the Hawke's Bay beaches are mixtures of gravel (shingle) and sand. This is significant in that these two beach

types differ considerably in how they respond to storms, and therefore ultimately how one manages these coasts to minimize the impacts of the ocean hazards to people living there.

Beyond these scientific issues that have interested me in becoming the Independent Facilitator for Coastal Issues, I looked forward to having the opportunity of working with kiwi coastal scientists and engineers, with whom I had become friends during my mini-sabbaticals and other visits. In addition, one of my hobbies is an interest in the history of architecture, with a particular fondness for Art Deco design and architecture; for me, working in Napier is an incredible fringe benefit.

Writing this report has been an education for me, as it has required that I become familiar with the research undertaken over the years about the geology and ocean processes along the New Zealand coast, and then specifically with that concerning Hawke's Bay. In reviewing this literature I have been fortunate to have a number of willing teachers. Foremost are the three scientists and one coastal engineer who have been most instrumental in undertaking the recent studies of the Hawke's Bay coast:

Dr. Jeremy Gibb	Coastal Management Consultancy Tauranga, Bay of Plenty
Richard Reinen-Hamill	Tonkin & Taylor Ltd. Auckland
Dr. Martin Single	Department of Geography University of Canterbury, Christchurch
Dr. Robert Kirk	Department of Geography University of Canterbury, Christchurch

They have had a long familiarity with Hawke's Bay through their work, and have been most kind in their willingness to convey their knowledge to me and to provide suggestions in reviewing this report (of course, any errors still found in this report must be attributed to me). I also want to acknowledge several other coastal scientists, who variously have shared information from their research, provided copies of their publications, and even have taken me on field trips to learn more about the New Zealand coast. These colleagues and friends include (in alphabetical order):

Dr. Robert Bell	NIWA, Hamilton
Dr. Kerry Black	ASR, Raglan
Dr. Derek Goring	Mulgor Consulting Ltd., Christchurch
Dr. Richard Gorman	NIWA, Hamilton
Dr. Judith K. Haschenburger	School of Geography and Environmental Science, University of Auckland
Prof. Terry Healy	Department of Geology University of Waikato, Hamilton
Dr. Murray Hicks	NIWA, Christchurch
Dr. Terry Hume	NIWA, Hamilton
Mr. Keith Smith	NIWA, Hamilton (now a private consultant)

I also want to acknowledge the considerable assistance of Dr. Jonathan Allan, a kiwi and graduate in Geography from the University of Canterbury, who has worked with me for the past several years, first as a post-doctoral student in Oceanography at Oregon State University, and now in his present position with the Oregon Department of Geology and Mineral Industries. He has been my most immediate contact whenever I have had questions about the coast of New Zealand, and has been a great help in editing and formatting this report.

Finally, I want to express my thanks to those individuals I am working with in Hawke's Bay, who have sought out copies of the many reports I have needed, or provided other information from their archives:

Michael Adye	Hawke's Bay Regional Council
Gary Clode	Hawke's Bay Regional Council
Bill McWatt	Napier City Council
John O'Shaughnessy	Napier City Council
Keith Rodel	Port of Napier Ltd.
Dennis Hoy	DHE Ltd., Consultant to the Port of Napier

Working with these individuals is a considerable pleasure, another fringe benefit to my having become the Independent Facilitator in Hawke's Bay.

Executive Summary

The focus of this report is on the Hawke's Bay shore that extends from Tangoio Bluff in the north to Cape Kidnappers in the south. Two littoral cells are recognized there, in effect self-contained stretches of beach, the Bay View Littoral Cell to the north and Haumoana Littoral Cell to the south, separated by Bluff Hill in Napier which together with the Port of Napier's breakwater restricts the exchange of beach sediment between their shores. This coast has experienced significant changes during the past two centuries, brought about by natural events and processes, but also caused by the impacts humans have had on the physical environment. In order to better understand the respective roles of these factors in the evolution of this coast, a number of research investigations have been undertaken by coastal scientists and engineers. Those reports have been important to the strategies that have been established to manage this stretch of shore.

The objective of this report is to provide an independent review of those past research investigations, to yield a synthesis of our present understanding of the causes of shoreline changes in Hawke's Bay, particularly those that have been significant to occurrences of beach and property erosion. This consideration has been wide ranging, from the geology and tectonics of the area that was responsible for the 1931 Hawke's Bay earthquake that altered land elevations along the coast, to examinations of programs directed toward the collection and analyses of wave and tide data, and of surveys to document the progressive changes in the beaches and their responses to storms. Also included in this report are reviews of the effects humans have had on the coastal environment, which includes examinations of the deforestation of the watersheds and the mining of gravel and sand from the rivers, inland changes that have altered the volumes of sediment delivered to the ocean beaches. This review of the human impacts has also included a detailed examination of the shoreline changes that occurred when the Ahuriri moles and then the Port's breakwater were constructed during the late 19th century, there having been a degree of divergence in the opinions of coastal scientists and engineers with respect to the significance of that construction to the erosion at Westshore. Of ultimate importance in this review has been the identification of missing elements in our understanding of the Hawke's Bay coast, in need of future research for the improved management of this shore.

The following sections summarize the principal findings and conclusions reached on the primary topics considered in this report.

TECTONICS AND LAND ELEVATION CHANGES

More so than on most coasts, the tectonics and geology of Hawke's Bay have been extremely important to its evolution and ongoing shoreline changes. With the collision and subduction of the Pacific plate beneath the Australian plate along the Hikurangi Trough close offshore, the resulting compression of the rocks beneath the land and in the range of mountains has generated earthquakes having Richter magnitudes of 7 to 8. Of immediate significance to the coast are the accompanying land elevation changes due both to the earthquakes and the compressional folding of the rocks, which have resulted in some areas being uplifted while others have undergone long-term subsidence. Most significant since European settlement was the 1931 Hawke's Bay earthquake, which had a magnitude of 7.8 and produced uplift on the order of 2 metres along the shore of the Bay View Littoral Cell, but smaller degrees of uplift southward along the shore of the Haumoana Littoral Cell until south of Awatoto there was some subsidence of the coast. Included in the conclusions reached by this review are the following:

- The uplift of the shore along the Bay View Littoral Cell at the time of the 1931 earthquake, and of the Ahuriri Lagoon leading to its drainage, represented a reversal in the general occurrence of subsidence of the land that had prevailed

there during the previous several thousand years, and possibly longer; it is uncertain whether another earthquake will again result in the uplift of the land, or will return to subsidence (with dire consequences to the coast);

- The uplift by 2 metres of the gravel beach ridge along the shore of the Bay View Littoral Cell at the time of the 1931 earthquake has reduced its hazards from beach erosion and backshore flooding, which previously had impacted that shoreline; the progressive erosion of this uplifted beach ridge will in time lead to the loss of its protection, with the return of more extensive shore-front property erosion and flooding;
- The subsidence of the shore of the Haumoana Littoral Cell south of Awatoto at the time of the earthquake has been correctly interpreted by researchers as a continuing factor in the high rates of erosion experienced there, the greatest extent of property damage presently found along the Hawke's Bay coast;
- The ongoing changes in land elevations along this coast are unknown, but likely are occurring as they are typical of subduction zones where the Earth's tectonic plates are colliding; this uncertainty is unfortunate in that it is important to determine the relative change in sea level along the coast, that is, how the land is changing relative to the ongoing global rise in sea level, a significant process in bringing about erosion and flooding of the coast;
- Research is underway based on measurements using the Global Positioning System (GPS), which relies on satellites to establish positions and elevations of the Earth's surface; within a few years its results may prove to be the key in determining the ongoing rates of land elevation changes throughout Hawke's Bay.

NATURAL PROCESSES

Of fundamental importance to the management of the Hawke's Bay coast is the collection and analysis of data for the range of ocean processes: the heights and periods of waves, particularly those that occur during major storms; the elevations of tides, both predicted and measured; the generation of storm surges and their extreme elevations that may result in coastal flooding and erosion; and a determination of the progressive rise in sea level. While measurement programs are underway to obtain quality data for these processes in Hawke Bay, undertaken by the Port of Napier, their collection was initiated only in recent decades so the record lengths are short, representing a limitation for their use in applications such as the establishment of coastal hazard zones.

Several conclusions can be offered with respect to the sufficiency of the process data that have been collected to date:

- Tide-level data have been obtained by the Port's tide gauge since 1986, but with high-quality data available only since 1998; while this length of record has been sufficient for analyses that permit predictions of the daily astronomical tides, the record length is too short for the confident assessment of extreme measured tides that are affected by atmospheric and oceanic processes, those that are important to episodes of coastal flooding and erosion;
- Tide-gauge records are commonly employed to determine the local relative change in sea level during the past 50 to 100 years, affected by both the global rise in sea level and any local land-elevation changes; this approach is not possible for Hawke Bay due to the short span of available tide measurements;

- The wave climate for Hawke Bay is based in part on the deep-water hindcasts of wave heights, periods and directions analyzed by NIWA for the years 1979-1998; while this data has been used in applications, there is evidence that the hindcast techniques may under predict the wave heights generated by major storms, those of primary interest in assessments of coastal hazards;
- Wave heights, periods and directions have been measured since August 2000 with a wave-rider buoy located in 15 metres water depth seaward from the Port's breakwater; with this limited record, at best one can only statistically project with confidence the 10 to 15-year potential extreme waves, again insufficient for assessments of coastal hazards where 50- to 100-year projections are needed;
- Due to the shallow water of Hawke Bay and with the shelter provided by Bluff Hill in Napier together with the Port's breakwater, the refraction of the waves as they travel from deep water and approach the bay's beaches is an extremely important processes, reducing wave energy levels along the shore; the recently completed studies by Tonkin & Taylor have made a significant contribution in analyzing this process, but the refraction analyses and wave transformations need to be extended to the nearshore to establish the climates of the surf zone processes on the Hawke's Bay beaches, those most important to hazards from erosion and flooding;
- A significant missing component in the studies of Hawke's Bay has been the collection of direct measurements of the nearshore processes, including wave breaker heights and swash runup elevations; such data are needed to test the results of the model analyses and predictions, but with sufficient measurements the data would establish how the heights of breaking waves and runup elevations statistically vary along the Hawke's Bay shore and depend on the morphology and sediments of the beach.

Some of the gaps noted here in the collection of process data for Hawke Bay can be filled only with the passage of time, when sufficiently long records become available to statistically define the potential for extreme measured tides and the highest potential waves generated by the most severe storm that could be expected to occur in a 50- to 100-year time frame, those required in coastal hazard assessments.

BEACH DYNAMICS

It is also important to have the ability to predict how the beaches respond to the ocean processes, in particular how their slopes and elevations change during a major storm, perhaps leading to the erosion and flooding of backshore properties. Such predictions have been a problem for Hawke's Bay in that the beaches are composed of mixtures of sand and gravel, a type of beach that has been the focus of much less scientific and engineering research than sand beaches. Because of this issue, this report has included a review of what is known about the processes and morphology changes of mixed sand-and-gravel beaches, in general based on research undertaken throughout the world, but with particular interest in the research completed on the mixed beaches of the Canterbury Bight, and then specifically for investigations of the Hawke's Bay beaches and information derived from its monitoring program.

The following conclusions and recommendations for additional research on the Hawke's Bay beaches are offered:

- The nearshore processes on mixed sand-and-gravel beaches are significantly affected by the proportions of sand versus gravel, which determines the

permeability of the beach deposit; most strongly affected are the wave swash runup energies and elevations, so that predictions based on relationships developed for sand beaches are unsatisfactory, reinforcing the need for direct measurements of these processes on the Hawke's Bay beaches;

- The studies on other coasts of mixed sand-and-gravel beaches have found a variety of patterns of cross-shore sediment transport and profile responses to the waves and tides during major storms; this in particular needs to be documented specifically for the Hawke's Bay beaches, so it is strongly recommended that following major storms beach profiles be surveyed at all sites generally included in the monitoring program, followed by analyses of the extent of the morphology changes;
- It is also recommended that a select number of profiles in the monitoring program be systematically surveyed more frequently than the present annual basis, that is, at least seasonally so as to better define their degree of variability and with analyses of the causes of this variation;
- While the directions of the longshore transport by waves of the gravel on the Hawke's Bay beaches can be established from the locations of the gravel sources (e.g., the Tukituki River) and the dispersal patterns of the gravel as it moves along the shore, it is difficult to evaluate the quantities of gravel transported on average each year, and the few attempts to do so have yielded highly divergent results; improvements in the analysis techniques are mainly dependent on additional research being undertaken by coastal scientists and engineers on mixed sand-and-gravel beaches, but in the mean time it may be possible to undertake efforts on the Hawke's Bay shore to monitor the longshore movement of gravel, for example by employing recently developed techniques to "tag" individual gravel particles with microchips imbedded in their interiors, that permits one to follow their movements for years to decades;
- With the Hawke's Bay beaches consisting primarily of gravel composed of greywacke, derived from the erosion of low-grade metamorphic rocks, the abrasion and reduction of that gravel to fine sand and silt represents an important loss of sediment from those beaches; while there has been considerable research devoted to the study of beach sediment abrasion, including experiments with the gravel of the Hawke's Bay beaches, it is still not possible to quantitatively determine with confidence this rate of loss.

While the beach-monitoring program has been underway at Hawke's Bay for a number of years and permits the projection of long-term trends of erosion or accretion, the problem remains in predicting the episodic erosion of the beaches during an extreme storm, the 50- to 100-year event. The primary focus of the recommendations offered here is to provide a better understanding the beach responses during extreme events, those that represent the principal threat to coastal properties from erosion and flooding.

HUMAN IMPACTS ON THE ENVIRONMENT

Humans have significantly altered the physical environment of the Hawke's Bay region, beginning with the arrival of the Maori about eight hundred years ago, but on a much larger scale when Europeans settled in the region beginning in about 1830. These impacts have been wide ranging, including the deforestation of the watersheds of the rivers that flow into the bay, the grazing of cattle on those cleared lands, the extensive modifications made to the rivers including the mining of gravel and sand, and the construction of embankments to prevent flooding of the newly developed agricultural and urban lands. Such impacts on the interior environments have

been important to the coast in that they have affected the quantities of sand and gravel supplied by the rivers to the beaches. At the same time, human impacts have been significant along the coast itself, including the mining of gravel directly from the beaches. There have also been environmental changes brought about by the natural variations in the Earth's climate, and it can be difficult to separate out the effects humans have had versus those caused by shifts in the climate. From the research that has been undertaken in Hawke's Bay, it is clear that both have been important.

The review completed in this report of the history of human settlement in the Hawke's Bay region and the environmental consequences, and of changes in the river watersheds that can be attributed to variations in the Earth's climate, include the following:

- A series of destructive floods occurred in the Hawke's Bay rivers during the 19th century, which severely damaged the recently established European settlements on the Heretaunga Plain and flowed through the streets of Napier;
- The earliest published study of the Hawke's Bay physical environment was that of Hill in 1897, which focused on the occurrences of the destructive floods and their causes; he concluded that they had been enhanced by the deforestation of the watersheds, which would have increased the flood discharges and quantities of sediment transported; Hill offered a number of recommendations directed toward the improved management of the watersheds, several of which have been adopted and continue to be practiced;
- Research undertaken by Patrick Grant, a hydrologist who worked in Napier during the period 1965 to 1985, demonstrated that there have been variations in New Zealand's climate extending back several centuries, which greatly affected the forests through the periodic occurrence of extreme storms that downed trees in the watersheds, leading to the transport of increased quantities of sediment down streams where it eventually was deposited to aggrade the rivers in their lower watersheds; these quantities of sediments were substantial due in part to the geology of the Hawke's Bay mountains where the rocks are highly shattered and easily eroded, so the sediment yields are greater than found in most other watersheds throughout the world;
- In spite of the large quantities of sediment being eroded from the Hawke's Bay watersheds and transported down the rivers, much of the gravel has been deposited along the middle reaches of the rivers where there is a change in channel slope so the coarser gravel cannot be transported any further; this aggradation of the river channels has increased the flooding, such that the commercial extraction of the gravel from the rivers has been viewed as a positive management strategy, but this practice likely has reduced the quantities of gravel and sand that reach the Hawke's Bay beaches;
- There is considerable anecdotal evidence for the historic mining of gravel from the Hawke's Bay beaches, including that needed for the bed of the railway line — even today there is active commercial mining of beach sediment at Awatoto; any sediment extraction from the rivers or after the sediment has reached the beaches can significantly alter the "budget of beach sediments", the balance between the contributions by the sediment sources versus the various losses from the beach, causing or exacerbating the erosion and flooding of backshore properties.

From the history of settlement and the scientific research that has been completed in Hawke's Bay, it is clear that both human impacts and natural variations in the Earth's climate have been important. This review has also shown that considerations of our coastal beaches cannot be

divorced from what happens in the interior, within the watersheds of the rivers where the erosion and transport of sand and gravel to the coast forms the beaches. Any changes in the watersheds eventually have consequences on the coast.

HARBOUR CONSTRUCTION AND SHORELINE CHANGES

The construction of jetties and breakwaters along the world's coastlines have resulted in beach and property erosion wherever they block the natural movement of the beach sediment along the shore. The question is whether harbour development on the shore of Hawke's Bay during the late 19th century had similar consequences, including the construction of the Ahuriri moles (jetties) in 1876-1879 and then the Port's breakwater in 1887-1890. Erosion subsequently occurred along Westshore, and some researches have concluded that the breakwater was the cause, while others have argued against these structures having been responsible for the erosion. Due the continuing importance of this issue, a detailed review has been undertaken in this report. In large part the disagreement involves the question of whether or not beach sediment had been able to bypass the Bluff Hill headland in Napier prior to the construction of the moles and breakwater, with the erosion at Westshore having occurred because it is located downdrift from those structures.

In summary, the principal assessments arrived in this review include the following:

- Some evidence exists that beach gravel probably was able to bypass Bluff Hill prior to the construction of the breakwater, carried from the Haumoana Littoral Cell into the Bay View Littoral Cell, but this occurred only episodically and involved only relatively small volumes of gravel; the evidence for bypassing includes the notation on an 1873 navigation chart of the presence of "shingle" (gravel) found locally along the shore of Bluff Hill, but differences in grain sizes, shapes and surface polish between the gravels of these two littoral cells (on the beaches north and south of Bluff Hill) support the conclusion that sediment bypassing could have involved only small quantities of gravel;
- At the time the Ahuriri moles were being constructed (1876-1879) there was little or no active bypassing of gravel around Bluff Hill to support a longshore gravel transport at Ahuriri to be blocked by its construction; this conclusion is supported by Saunders' observation in his 1882 report that the Marine Parade beach was "much reduced" in its width and sediment volume, inadequate to support bypassing, and by the observed shoreline responses adjacent to the moles as they were being constructed;
- According to Saunders, the rate of gravel accumulation to the east of the constructed moles was so rapid it kept pace with their extension, the rate of accumulation having been on the order of 50,000 m³/year; such a large rate is unrealistic for the sediment volumes that could have bypassed Bluff Hill;
- The observed gravel accumulation to both the east and west of the constructed moles can be best interpreted as the expected response to jetty construction on a shoreline that has a near-zero net littoral drift of sediment, with the beach and shoreline accretion supported by the rapid onshore movement of gravel from the bay-mouth bar; this interpretation is made complex by the simultaneous practice of having disposed of the sediment dredged from the Inner Harbour to the west of the moles, but this would mainly have involved sand whereas it appears that most of the accretion resulted from the arrival of gravel;
- The construction of the breakwater (1887-1890) has had the effect of enhancing the natural headland of Bluff Hill, producing a localized seaward progradation of

the shoreline to its south and a greater degree of wave sheltering along the shore to its north; as an enhanced headland, the breakwater has impounded the beach sediment that is transported from the south; there is no evidence for beach gravel or coarse sand having bypassed the breakwater during the century since its construction; fine and very-fine sand continues its transport to the north offshore from the beach, carrying along the breakwater's arm where much of it is then trapped in the harbour's Fairway and has to be periodically dredged;

- The erosion at Westshore at the time the breakwater was being constructed was most likely associated with the major storms which occurred at that time, the storms that also caused beach erosion to the south of the breakwater and the flooding of downtown Napier; another factor in the Westshore erosion was the cessation in 1888 of placing the sediment dredged from the Ahuriri Inner Harbour along that shore west of the moles.
- The orientation and shape of the shoreline along the Bay View Littoral Cell in effect represents a quasi-equilibrium condition with a net-zero longshore transport of the beach sediments, that is, there can be periodic reversals from year to year and decade to decade in the directions of the transport, but in the long term the net is effectively zero; it follows that any changes in the shoreline position within the Bay View Littoral Cell need to be interpreted primarily in terms of redistributions of a nearly fixed total volume of beach sediment contained within the cell (but accounting for some losses to abrasion), with its redistribution caused by the changing waves and currents;
- The periodic erosion at Westshore over the years may have been caused in part by cycles between accretion and erosion of sediments on its beach, the accretion having occurred whenever there is a subtle shift in the waves and currents that produced a southward transport of beach sediment, while the episodes of beach erosion at Westshore have occurred when those processes produced a temporary northward transport of the beach sediments.

My conclusion is that there is no firm evidence that the construction of the Ahuriri moles and then the Port's breakwater blocked a northward longshore transport of beach gravel derived from sediment that was actively bypassing Bluff Hill, finding instead that there is evidence to the contrary. While the construction of the moles and the breakwater undoubtedly did alter the local environment, the consequences were both positive and negative, and with its overall impacts have been minor compared with those experienced on other coasts where jetties or breakwaters have been constructed (e.g, Timaru). Accordingly, the erosion at Westshore was characterized by one coastal engineer who investigated its causes as having been "relatively minor" and "not been severe in coastal engineering terms". Although disagreements may continue regarding this issue, it is ancient history and has largely become irrelevant to the successful management of the Hawke's Bay coast.

MANAGEMENT ISSUES

A primary goal of the scientific and engineering studies of the Hawke's Bay coast has been to collect and analyze environmental data such as the wave heights and periods, or to document environmental conditions such as the beach variations and the factors related to the sources of the beach sediments. The reports that have resulted from those studies are important in serving as the basis for the management of the Hawke's Bay coast.

The conclusions and recommendations reached in this review, those that have direct relevance to management issues, include the following:

- Important to sound coastal management is the availability of process measurements collected over a sufficient span of time to characterize their extremes, for example, the heights and periods of the waves generated by major storms; while wave hindcast analyses have characterized the deep-water wave climate and waves have been measured daily since August 2000 in shallow water, uncertainty remains in the projections of the extreme-wave conditions, those having a probability of occurring only once or so during the next 50 to 100 years, posing the greatest threat to the erosion and flooding of the coast;
- Tide-level measurements have been collected only since 1986, and again this record is too short for the confident assessment of extreme measured tides that are elevated by processes such as the occurrence of a storm surge; the tide-gauge record is also far short of that needed to determine the local relative change in sea level, affected by both the global rise in sea level and any local land-elevation changes;
- Only the passage of time, with the continued measurement of waves and tides, will yield records having sufficient lengths to yield confident projections of the extreme values required in coastal hazard assessments; in the mean time, the assessments will remain uncertain, so judgments of hazard zones need to be cautious in providing a sufficiently high level of projection to coastal developments;
- Another significant uncertainty in the establishment of hazard zones is the undocumented responses of the slopes and elevations of the Hawke's Bay beaches at times of major storms, there having been insufficient research undertaken on its mixed sand-and-gravel beaches to make this possible;
- Analyses of the extreme total water levels at the shore during a major storm, resulting from the addition of the tide elevated by the storm surge and the swash runup of the storm waves on the sloping beach, serve as the basis for assessments of the potential erosion and flooding of backshore properties; while this analysis approach has been common practice for beaches composed of sand, assessments for the mixed sand-and-gravel beaches of Hawke's Bay remain uncertain, resulting in wide ranges of predicted hazard zones derived by different studies; additional research in this area should have the highest priority, including the collection of measurements of wave breaker heights and swash runup elevations at times of major storms, and resurveys of the beach profiles to document the beach responses to those storm processes;
- Also important to the management of the Hawke's Bay coast is the development of a strategy to insure that there are sufficient volumes of sand and gravel on the beaches so they provide a natural protection to the backshore properties from erosion and flooding; this requires the development of improved sediment budgets that include assessments of the sediment gains and losses in both the river watersheds and ocean beaches, an integration of both the inland and coastal sediment budgets, and with considerations of the unsteady variations in the volumes of sediment supplied from the rivers and in the changing wave conditions that affect the longshore dispersal of the gravel and sand after it has reached the beaches.

The coast of Hawke's Bay is extraordinarily well managed, based in part on an unusually high level of knowledge concerning its ocean processes and how they have been responsible for past erosion problems. This report has offered suggestions for additional investigations, with those assessed as having the highest priority directed toward the development of improved analysis techniques for the establishment of hazard zones for the safer development of this coast.

1 Introduction: The Coast of Hawke's Bay

The shoreline of Hawke's Bay extends along the east coast of New Zealand's North Island, from the Mahia Peninsula in the north to Cape Kidnappers in the south. This stretch of coast has experienced significant changes during the past two centuries, induced by tectonic activity that included the major 1931 earthquake, changes in the beaches and sea cliffs produced by the natural ocean processes of storm waves and tides, and alterations in the environment induced by a variety of human activities that have included the extensive mining of gravel from the rivers and beaches, the construction of the moles on the entrance to the Ahuriri Lagoon, followed a few years later by the construction of the Port of Napier's breakwater. The uncertain consequences and continued effects of these natural and human-induced factors have made it a challenge to manage the Hawke's Bay shore.

The absence of a full understanding of the factors important to shoreline change, and specifically of those that might be responsible for locally inducing erosion that threatens shore-front properties, is not due to the lack of research by coastal scientists and engineers. Indeed, few stretches of the coast worldwide have been the subject of so many studies that have generated a great number of reports and published papers (my current bibliography dealing with Hawke's Bay coastal issues, including its management as well as the environmental studies, contains more than 80 entries, ranging in dates from 1882 to 2005). This number of reports is actually part of the problem in that at times their conclusions are seemingly at odds with one another, leading to confusion when management decisions have to be made. The objective of this report, adding to the number, is to provide an independent review of those earlier studies in order to summarize the status of our understanding of the causes of shoreline change at Hawke's Bay, especially those that may have been significant in producing beach and property erosion.

Coastlines are frequently divided by coastal scientists and engineers into what is termed "littoral cells", representing stretches of shore containing a beach that can be considered to be partially to completely isolated from other beaches. For example, an assessment of a sediment budget for a beach is usually based on a littoral cell, the budget including evaluations of the contributions of sand and gravel to the cell's beach versus the losses, with the balance in the budget reflected in the extent of net beach erosion or accretion experienced in that littoral cell as a whole. Littoral cells are most easily defined where rocky headlands provide barriers at the ends of the beach, and this is the situation at Hawke's Bay where one can clearly define the three littoral cells delineated in Figure 1-1. To the north is the cell extending alongshore from the Mahia Peninsula southward to the stretch of rocky coast that contains the small settlement of Waipatiki Beach. To the south of that rocky shore, beginning at Tangoio and extending 18 kilometres to Bluff Hill (Scinde Island) within the City of Napier is the second littoral cell, with the third being the 23-kilometre shoreline from Napier (Bluff Hill and the Port's breakwater) to Cape Kidnappers. For convenience, in this report I will refer to these three littoral cells respectively as the Wairoa Cell, the Bay View Cell, and the Haumoana Cell, following the usual convention of identifying littoral cells by centrally-located communities.

The rocky headlands that separate the three Hawke's Bay cells provide varying degrees of isolation, that is, they appear to differ in the extent to which they inhibit sediment exchange between the beaches of the cells. The Waipatiki stretch of rocky coast north of Tangoio appears to be highly effective in preventing an exchange of sediment between the Wairoa and Bay View

Cells, indicated by distinct differences in beach sediment compositions and grains sizes in those two cells. At the south end of Hawke's Bay, Cape Kidnappers also clearly isolates the Haumoana Cell from the small pocket beaches further to the south, with the former composed of mixed sand and gravel while the pocket beaches at Ocean Beach and Waimarama consist of fine to medium sand that also differs in its mineral composition. Less clear is the degree to which Bluff Hill in Napier has prevented the exchange of beach sediment between the Bay View and Haumoana Cells, prior to the construction of the Port of Napier's breakwater in 1887-1890, following its completion, and with the changes produced by the 1931 earthquake that altered land elevations and shoreline positions. This issue will be addressed in Section 6 of this report, which provides a detailed review of the potential environmental consequences of the harbour development.

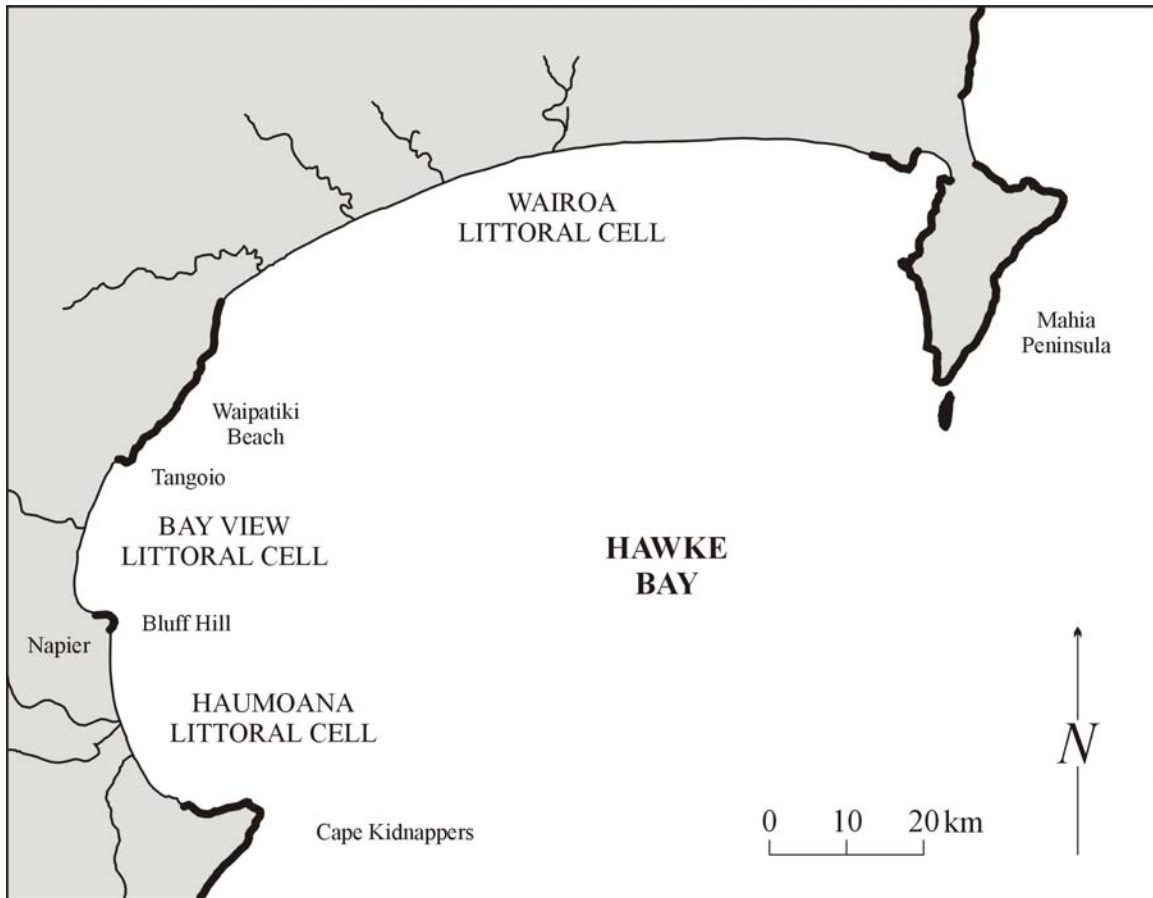


Figure 1-1 The coast of Hawke's Bay and its three littoral cells, stretches of beach separated by rocky shores and headlands.

The review undertaken in this report is limited to the stretch of shore from Tangoio to Cape Kidnappers, that is, to the Bay View and Haumoana Littoral Cells, Figure 1-2. This stretch of shore is the most heavily developed, containing the communities of Napier, Whirinaki, Bay View, Awatoto, East Clive, Haumoana, Te Awanga and Clifton. Shoreline erosion with its threat of property losses has occurred at Westshore north of Bluff Hill and the inlet to the Ahuriri Lagoon, and especially at Haumoana, Te Awanga and Clifton at the south end of the Haumoana Cell. Because of this heavy development and experience with erosion, these littoral cells have been the primary focus of research attention and the subject of nearly all of the reports written about the Hawke's Bay coast.

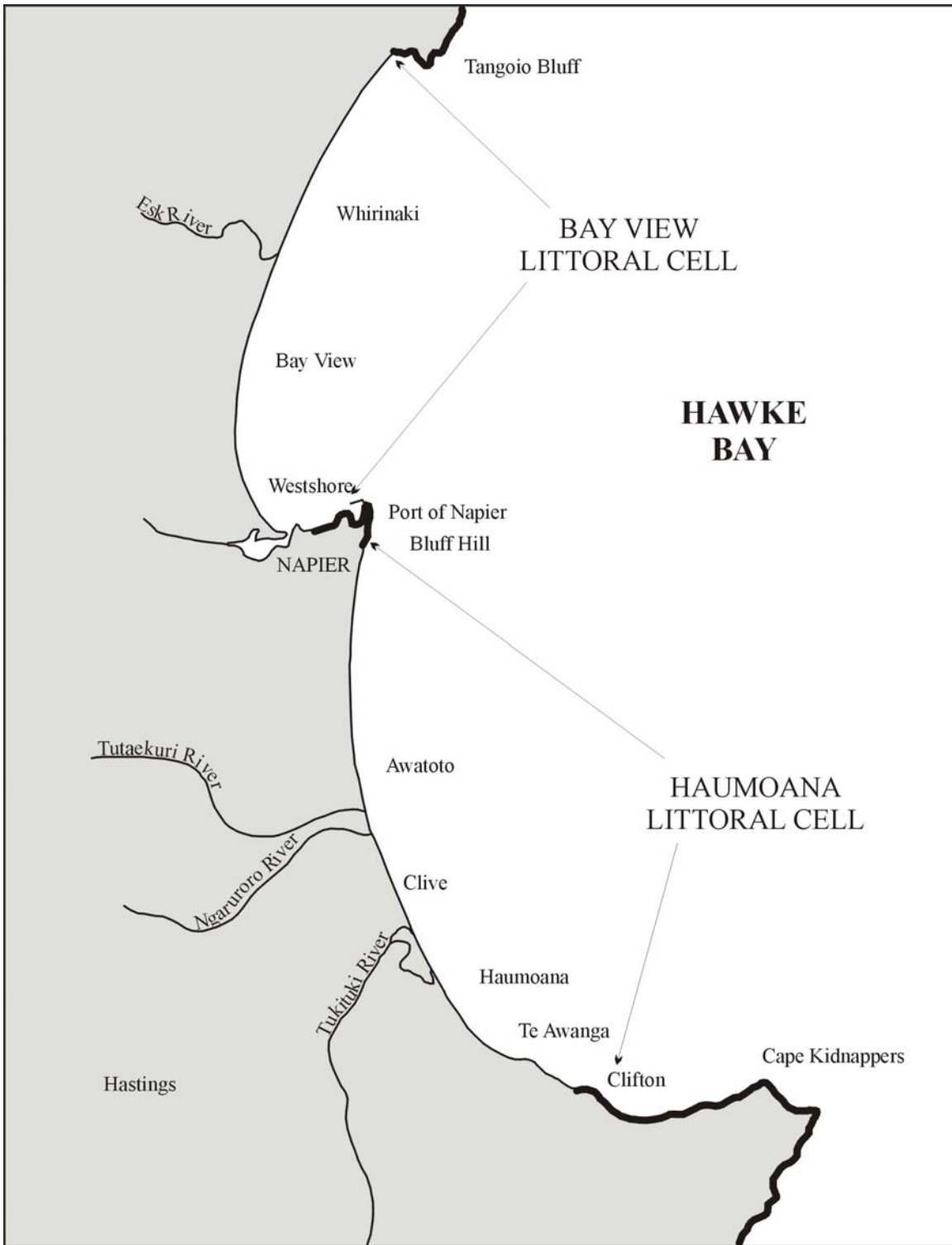


Figure 1-2 The Bay View and Haumoana Littoral Cells, the focus of this review.

A comprehensive review is required of the Hawke's Bay coast in that multiple factors need to be considered in its management, including both natural and human-induced changes. Section 2 examines the tectonic setting of New Zealand, which accounts for the occurrences of major earthquakes in the Hawke's Bay region, including that in 1931 that brought devastation to Napier,

Hastings and Havelock North, and was extremely important to the coast in that the quake altered land elevations relative to the level of the sea, a profound change that still exerts a degree of control on the patterns of shoreline erosion. This tectonic setting has also determined the geology of Hawke's Bay, including the resistant rocks that form headlands such as Cape Kidnappers, and the rocks within the inland watersheds that are being eroded to yield sediments carried to the coast by rivers to form the beaches. In particular, the greywacke rocks found in the Ruahine and Kaweka Ranges have yielded the gravel found in the beaches of the Hawke's Bay littoral cells.

Section 3 provides an historic assessment of the effects humans have had on the Hawke's Bay region, including those by the Maori since their arrival in New Zealand, and especially the environmental changes brought about since the arrival of Europeans beginning in the 18th century. These impacts included deforestation and grazing in the river watersheds, which would have enhanced the erosion and increased the quantities of sediment delivered to the coast, and the countering effect of sand and gravel mining from the rivers and beaches, human activities that have been particularly significant. The potential consequences of harbour construction, initially the Ahuriri moles and then the Port of Napier's breakwater, are of sufficient importance and with a degree of controversy that the entire Section 6 later in this report deals with its history and provides an analysis of the potentially related shoreline changes.

Basic to an understanding of coastal change is the collection and analysis of measurements of the natural processes that ultimately are responsible for that change — the heights and periods of the ocean waves, particularly those generated by the most extreme storms, the runup elevations of the waves when they reach the beaches of Hawke's Bay, the water-level controls of tides and changing sea levels, and the occasional destructive impacts of tsunamis. These processes are reviewed in detail in Section 4, followed by a summary in Section 5 of the beach responses brought about by those processes. As noted above, the beaches of the Bay View and Haumoana Littoral Cells are composed of mixed sand-and-gravel sediments. While there has been a great deal of scientific and engineering research on sand beaches, and to a degree on beaches consisting entirely of gravel and cobbles, there has been comparatively less study of mixed sand-and-gravel beaches that can serve as a guide to the probable responses of the Hawke's Bay beaches during extreme storms, potentially leading to the erosion of backshore properties. Section 5 provides a brief review of mixed sand-and-gravel beaches in general in order to provide a summary of their unique dynamics, followed by a review of the research that has been undertaken specifically on the Hawke's Bay beaches, including the monitoring program that in particular has been important to the management of this coast.

As indicated above, Section 6 reviews the coastal changes produced by the construction of the Ahuriri moles in 1876-1879, and then the Port of Napier's breakwater in 1887-1890. This examination is delayed until late in the report, after reviews of the ocean processes and beach responses have been completed. It also sets the stage for the review in Section 7 of the research that has focused specifically on the Haumoana and Bay View Littoral Cells, where an attempt is made to bring together information from the many reports that have addressed issues such as beach sediment sources, the transport of the sand and gravel along the coast by waves and currents, and the probable causes of erosion in communities such as Te Awanga, Haumoana and Westshore. This review will also examine the past success and sustainability of management activities such as the gravel nourishment program begun at Westshore in 1987, and will consider strategies that potentially could provide increased shore protection and improve the recreational use of the beaches.

An important underlying objective of this review is to assess where there might be missing elements in our understanding of the Hawke's Bay shore, in spite of the considerable number of past studies. While the earlier Sections will have pointed out this missing information, Section 8 provides an overall summary that includes recommendations as to priorities for future investigations.

2 Tectonics and Earthquakes: Their Roles in the Evolution and Erosion of the Hawke's Bay Shoreline

2.1 INTRODUCTION

New Zealand straddles two of the major tectonic plates of the Earth, the Pacific plate and Australian plate, which are colliding and sliding past one another. In the process they generate destructive earthquakes on both the North and South Islands, and alter land elevations including the rapid uplift of the Southern Alps. The Hawke's Bay region is dominated by the collision of these plates, with the Pacific plate giving way and sliding beneath the Australian plate, which includes the land and offshore continental shelf. The forces of collision deform the rocks on the land, folding them and at times causing them to fracture along faults, generating earthquakes. The particularly destructive Hawke's Bay earthquake in 1931 owed its origin to the collision of these tectonic plates, an event that also illustrates the significant land elevation changes that can abruptly occur due to this tectonic activity.

The objective of this Section is to review the tectonics of Hawke's Bay, with a particular focus on the 1931 earthquake and how it altered the elevations of the Bay's shore, and likely accounts in part for continued problems with beach and shore-front property erosion. Important was the abrupt rise of the land that elevated the Ahuriri Lagoon, so that a major portion of it drained into the sea and was converted into land. The increase in land elevations at the time of the earthquake raised the beaches to the north of Napier, up to Tangoio and beyond, whereas to the south at Haumoana, Te Awanga and Clifton, the land subsided so the Bay's water flooded over the beaches, allowing the ocean's waves to directly attack coastal properties. This change in land elevations along the Hawke's Bay shore, relative to the level of the sea, has had a profound effect on the evolution of the coast in the decades subsequent to the 1931 earthquake, and likely is still an important factor in accounting for the erosion being experienced from Haumoana to Clifton, the area of greatest threat for property losses in the Hawke's Bay region.

2.2 THE BIG PICTURE — GLOBAL PLATE TECTONICS

In the 1960s scientists began to develop a fuller awareness of the mobility and impermanence of the Earth's surface. The concept of what has become known as plate tectonics arose primarily from discoveries in the ocean's depths, where chains of mountains and elevated portions of the sea floor were found forming continuous ridges and rises around the Earth. Furthermore, these ridges are characterized by high earthquake activity and unusual rates of heat flow from within the interior of the Earth, evidence for their ongoing tectonic activity. As depicted in Figure 2-1, this chain of ridges is now recognized as the zone where new ocean crust is being formed as molten rock arrives from the interior of the Earth, filling the fracture zone at the spreading ridge where the crust is being pulled apart by slowly moving convection cells in the interior (the Earth's mantle or asthenosphere). The newly formed crust or lithosphere (which includes the "solid" upper portion of the mantle as well as the crust) moves in opposite directions away from the

ridge, giving rise to two areas of new lithosphere. This newly formed lithosphere constitutes a series of tectonic plates that cover the Earth's surface, and in addition to containing the crust of the ocean they also include the land masses, which being less dense than the ocean rocks are in effect "rafted" along within the moving plates.

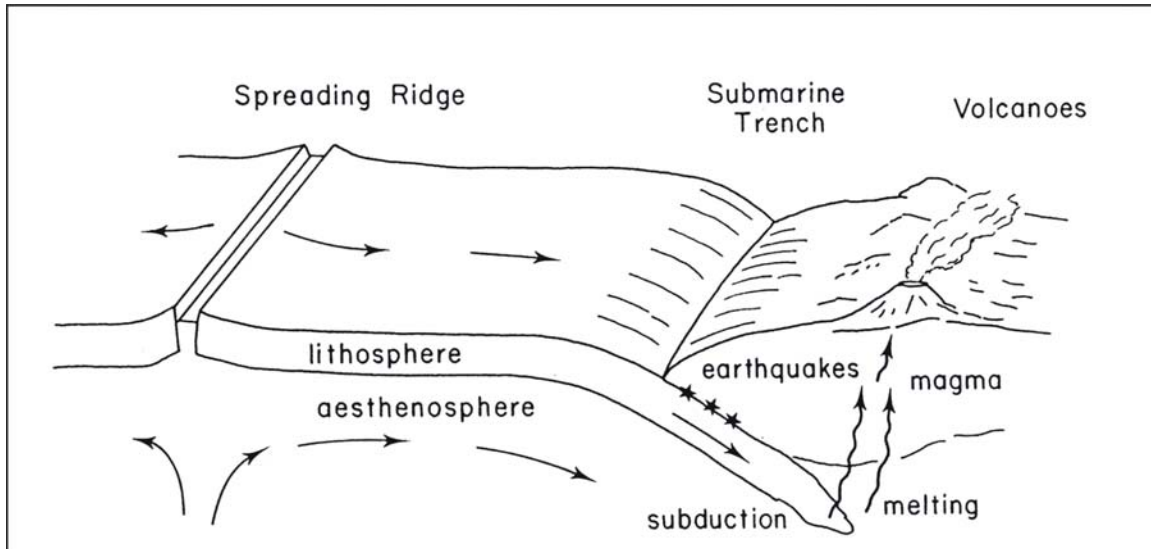


Figure 2-1 The formation of ocean crust at a spreading ridge and its subduction in a submarine trench where the oceanic plate collides with a continental mass. The stars denote earthquakes formed by the plates scraping together during subduction.

Taken alone, the formation of new crust at the ocean ridges would suggest that the surface area of the Earth is slowly increasing with time. This would be the case except that crust is simultaneously being destroyed by a process termed "subduction", also depicted in Figure 2-1. The down buckling of the ocean crust forms a submarine trench, and is the zone where one plate, the ocean crust, descends or is being subducted beneath another plate, which can either be another portion of ocean crust or more typically and as depicted in Figure 2-1, is a portion of a continent that is less dense and therefore refuses to be subducted when the two plates collide. The slab of descending ocean crust scrapes against the underside of the continental mass and creates another zone of earthquake activity, including the most intense quakes experienced on Earth. The subducting plate eventually reaches sufficient depths within the Earth's mantle, heating as it descends, that its rocks remelt to supply lava that emerges at the surface to form a chain of volcanoes that roughly parallels the subduction zone.

This basic pattern is found around the margin of the Pacific Ocean, which has come to be known as the "Ring of Fire" due to the combined earthquake and volcanic activity. The Earth's entire surface is divided into eight major plates, plus five that are significantly smaller. The area of the Pacific Ocean is accounted for mainly by two plates, the Pacific and Nazca plates. Figure 2-1 is actually a simplified depiction of the creation of these two plates at the East Pacific Rise, the spreading ridge to the west of South America, forming the new crust of the Nazca plate that moves at a rate of about 50 mm per year toward South America where it is being subducted off the coast in the Peru-Chile Trench. This collision and subduction of the Nazca plate gives rise to frequent, extremely strong earthquakes, including a magnitude 9.5 quake in 1960 in Chile that is the strongest on record. The associated volcanic activity has created the Andes Mountains. Nearly three quarters of the major earthquakes that occur on the Earth take place along the edges of the Pacific Ocean, where the oceanic tectonic plates are being subducted at deep-sea trenches.

The westward moving plate created at the East Pacific Rise, its eastern edge just appearing in Figure 2-1, is the southern portion of the Pacific plate which spans most of the ocean's area. It dominates the tectonics of New Zealand in that it collides with the Australian plate (sometimes called the Australasian plate or Indian plate) that is generally moving toward the east. This zone of collision straddles New Zealand as shown in Figure 2-2, where it is seen that there are three different tectonic responses to the collision: an east-to-west subduction zone along the east coast of the North Island, a west-to-east subduction along the Fjordland coast of the South Island, and with the stretch between these subduction zones grinding sideways past one another along the Alpine Fault. To the east of the North Island the relative rate of movement of the Pacific plate toward the Australian plate is on average about 50 mm per year, and in usual fashion the denser and thinner Pacific plate is subducted, forming the Hikurangi Trough centered about 160 km east of Napier. In a reversal of this pattern, where the collision of these two plates occurs to the southwest of New Zealand, it is the Australian plate that gives way and is subducted, forming the deeper Puysegur Trench. Along the Alpine Fault where the primary movement is horizontal, the landmass north of the fault is shifting to the northeast relative to that on the south side of the fault. The long-term average rate of movement is about 37 mm per year, though it actually occurs in periodic jumps along segments of the fault at times of earthquakes rather than being continuous. The Alpine Fault has been the source of four major earthquakes approaching magnitude 8 during the past 900 years, when each horizontal "jump" was some 6 to 8 metres; the two most recent of these major quakes have been dated to AD 1720 and 1620, although there have been more recent lower magnitude quakes (Atkin, 1999).

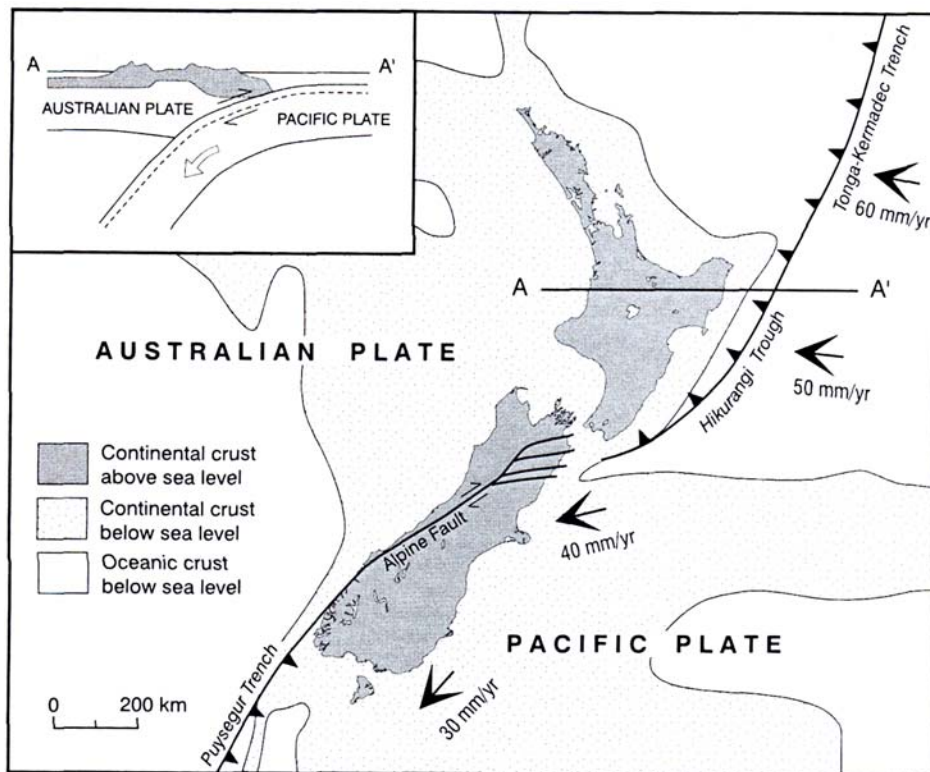


Figure 2-2 The tectonics of New Zealand determined by the collision of the Australian and Pacific plates, with plate subduction occurring at the Hikurangi Trough and Puysegur Trench, and the two plates sliding horizontally past one another along the Alpine Fault. [from Atkin (1999)]

The Alpine Fault is an example of what geologists term a "transform fault", of common occurrence across the Earth's surface linking portions of offset spreading ridges and creating plate edges that link the ridges to the subduction zones. Individual plates are therefore outlined by zones of earthquakes, with relatively shallow near-surface quakes tracing the paths of spreading ridges and following the lines of transverse faults, and then along the subduction zones where the most intense earthquakes are felt and extend to much greater depths below the ground. As depicted in Figure 2-1, the quakes associated with plate subduction follow the path of the descending plate, being shallowest near the trench and having progressively greater depths into the mantle with distance from the trench, with many of the deepest quakes occurring beneath the adjacent continent.

2.3 THE TECTONICS OF HAWKE'S BAY

The tectonics of plate subduction along the Hikurangi Trough east of the North Island exhibits the principal features typically found in subduction zones as depicted in Figure 2-1: an offshore oceanic trench, earthquakes whose depths below the ground progressively increase in the landward direction, and volcanoes that are positioned further inland. However, plate subduction along the Hikurangi Trough is more complicated than generally found, and this is important to occurrences of earthquakes and land elevation changes in the Hawke's Bay region. First, as the Pacific plate is subducted and descends beneath the North Island, it initially does so at a much lower angle than typical of subduction zones. One result of this is that a deep trench is not formed, but instead a shallower depression whose depths have been further decreased by the accumulation of marine sediments. Due to its shallow depths the depression is referred to as a "trough" rather than as a "trench". Still more of a complicating factor is that subduction along the Trough's length is not uniform in either its rate or direction, but instead has a maximum rate of about 60 mm per year north of Gisborne, 50 mm per year offshore from Hawke's Bay, and reduces still further to 30 mm per year where the Pacific plate is being subducted to the east of the Cook Strait and Wellington. Furthermore, these rates of convergence between the two plates are not head on, but instead take place obliquely at varying angles from north to south. The result is an overall slow rotation of the zone of convergence, but more important, there is not a simple compressional collision between the Pacific and Australian plates along the Hikurangi Trough, but instead there is also a horizontal sliding between them with the Pacific plate slipping to the south relative to the Australian plate in a motion that continues along the Alpine Fault, though their respective movements are linked in the North Island by a series of faults located between Blenheim and Kaikoura (Figure 2-2). This combination of collisional convergence and horizontal movement in the Hikurangi Trough is transferred to the landmass of Hawke's Bay, explaining the movement on faults including that which generated the 1931 earthquake. This pattern also accounts for the deformation of the land so it is folded as well as fractured, the combined compression and horizontal movement producing land elevation changes like those that occurred along the coast during the 1931 earthquake.

It is important to distinguish between the earthquakes directly associated with plate subduction and those that occur as a result of deformation and faulting within the continental rocks of the North Island, those within the body of the Australian plate. The former, the subduction earthquakes, occur along the interface of the descending Pacific plate where it scrapes against the underside of the Australian plate, just as depicted by the stars in Figure 2-1 for earthquakes formed by the subduction of the Nazca plate beneath South America. Along the Hikurangi Trough there has not been a major subduction earthquake in historic times, a quake having a magnitude greater than 7. However, in some areas of plate subduction there have been minor earthquakes having progressively greater depths inland toward the west beneath the landmass of the North Island, tracing the path of the subducting plate. This reveals that the Pacific plate initially descends at about a 5° angle immediately west of the Trough, but then steepens to about 25° as it passes beneath Hawke's Bay (Aitken, 1999). While the earthquakes occur at shallow depths near the Trough, below Hawke's Bay they are on the order of 25 kilometres beneath

Napier and 40 kilometres beneath the Ruahine Range further to the west. The deepest earthquakes associated with the subducting Pacific plate are found along the west coast of the North Island at depths of 300 to 700 kilometres below the ground, but the quakes are relatively weak in magnitude and are not generally felt because they also take place at such great depths.

In addition to the subduction earthquakes occurring along the path of the descending Pacific plate, there are numerous shallow crustal earthquakes closer to the surface within the body of the Australian plate, occurring on active geologic faults and resulting from rock deformation in the brittle crust above the subduction zone. The zone landward from the Hikurangi Trough is one of intense deformation due to the compression developed between the colliding plates, producing rock folding and faulting. While some of this deformation can be seen in the rocks exposed at the surface, seismic surveys undertaken by geophysicists tracing the propagation of ground motions yield maps of their underground extensions. A simplified version of what is found beneath the Hawke's Bay area, and along the full length of the east coast of the North Island, is shown in Figure 2-3 from Cole and Lewis (1981) and Berryman (1988). The main feature is a series of northeast trending reverse faults, "reverse" in the sense that with depth down into the ground they slope (dip) toward the northwest and when an earthquake occurs the crust above the fault plane moves upward relative to that below. This pattern is commonly found in zones of plate collision, and such faults are termed "imbricate thrust faults" by geologists, and are directly associated with plate subduction in that as the faults extend downward they merge with the actual zone of plate subduction that is creating them through compression. Hawke's Bay is again a bit unusual in that while there is a degree of reverse movement on these faults at times of earthquakes, there is also a horizontal component to the movement, a "strike-slip" motion, so the ground is simultaneously displaced both vertically and horizontally. Typically in the Hawke's Bay area the horizontal movement is some 5 to 6 times greater than the vertical displacement.

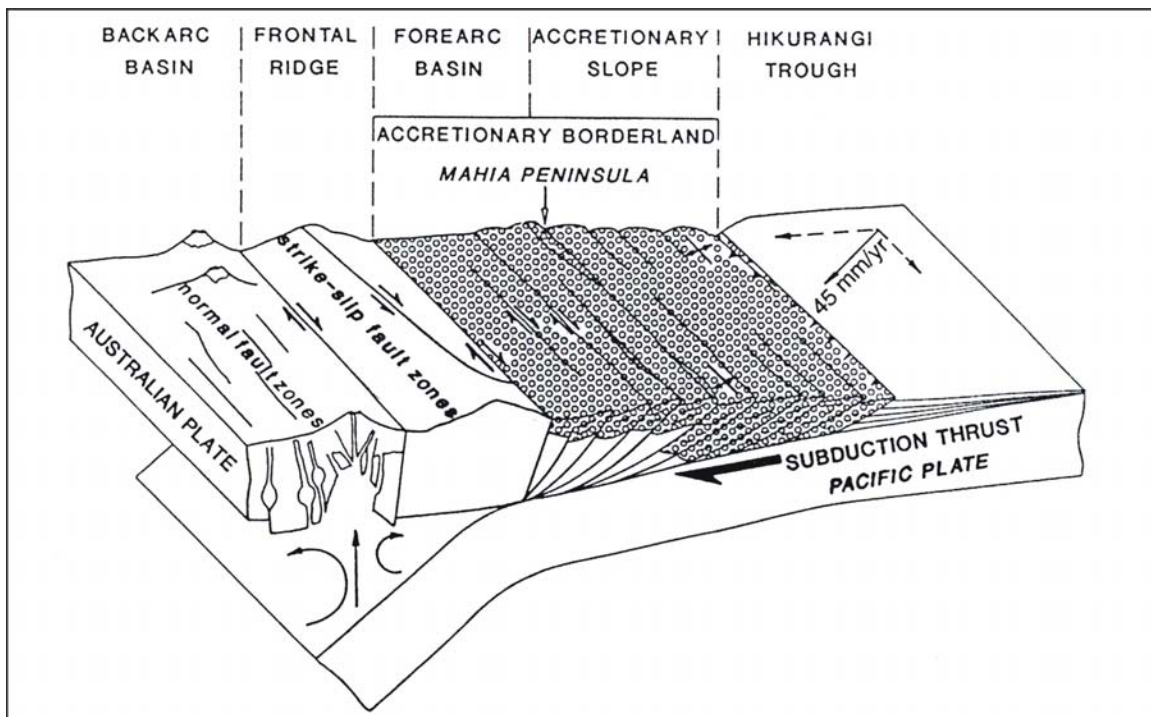


Figure 2-3 The series of reverse faults that dominate the zone of rock compression within the Australian plate due to the subduction of the Pacific plate along the Hikurangi Trough. These faults are found mainly within rocks of the Accretionary Borderland, consisting in part of marine sediments that have been scraped off the Pacific plate as it was being subducted. [after Cole and Lewis (1981) and Berryman (1988)]

The primary area of rock deformation, including the series of reverse faults, defines the Accretionary Borderland, Figure 2-3, which includes an offshore portion (accretionary slope) and a forearc basin on land. In the case of the east coast of the North Island, the rocks found in these zones range from conglomerates to sandstones to mudstones, and even limestones, rocks that were originally deposited as sediments in the ocean atop the Pacific plate during the past 10 million years, but were then accreted to the Australian plate, in effect scraped off the surface of the Pacific plate as it was being subducted. Geologists have documented the presence of reverse faults on land and the accompanying rock deformation, and associated them with historic and pre-historic occurrences of major earthquakes. There are similar features in the offshore, found in seismic surveys by geophysicists undertaken from ships. It was found that the offshore topography of the sea floor consists of a series of depressions and ridges aligned parallel to the Hikurangi Trough. Reverse faults exist along the eastern limb of many of the ridges; at least fourteen reverse faults have been found that cross the width of Hawke Bay.

To the west of the Accretionary Borderland is a Frontal Ridge, Figure 2-3, including the Ruahine Range of mountains that rise to over 1,700 metres elevation. This mountain range has also been uplifted by the subduction process, with the major Mohaka Fault extending along its eastern edge, forming the margin with the Accretionary Borderland. The uplift of the Ruahine Range has taken place at an incredibly rapid rate, having occurred during the past one million years of the Pleistocene. The uplift, estimated by geologists to have been on the order of 2,000 metres, was offset by the processes of erosion due to the high precipitation, erosion that is evident in the large quantities of coarse river gravels that have been shed from the rocks contained in the Range. The Ruahine mountains contain much older rocks than the Borderland, including the resistant Mesozoic greywacke whose erosion yields cobbles and gravel, which are then transported by rivers flowing toward the east, reaching the coast where they constitute the most important sediment component of the modern-day Hawke's Bay beaches. The Heretaunga Plains is a tectonic depression that has developed during the past 1.5 million years between the compressional folds within the Accretionary Borderland. In the Hawke's Bay area the changing courses of the Tukituki, Ngaruroro and Tutaekuri Rivers have deposited their loads of cobbles, gravel and sand, building up the level of the Plain by as much as 1 kilometre of accumulated sediment atop the basement marine sandstones and limestones.

Along the western edge of the Frontal Ridge there is a rapid descent in elevation into the Taupo Volcanic Zone, Figure 2-3, a narrow north-to-south basin that extends from White Island in the Bay of Plenty, 300 kilometres south past Rotorua and Lake Taupo to Mt. Ruapehu. This Zone is also associated with plate subduction at the Hikurangi Trough, which is pulling both the Borderland and Frontal Range toward the Trough to form a Back Arc Basin, stretching and thinning the crust of the Taupo Volcanic Zone so it is only 8 to 10 kilometres thick, less than half the thickness of the crust to the east. The Volcanic Zone has developed within the past 2 million years, and is presently widening at an average rate of 8 to 10 millimetres per year (Aitken, 1999). In contrast to the compressional Accretionary Borderland with its reverse faults, the Taupo Volcanic Zone has normal faults where the crust above the fault plane drops down at the time of an earthquake, the crust having experienced tension rather than compression. Of course the hallmark of this Zone is its volcanoes and associated hydrothermal activity, in part the result of the thin crust but also the melting of the subducted Pacific plate, yielding magma that moves upward to the surface to feed the volcanoes, just as shown in Figure 2-1 for the Andes volcanoes of South America. The volcanic activity of the Taupo Volcanic Zone has contributed to the upward growth of the Heretaunga Plains in Hawke's Bay, whenever ash emanated from the volcanoes drifted in that direction. The most recent major eruption of Taupo occurred about 1,800 years ago, resulting in the rapid accumulation of pumice up to 10 metres thickness on the Plains, so this contribution has been significant.

It is evident from this brief review that different assemblages of landscape features are found in various parts of the study region as characterized by the tectonic zones defined in Figure 2-3. These variations are further examined by Berryman (1988) who documented the changing geomorphology along a transect across Hawke's Bay and how it relates to the tectonics of the

region, while the accompanying paper by Kamp (1988) examined the alongcoast differences in the geomorphology as a response to the different rates of plate subduction. The rates of landscape evolution were concluded to be unusually rapid as a result of the tectonic setting, the generally high precipitation, and the mid-latitude location of Hawke's Bay that has exposed it to the effects of climate fluctuations during the Pleistocene. For example, the high rates of regional uplift of the land north of Tangoio to Wairoa are reflected in the downcutting of the major rivers such as the Mohaka, producing deep gorges. The resulting high relief of the land and occurrences of major earthquakes has resulted in the development of large, deep-seated landslides in that region. Two major landslides have dammed lakes: Lake Tutira about 30 kilometres north of Napier, and Lake Waikaremoana 45 kilometres northwest of Wairoa (Adams, 1981; Berryman, 1988). The Waikaremoana slide has a volume of 1.9×10^9 cubic metres, and involved the movement of Miocene siltstone rocks about 2,200 years B.P. ("before the present"), presumably initiated by a major earthquake in the Accretionary Borderland.

Together with the north to south decrease in the rates of plate convergence along the length of the Hikurangi Trough, there are regular variations in the frequencies and intensities of earthquakes. The study by Reyners (1998) deployed a large number of portable seismographs during 1993-95 to better document movements on the subduction zone where the descending Pacific plate scrapes beneath the Australian plate. He concluded that at present the subduction zone along the Trough at its southern-most end, where it dips beneath Marlborough on the South Island, is actually locked; that is, it has not been slipping to create subduction earthquakes, although quakes have been experienced in the overlying crust due to the continued compression and shear between the plates. As summarized in Figure 2-4, toward the north along the Trough the coupling between the two plates progressively weakens so movement and earthquakes are more frequent. East of Wellington the coupling is still quite strong, which means that while subduction earthquakes there are relatively infrequent, they can occur and when they do they may have high magnitudes because there is a long period of time for the energy to be stored in the temporarily locked subduction zone; the longer the period between earthquakes, the greater the stored energy and the higher the magnitude of the subduction earthquake when it eventually does occur. Under Hawke's Bay the plate coupling is moderately weak, while it is still weaker at the north end of the Trough and beneath East Cape so earthquakes there are more frequent, but generally would have lower magnitudes than those east of Wellington.

Reyners (1998) has made estimates of the potential magnitudes of subduction earthquakes based on the areas of the locked plates and rates of plate convergence. He estimated that east of Wellington, when the locked plates finally do rupture, it would yield a magnitude 8.0 earthquake. In the other extreme, at East Cape on the north end of the Trough, the estimated magnitude is reduced to 6.9. Interpolating his estimates, at Hawke's Bay a subduction earthquake might be expected to have a magnitude of 7.0 to 7.5. The greatest subduction earthquake would occur if the entire 500 kilometres of plate boundary between the Cook Strait and East Cape were to rupture in a single event; Reyners (1998) estimated that this would produce a magnitude 8.3 quake. While these predicted magnitudes of subduction earthquakes are generally smaller than historic earthquakes that have occurred by faulting within the overlying Australian plate, this does not necessarily mean that they will be less destructive. While the ground shaking produced by even the most intense subduction quake might be no more intense than the peak shaking of a magnitude 7.0 earthquake in the overlying plate, it could be expected to last longer and with the motions themselves extending to longer period "rolls" of the ground, the type of motion that potentially can result in the greatest damage (Reyners, 1998). Another factor, while the portion of the locked plates along the east coast of the North Island is narrower than found at most subduction zones, it represents a significant hazard since it lies directly beneath the land, in contrast to most other subduction zones where the locked region is located offshore.

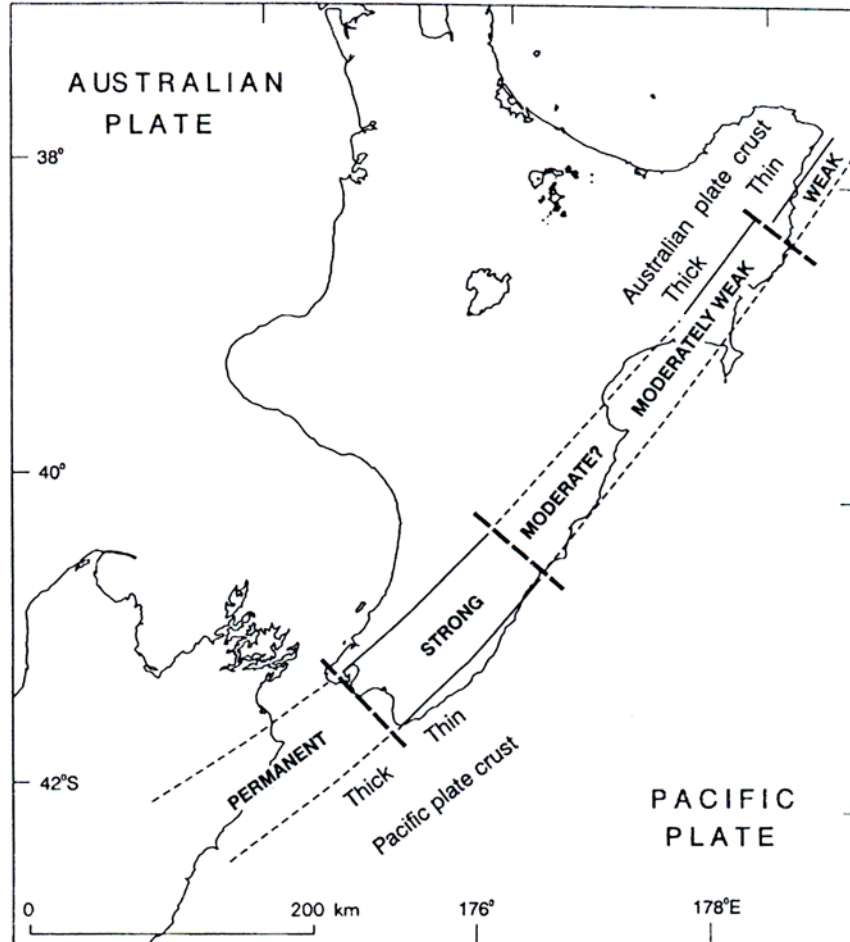


Figure 2-4 The degree of coupling between the Pacific and Australian plates along the Hikurangi subduction zone, the weaker the coupling the more frequent the occurrence of subduction earthquakes but the lower their magnitudes when they do occur. [from Reyners (1998)]

The Wellington to Hawke's Bay stretch of the Accretionary Borderland is the region having the most active deformation with strong near-surface earthquakes due to the colliding plates, the activity being greatest there because the deformation of the crust has to make up for the strong coupling at the subduction zone, with it being locked for long periods of time. The strongest historic earthquake was the magnitude 8.1-8.2 Wairarapa event in 1855 that resulted in major damage to Wellington (Grapes, 2000). Next in strength was the magnitude 7.8 Hawke's Bay earthquake in 1931. Each of these events involved faulting within the Australian plate above the subduction zone, providing a demonstration of what deformation within the Accretionary Borderland is capable of in terms of storing a significant amount of elastic strain energy and then releasing it suddenly as a major earthquake. With this area being particularly important to plate subduction and associated earthquake activity, it has received the greatest research attention by geologists who have studied the patterns of ongoing rock deformation and faulting, in order to learn more about the pre-historic occurrences of earthquakes that may have had even greater magnitudes than the historic quakes (e.g., Kelsey et al., 1995; Beanland et al., 1998).

An interesting study of the frequency of pre-historic movements on a fault, with each movement having been associated with an earthquake, is that of Froggatt and Howorth (1980) who analyzed the history of movement on the Wairarapa Fault where it crosses Lake Poukawa southwest of

Hastings. The fault at that location was last active at the time of the 1931 Hawke's Bay earthquake, although it was not the source of that earthquake. At that time a surface fracture known as the Poukawa Shear formed (Henderson, 1933), with a maximum vertical displacement of 0.5 metre and horizontal (right lateral) movement of 2.0 metres. Surrounding the lake's edge are peat deposits whose accumulation history spans thousands of years. Within the peat are four layers of volcanic tephra (ash) derived from eruptions in the Taupo region. The ages of these ash layers were established by radiocarbon dating of peat collected from immediately above and below each ash layer; the ages ranged from 2039 ± 60 years B.P. to 6365 ± 145 years B.P. ("before the present"). In addition, there are two layers of pure calcium carbonate within the peat, analogous to the carbonate that is presently accumulating on the lake bottom, and must have been deposited during intervals when the lake was significantly larger. A cross-section based on a series of bore holes drilled down through the peat revealed that the ash and carbonate layers are displaced vertically where they cross the Wairarapa Fault, with the degrees of offset ranging from 0.56 to 1.51 metres, systematically increasing with the age of the layer — the older and deeper the layer, the greater the number of earthquakes and fault movements it has experienced, and hence the greater the cumulative offset. A graph of the degree of offset versus the layer's age yielded a linear trend indicating that the long-term average rate of vertical displacement on the fault has been 0.2 mm/year. In that the horizontal movements on faults in this region are typically some 6 times the vertical movement, Froggatt and Howorth (1980) suggested that the long-term average horizontal movement on the Wairarapa Fault has been at least 1.2 mm/year. While these are the long-term averages, the movement would actually have involved discrete events at times of major earthquakes, not a slow creep at the above rates. Froggatt and Howorth therefore undertook a series of step-function analyses, and the best-fit agreement with the measured offsets led them to conclude that eight steps (earthquakes) have occurred during the past 6,500 years, representing on average an earthquake every 800 to 900 years for this site.

The study of most immediate interest to the history of earthquakes in Hawke's Bay and associated land-elevation changes is that of Hull (1986), who investigated the stratigraphy of sediments deposited on the western margin (near Poraiti) of the Ahuriri Lagoon. The stratigraphy exposed by excavation, Figure 2-5, shows that at depths on the order of 4 metres below the ground's surface (3.6 metres below the present mean sea level) a sandy silt containing roots is present, interpreted as having been deposited on land. Immediately above that layer is a deposit of coarse volcanic ash having a variable thickness; it was identified as the Waimihia Lapilli dated at about 3,500 years B.P. The stratigraphic section is dominated by a peat that contains several tree stumps that are still in their standing positions, surrounded by a forest litter of well-preserved twigs and leaves. Upward in the section the peat is abruptly replaced by a gray-brown silty sand containing abundant articulated shells of estuarine organisms, clear evidence that the former marsh and forest had been inundated by the water of the Ahuriri Lagoon. Radiocarbon dates indicate that the peat deposition and forest had existed up to about 1,750 years B.P., with flooding by the Lagoon having occurred at about 500 years B.P.; the water remained until this area was uplifted by the 1931 Hawke's Bay earthquake. Two sets of human bones, Maori burials, were found near the top of the peat deposits, and were dated at 481 ± 58 years and 551 ± 58 years B.P., roughly when the area was inundated by the Lagoon.

Hull (1986) interpreted this stratigraphy as having been produced mainly by subsidence of this area (and probably most of the Lagoon basin) spanning at least the past 4,000 years. However, most of this subsidence would have occurred between 3,500 years B.P. and 1,750 years B.P., the period of peat accumulation, that is, at an average rate of 4.6 metres per thousand years. The hiatus in peat growth between about 1,750 years B.P. and 500 years B.P. was interpreted by Hull (1986) as possibly having been the result of tectonic uplift, or at least stability. The inundation of the area by the Ahuriri Lagoon in about 500 years B.P. may have been the result of renewed tectonic subsidence, or possibly a barrier such as a beach ridge had been breached on the western shore of the Lagoon, permitting the inundation without necessarily indicating renewed subsidence.

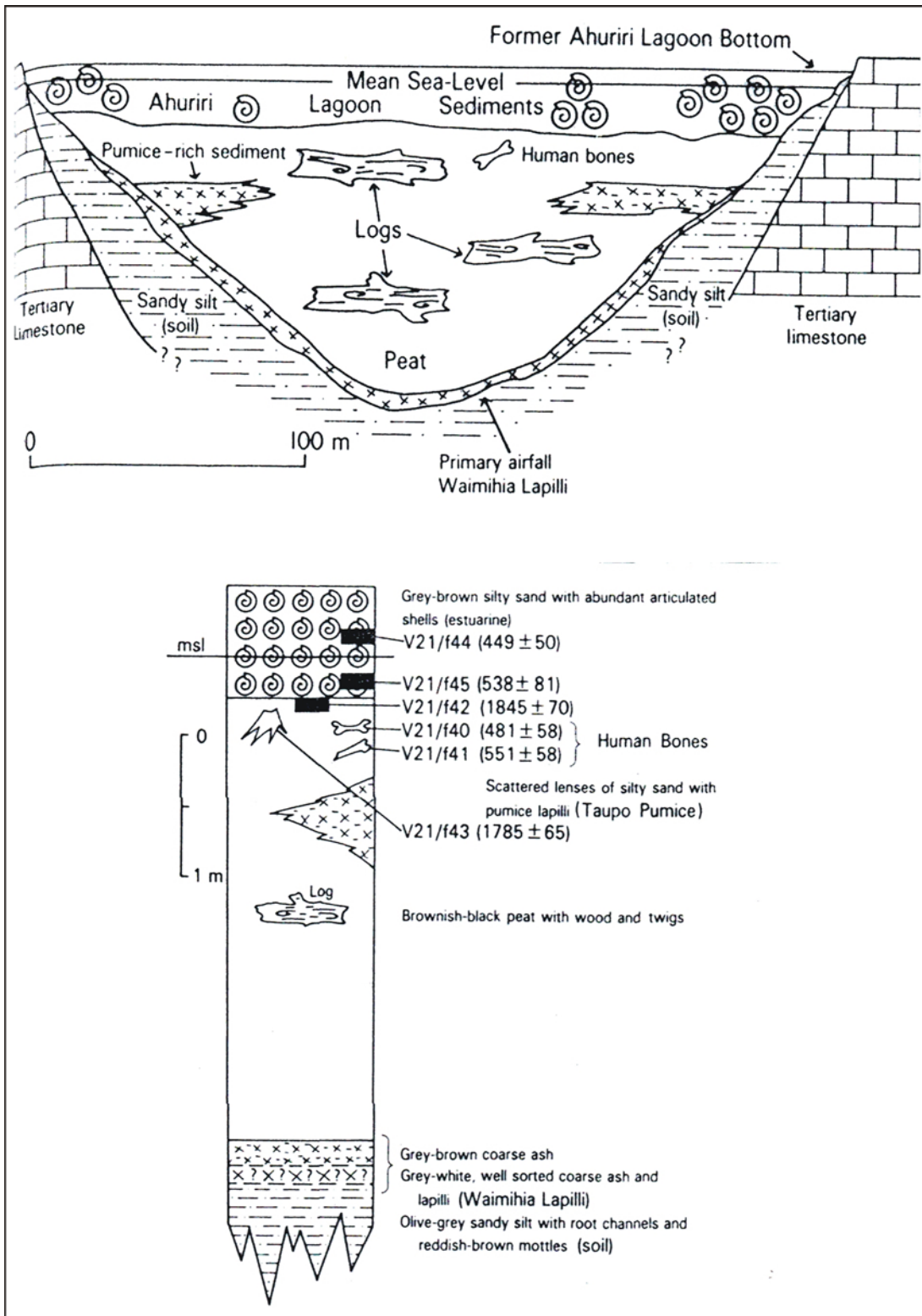


Figure 2-5 (Upper) Schematic cross-section of the peat-filled valley on the western shore of the Ahuriri Lagoon. (Lower) The stratigraphic section of the sediment deposits, and radiocarbon dates of organic material and human bones. [from Hull (1986)]

As will be reviewed below, the 1931 Hawke's Bay earthquake resulted in nearly a 2 metre uplift of this region, resulting in a significant portion of the Ahuriri Lagoon draining into the sea and its conversion to dry land and marshes. The general view is that this event represented a distinct shift from the subsidence that had prevailed prior to that earthquake, with the results of Hull (1986) cited as the primary evidence. However, as discussed above, he actually concluded that most of the subsidence took place prior to 1,750 years B.P, and that the hiatus in peat growth between about 1,750 years B.P. and 500 years B.P. indicates either a prolonged period of stability or a degree of uplift. From this alone, we cannot be certain as to whether the next earthquake will produce additional uplift, or there will once again be subsidence of the Ahuriri region.

Of possible relevance to this question is the fact that the 1931 Hawke's Bay earthquake did not occur in isolation. Between 1929 and 1934 there were five earthquakes having magnitudes greater than 7, an unusual cluster of significant quakes, all having occurred along the east coast of the North Island (Aitken, 1999). It may be that this cluster reflected a change in response of the rocks within the Accretionary Borderland to the compression and shear produced by plate subduction at the Hikurangi Trough. Following that cluster of significant quakes in the 1930s, there has been a prolonged period of relative inactivity, so it remains uncertain what future quakes will produce in terms of magnitudes and associated land elevation changes.

The past predominance of land subsidence in the Hawke's Bay region was centered over the Ahuriri Lagoon and south to Hastings, while other areas demonstrate the primary occurrence of uplift spanning thousands to millions of years. The area to the north up to Wairoa contains rocks of Plio-Pleistocene marine sediments now found at elevations up to 500 metres above sea level, providing clear evidence for a net tectonic uplift spanning a least the past 2 million years (Hull, 1990). Plio-Pleistocene sediments are also found offshore at depth beneath Hawke Bay, indicating net subsidence during the same span of time. Water wells at Hastings have penetrated estuarine sediments at a depth of 10 to 16 metres below the present sea level, sediments that are on the order of 6,500 years old, again indicating pervasive subsidence, just as occurred there during the 1931 Hawke's Bay quake (Gibb, 1980). The interpretation by geologists of such evidence is that compression of the Accretionary Borderland by plate subduction has broadly folded the crust into anticlines and synclines, respectively representing net upward and downward movements of the crust. As such, the region extending from the Ahuriri Lagoon to Hastings is central to a developing syncline, while the area to the north where the Plio-Pleistocene sediments have been uplifted is one anticline, with another found to the south in the Cape Kidnappers area.

Further evidence for this broad folding of the crust, as well as the effects of faulting, is derived from the study of elevated ancient beaches and wave-cut terraces found on the flanks of Cape Kidnappers and especially on the slopes of the Mahia Peninsula, respectively at the south and north ends of Hawke Bay. An investigation of the uplifted benches/terraces at Cape Kidnappers by Hull (1987) indicated rapid uplift of up to 5 metres since about 2,300 years B.P., the Cape being on the eastern flank of the north-south trending Kidnappers Anticline. This uplift of Cape Kidnappers and its anticline may therefore correspond to the subsidence of the Ahuriri Lagoon as part of the adjacent syncline, the subsidence recorded by the peat accumulation between 3,500 years B.P. and 1,750 years B.P. found by Hull (1986) on the western shore of the Lagoon.

A spectacular series of "stair step" marine terraces covered by ancient beach deposits is found on the flanks of the Mahia Peninsula, recording a long history of significant uplift. The most detailed studies of the Mahia terraces are those carried out by K. Berryman (Berryman et al., 1989; Berryman, 1993a, 1993b). Each terrace platform represents a period of relative tectonic stability during which time waves cut into the rocks of the Peninsula at the intertidal level. It is the rise between successive terraces that provides a record of a tectonic event, with the change in level likely reflecting the magnitude of the earthquake. Individual amounts of uplift between successive terraces range from about 1 metre to 4 metres, suggesting that there has been a significant range in earthquake magnitudes. Barryman's extensive program of radiocarbon dating of intertidal shells found in the beach deposits showed that the terraces located in widespread

parts of the Peninsula cluster into five distinct ages: 250, 1600, 1900, 3500 and 4500 years B.P. He concluded that the stair-step series of terraces is the product of the movement on a major reverse fault, the Lachlan Fault, which parallels the Hikurangi Trough in the offshore along the length of the east coast, crossing Hawke Bay as well as extending north to beyond Gisborne. Immediately landward of this fault but still in the offshore is the crest of the Lachlan Anticline, so the long-term uplift of the Mahia Peninsula is due to its position on the western flank of that anticline, with the movement recorded in the episodic uplift of the terraces and their beach deposits. While the uplift is not directly associated with subduction earthquakes, even though the Mahia Peninsula is the closest point of land on the North Island to the Hikurangi Trough, it is again the intense deformation within the Accretionary Borderland, and specifically movement on the Lachlan Fault and folding of the Anticline, that is responsible for the terraces on the Mahia Peninsula.

Berryman (1993a) estimated that if the entire length of the Lachlan Fault (about 150 kilometres) were to rupture in a single event, the magnitude of the resulting earthquake would be on the order of 7.5 to 8.0. He further suggested that the ancient earthquakes recorded in the terraces of the Mahia Peninsula must have been within that range of magnitudes, evidence that there has been a long history of major earthquakes in the Hawke's Bay region that were comparable to the 1931 earthquake. As noted above, the range of terrace uplift distances suggests that there has been a corresponding range of earthquake magnitudes, and that small uplift events are followed by shorter intervals of stability than are the large uplift events. Of concern, the youngest terrace that formed about 250 years B.P. produced a relatively small uplift, suggesting that in the not-too-distant future there will be another earthquake along the Lachlan Fault. With this Fault and Anticline located directly offshore from Hawke's Bay, there is the potential for direct earthquake damage and also the generation of a destructive tsunami that would impact its shore.

A new tool has recently come into use to measure the movement of the Earth's tectonic plates, or to measure local crustal movements like those occurring within the Accretionary Borderland along the east coast of the North Island. This involves use of the Global Positioning System (GPS) that relies on satellites to establish positions on the surface of the Earth with millimetres accuracy, and how those positions change even during the span of a year, a degree of accuracy that can detect the slow horizontal movements of the tectonic plates. While this technique has strong potential to improve our understanding of crustal movements in Hawke's Bay, the applications specific to this area have thus far been limited, at least in terms of published results. Aitken (1999, p. 50-52, figs. 11 and 12) reviews the GPS application to New Zealand as a whole, where the crustal movements are being measured at 260 stations. She shows the velocity vectors of the motion relative to the central Australian plate, based on the measured shifts in the GPS stations from 1996 to 1999. As expected, the results show major spatial variations in velocities across the Hikurangi Trough offshore from Hawke's Bay, and also a variation in the rates of movement within the Accretionary Borderland, the velocities generally being directed toward the southwest but with progressively decreasing rates inland. Wherever there is a change in velocity or in the direction of movement, this reflects rock deformation and the development of accumulated stress in the rocks, or records the movement on faults to release that stress if an earthquake has occurred.

The one published study that has applied GPS data to the North Island subduction zone is that of Larson and Freymueller (1995), based on survey results from 1991 to 1994. They found that while there is no evidence for significant horizontal deformation within the Australian plate on the western half of the North Island, Wellington has moved at a rate 20 ± 5 mm/year west-southwest relative to that stable portion of the Australian plate, reflecting its position within the Australian-Pacific plate boundary zone affected by subduction, a velocity that lies midway between the respective relative velocities of the two plates.

In the future we can expect a great deal more information on the horizontal crustal movements throughout New Zealand, providing an improved understanding of the deformation that can lead to major earthquakes. Unfortunately, it will take a much longer period of GPS measurements to

detect the vertical movements of the crust. While the GPS surveys are able to detect the rapid horizontal movements of the crustal plates, the vertical movements are generally very small, unless an earthquake of significant magnitude has occurred. For example, as will be discussed below, the vertical changes in elevations within the Hawke's Bay region at the time of the 1931 earthquake were on the order of 2 metres, the maximum having been 2.7 metres; such large elevation changes could easily be detected by GPS surveys. However, there can be much smaller annual changes in land elevations having a tectonic origin, sufficiently small that it would take at least a decade or two of GPS elevation measurements to confidently establish a net rate of change. This is unfortunate in that it is the vertical movements that are of particular relevance to the evolution of the coast on a time scale of decades to centuries (this will be discussed in Section 4). Where land elevation changes have been documented on coasts that are being affected by plate subduction (for example, the coast of Oregon), the measurements available thus far have been derived from repeated conventional ground surveys rather than with GPS data. As shown schematically in Figure 2-6, the results document that during the quiet aseismic periods between earthquakes, the accumulation of stress between the locked plates produces a slow uplift of the inland continental crust, while the crust closer to the subduction zone is pulled downward by the descending ocean plate. When an earthquake occurs the crustal movements are suddenly reversed; inland, the crust abruptly drops down by a metre or more, while that close to the subduction zone is raised. This cycle of ups and downs of the coast, spanning decades to centuries, can have a profound effect on the patterns of coastal erosion, as will be discussed below and at greater length in Section 4. At present we can only guess that such tectonically controlled changes in land elevations may be occurring along the shores of Hawke's Bay, but that hopefully in the future the GPS surveys will provide data on their directions (up or down) and magnitudes, affecting the relative rate of sea-level change.

2.4 THE 1931 HAWKE'S BAY EARTHQUAKE

Being located within the Accretionary Borderland of the Hikurangi subduction zone and therefore experiencing intense tectonic deformation, Hawke's Bay is one of the most earthquake prone areas of New Zealand. It has a history of at least nineteen earthquakes felt since settlement by Europeans in 1840 (Aitken, 1999). Of those, five had magnitudes of 7.0 or greater, with the magnitude 7.8 of the 1931 Hawke's Bay earthquake having been the strongest. The seismic energy released by an earthquake of that magnitude is greater than the energy of a 50-megaton hydrogen bomb detonated underground. The main shock was followed by a number of weaker aftershocks. Shallow earthquakes are particularly prone to occurrences of aftershocks, and the strongest may approach the main quake in magnitude. This was the case for the Hawke's Bay earthquake, as the most energetic aftershock occurred ten days later with a magnitude of 7.3. The magnitude of an earthquake is a measure of the released energy at its source, but the energy of the ground motions is reduced as it spreads out with distance from the quake's origin. The energy as measured at a particular location distant from the source is called the "intensity", which is assessed using the Modified Mercalli Intensity Scale as a measure of the degree of shaking and the resulting damage experienced at that site on the Earth's surface. The Mercalli scale is recorded with Roman numerals to distinguish it from the magnitude of the energy at the quake's source. On the Mercalli scale the original 1931 Hawke's Bay earthquake earned a ranking of X, which denotes "general panic, wooden buildings seriously damaged, landslides widespread, and rivers slop over banks" (Aitken, 1999, p. 33). The strongest aftershock ten days later was VII on the Mercalli scale: "General alarm, difficult to stand up, damage to weak masonry buildings, small slides and rock falls". The resulting damage throughout the Hawke's Bay region is recounted in the recent book *Quake* by Matthew Wright, which contains a number of historic photographs.

The first in a team of scientists reached Hawke's Bay about 12 hours after the earthquake, with others arriving a few days later. Their objective was to undertake a reconnaissance of the earthquake damage and landscape changes, with their reports having appeared as a series of

papers in a 1933 issue of the *New Zealand Journal of Science and Technology*. The epicenter of the earthquake was determined by Bullen (1938) to have been 32 kilometres northwest of Napier, with the focus having been at a depth of 15 to 20 kilometres beneath the surface, that is, within what is now recognized as the Australian plate above the subduction zone of the Pacific plate. Henderson (1933) provided detailed descriptions of the surface faulting, areas of uplift and subsidence, and position changes derived from ground surveys. Marshall (1933) examined the coastline between Cape Kidnappers and Wairoa, and estimated the amount of land-elevation change from tide-gauge data and pre-earthquake high-tide levels.

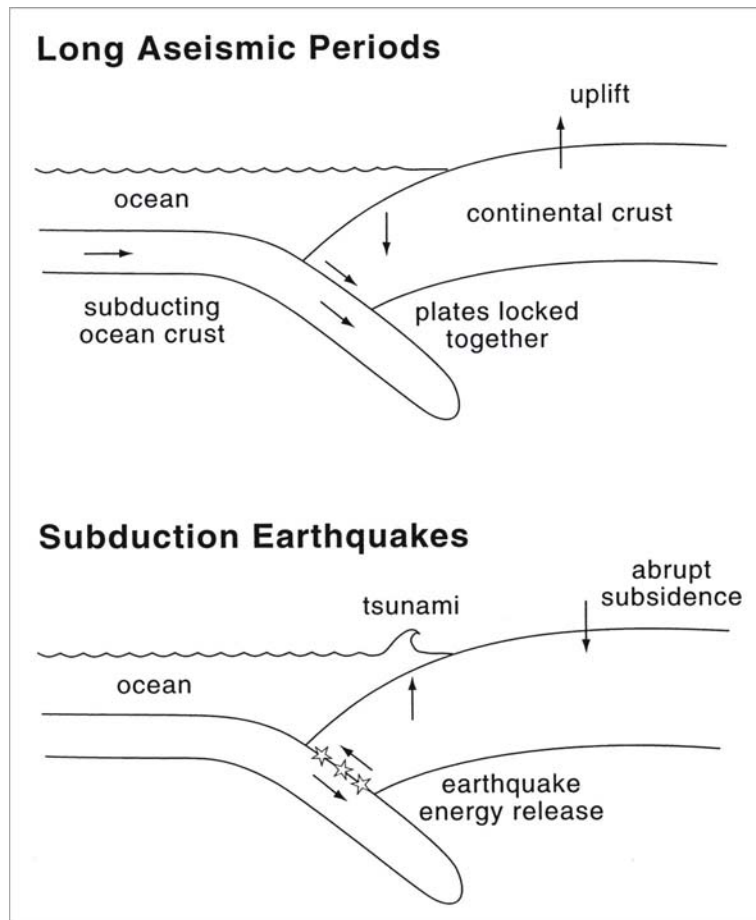


Figure 2-6 The contrasting land-elevation changes that occur during the aseismic period between earthquakes when the plates are locked in the subduction zone, with those that abruptly occur when an earthquake takes place, releasing the accumulated strain of the locked plates.

The 1931 Hawke's Bay earthquake is typical of those that occur on the imbricate faults within the coastal Accretionary Borderland of the Australian plate, that is, it took place on a reverse fault that dips steeply to the northwest, but also had a horizontal strike-slip motion. Hawke's Bay has at least twenty-two known active faults on land and in the immediate offshore, with five being capable of producing strong earthquakes comparable to that experienced in 1931. It is believed that the 1931 quake occurred due to movement on the Napier-Hawke Bay Fault.

It was immediately apparent at the time of the earthquake that significant changes had occurred in land elevations. In particular, the uplift of the Ahuriri Lagoon caused it to rapidly drain into the sea, permanently reducing its area. That event was described by Marshall (1933, p. 80):

At Port Ahuriri the tide had just begun to ebb. It has been stated by the Harbourmaster (Captain White-Parsons) that for some minutes the ebb maintained its ordinary flow, but it soon gathered force, and within a few minutes flowed with an estimated velocity of fifteen miles per hour, and this was maintained until well past the proper time of low water, and even past the next period of high water.

Marshall (1933, page 85) provides a map that shows the aerial extent of the uplifted floor of the Lagoon, and estimated that the total area of new dry land was 3,170 acres or 5 square miles.

Marshall's inclusion in the reconnaissance team was fortunate in that he had just completed studies of the Hawke's Bay beaches, published in 1927 and 1930 [this work will be reviewed in Section 5]. His report on the effects of the earthquake on the beaches focused primarily on their elevation changes relative to mean sea level, based mainly on the altered high-tide strand lines. His observations led to the conclusion (Marshall, 1933, p. 83):

The upraised condition of the shore became gradually more pronounced as Napier was approached, so far as could be judged by the position of the line of detritus deposited by the wash of the waves. Close to the eastern side of Scinde Promontory there is an outlying reef of rocks which was rarely uncovered by the water before the earthquake, but afterwards it was awash even at high water.

Of special interest was the degree of uplift of the Port's breakwater and the entrance to the Ahuriri Lagoon:

The rise in level at the breakwater tide-gauge was 6 ft., and this appears to have been uniform throughout its extent. Calcareous seaweeds were growing generally on the surface of the piles of the wharf that extended northwards from the shoreward part of the breakwater. After the elevation these became bleached by the sun and indicated clearly the previous sea-level. Between the breakwater and the entrance to Port Ahuriri the effect of the 6 ft uprise was most evident. The shore here had a wide apron of limestone boulders which had been shed from Scinde Promontory. Beneath the low-tide level these had become coated with calcareous algae, which died when exposed after the elevation. The remains of these soon bleached, and Plate II shows the extent of new foreshore exposed at low water.

Marshall (1933) further noted that the tide gauge opposite the Harbour Board's office in the Ahuriri Lagoon had experienced an uplift of 5 feet. He continued his observations of the extent of beach uplift further to the north, finding that from Ahuriri to Petane (Bay View) the uplift continued to be about 6 feet, but then gradually increased to approximately 6 feet 6 inches at Tangoio, to 9 feet at Moeangiangi, but then two miles further north near Old Man's Bluff the amount of uplift rapidly decreased.

Henderson (1933) extended the assessment of the land elevation changes accompanying the 1931 earthquake by compiling earlier land surveys and comparing them with post-quake re-surveys. He relied on two survey series (p. 61):

The Public Works Department and New Zealand Railway have relevelled the railway from Wairoa in the north to Opapa, twenty-eight miles south of Napier, a total distance of nearly one hundred miles, and have connected the readings to the new mean sea-level as given by tide gauges at Napier and Waikokopu. . . The Hawke's Bay Rivers Board have constructed stop-banks for miles along the lower channels of these streams [the Tukituki, Ngaruroro and Tutaekuri Rivers], and in the course of this work carried out extensive levelling and established bench-marks along the levees and elsewhere.

Henderson (1933) provides a map of the region south of Napier, centered on Hastings and the Ngaruroro and Tukituki Rivers, and on it he plotted the re-surveyed land-elevation changes, those extending along both the railway line and up the rivers. Another diagram (p. 62) graphs three cross-sections of land-elevation changes across the Heretaunga Plain, with each graph showing uplift to the northwest and down-drop of the land to the southeast. Plate X in Henderson's paper shows the results of the re-leveling of the railway from Westshore to Waikokopu, a distance of 94 miles. In this graph the pre-earthquake elevations are taken as the datum, and included are the results of two re-surveys, one carried out between June and October 1931 and the second in March and April 1932. An interpretation of the results is confusing since the surveys followed the somewhat circuitous route of the railway line, which first follows the coast from Westshore to Riverlea near the mouth of the Esk River, then turns inland in an east-west course, and finally proceeds northward. However, of particular interest on this graph is the documentation that during the four to five months between the two re-surveys following the earthquake, there was a degree of land subsidence, the amount having been greatest where the uplift was initially the most, while areas like that around Wairoa that had subsided at the time of the earthquake, sank a little further; on average, the amount of subsidence was typically 10 to 15% that of the initial uplift.

The most recent analysis of this post-earthquake survey data is that provided by Hull (1990), with the results shown in Figure 2-7, which include the subsidence found by the second re-survey. The results document a zone of uplift defined by a northeast trending elongate dome having a maximum length of about 90 kilometres and a width of at least 17 kilometres. The maximum uplift of 2.7 metres occurred near Oldmans Bluff on the coast just north of the mouth of the Aropaoanui River, about 5 kilometres north of Tangoio. The tide gauge at Napier recorded an uplift of 1.8 metres, but further to the south along the coast the amount of uplift was progressively less, becoming 0 at about Awatoto, and with a zone of subsidence found still further to the south, centered on Hastings where the land elevation dropped by about 1.0 metre. The line of zero change, the so-called "hinge line" in this tectonic event, extended in the southwest direction from from Awatoto on the coast, through Bridge Pa west of Hastings. The area having the greatest concentration of surface faulting lay to the southwest of Bridge Pa (Henderson, 1933). However, those surface faults were probably not the surface traces of the faults that produce earthquakes, but rather are a result of adjustments to the folding and faulting that occurred at the 15 to 20-kilometre depth of the epicenter.

Of particular significance to the evolution of the Hawke's Bay shore are the elevation changes along the coast itself produced by the 1931 earthquake. The best measure of that change was the vertical displacement experienced by the tide gauge on the Port's breakwater, which documented an uplift of 1.8 metres. The same degree of uplift occurred in the Inner Harbour at Ahuriri, confirmed by Marshall's (1933) observations of limestone boulders covered with calcareous algae, which had died and become bleached when exposed to the atmosphere after its elevation above the water. It was this degree of uplift that resulted in the draining of much of the Ahuriri Lagoon at the time of the quake, changing the Westshore area from a narrow spit backed by the Lagoon into a barrier beach ridge that now fronts a large expanse of land, including the commercial airport. Having a much smaller surface area and shallower water depths, the tidal prism of the Ahuriri Lagoon, the average volume of water entering and exiting the Lagoon during a tidal cycle, is now much smaller than it was prior to the 1931 earthquake. This has changed the dynamics of the inlet connecting the Lagoon with Hawke Bay, which had been a tide-dominated inlet prior to the earthquake but is now a wave-dominated inlet. Also affecting this water exchange between the Lagoon and Bay was the diversion of the Tutaekuri River a few years after the earthquake (1934), which now flows directly into Hawke Bay south of Napier, rather than discharging water into the Lagoon.

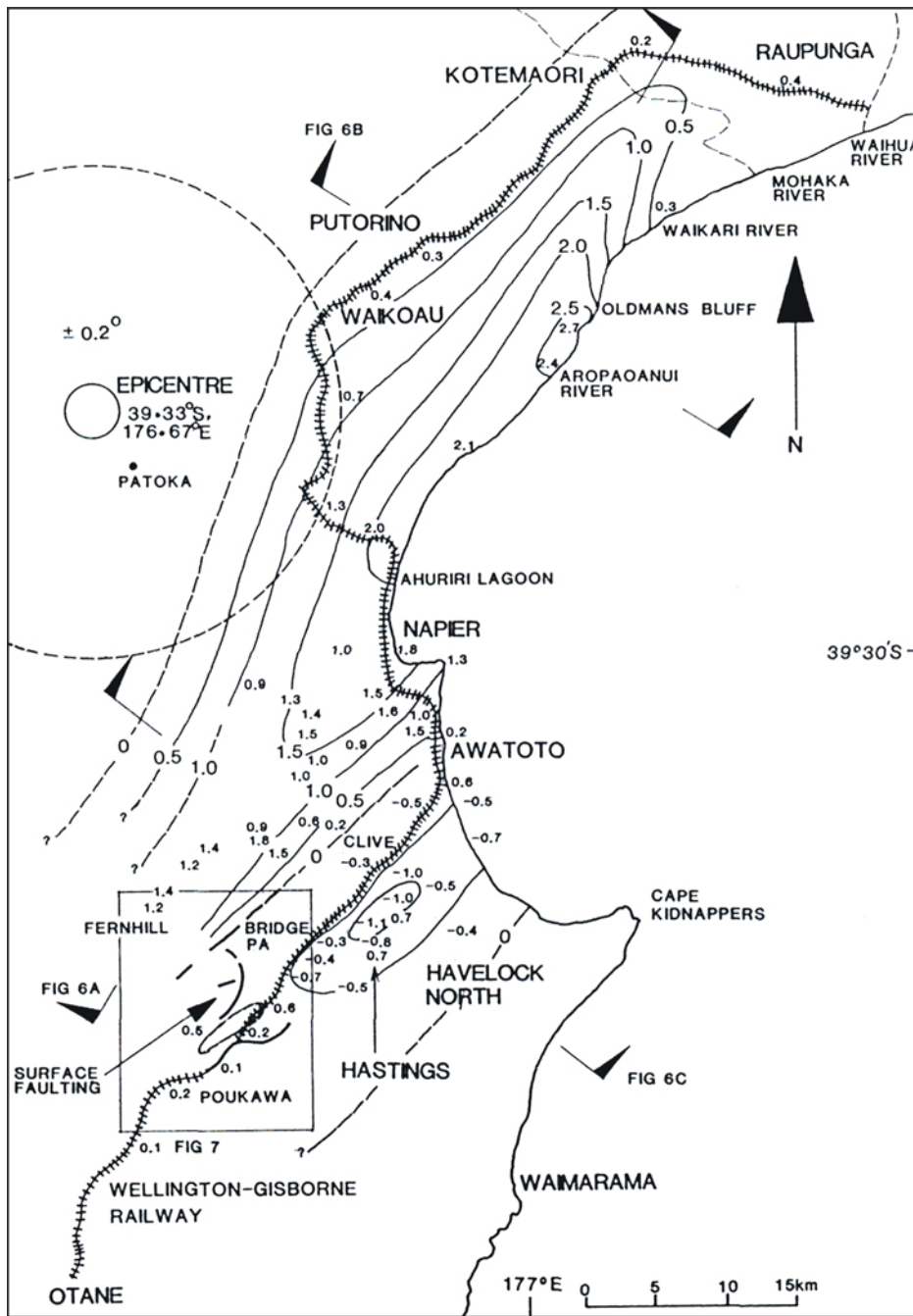


Figure 2-7 Land elevation changes produced by the 1931 Hawke's Bay earthquake. Negative values centered on Hastings denote land subsidence. [from Hull (1990)]

The general uplift of the coast at the time of the 1931 earthquake had an immediate effect on the fronting beaches, with their widths increasing in proportion to the degree of uplift. This change was noted by Marshall (1933, p. 33): "Two weeks after the earthquake it was found that the shingle beach on the south side of the breakwater had been built out by wave action as much as 1 chain." [1 chain = 20 metres]. That extent of beach expansion could have been produced by a 2-metre uplift of a beach having a 1-in-10 slope, so it is unclear whether "wave action" had any significant role as suggested by Marshall. Local residents noticed that the water had receded,

leaving a considerable width of additional beach exposed above the high-tide levels. Prior to that uplift and beach widening, storm waves were at times able to wash across the Marine Parade and flow into the buildings of downtown Napier; the uplift therefore provided significantly increased protection from storms. The Parks and Reserves Department leveled the uplifted beach and then added debris from the ruined buildings to provide a foundation for recreational developments, including the park lands of the Marine Parade. A new seawall was constructed closer to the sea.

The same degree of beach expansion would have occurred along the gravel beach ridges to the north of Bluff Hill, but of particular interest there is the purported formation of a sand beach at Ahuriri and along Westshore, fronting the uplifted gravel ridge. It is curious, however, that Marshall (1933) makes no mention of the development of this sand beach; in his 1930 paper he had taken particular interest in the occurrence and origin of the sand immediately offshore from the gravel beaches, so he certainly would have noted the formation of an uplifted sand beach at Westshore. The photo in Plate II in his 1933 paper, directed toward Hardinge Road, shows a low flat area seaward from the former steep beach with conspicuous high- and low-tide strand levels, but with the flat covered by gravel and cobbles of a size that makes it likely to have been limestone derived from Bluff Hill seen in the background of the photo. There is historic evidence that with time a sand beach did develop. According to Campbell (1975, p. 161), the uplift of the shore altered the beach from a "dangerous shingle bank to a placid sand expanse", and as a result this beach became increasingly popular for recreational use during the next twenty-five years. According to Smith (1986), this fronting sand beach formed by the onshore transport of the sand by the waves in the weeks to months after the uplift of this area, but in the subsequent decades that sand has been progressively lost, being essentially gone by the late 1950s or 1960s. Purported remnants of the sand beach are shown in photos taken between 1978 and 1981 at Westshore, presented in the ASR Report (Mead et al., 2001); however, at that late date the sand is more likely part of the cycle of its gains and losses under the changing waves and currents. The sources of this sand at Westshore will be examined in more detail in Section 7.

Beyond the immediate area of Napier, the elevation changes in the beaches were documented by Single (1985), who surveyed cross-shore profiles of the beach and backshore ridge in 1985 at twelve sites north and south of the city. His results are graphed in Figure 2-8 in terms of the height differences between the relict beach ridges that were active prior to the 1931 earthquake and the present-day elevations of the tops of storm berms on his surveyed profiles. Also shown in the graph are the vertical displacements derived from re-leveling the railway line by the Public Works Department, where the line was positioned immediately landward from the beach. Single's surveyed beach-elevation changes and the increased elevations of the railway line after the earthquake both show gradual increases in uplift toward the north, Figure 2-8. For the most part the two assessments show reasonably good agreement, the main divergence being at Whirinaki immediately north of the mouth of the Esk River; there, Single's assessed 5-metre uplift based on the beach survey is too large, probably because the morphology of the beach had been affected by the presence of the mouth of the Esk River.

The gravel beaches of Hawke's Bay have slopes that are typically on the order of 1-in-8 to 1-in-9, so the approximate 2 metres uplift during the earthquake along much of this shore should immediately have produced a 16 to 18 metres seaward shift in the shoreline and expansion of the beach width. Depending on the degree of exposure of previously sub-tidal sand at Westshore, the beach width increase there may have been greater. This change would have altered the equilibrium conditions of the beaches, so with time one could expect that the waves would move the beach gravel across and along the shore, modifying the beach profiles into a new equilibrium brought about by the earthquake. However, it is unclear what that new equilibrium condition would be, and whether it would result in erosion of the gravel beaches or their accretion. As will be discussed in Section 5, while coastal scientists and engineers have given considerable thought to the beach responses caused by a rise in the sea relative to the land, of special interest due to the on-going global rise in sea level with the melting of glaciers, there has been little consideration given to the case where the level of the sea has dropped relative to the land, such

as experienced along the Hawke's Bay shore at the time of the 1931 earthquake. Furthermore, the responses of mixed sand-and-gravel beaches as found in Hawke's Bay can be expected to differ from sand beaches, which generally have been the primary focus of studies by coastal scientists and engineers.

Analyzing this response of the Hawke's Bay beaches was the primary objective of the thesis research undertaken by Single (1985), who also wanted to determine the degree to which the present beach morphology and erosion is a response to the tectonic vertical displacements of the land that had occurred back in 1931. He found that the beach response has been markedly different for various sections of the coast, depending on the amount of uplift that occurred and the differing beach morphologies found in each section. The response of the beaches at Westshore and to the north included erosion of the upper beach face, with the formation of an erosional scarp at the limit of storm wave attack. This trend of erosion is continuing, evident in the active retreat of the scarps where the waves at times of major storms cut into the elevated 1931 beach ridge (Figure 2-9). The contrast with the pre-earthquake condition is evident at those sites, where it is apparent that prior to the 2-metres uplift caused by the earthquake, storm waves were able to wash over the top of the beach ridge and carry gravel from the beach to the marshes and shallow water of the Ahuriri Lagoon, that is before it had drained in response to the uplift of the earthquake. Based on the continued erosion of the uplifted beach ridge, Single (1985) concluded that the on-going beach change is still in part a response to the 1931 earthquake, and that while over 80% of the expected response has transpired, it still remains a significant component of the present morphological fluctuations and erosion problems.

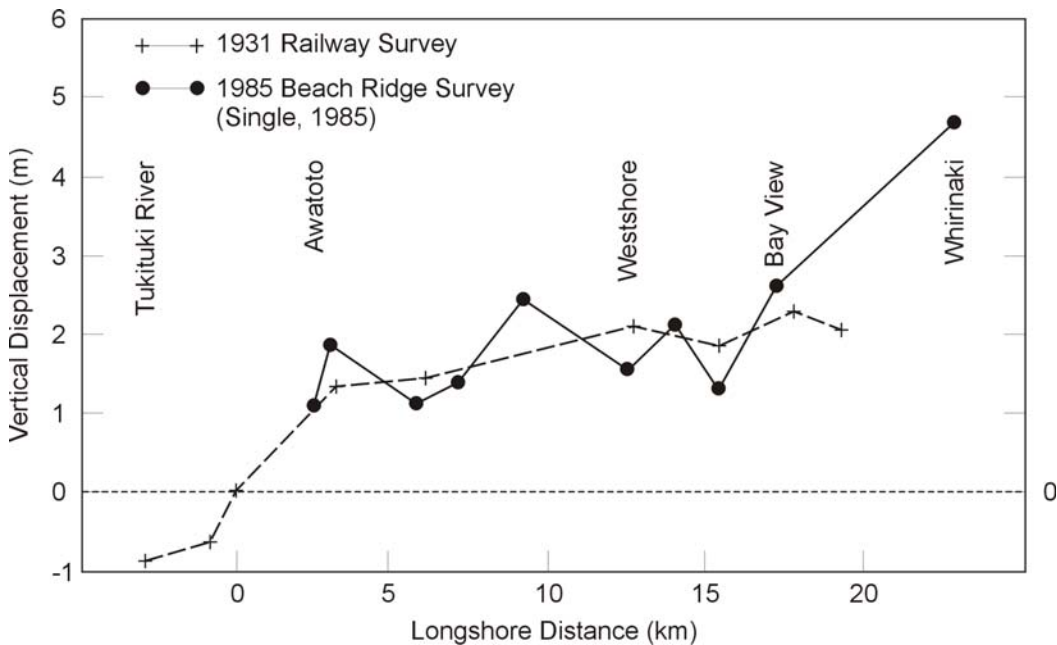


Figure 2-8 Land elevation changes along the shore of Hawke's Bay produced by the 1931 earthquake. The dashed line is from the 1931 resurvey of the railway line and the solid curve is based on Single's (1985) surveys of profiles across the elevated beaches. [after Single (1985)]

While the coastal response to uplift produced by the 1931 earthquake generally resulted in the expansion of the beaches, providing additional protection to shore-front properties, the subsidence experienced south of Awatoto would have had the opposite effect, an immediate landward retreat of the shoreline by tens of metres, followed by a prolonged period of continued

erosion. Studies of that area have concluded that the chronic erosion at Haumoana, Te Awanga and Clifton is still in part a response to the shoreline retreat induced by the earthquake and accompanying subsidence along that stretch of shore, and can be expected to continue for an indefinite period into the future before equilibrium is once again established (Smith, 1977).



Figure 2-9 Erosion scarp cut into the beach ridge at Whirinaki north of Napier, which had been elevated by 2 metres at the time of the 1931 Hawke's Bay earthquake. [May 2003 photo]

2.5 SUMMARY AND DISCUSSION

The tectonic setting of Hawke's Bay has been profoundly important to the long-term geologic evolution of the region, spanning millions of years, and to the development of the Bay's shoreline in both the long term and as an ongoing response to the 1931 earthquake. Subduction of the Pacific plate along the Hikurangi Trough close offshore has resulted in the marine sediments being "scraped off" and added to the land, the origin of most of the rocks in the Accretionary Borderland along the North Island's east coast, with the continuing compression and deformation of those rocks producing occasional earthquakes having magnitudes of 7 to 8. Important has been the accompanying land elevation changes, in the long term resulting in the uplift of much of the region, including the Ruahine and Kaweka Ranges that contain the resistant greywacke rocks whose erosion has supplied the gravel and cobbles that form the Hawke's Bay beaches. At the same time, deformation of the crust by the compression from plate subduction has produced the general subsidence of the Ahuriri Lagoon, although its uplift by nearly 2 metres at the time of the 1931 earthquake reversed that general pattern. As reviewed in this Section, it is uncertain whether this change from subsidence to uplift represents a shift in the tectonics of the area such that future earthquakes will again produce uplift, or whether the next event will result in renewed land subsidence. At the same time there is the threat of fault movements and earthquakes in the

offshore that could result in the generation of large tsunami waves, posing a danger to people living along the Hawke's Bay shore.

Of most immediate interest in this Section were the effects of the 1931 earthquake that altered the elevations of the land along the shore, as this clearly has had lasting consequences to the alongcoast patterns of shoreline erosion versus accretion, foremost being its role in the continuing erosion at Haumoana and Te Awanga. That stretch of coast south of Awatoto to Clifton abruptly dropped down by as much as 0.7 metre at the time of the earthquake, partly submerging the beach and permitting the ocean waves to more directly attack the shore-front properties. While that event occurred 75 years ago, assessments reviewed later in this report indicate that the subsidence along this stretch of shore remains an important factor in its erosion.

North of Awatoto up to and beyond Tangoio the elevations along the shoreline were raised at the time of the 1931 earthquake, by on the order of 2 metres at Napier. This uplift drained much of the Ahuriri Lagoon, raised the elevations of the beach ridge along this stretch of shore, and resulted in an immediate expansion of the fronting beach when the shoreline shifted seaward by some 20 metres. This represented a profound change along this coast; for example, prior to its uplift, what today is Westshore was then a narrow gravel spit immediately backed by the Lagoon, with the spit having low elevations that could be overtopped by waves during severe storms, washing the beach gravel into the Lagoon. Similarly, the low level of the beach along the present-day Marine Parade extended landward nearly up to the fronts of the buildings in the downtown area of Napier, resulting in their flooding at times of storms. All of this changed in response to the uplift caused by the 1931 earthquake, with the increased elevations along this stretch of shore now preventing the overtopping of the beach ridges by the storm waves, and the flooding of downtown Napier. It was only following this change that the development of this stretch of shore could be undertaken without the expectation that homes and others structures would experience frequent flooding damage during storms and severe erosion of their properties.

While the objective of this Section has been to review the tectonics of Hawke's Bay and to consider its general effects on the coast, further consideration will be given in subsequent sections to the details of the tectonics as being one factor in the continued evolution of the coast, locally contributing to its erosion problems or enhancing its stability.

2.6 REFERENCES

- Adams, J. (1981) Earthquake dammed lakes in New Zealand: *Geology*, v. 9, p. 215-219.
- Aitken, Jeffrey J. (1999) *Rocked and Ruptured: Geological Faults in New Zealand*: Reed Books, Auckland, 88 pp.
- Beanland, S., et al. (1998) Structure and deformational history of the inner forearc region, Hikurangi subduction margin, New Zealand: *New Zealand Journal of Geology and Geophysics*, v. 41, p. 325-342.
- Berryman, K. R. (1988) Tectonic geomorphology at a plate boundary: a transect across Hawke Bay, New Zealand: *Zeitschrift für Geomorphologie N.F.*, Suppl.-Bd. 69, p. 69-86.
- Berryman, K. R. (1993a) Age, height, and deformation of Holocene marine terraces at Mahia Peninsula, Hikurangi subduction margin, New Zealand: *Tectonics*, v. 12, p. 1347-1364.
- Berryman, K. R. (1993b) Distribution, age, and deformation of Late Pleistocene marine terraces at Mahia Peninsula, Hikurangi subduction margin, New Zealand: *Tectonics*, v. 12, p. 1365-1379.

- Berryman, K. R., Y. Ota, and A. G. Hull (1989) Holocene paleoseismicity in the fold and thrust belt of the Hikurangi subduction zone, eastern North Island, New Zealand: *Tectonophysics*, v. 163, p. 185-195.
- Bullen, K. E. (1938) An analysis of the Hawke's Bay earthquake during February 1931: *New Zealand Journal of Science and Technology*, v. 19, p. 497-519.
- Campbell, M. D. N. (1975) *Story of Napier 1874-1974*: Napier City Council.
- Cole, J. W., and K. B. Lewis (1981) Evolution of the Taupo-Hikurangi subduction system: *Tectonophysics*, v. 72, p. 1-21.
- Froggatt, P. C., and R. Howorth (1980) Uniformity of vertical faulting for the last 7000 years at Lake Poukawa, Hawke's Bay, New Zealand: *New Zealand Journal of Geology and Geophysics*, v. 23, p. 493-497.
- Gibb, J. G. (1980) *Late Quaternary Shoreline Movements in New Zealand*: Unpublished Ph.D. thesis, Victoria University, Wellington, 217 pp.
- Grapes, Rodney (2000) *Magnitude Eight Plus: New Zealand's Biggest Earthquake*: Victoria University Press, 208 pp.
- Henderson, J. (1933) The geological aspects of the Hawke's Bay earthquakes: *New Zealand Journal of Science and Technology*, v. 15, p. 38-75.
- Hull, A. G. (1986) Pre-AD 1931 Tectonic subsidence at Ahuriri Lagoon, Napier, Hawkes Bay, New Zealand: *New Zealand Journal of Geology and Geophysics*: c. 29, p. 75-82.
- Hull, A. G. (1987) A late Holocene marine terrace on the Kidnappers coast, North Island, New Zealand: some implications for shore platform development processes and uplift mechanisms: *Quaternary Research*, v. 28, p. 183-195.
- Hull, A. G. (1990) Tectonics of the 1931 Hawkes Bay earthquake: *New Zealand Journal of Geology and Geophysics*, v. 33, p. 309-320.
- Kamp, P. J. J. (1988) Tectonic geomorphology of the Hikurangi Margin: surface manifestations of different modes of subduction: *Zeitschrift für Geomorphologie N.F.*, Suppl.-Bd. 69, p. 55-67.
- Kelsey, H. M., and others (1995) Structural evolution along the inner forearc of the obliquely convergent Hikurangi margin, New Zealand: *Tectonics*, v. 14, n. 1, p. 1-18.
- Larson, K. M., and J. Freymueller (1995) Relative motions of the Australian, Pacific and Antarctic plates estimated by the Global Positioning System: *Geophysical Research Letters*, v. 22, p. 37-40.
- Marshall, P. (1933) Effects of the earthquake on the coastline near Napier: *New Zealand Journal of Science and Technology*, v. 15, p. 79-92.
- Mead, S., K. Black, and P. McComb (2001) *Westshore Coastal Process Investigation*: ASR Consultants, prepared for Napier City Council, 142 pp + Appendices.
- Reyners, M. (1998) Plate coupling and the hazard of large subduction thrust earthquakes at the Hikurangi subduction zone, New Zealand: *New Zealand Journal of Geology and Geophysics*, v. 41, p. 343-354.

- Single, M. B. (1985) *Post-Earthquake Beach Response, Napier, New Zealand*. Master of Arts Degree, University of Canterbury, 150 pp.
- Smith, R. K. (1977) *Coastline Changes and Beach Sediments in Southern Hawke Bay*. Unpublished report, Ministry of Works and Development, Napier.
- Smith, R. K. (1986) *Coastal Erosion at Westshore, Hawke Bay*. Ministry of Works and Development, Water Quality Centre, Hamilton, Internal Report No. IR/85/11.
- Wright, Matthew (2001) *Quake: Hawke's Bay 1931*: Reed Books, Auckland, 158 pp.

3 Human Settlement and Impacts on the Environments of Hawke's Bay

3.1 INTRODUCTION

The arrival of people in New Zealand is reckoned only in terms of hundreds of years. First to reach these shores were the Maori about eight hundred years ago, while the discovery of these islands by Europeans did not occur until 1642 when a Dutch ship under the command of Abel Janszoon Tasman stumbled upon the northwest corner of the South Island during his search for *Terra Australis*, the southern continent. Tasman was greeted by Maori war canoes, and in the ensuing conflict four Dutch sailors were killed; as a result Tasman and his men did not actually set foot on land. Another century would pass before Captain Cook reached the shores of New Zealand, including a brief visit to Hawke's Bay, and it would not be until the mid 19th century when European settlement occurred in significant numbers.

It is sometimes difficult to comprehend the extent of the changes in the physical and biological environments of New Zealand during the few hundred years since the arrival of humans on these shores. Research by archeologists has documented that after their arrival the Maori drove the flightless Moa into extinction in only two to three hundred years. And their environmental impacts included extensive deforestation, probably by burning to improve hunting and to convert the land for agricultural use; it has been estimated that about a third of the native forest had been lost prior to European arrival (Chambers, 2004). Settlement by Europeans greatly accelerated the rates of human impacts on the environment, becoming particularly significant beginning in the mid 19th century as increasing numbers of Europeans arrived to settle and transform this land into a reproduction of what they had left behind in the old country.

Of interest in this Section is the history of settlement in the Hawke's Bay region, first by the Maori and beginning in about 1830 by Europeans, with a particular focus on their effects on the physical environment that are relevant to the conditions and evolution of the coast. Their impacts were wide ranging, including the deforestation of the river watersheds, the subsequent grazing of cattle on those cleared lands, the extensive modifications made to the rivers including the mining of sand and gravel, and the construction of dikes to prevent flooding of the new agricultural and urban lands. As a result of such modifications to the environment, it can be expected that there were also significant changes in the discharges of rivers and in the volumes of sand and gravel released from the cleared land, carried to the coast by the rivers. On the coast itself there were additional environmental changes, including what appears to have been the extensive removal of sand and gravel, during the period of settlement and continuing up to the present. At the end of the 19th century the changes included the construction of the moles on the inlet to the Ahuriri Lagoon and soon thereafter the Port of Napier's breakwater, in both cases required to provide a harbour for the commerce of the expanding population of Hawke's Bay.

Having recognized the occurrence and diversity of these human impacts on the environment of the Hawke's Bay region, it raises questions regarding their effects on the coast and

whether the modifications have been a primary factor in bringing about the problems we face there today. For example, have the occurrences of beach erosion and property inundation during storms been at least in part the result of the loss of beach sediments, this loss having been caused by the mining of sand and gravel from the rivers and beaches? On the other hand, deforestation and the use of the river watersheds for agriculture may have had the opposite effect, having increased the rates of soil and rock erosion, with the development of massive landslides that would have released huge volumes of sediment so that the rivers actually supplied greater quantities of sand and gravel to the Hawke's Bay beaches. To further complicate these issues, making it more difficult to answer questions such as these, is that the Earth's changing climate might also have been important. Is there evidence that the climate of New Zealand has changed sufficiently during the past few hundred years, perhaps with periods of greater rainfall, so we need to consider such natural variations as well as the environmental impacts of people?

These are the types of issues considered in this Section. It begins with a review of the settlement by the Maori and their environmental impacts, in general and nationwide, and then specifically in the Hawke's Bay region. This review then turns to the settlement and impacts of Europeans in Hawke's Bay, with the focus being particularly on the environmental changes that could have affected the quantities of sand and gravel found on the beaches. This will principally include the changes in the river watersheds — deforestation, animal grazing, sediment extraction from the rivers, and controls implemented to reduce flooding. This consideration will then be extended to the coast itself, similarly examining the sand and gravel extraction from the beaches, the effects of the placement of sewage outfalls that cross the beach, and finally the harbour development in Napier which involved the placement of the moles in 1876-1879 to control the entrance to the Ahuriri Lagoon and the construction of the Port's breakwater in 1887-1890. An assessment of the possible impacts of harbour development is more involved as it includes analyses of ocean waves, tides and other coastal processes, which ultimately bring about the shoreline changes, so the primary examination of their effects on the coast are deferred until Section 6 after those processes have been reviewed.

3.2 THE ARRIVAL OF THE MAORI AND THE ENVIRONMENTAL CONSEQUENCES

New Zealand appears to have been the final significant landmass reached and settled by the Polynesians through the South Pacific islands. There is general agreement amongst archeologists that the Maori arrived from eastern Polynesia, probably the Society Islands, though the date of their arrival in New Zealand is uncertain. The best estimate is that it took place around AD 1300, and it is also believed that their first landfall took place on the northeast coast of the North Island.

Recent DNA analyses indicate that there were perhaps only about 70 women in this group of Maori settlers (Chambers, 2004), suggesting that it may have involved only a few canoes. It is clear that their intention was to find new land for settlement, as they carried a stock of plants and animals. The plants included coconuts, yams, taro, gourd seeds, paper mulberry cuttings, sweet potatoes (kumara) and colocasia tubers. There perhaps would also have been plantains and breadfruit, which they would have needed to plant and cultivate immediately upon their arrival. Dogs and the Polynesian rat were the most important of the animals they brought with them. The evidence suggests that this was the one and only Polynesian immigration to reach New Zealand, as there is no indication of a subsequent two-way trade with New Zealand-derived materials such as greenstone having reached the other South Pacific islands. Furthermore, hogs were never imported into New Zealand by the Maori, which certainly would have been the case had there been later trade and additional immigration.

New Zealand represented the most southerly latitudes settled by the Polynesians, so the newly arrived immigrants faced a much colder climate that demanded new adaptations. The fact that their important plants such as kumara survived at all is evidence of their having arrived in the north of the North Island. Only after a period of trial and error, did they find a way to grow kumara further inland and to the south. Their other crops, taro, gourds and paper mulberry survived, but hardly flourished. Fortunately, their new surroundings teemed with fish, and a much greater variety of shellfish than they had found on the more tropical islands of the Pacific. Seals and sea lions were present in great numbers, and could fairly easily be approached and clubbed to death. They also found the great variety of birds endemic to New Zealand, including geese, ducks, swans, countless seabirds, and the variety of flightless birds.

Most fortunate for the survival of the newly arrived Maori was the presence of the moa, which soon became an important food source. The moa ranged in size from that of a large turkey to the huge Great Moa that was some 2 metres tall and weighed about 200 kilograms. Their population densities were relatively low; even on the South Island where the moa were most prolific, their density is estimated to have been no greater than about 2 animals per square kilometre. It appears that much of the first two centuries of Maori settlement and expansion in New Zealand involved their pursuit of the moa for food. A great number of archeological sites have been identified from throughout both the North and South Islands, where the Maori had butchered, cooked and consumed thousands of moa. Moa eggs would also have been consumed, with each egg being equivalent to ninety or more chicken eggs. Hunting of moa seems to have reached its greatest during the late 1300s, that is, soon after the arrival of the Maori in New Zealand. The archeological evidence also indicates that the consumption of the moa was extraordinarily wasteful, the Maori having selected for food only the most valued portions of the birds. Probably few moa remained after about 1500, with extinction soon thereafter.

Thanks to the high protein intake from eating moa during those first two centuries of settlement, the Maori were able to expand their population considerably, and the pursuit of the moa required that they explore the full expanse of the islands. It has been estimated that the Maori population doubled every 30 years (Chambers, 2004), and had that rate continued the population would have been more than 86,000 in 1769, the year Captain Cook first arrived. Archeologists have found that except for the high mountains of the South Island, all of New Zealand had been occupied within about a century, although most areas would have been sparsely populated. When the first Europeans arrived in the late 1700s, the entire country was claimed by one tribe or another. However, with the extinction of the moa most of the Maori retreated to the warmer climate of the North Island, and at the time of Cook's visit probably more than 85 percent of the Maori population lived on the North Island.

The loss of the moa as a source of protein was serious for the Maori, and human skeletons in archeological sites show clear evidence of recurring famine. While many other food sources were then utilized, they were not nearly as nutritious. The staple elements of the diet were fish and shellfish, fern roots that are difficult to digest, and kumara that was difficult to raise. Also coincident with the decline in the number of moa, in about AD 1400 there seems to have been the inception of endemic tribal wars resulting in the construction of extensive hill forts (pa) throughout the country. This may also have been the period during which the more extensive removal of brush and forest by burning occurred, probably to provide more permanently cleared land for agriculture. As noted earlier, it has been estimated that about a third of the native forest had been lost prior to European arrival.

This general history of Maori settlement throughout New Zealand as a whole appears to have been much the same specifically in the Hawke's Bay region. Gibb (1996) presents a summary of the history of Maori settlement in Hawke's Bay based in part on the longer accounts of Judge Harvey (1948) and Parsons (1995), and also on discussions with local

Maori to obtain their perspectives. The original Maori name for the Ahuriri Estuary was Te Wahanganui-a-Orotu, with Te Orotu being the name of a person and Wahanganui signifying a fresh-water lake: literally, the translation is "Te Orotu's lake". Te Orotu was one of the first Maori to settle in this area, approximately 28 generations ago (about 700 years B.P. — before the present), that is, soon after the estimated arrival of the Maori in New Zealand. One generation later another important Maori leader arrived, named Tara. He came by canoe from Wairoa, and entered the lagoon through an entrance he named Keteketerau, located approximately 6.5 kilometres north of the present-day Ahuriri entrance. According to Gibb (1996), physical evidence for the former Keteketerau entrance is still evident as a depression near Fannin Street and Ferguson Street South in Bay View. In that the Keteketerau inlet to the Lagoon was still open at the time of Captain Cook's arrival in 1769, it appears to have remained the dominant inlet for at least 1,000 years, although Judge Harvey (1948) concluded that it had to be physically opened from time to time when storm waves blocked it with beach gravel.

According to Maori ancestral knowledge, about 22 generations ago (about 550 years B.P.) the name of the Lagoon was Te Maara-a-Tawhao, which means "the Garden of Tawhao" (Gibb, 1996). This name reflects the importance of the Lagoon to the Maori as a prolific source of food, and would account for their settlement along its shore. It appears that the hunting of moa was also important to the Maori diet, as moa remains have been found in the Hawke's Bay region (Price, 1963; McFadgen, 1979). Otherwise the evidence for the environmental impacts of the Maori is circumstantial. For example, when Europeans arrived and began to settle Hawke's Bay during the mid-19th century there were extensive expanses of grasslands where one would naturally expect forests, possible evidence for deforestation by the Maori having set fires (Reed, 1958).

The most permanent modification in the landscape produced by the Maori was the change in the location of the tidal inlet connecting the Ahuriri Lagoon with Hawke Bay. As will be recounted below, when Captain Cook sailed along the Hawke's Bay coast in 1769, according to his description it was the Keteketerau entrance that still connected the Lagoon to the Bay. By the time of the subsequent arrival of Europeans during the 1820s, the entrance had shifted to its present-day Ahuriri site. According to local Maori legend, the natural inlet at Keteketerau had become blocked by sand and gravel so that water could not flow out of the lagoon. This presented a problem to the Maori as the rivers flowing into the lagoon raised water levels and drowned their shoreline cultivations; it would also have altered the salinity from being brackish to more fresh water, and this could have had an adverse effect on the fish and shellfish, their food sources. According to the legend, a visiting chief from the north, Tu Ahuriri, set his men to digging a new channel, and chose a site further to the south, just north of Bluff Hill (Scinde Island). The legend relates that this initially narrow channel was soon enlarged by the rush of water flowing from the lagoon into the sea, until the level of water in the lagoon corresponded with that in the Bay. In honor of Tu Ahuriri's help, the local Maori named the lagoon after him. [William Colenso, one of Napier's most notable early citizens, suggested instead that the name Ahuriri meant "fierce rushing", a reference to the strong tidal currents in the channel.]

The decision by Tu Ahuriri to dig the new channel in the sheltered region immediately north of Bluff Hill was a wise one in view of the expected hydraulics and stability of the tidal channel. Being sheltered from the highest storm waves arriving from the southeast, the new channel would have been less apt to be closed by waves carrying sand and gravel across its mouth, which apparently had been a frequent problem at Keteketerau, a site fully exposed to the storm waves. The forces of the tidal currents acting to maintain the inlet open would have been much the same at either site, but whenever the Tutaekuri River flowed into the Lagoon rather than following a course more to the south where it entered directly into the Bay, its discharge would also have contributed to maintaining the Ahuriri channel open. Because of these multiple factors, the Ahuriri entrance maintained a relatively stable position during the

approximately one hundred years between its establishment by the Maori and the construction of the moles in 1876-1879, which firmly fixed its location.

In summary, the Maori apparently had reached Hawke's Bay in the late A.D. 1300s, four to five hundred years prior to the arrival and settlement of Europeans. The population of the Maori in Hawke's Bay is uncertain, but likely numbered on the order of a few thousand to ten thousand. Their main impacts were biological, including the extinction of the moa and other species of birds. The consequences to the physical environment were less, the primary one having been deforestation that may in part have been associated with their hunting moa but more likely involved clearing land for agriculture. As will be reviewed later, there is evidence for extensive changes in the landscape during the 17th century, primarily having affected the forests of the upper watersheds (Grant, 1965), changes that might have been induced by the Maori but equally could have resulted from natural variations in the climate. The one significant change in the physical environment that clearly was brought about by the Maori was the shift in the location of the inlet connecting the Lagoon and Hawke Bay, the artificial relocation to its present site at Ahuriri, a modification that can be viewed as having been positive.

3.3 EUROPEAN EXPLORATION, SETTLEMENT AND CHANGES IN THE ENVIRONMENT

Although it came more than a century after Tasman's explorations, Captain Cook's First Voyage to the South Pacific in 1768-1771 aboard the *Endeavour* again had the objective of a search for *Terra Australis*, the southern continent. As part of that search Cook sailed to New Zealand, which Tasman had suggested was the corner of that continent. Circumnavigating both the North and South Islands in six months and producing the first detailed map, Cook showed that Tasman had been mistaken. Arriving from the east, the *Endeavour* first reached the shore of Poverty Bay, and then sailed south along the coast, bringing them to the shores of Hawke's Bay in December 1769; Cook named the bay in honor of Sir Edward Hawke, First Lord of the Admiralty. Although Cook's exploration of this stretch of coast was brief, the entry in his journal provides the first written description of the region (Beaglehole, 1955):

. . . on each side of this bluff head is a low narrow sand or stone beach, between these beaches and the mainland is a pretty large lake of salt water as I suppose; on the SE side of this head is a very large flat which seems to extend a good way inland to the westward, . . .

The "bluff head" feature mentioned by Cook is Bluff Hill (Scinde Island), which would have been a very prominent feature on this otherwise low-lying coast, while the "large lake" referred to the Ahuriri Lagoon, which at that time had an area of about 3,000 hectare. Also, as discussed above, at the time of Cook's visit the inlet to the lagoon would have been located about 6 kilometres to the north of its present position.

Cook's favorable reports and charting of the New Zealand coast kindled British interest, which eventually led to its annexation and settlement. However, European settlement of Hawke's Bay did not begin until more than a half-century had passed. Other than a couple of brief stops by Europeans during the 1820s, the first residents of Hawke's Bay were shore whalers who arrived in the late 1830s. There were two types of whaling, ocean or pelagic which had begun in the 1790s, and bay or shore whaling which began in New Zealand in the 1820s, including the establishment of a station south of the Mahia Peninsula. Shore whaling involved hunting the docile southern Right Whale, setting out from shore in five-oared boats. More transient shore stations were set up along the shore of Hawke's Bay during the 1830s, including one at the mouth of the Ahuriri Lagoon, in the area still known as the Iron Pot and what was to become the Inner Harbour for Napier. Other than the presence of the Lagoon to

serve as a harbour, there was little to recommend this site for settlement. A report written in 1860 described Napier as: "A precipitous island [Bluff Hill] of barren, uninhabited ridges, covered with fern and rough grass, dissected by gorges and ravines, with a narrow strip of shingle skirting the cliffs, and joined to the mainland south by a five mile shingle bank . . . A hopeless spot for a town site." With the harbour having been the primary reason for settlement, the initial European development was centered at Ahuriri, on that "narrow strip of shingle" forming what was called the East Spit (Hardinge Road) and West Spit (Westshore), and along the shore of the Lagoon next to the Iron Pot, including Gough Island just inside the Lagoon from the entrance.

Following the whalers, the next Europeans to reach Hawke's Bay were the missionaries and traders, and finally settlers interested in establishing inland farms. In 1833 William Williams was the first missionary to reach Hawke's Bay, having come down from his station at the Mahia Peninsula. The first missionary to be stationed in Napier was William Colenso, who arrived in 1844 with his wife and daughter. Colenso was to be the most illustrious citizen of Hawke's Bay, already having been New Zealand's first printer while in Auckland, where he published the New Testament in Maori. Colenso was also something of a naturalist, recognized in his becoming a member of the Royal Society, providing the earliest accounts of the physical and biological environments of the Hawke's Bay region. The first European who might be justly termed a Hawke's Bay settler was an educated Scotsman Alexander Alexander, who arrived in 1846 when he was about twenty-six years of age. He farmed land on the foothills to the northwest of Napier, and constructed the first building in Napier, a store and bacon-curing venture on the harbour shore next to the mouth of the Tutaekuri River, where he kept a schooner and traded with the Maori. In December 1850 the first two families, the McKains and Villers, arrived and built their homes on the Western Spit, now Westshore. Villers maintained an accommodation house there until 1855, but then moved inland to become a sheep farmer. The first sheep had been imported into the area in 1849 when 3,000 merino sheep were driven overland to Hawke's Bay.

The first prominent land developer was Donald McLean who took interest in this area primarily due to the presence of the Ahuriri Lagoon, which he described as: "the safest and the only [harbour] on this side of the island between Wellington and Tauranga on the North East Coast." In 1850 he purchased large blocks of land from the Maori in what was to become the site of Napier. The first sale of town sections occurred in 1855 as increasing numbers of settlers arrived. An early map of the properties shows a number of lots extending along the length of East Spit landward of Hardinge Road, while the development of West Spit was confined to its bay side, with a wide zone of undeveloped land on its seaward side, presumably due to its low-lying character so that erosion and periodic inundation during storms prevented it from being developed.

Early charts of the area focused on the Ahuriri Inner Harbour and the Lagoon as a whole. Figure 3-1 is more of a sketch, but with soundings of water depths, prepared in 1837 by Thomas Wing, Master of the schooner *Trent*. It labels the East and West Spits as "Shingle stones", the former decreasing in its width and pinching out before reaching Bluff Hill which is labeled as "Yellow bluff head", the color of the limestone rocks of that promontory. Within the lagoon, shingle was also found on the shoals near the inlet, but apparently the bottom was sand further into the lagoon. Conspicuous on the sketch is the Maori pa on an island of shingle just within the entrance.

Figure 3-2 is the first surveyed chart of the Ahuriri entrance prepared in 1855 by Commander B. Drury of the *H.M.S. Pandora*. The objective was the collection and presentation of information on water depths needed for the safer navigation into the Inner Harbour. Of interest is the presence of a "Sand Bank" offshore from the inlet, which would have been sub-tidal but sufficiently shallow for wave breaking as the chart notes "breaks heavily". The West Spit is identified as being shingle, and the sole development shown is "McLain's Hotel" near the lagoon shore; four dwellings are shown on the lagoon shore of the East Spit.

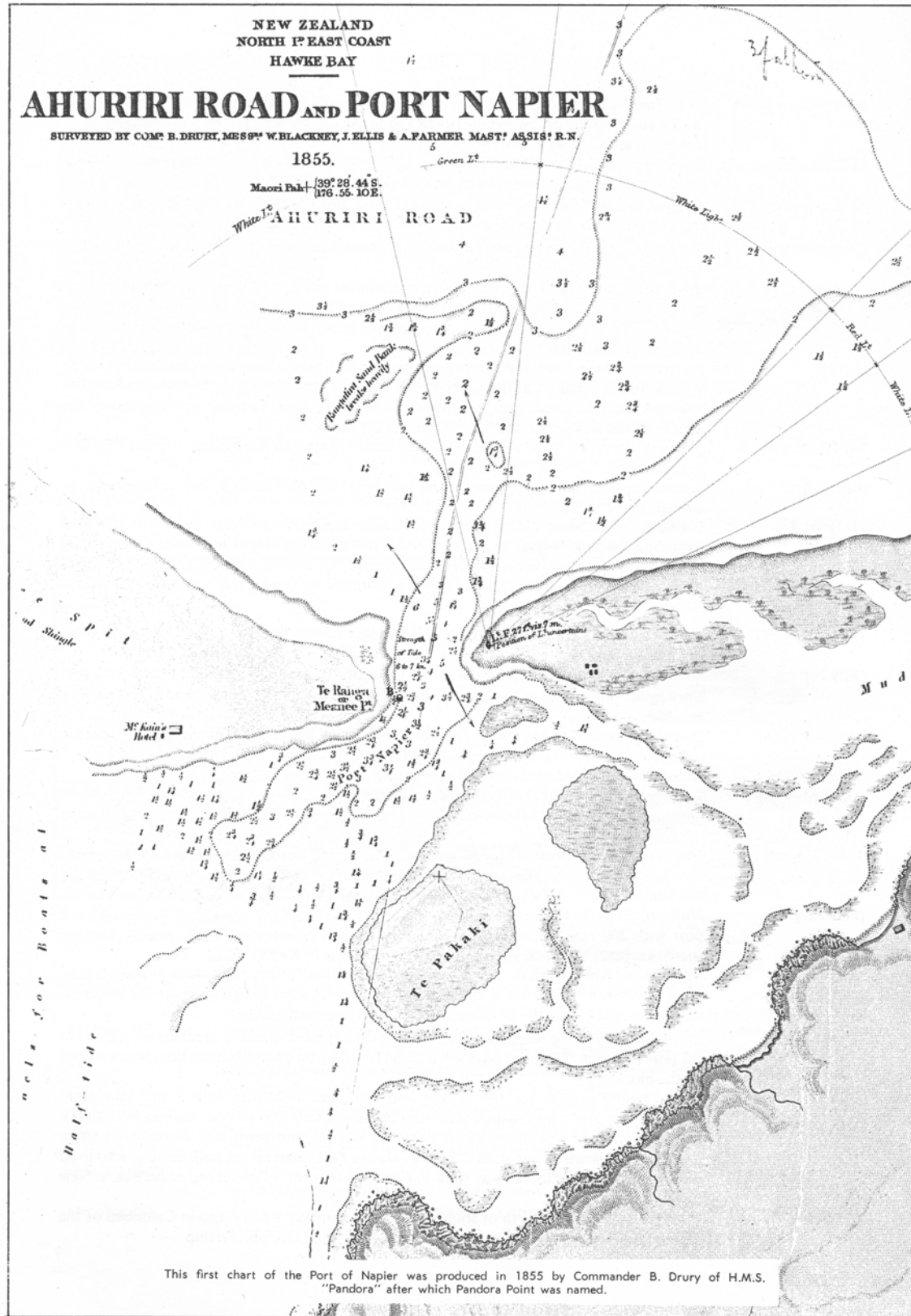


Figure 3-2 The first detailed chart of water depths at the Ahuriri Inner Harbour, surveyed by the *H.M.S. Pandora* in 1855. [from Stevenson (1977)]

Figure 3-3 is another early chart of the Ahuriri area prepared by the Harbour Board's first engineer, C. H. Weber, in May 1873. Of interest is the apparent widening of the harbour entrance with the presence of "rocks" at the tip of West Spit; it was this widening of the inlet together with its shoaling that led to the decision to construct the moles on the entrance in 1876 to provide safer navigation. The expanded development is seen, with "breast works" under construction on Gough Island, the existence of Hardinge Road along the length of the East Spit together with a greater number of dwellings, while the West Spit is simply labeled "Town", suggestive of the development there. Of particular interest in this chart is the depiction of East Spit and its relationship to the rocky shore of Scinde Island (Bluff Hill). The Spit itself is identified as being a "Shingle Bank", and there is a long stretch of rocky shore at the base of the headland with a scatter of rocks offshore from its point, while the surveyed depths show the existence of rapidly increasing water depths offshore. In the offshore the chart indicates the presence of sand on the sea floor, while on the shore itself at two sites sheltered from the storm waves arriving from the southeast is an indication of the localized presence of shingle, probably in small pockets between the rocks. As will be discussed in Section 6, the presence of shingle there provides evidence that at least periodically there had been some bypassing of beach gravel/shingle around Bluff Hill, an exchange between the beaches to the north and south of this headland, although this bypassing probably was only periodic and involved small quantities of gravel.

Figure 3-4 is a representation of the geography of the Ahuriri Lagoon and its surroundings during the early period of settlement, as presented by Stevenson (1977). As indicated on the chart, it was based on surveys in 1851 and 1856-59 and on "Very historical" Lands & Survey Records. It shows a complex of shoals and islands throughout the lagoon, composed variously of shingle near the entrance and sand, shells and mud elsewhere; this demonstrates the shallow-water character of the lagoon. The Tutaekuri River is shown flowing into the lagoon from the south, with its main channel boarded by a wide expanse (hatched) that is "covered during high floods" and with a "very shallow lagoon" and mudflats to its immediate west. According to Judge Harvey (1948), the Tutaekuri River: "... changed its course [to enter the lagoon] in about 1767 and turned the whole area into one sheet of water." Prior to that change in its course, the river had its mouth to the south of Bluff Hill, where it flowed directly into Hawke Bay. It continued to flow into the lagoon until after the uplift of this area at the time of the 1931 earthquake, when in 1934, to reduce the danger of river floods in the city, engineers diverted the Tutaekuri River to its present course to the south of Napier where it again flows into the bay at Waitangi. This chart in Figure 3-4 illustrates well the limited developable land for the Napier settlement prior to the 1931 earthquake, with the high Bluff Hill appearing much like an island between the bay and lagoon, and with only a narrow shingle beach ridge along Westshore north to Keteketerau, and forming the narrow shore ridge south of Bluff Hill backed by low-lying areas affected by frequent floods on the Tutaekuri River.

Flooding of the rivers across the Heretaunga Plain and in Napier was a significant problem for the early settlers. A major flood occurred in April 1867 when fifteen inches of rain fell in four days; it was the largest flood that the Maori could remember. Another flood occurred in 1897 when water from the several rivers combined to cover three-fifths of the Plain, so that many farmers lost their houses, stock and equipment. In Napier the floodwater flowed through much of the city (Campbell, 1975, p. 82):

It was quite easy to row a boat along Carlyle street to the commencement of Clive Square, while in Emerson street and Dickens street the flood waters reached to beyond Dalton street, and in Thackeray street, Munroe Street, Owen street, Craven street and Miller street, water was about two feet deep, [as it was at] the Recreation Ground. In many of the houses along Carlyle street, Owen street, and in Faraday street . . . the water was 18 inches above the house floor.

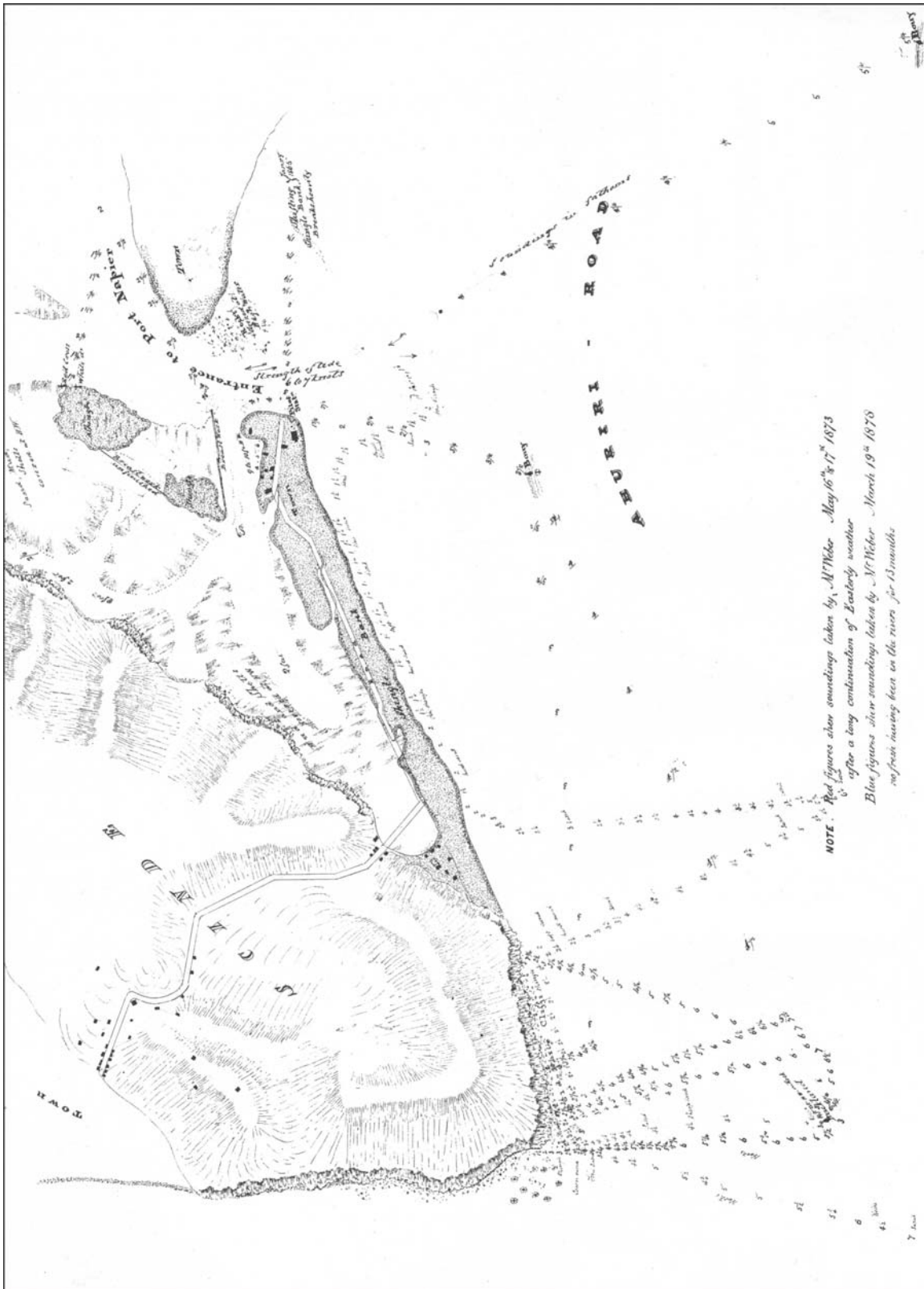


Figure 3-3 A chart prepared by the Harbour Board's engineer C.H. Weber in 1873, showing the East Spit and the shoreline of the Bluff Hill headland. [from Stevenson (1977)]

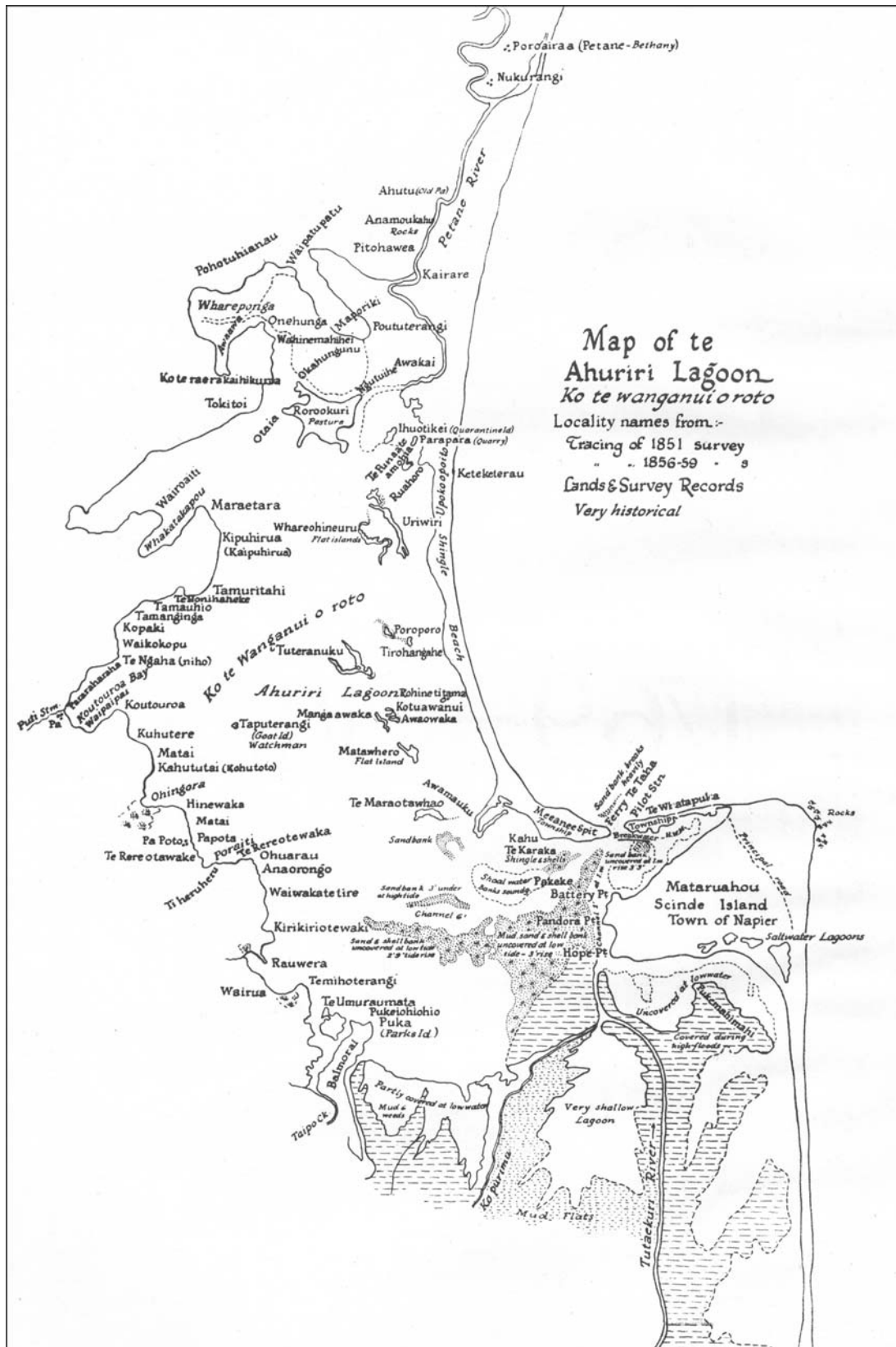


Figure 3-4 The Ahuriri Lagoon during the historic settlement period. [from Stevenson (1977)]

Subsequent floods in January 1876, February 1877, December 1893 and April 1897 again covered the Heretaunga Plain with water. The seemingly increased river flooding would have been exacerbated by deforestation of the watersheds, which had begun under the Maori and was continued by the European settlers. At the time of the arrival of the Europeans there were still large areas of dense bush. Reed (1958, p. 263) provides the account:

In July 1885 a settler's wife on a lonely section near Norsewood went into the bush to look for a cow, leaving four young children in the house, telling them not to leave it until she returned, and that she would not be away long. The father was working away from home, and only able to return occasionally. A day or two later another settler, also looking in the bush for stray cattle, happened to call at the house, and found the children in a state of wild alarm at the lengthy absence of their mother. Eventually the body of the unfortunate woman was found, in the jungle of undergrowth, only six or seven chains [120 to 140 metres] from home.

A primary activity of the newly arrived settlers was the removal of this dense bush, in part to provide more grassland for grazing sheep and cattle. But the timber was also required for the construction of homes and for the vast numbers of fence posts needed to confine their cattle and sheep. It was inevitable that as the homesteads and settlements were being hacked out of the bush, runaway fires would occur during the dry summer months. Reed (1958) also provides accounts of their devastating consequences. The most disastrous of the fires took place in March 1888, in the dense bush at Norsewood (Reed, 1958; p. 264-265):

. . . it was said that the whole countryside was in flames which, driven by a furious gale, spread with dreadful rapidity. . . "As the main body of the fire swept on and past Norsewood," wrote an eyewitness, "the higher bush, parallel with the road to Ormondville, presented the appearance of a vast furnace." The terror caused by the flames and smoke were heightened by the roaring of the wind, which lifted huge tongues of fire skyward, and bore before it heavy masses of smoke, lit up by continuous showers of sparks, and flakes of burning scrub. To add to the terror, as the fire swept along, and the daylight began to die, a fearful storm of lightning, accompanied by thunder, came rolling along overhead from the direction of the Ruahine mountains.

This storm proved to be a blessing, as it released a cloudburst of rain just as the fire had reached the doorsteps of homes in Ormondville. Over thirty buildings had been destroyed, including a score of houses, a library, the temperance hall, and two Maori churches.

With these losses of the forest cover, the land was less able to absorb the water of heavy rains, leading to increased discharges in the rivers and the flooding of the lower watersheds. Deforestation together with the use of the land for grazing sheep and cattle would have resulted in increased rates of soil erosion, and on the steeper slopes the more frequent occurrence of landslides. This would have added greater quantities of sediment to the rivers, mostly silt and sand, but also gravel from the erosion of the rocks and landslides in the upper watersheds.

One major response to these floods was the construction of levees throughout the Heretaunga Plain, to confine the water to the river channels where it would more rapidly flow into the bay, keeping the water out of the settlements and pasturelands. These levees were constructed of sand and gravel extracted from the river channels, this practice also having the positive aspect of deepening those channels so they had an improved capacity to contain the river's discharges at times of floods. It is also likely that sand and gravel was mined from the river channels, beginning during the earliest times of settlement, to be used in a great many ways such as the filling of marshes and ponds across the Plain to further improve the grazing lands, and perhaps even transported to the growing community of Napier to raise its land elevations and expand the area of developable land. We can only guess at the volumes

of sand and gravel mined from the rivers during the settlement period, as there was essentially no regulation of this activity and therefore no monitoring. It likely was viewed as a positive activity, as this sediment extraction would have deepened the channels and thereby reduced the flooding impacts. Even today, as will be reviewed in Section 7, large volumes of sand and gravel are extracted from the rivers, in part to reduce the impacts of floods.

These practices of removing the sand and gravel from the river channels can be expected to have decreased the quantities of those sediments reaching the coast, where they had naturally accumulated to form the beaches. Thus, what may have been a positive management strategy to reduce flooding in the river watersheds, likely had negative consequences on the bay's beaches, resulting in increased shoreline erosion problems and the inundation of low-lying backshore properties under the high tides and waves generated by storms. To make matters worse, there appears to also have been a long history of mining gravel from the beaches, beginning during the earliest period of settlement. The beach would have provided a too-ready source of clean gravel and sand not to have been used, and again with the lack of regulation there was no obstacle to its extraction. Without having been monitored, there is only anecdotal information concerning these early beach sediment mining activities. The one early account is that of Hill (1897) in his analysis of the geological development of the Heretaunga Plain; he noted that the "Washout" was a weak spot in the beach south of Napier, which had been weakened by the extraction of shingle from that beach for the construction of the railway line. Raising the bed of the railway line would have required large volumes of sediment fill, and again the bay's beaches would have been a prime source, not just at the Washout but also to the north in the Bay View Littoral Cell. This extraction apparently was not limited to local needs of sand and gravel; for example, in the construction of the huge concrete pier in Tolaga Bay north of Gisborne, the gravel needed in its concrete came from Hawke's Bay, almost certainly from the beaches of the Bay View Littoral Cell (based on my inspection of the Tolaga Bay pier).

At the same time the inland settlers faced problems with forest fires and river flooding, people living along the coast had problems with periodic shoreline erosion and the inundation by the sea during major storms, likely exacerbated by these early practices of removing sand and gravel from the beaches. The coast during this period of settlement was on average lower in elevation than at present, prior to its having been uplifted by 1 to 2 metres at the time of the 1931 earthquake (Section 2). With those lower elevations of the fronting gravel beaches, during storms with a combination of elevated tides and storm wave runup it was much more likely to have experienced shoreline erosion and the flooding of backshore properties. Mention of these problems is included in the histories of Hawke's Bay (Reed, 1958; Campbell, 1975), and Stevenson (1977) provides a summary of specific storm events, particularly those that occurred at the time of construction of the Port of Napier's breakwater in 1887-1890. Those historic accounts focused primarily on the stretch of shore along the Marine Parade in Napier where the elevated water created by storms was able to overtop the beach and road, with the waves damaging dwellings and the Court House. Improvements to this area initially included the construction of a timber seawall, but it proved to be ineffective in protecting the Marine Parade. In March 1888 the sea broke down part of that seawall, exposing the water piping under the road. Another storm three months later cut away more of the road until parts of it were "almost too narrow for a cart to pass" and "more or less damaged every house along it". A new seawall was constructed, this time of concrete with an "apron" to protect its foundation; work on this wall began in November 1888 and was completed in June 1889. According to Campbell (1975, p. 64): "Nine months later, the wall 'proved itself of great service to the town' during another heavy sea. Without it 'hardly a house on the Marine-parade eastward of Emerson Street would have been habitable'."

In spite of such environmental problems, European settlement continued to expand during the late 19th century. According to Reed (1958, p. 137), at the close of 1860, two years after the establishment of Hawke's Bay as a Province, a census disclosed a total population of 2,611, with 1,667 being males and 944 females. As expected, the settlers were young; in

total only about 50 people were older than 55. The humans were greatly outnumbered by their stock, as the census reported 312,459 sheep and 1,782 horses. By the close of 1864 the population (of humans) had increased to 4,107, a 57 percent increase in only four years. According to Campbell (1975, p. 19), in Napier itself during the years 1871 to 1874 its population rose from 2,179 to 3,514, a gain of 61 percent, while in the province as a whole the population had increased by 52 percent during those four years. By 1878 the population of Napier had reached 5,415.

This rapidly expanding population was accompanied by increased commerce and the need for improved harbour facilities. With hundreds of thousands of sheep having been part of the 1860 census, wool exports immediately became the most important commercial product, with some export also of preserved meat and tallow. According to Reed (1958, p. 186), in 1873 the export of wool from Hawke's Bay exceeded that of all other New Zealand districts combined. Other commercial ventures were established, but of a more local nature. The earliest vineyards date back to the 1890s: Mission Vineyard owned by the Marist Order, the Greenmeadows Vineyard founded in 1891, and Steinmetz's (later McDonald's) Vineyard established in 1897 (Campbell, 1975, p. 93). This appears to have been insufficient to quench the thirst of the population, as it is reported that more than 10,000 gallons of spirits had to be imported annually.

This commerce, including both exports and imports, resulted in greatly increased demands on the harbour within the Ahuriri Lagoon. Potential improvements in the harbour were an early subject for consideration and debate. As early as August 1859 dredging and reclamation work was suggested, which would permit the entry into the harbour of larger vessels. In response, in May 1860 a steam dredge was purchased, but in spite of its use, in July 1862 it was reported that there was a gradual silting up of the harbour and inlet and that the Iron Pot was filling up with sediment. This raised doubts as to the future use of the Inner Harbour, generating the first interest in the possible construction of a breakwater.

A prolonged period of debate ensued concerning the relative merits of improving the Inner Harbour within the Ahuriri Lagoon, primarily with the construction of moles (jetties) to control its entrance, versus the development of an Outer Harbour sheltered by a breakwater. To complicate matters, an alternative location for a breakwater was suggested in the lee of Cape Kidnappers. That site received the strong support of Sir John Coode, the most eminent English engineer responsible for the construction of harbours, who said of the Cape Kidnappers site: "nowhere in the North Island are there so good natural facilities for a harbour of refuge." However, it was quickly pointed out that while this may be true for a harbour of refuge, it was not the case for a commercial port due to its isolated location and difficulty of access with a railway line.

A *Hawke's Bay Herald* lead article in June 1875 declared that the future of Napier depended on the construction of a "groin" [the moles for the Inner Harbour], and that failing adequate shipping facilities: ". . . the provincial capital might, within six or seven years, sink into the insignificance of a mere fishing village" (Reed, 1958, p. 278). That same year twelve members were appointed to form the Napier Harbour Board, and funds were allotted to carry out works recommended by the engineer-in-chief. Construction of the Ahuriri moles began in 1876, and were completed in 1879. In spite of this improvement, the Inner Harbour was still suitable only for small vessels, while larger ships had to lie outside, necessitating the use of lighters to transfer the shipped goods to the wharf. In February 1884 the Board approved the construction of a breakwater that would be 2,470 feet in length, of which 1,000 feet would have a depth of from 31 to 34 feet. Approval of the project was required of the voters, and an incredible 96 percent of the eligible citizens voted, probably a record for a New Zealand local body poll (Reed, 1975, p. 284). The total number of votes in favor of the project was 2,562, with only 180 voting against it. The ceremony of laying the first block of the breakwater took place in January 1887, culminating a procession that had set out from Clive Square. As related by Stevenson (1977), the construction of the breakwater turned out to be a

challenging undertaking, in large part because it coincided with a period of unusually severe storms, those discussed above that had resulted in property damage along the Marine Parade, requiring the construction of a new sea wall in 1888.

One normally might expect that this construction of the moles and breakwater to serve as a harbour for Hawke's Bay would have had negative environmental consequences; this has been the general rule along the world's coastlines when such structures have interrupted the natural movement of beach sediment along the shore. However, these consequences were much less obvious in the case the construction at Hawke's Bay. Beach erosion did occur at Westshore, and this occurrence is often attributed to the moles and breakwater having blocked a northward transport of beach gravel that had bypassed Bluff Hill. However, as noted, this period was one of unusually severe storms so there was also erosion and flooding at Marine Parade; it is therefore possible that the Westshore erosion was similarly a response to the storms, not a result of the structures having blocked the longshore transport of the beach gravel. Such issues will be examined at length in Section 6 to more fully consider the possible environmental consequences of having constructed the moles and breakwater in the late 19th century. Irrespective of the causes of the ensuing erosion, the extent of the change was fairly negligible. In studying the causes of the beach erosion at Westshore, O'Callaghan (1986, p. 7) concluded that it "has not been severe in coastal engineering terms" and is "relatively minor". I concur with his assessment.

It is apparent from this review that humans have had a significant impact on the environments of Hawke's Bay. The extent of the changes is perhaps surprising, considering that the settlement of this region by Europeans began a mere 175 years ago, in the 1830s. It is important to consider the degrees of these human impacts in comparison with those of Nature, the natural variations in the Earth's climate, and changes specific to Hawke's Bay, the most significant having been the major earthquake in 1931 and the associated alterations in land elevations. Which of these have been most important to the evolution of the Hawke's Bay coast, through their effects on the quantities of sand and gravel found on its beaches and the capacity of the tides and waves to damage properties by erosion and flooding during storms? Answering this question is often the underlying objective of research undertaken by scientists and engineers, on a worldwide basis and specifically in studies of Hawke's Bay.

3.4 RESEARCH INTO THE CHANGING ENVIRONMENTS OF HAWKE'S BAY

Hawke's Bay is fortunate to have had several citizen-naturalists over the years who focused their investigations into the region's physical environment and how it has changed over the centuries, and into the causes of those changes. It is surprising how early this interest was aroused, even during the settlement period of the 19th century, through the environmental observations by William Colenso and the investigations of H. Hill who was interested in the causes of the extreme floods experienced during that period and the long-term formation of the Heretaunga Plain.

As noted above, Colenso was the first missionary to be stationed in Napier, having arrived in 1844. Common to that period, as well as having been a missionary he was also a naturalist, with his contributions eventually recognized in his having been elected a member of the prestigious Royal Society of London. Most important, his role as a missionary required that he travel throughout Hawke's Bay to visit his "flock", the Maori, recording in his journals the earliest accounts of the physical and biological environments of this region. For example, in his first crossing of the Ruahine Range in February 1845 by way of the Waipawa and Makaroro Rivers, he observed that the narrow, steep stream beds were: ". . . partly choked with dead trees and shrubs, and masses of stones". Later during this same crossing he commented that the:

. . . fine forests of *Fagus* on the top, the trees of which were continually falling down along with earth into the river beneath. Here and there an immense mass of earth had slipped quietly down the upright cliffs bringing the large trees with it.

As will be reviewed below, more than a half century later Grant (1965) was to repeat these observations of the disrupted forests and active erosion in the upper watersheds of the Waipawa and Tukituki Rivers, noting these early descriptions made by Colenso as evidence for their age. Grant went on to conclude that disruption of the forests must have been caused by an intensification of storms prior to European settlement.

Colenso also influenced his contemporary, H. Hill, who shared a mutual interest in the natural environment. In Hill's 1897 published paper, he commented on his meeting and discussions with Colenso, and quoted directly from Colenso's journal concerning the extent of changes on the Heretaunga Plain (Hill, 1897, p. 521):

I have mentioned the trackless mountain forests of the Ruahine Range, but, if anything different, some of the open swampy plains near the sea in Hawke's Bay were worse . . . all but impassable. I have often of late years asked myself, when contemplating from the hill [Scinde Island] the rising township of Napier and the inland grassy plains, with their many houses, gardens, and improvements, which of the two wonderful alterations — the building of the town of Napier or the great transformation of those swamps — I consider the most surprising, and I have always given it in favour of the plains.

Of interest is Colenso's reflection on the extent of the modifications of the Hawke's Bay environment during the first half century of European settlement. This was also a prime interest of Hill in his 1897 paper, specifically the impacts of deforestation in the watersheds as a partial cause of the major floods that had been experienced in the rivers that cross the Heretaunga Plain.

To my knowledge, the paper written by Hill that appeared in the *Transactions New Zealand Institute* in 1897 was the first scientific publication that dealt with the Hawke's Bay physical environment. His specific interest in that paper was the major floods on the rivers that occurred in April 1897, together with assessments of the importance of such floods in the geologic development of the Heretaunga Plain. That flood had major consequences to the physical environment and to the settlers. According to Hill (1897, p. 524): ". . . the country, and Napier in particular, has to deplore the loss of life and property beyond anything previously experienced in the history of settlement in Hawke's Bay." During the thirty hours of the storm 21 inches of rain fell in some areas of the basin, and the resulting floods in the rivers spilled over the banks of the channels, carrying with it large quantities of sediment derived from the erosion of the upper watersheds. Hill documented that 3 to 4 feet of sediment had accumulated in places, while hundreds of acres were covered with silt to a depth of 18 inches or more. The extent of the re-sculpting of the land by this single flood induced Hill to reflect on the long-term formation of the Heretaunga Plain as having been the product of such floods spanning thousands of years (Hill, 1897, p. 520):

We have fifty years of unbroken history in the settlement of this district, and the changes that have come over the facies of the plain during this period must be set down as very great and striking. The flood that was so disastrous in April [1897] is not exceptional or even unusual, and we may look for a recurrence with as much certainty as we look for changing seasons. That the plain is growing at a rapid rate there is certain proof.

Hill (1897) recognized that the Plain is not limited to the area exposed on the land, but instead continues under water, with it having an equal area offshore to that seen on the land.

He concluded that most of the material forming the Plain had been brought down by the rivers, mainly during floods, and that the modern beach is a separate entity from the materials otherwise forming the Plain (Hill, 1879, p. 519): "The shingle beach that now forms such a characteristic feature along the coast between Tangoio and the Kidnappers really forms no portion of the plain." Hill calculated that the Heretaunga Plain contains 40,397,870,000 cubic yards of sediment derived from the rivers. He estimated that the volume of water contained in the April 1897 flood, based on the average rainfall and areas of the watersheds, was on the order of 1,790,000,000 cubic yards. With an assumption that "one part in every two hundred by volume was sediment", he then estimated that the flood brought down 8,960,000 cubic yards of sediment, silt through gravel. This finally led him to the conclusion that if this quantity of sediment was delivered on average by the rivers each year, it would have taken 4,515 years for the Heretaunga Plain to have formed. This is certainly a gross underestimate of the total age involved in the formation of the Plain, but one can still admire Hill's attempt at making this estimate.

Hill (1897) also considered the geomorphology of the Plain as a reflection of its formation by floods. Having recognized that most of the material forming the Plain had been brought down by the rivers, he focused on the regional slopes of the land to document how the sediments carried by the rivers "spread out fan-like over the bay." His analyses of the land and channel slopes led him to conclude that a relatively marked change in slope midway across the Plain has been important to the movement of sediments from the steep slopes of the upper watersheds to the lower watersheds and bay (p. 526):

These waters for the greater part of their course are swollen by numerous mountain streams, and they reach the plain at a rate which makes it impossible for the beds in the lower course to carry them away without spreading over the plain. Being full of sediment, deposition begins at once; the beds become partially silted, and a deltoid area is formed in the direction of the general flow to the sea.

As will be reviewed below, Grant (1965) also recognized the significance in the change in slopes as a factor that controls the accumulation of sediment in the middle reaches of the Tukituki River, contributing to its flooding, while decreasing the quantities of coarse-grained sediments that are able to reach the coast.

Perhaps the most interesting aspect of Hill's (1897) study is his almost modern-day environmentalist concerns about the impacts humans have had on the Heretaunga Plain. In particular he recognized the importance of human environmental modifications on the discharges of the rivers and quantities of sediment eroded (Hill, 1897, p. 523):

The diminution of forest lands, clearing, burning, and grassing of fern lands, and the drainage of swamps, have increased the tendency to quicker movement of the surface waters, and every act of the settler as he moves further and further back towards the watershed of the country operates in a like manner.

Continuing this theme and making recommendations as to the management of the rivers to minimize these impacts, Hill (1897, p. 526) wrote:

The bush is rapidly disappearing from within the basins of each river under notice, and the very mountains are losing, in many places, their capping of vegetable soil. . . Denudation under such conditions is most rapid, and the scour in the rivers will increase in intensity unless the settlers themselves replace in certain areas what has been in too many cases wantonly destroyed. I refer to the destruction of scrub and small bush areas. Planting along the banks of rivers and streams is becoming a necessity, and were this carried out in the upper parts

of the river-basins in Hawke's Bay it would be one sure and economical way of retarding the flow of water into the rivers at times of excessive rainfall.

Hill (1897) argued against the construction of embankments or levees to confine the floodwaters to the river channels, based on the results of such practices on European rivers. He noted that the result there, in some cases having been initiated as early as Roman times, is that the river channels are now perched well above their flood plains and that ". . . the danger of such a scheme must ever be on the increase." With respect to the Hawke's Bay rivers, another argument offered by Hill against embankments was (p. 528): "Here the difficulty is not merely one of an over-supply of water, but an over-supply of sediment." He instead repeated his recommendation (p. 528):

Planting along the main streams and the numerous tributaries has become a necessity, and this should form a part of any river-conservation scheme, otherwise there will certainly be more marked changes in the coming years over the Heretaunga Plain than even the past half-century has shown.

Hill also recommended that the lower courses of the rivers be rerouted so their mouths are located at the bay's shore south of Napier, known as the "washout", which had been weakened by the extraction of beach gravel for the construction of the railway line (Hill, 1897, p. 529): "I have named this place because there is no other along the whole line of beach so weak and yet so possible to control." Part of this "control" involved the ability to keep the river's mouth open, to prevent its blockage by the ocean's waves building up a gravel ridge.

In conclusion, Hill (1897) adopted a holistic view of the management of the Hawke's Bay rivers (p. 530):

When people are made aware that floods are certain to occur, they should anticipate the danger in the construction of their homes, the arrangement of their fences, the planting of their trees, and the direction of their drainage. Information bearing on these important matters should be supplied to settlers either by Government or Conservancy Boards, and, above all things, the drainage over the entire district should form part of a connective whole, no settler being permitted to drain his land except on one general and approved plan, devised for the common good.

To some degree Hill's recommendations have been followed in the years up to the present, such as the planting of vegetation to reduce the extent of water runoff and sediment erosion in the upper watersheds of the rivers, with some areas having been fenced to prevent animal grazing. Efforts have been directed toward controlling the courses of the rivers as they cross the Heretaunga Plain, and to maintain their mouths open to the sea. However, in spite of Hill's arguments, the management of the Hawke's Bay rivers has included the construction of embankments (stopbanks) to reduce the flooding of adjacent lands.

Another significant contributor to understanding the Hawke's Bay watersheds and rivers was Patrick Grant, who wrote a series of papers from 1965 to 1985 (Grant, 1965, 1982, 1983, 1985); in 1996 he summarized his research in the book *Hawke's Bay Forests of Yesterday*. He undertook these studies initially as a hydrologist with the Hawke's Bay Catchment Board, and later with the Water and Soil Division of the Ministry of Works and Development in Napier. His interests focused on the evidence for enhanced erosion in the upper watersheds of the rivers and the concurrent accumulation of sediments forming flood deposits and fluvial terraces in the lower watersheds, which he then related to climate periods having more intense storms.

In his 1965 and 1982 papers, Grant investigated the watershed of the Tukituki River and found evidence for a major episode of erosion and sediment transport dating back to

approximately AD 1650. He had earlier recognized this event in the Huiarau Range to the north, and it had also been recognized in the watersheds of the rivers that flow into Poverty Bay. In all of these areas, including the upper watershed of the Tukituki River, the forests were greatly devastated by downed trees, probably by gale-force winds, and this was immediately followed by a relatively short period of intense erosion that supplied gravel to form terraces in the middle reaches of the rivers. The dating of this event to AD 1650 by Grant (1965) was based on the ages of the trees that had been downed by the gale, and the ages of the trees that were the primary colonizers of the newly-formed terraces. He named this event, and the sediments it deposited, the Matawhero. The Matawhero gravels found in the terraces formed by that event are gray, clean, and obviously little weathered, and the surface soil is only weakly developed. Major bank overflows occurred along the middle section of the Tukituki River, resulting in the extensive deposition of alluvium. It was clear that this must record a significant climate event, a major storm or series of storms that affected a large area of at least the eastern North Island, storms that were responsible for the disruption of the forests, followed by extensive erosion in the upper watersheds and the transport of that sediment by the rivers to the lower watersheds.

The history of erosion and sediment transport in the Tukituki River that occurred following AD 1650 was determined by Grant (1965) on the basis of the gravel that had been deposited on top of the Matawhero sediments. In the upper watershed he identified traveling bedload "waves" that were large and produced intermittent bed aggradation. He associated their development with high-intensity rain storms that again damaged the vegetation, resulting in the enhanced supply of rock waste to the channels. Along the middle section of the river, he found 3 to 4 feet of gravel accumulation atop the Matawhero deposits, providing clear evidence for significant channel aggradation at some time since 1650. Based on the observations of Colenso describing the forests during his crossings of the Rhauhine Range in February 1845, quoted above, Grant (1965, p. 23) determined that: "No matter what the cause, the conclusion is inescapable that much of the scarring we see today on the Ruahine Ranges had its origin before the time of extensive European settlement and the introduction of animals." From this Grant concluded that there is a reasonable basis for proposing that the unstable cycle of erosion in the upper Tukituki watershed began a little before 1800. He further concluded that the sediment aggradation in the middle reach of the river had resulted from increased flood sizes, producing increased bedload quantities and overflow events, but that the floods had insufficient discharges and flow energies to carry the sediment through the lower reach of the river (p. 26):

No matter what the cause, aggradation was certainly initiated some time after the Matawhero deposition of 1650, possibly around 1800-1850, and general indications are that the tendency to aggrade in the portion of the middle section still exists. In essence the middle section functions as a storehouse for much of the alluvium from up-river.

In essence this is comparable to the conclusion of Hill (1897) where he noted that due to the significant reduction in the slopes of the river, sediments that had been eroded from the upper watershed were deposited, resulting in aggradation along the middle stretch of the channel length, the discharges not generally having the competence to transport the coarse sediments the full length of the river such that it does not reach the coast.

Continuing his analyses to examine the possible regime changes in the Tukituki River, Grant (1965) provides a table (p. 22) that demonstrates the occurrence of progressively increasing channel widths (from 239 to 330 feet) and mean bed levels from April 1955 to April 1965. He further concluded that this high rate of erosion could not have existed all the way back to 1650, otherwise the Matawhero deposits would have been entirely eroded away, and it is not even likely that this high rate of erosion extended back to the 1800s. Grant instead suggested that this accelerated erosion began in the 1930s and became pronounced in the late 1940s. At Red Bridge in the lower section of the Tukituki River just upriver from its

mouth, flood records for the period 1917 to 1964 analyzed by Grant (1965), led him to conclude that the Matawhero surface had been inundated on at least 12 occasions. Subsequent to a major flood in 1917, which had a peak discharge of about 130,000 cusecs, the channel width has decreased and the channel had cut down to basement rock. From this Grant concluded (p. 27):

Since some time after 1917, bed loads in the upper and middle sections have increased but the bulk has been trapped in middle reaches. As a consequence, lower reaches have received "undersized" bed load quantities and these have been either readily transported in the deep meandering channels or deposited laterally to increase the width of the Modern accumulations.

In connection with these recent changes in the river regimes, Grant (1965) noted that there appeared to have been a change in the type of storms experienced in Hawke's Bay, that infrequent intense storms affecting a small area were more common so that only one catchment tended to flood at any given time.

In his paper published several years later in 1985, Grant continued his analyses of changes in river regimes, relating them to possible shifts in the climate, but in the intervening years he had expanded his consideration to rivers found throughout New Zealand. Based on those analyses he identified eight major periods of erosion and alluvial sedimentation that had occurred during the last 1,800 years: Taupo (1,764 years BP), Post-Taupo (1,600-1,500 years BP), Pre-Kaharoa (1,300-900 years BP), Waihirere (680-600 years BP), Matawhero (450-330 years BP), Wakarara (180-150 years BP), Tamaki (AD 1870-1900), and Waipawa (1950 to the present). The Taupo period was identified only on the North Island, and was interpreted by Grant as possibly having resulted from heavy rainfalls induced by the Taupo Pumice eruption. The other seven periods were identified on both the North and South Islands, and it was concluded that they were caused by periods of increased northerly airflow and atmospheric warming over New Zealand, which should have resulted in increased magnitudes of major rainstorms and floods that would have produced the observed increased rates of erosion and sediment transport. Such changes in the climate were interpreted as having been related to a temporary strengthening of the meridional upper atmospheric circulation in the Southwest Pacific region. Grant also concluded that the total amount of sediment eroded and transported during these successive erosion periods has generally decreased, even though since circa 1,000 years BP human populations and their impacts on the environment have generally increased.

Grant's 1982 paper differed from his others that had dealt primarily with climate-induced changes in the river regimes; it instead provided analyses of the floods and erosion that were generated in the Tukituki River watershed by cyclone Alison in March 1975. That study focused on the Waipawa River, the north branch of the Tukituki, in the upper-most reaches of its watershed in the Ruahine Range. The bulk of the sediment from erosion in that area of the watershed came from exposed, highly shattered bedrock. Grant undertook comparisons, using aerial photographs of the area before and after cyclone Alison, to establish that the areas supplying sediment represent 22% of the North Branch drainage and 55% of the Armstrong tributary. Surveys were obtained at multiple cross sections along reaches of the channels to determine the volumes of sediment that had accumulated at the time of the cyclone. The Alison deposits overlay a bed of much coarser material so could be clearly distinguished. Analyses of the deposited sizes larger than 8 mm yielded a median of 38 mm and D_{90} of 891 mm. The surveys established that the cyclone had transported more than 44,400 m³ of sediment, representing a specific yield of 28,000 m³/km² of drainage area. From this Grant estimated that the average annual sediment yield for the North Branch is 4,500 m³/km² per year, which he considered "realistic" but still likely to be a conservative estimate. Of particular interest were the results of his comparisons with other river watersheds, concluding that the coarse-sediment yield from the upper branches of the Waipawa River may be one of the highest, if not the highest, in New Zealand. Furthermore,

the values also far exceeded those reported for California, Japan, the Alps, Himalayas and Papua-New Guinea; they were comparable only to those reported for Taiwan. These high sediment yields can be attributed in large part to the geology of the Ruahine Range, with its highly shattered bedrock that is easily eroded. Because of this, following an erosion event that transports the available sediment away, there is a very rapid replacement of the loose sediment supply, mainly by renewed bedrock erosion; Grant (1983) established that replenishment had occurred within 11 months after cyclone Alison.

3.5 SUMMARY AND DISCUSSION

Of interest in this Section has been the history of human settlement in the Hawke's Bay region, first by the Maori in about AD 1300 and then by Europeans that began in about 1830. An awareness of this history can be important to the present-day management of the Hawke's Bay coast, specifically through the impacts we have had on the physical environment of this region. These impacts have been wide ranging, having included the deforestation of the watersheds, the subsequent grazing of cattle on those cleared lands, the extensive modifications made to the rivers including the mining of sand and gravel, and the construction of levees (stopbanks) to prevent flooding of the new agricultural and urban lands. As recounted here, the low-lying nature of the Heretaunga Plain renders the lower reaches of the rivers prone to flooding. This flooding would have been exacerbated by the clearing of the forests, initially by the Maori but particularly following the arrival of Europeans who needed grasslands to graze their sheep and cattle. Researchers have shown that the deforestation of watersheds leads to increased water runoff which enters the streams and rivers, significantly increasing their discharges, and that the cleared land is significantly more prone to erosion and landslide development, supplying substantially larger quantities of sediments that are transported by the rivers [e.g., Beschta, 1978; Harr et al., 1982; Komar et al., 2004]. Although this has not been specifically documented through research in the Hawke's Bay watersheds, deforestation there by human activities undoubtedly has had the same consequences.

Research undertaken by Patrick Grant in the Hawke's Bay watersheds has demonstrated that variations in New Zealand's climate have also greatly affected the forests through periods characterized by extreme storms that episodically downed trees throughout the country. Specifically in Hawke's Bay, Grant showed that these periods of storm impacts on the forests immediately resulted in greater rates of erosion of the upper watersheds, and the transport of increased quantities of sediments down streams where they were eventually deposited to aggrade the rivers and form fluvial terraces in the lower watersheds. The conclusion is that there have been significant changes in the Hawke's Bay watersheds, due both to natural variations in the climate and caused by human impacts that resulted in the loss of large areas of forest lands. On the whole these changes in the forests have resulted in increased rates of erosion in the watersheds that supplied greater quantities of silt, sand and gravel that was transported down the rivers. According to the research results of Grant (1982), these quantities could have been substantial due to the geology of the Ruahine Range where the rocks are highly shattered and easily eroded, the sediment yields being greater than found in most other watersheds throughout the world.

In spite of these large quantities of sediments being eroded from the Hawke's Bay watersheds and transported down the rivers, the investigations of both Hill in 1897 and by Grant during the 20th century found that much of this sediment has been deposited along the middle reaches of the rivers, where there is a sufficient change in channel slope that the coarser gravel cannot be transported any further, while the smaller-sized gravel, sand and silt continues to be carried to the mouths of the rivers where it enters Hawke Bay. As will be examined in Section 7, this has had consequences to the supply of gravel to the Hawke's Bay beaches. The aggradation in the middle reaches of the rivers has also had consequences to

increased flooding in these rivers, such that the commercial extraction of the gravel has been viewed as a positive management strategy to reduce the river flooding.

The mining of gravel and sand from the rivers is likely to have reduced their quantities reaching the bay's beaches, a negative consequence. As related here, there is considerable anecdotal evidence also for the historic mining of the beach sediments, including that needed for the bed of the railway line. Even today there is active commercial mining of beach gravel and sand at Awatoto that annually removes tens of thousands of cubic metres. Any sediment extraction, whether from the rivers or after the sediment has reached the beaches, can significantly alter the "budget of beach sediments", the balance between the contributions by the sediment sources versus the various losses after the sediments have reached the beaches; the sediment budgets developed for the Hawke's Bay beaches will be reviewed in detail in Section 7.

The harbour development in Napier, which involved the construction of the moles in 1876-1879 to control the entrance to the Ahuriri Lagoon and then the Port's breakwater in 1887-1890, may also have resulted in environmental impacts, particularly if those structures blocked a natural longshore transport of the beach sediment by the ocean waves and currents. An assessment of those possible impacts is more involved as it includes analyses of the ocean waves and currents, so its consideration has been deferred until Section 6.

3.6 REFERENCES

- Beagleshole, J. C., editor (1955) *The Voyage of the Endeavour 1768-1771: Volume 1*, Hakluyt Society, Cambridge, England.
- Beschta, R. L. (1978) Long-term patterns of sediment production following road construction and logging in the Oregon Coast Range: *Water Resources Research*, v. 14, p. 1011-1016.
- Campbell, M. D. N. (1975) *Story of Napier, 1874-1974 (Footprints Along the Shore)*: Published by the Napier City Council, 252 pp.
- Chambers, John H. (2004) *A Traveller's History of New Zealand and the South Pacific Islands*: Interlink Books, 400 pp.
- Gibb, J. G. (1996) *Coastal Hazard Zone Assessment for the Napier City Coastline between the Ahuriri Entrance and Esk River Mouth*: Report prepared for Napier City Council, C.R. 96/2, 80 pp.
- Grant, P. J. (1965) Major regime changes in the Tukituki River, Hawke Bay, since about 1650: *Journal of Hydrology (New Zealand)*, v. 4, n. 1, p. 17-30.
- Grant, P. J. (1982) Coarse sediment yields from the Upper Waipawa River Basin, Ruahine Range: *Journal of Hydrology (New Zealand)*: v. 21, p. 81-97.
- Grant, P. J. (1983) Recently increased tropical cyclone activity and inferences concerning coastal erosion and inland hydrology regimes in New Zealand and eastern Australia: *Climatic Change*, v. 3, p. 317-332.
- Grant, P. J. (1985) Major periods of erosion and alluvial sedimentation in New Zealand during the Late Holocene: *Journal of the Royal Society of New Zealand*, v. 15, n. 1, p. 67-121.

- Grant, P. J. (1996) *Hawke's Bay Forests of Yesterday*. Touchwood Books, Box 610, Hastings 4221, New Zealand.
- Harr, R. D., A. Levno, and R. Mersereau (1982) Stream-flow changes after logging 130-year-old Douglas Fir in two small watershed: *Water Resources Research*, v. 18, p. 637-644.
- Harvey, Judge J. (1948) Report and recommendation on Petition No. 240 of 1932, of Hori Tupaea and four others, praying for relief in connection with Whanganui-O-Rotu (or Napier Inner Harbour) and their right of property therein: Memorandum for the Right Hon. the Minister of Maori Affairs, Maori Land Court, Wellington, 91 pp.
- Hill, H. (1897) Hawke's Bay plain: past and present: *Transactions New Zealand Institute*, v. 37, p. 515-537.
- Komar, P. D., J. McManus and M. Styllas (2004) Sediment accumulation in Tillamook Bay, Oregon: Natural processes versus human impacts: *Journal of Geology*, v. 112, p. 455-469.
- McFadgen, B. G. (1979) The antiquity of man at Lake Poukawa, New Zealand: *Journal of the Royal Society of New Zealand*, v. 9, p. 375-382.
- O'Callaghan, R. B. (1986) *Report on the Coastal Protection of Westshore Beach, Napier*. 11 pp + diagrams.
- Parsons, P. (1995) *Ahuriri Estuary and Surroundings. Places of Spiritual Significance to the Maori*: Unpublished Report to Napier City Council, 35 pp.
- Price, T. R. (1963) Moa remains at Poukawa, Hawke's Bay: *New Zealand Archaeological Association Newsletter*, v. 6, p. 169-174.
- Reed, A. H. (1958) *The Story of Hawke's Bay*. published by A. H. & A. W. Reed, Wellington, 312 pp.
- Stevenson, H. K. (1977) *Port and People: Century at the Port of Napier*. Hawke's Bay Harbour Board.

4 Ocean Processes in Hawke Bay: Waves, Tides and Changing Sea Levels

4.1 INTRODUCTION

Important to understanding the physical changes observed on the coast, including those that have resulted in erosion problems, is the collection and analysis of data for the range of ocean processes — tides, storm-surge generation, wave heights and periods, and in the longer term the local relative change in sea level. Furthermore, assessments of the hazards to shore-front properties include considerations of the potential for the impacts by tsunami waves. The objective of this section is to review the availability of such data for Hawke Bay to assess whether the programs of measurement have been sufficient to serve as the basis for analyzing the causes of shoreline change and erosion. Closely related is an examination of how the processes interact during storms to yield combinations that potentially result in beach erosion and represent significant hazards to shore-front properties. This includes analyses of the wave energies and swash runup levels on the beaches calculated from storm wave heights and periods measured in the offshore, and assessments of potential storm surge elevations that raise the measured tides above the predicted astronomical tides; it is the combinations of these processes in the nearshore that act to erode and overtop beaches, representing the primary natural hazard to coastal developments.

4.2 PREDICTED AND MEASURED TIDES

Tides are a significant factor that affects beach and property erosion through its control on the mean water levels, above which waves break and swash up the beaches. Whether or not a storm results in beach erosion and property damage can depend on the timing of the occurrence of the highest storm waves, reaching the shore coincident with the high tide rather than at low tide which would minimize the damage. Tides are the most significant factor affecting variations in mean water levels along the New Zealand coast; overall, they account for 96% of the variation (Goring, 1997). Other oceanic and atmospheric processes give rise to the remaining 4% of the variation. These include the surge created by the winds and lowered atmospheric pressures of a storm, which can raise the measured tides above predicted levels by on the order of a metre, and therefore could play a significant role in the resulting coastal erosion and flooding.

The tide is the periodic rise and fall in the level of the sea during the span of a day, caused by the gravitational attraction of the Moon and Sun on the ocean's water, with the resulting tidal variations affected by the rotation of the Earth on its axis. As such, they are the "astronomical" or predicted tides, based on analyses of the relative motions of the Earth, Moon and Sun, but with the resulting tidal responses made complex by the irregular depths of the ocean. When predicting the tides along the coast, they are also strongly influenced by the irregularities of the shoreline, including the presence of bays and capes. In spite of such complexities, model predicted tides are generally close on average to the measured tides, so we have reasonably good predictions of the astronomical tides around the coasts of New Zealand (Walters et al., 2001).

New Zealand's tides are semidiurnal, that is, there are two high tides per day having nearly the same heights, separated by low tides that similarly have nearly the same levels. However, the tides vary considerably from place to place along the coast, in both their amplitudes and in their general patterns of varying water levels. There is a monthly variation in tidal ranges, but this pattern of change differs markedly between the west and east coasts of New Zealand. On the west coast there is a monthly variation of spring tides when the range is greatest, and neap tides when the range is lowest, the spring tides occurring when the forces of the Moon and Sun are aligned to reinforce one another (that is, at times of full and new Moon), while the neap tides occur when the forces of the Moon and Sun oppose one another. This is the pattern and cause of spring-neap monthly variations in the tides generally found throughout the world's oceans. The monthly variations in the tides on the east coast of New Zealand differ in their timing and origin. As seen in Figure 4-1 for the tides measured by the Port of Napier's tide gauge during January 2000, there is the usual semidiurnal cycle with two highs and two lows each day, one high tide reaching to a slightly higher elevation than the other (there being a small diurnal inequality). The monthly cycle is also apparent in this example, with the highest tide of the month being about 0.5 metre higher than the lowest tide. However, unlike the normal pattern of monthly tidal variations found on the west coast, there is not a correspondence with the astronomical alignment of the Moon and Sun; the highest tides do not occur during full and new Moon when their forces combine. The monthly variation on the east coast seen in Figure 4-1 is instead produced by the varying distance of the Moon from the Earth, this distance determining the force of attraction by the Moon on the Earth's ocean water, being greatest when the Moon is closest to the Earth at perigee in its monthly orbit, resulting in the highest tidal range (Goring, 1997). The lowest tidal range occurs at apogee, when the Moon is farthest from the Earth. Every seven months the full or new Moon coincides with the Moon's perigee, and this produces somewhat larger than normal perigean spring tides, the highest predicted astronomical tides of the year.

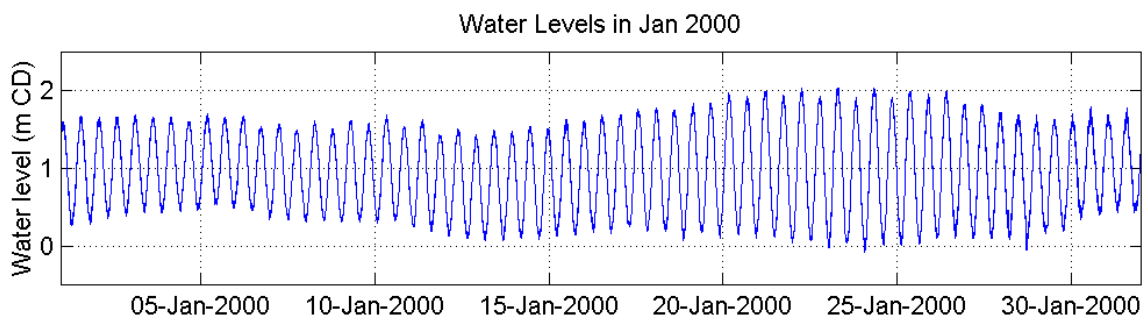


Figure 4-1 Tides measured by the Port of Napier gauge during January 2000. [from Worley (2002a)]

Table 4-1 lists the water-level statistics for the predicted astronomical tides at Napier as published in the *New Zealand Nautical Almanac*, based on harmonic analyses of the measured tides to determine their primary tidal constituents (As expected, the M2 semidiurnal constituent dominates the signal). The water levels listed in Table 4-1 are related to two elevation datums: the Chart Datum (CD) is that generally used in reporting tidal elevations and water depths, while the LINZ datum is relative to mean sea level (MSL) and is employed in land surveys — the two differ by 0.95 metre. It is seen that the mean high water at the time of spring tides (MHWS), 1.91 metres CD, is on average 0.35 metre higher than during neap tides (MHWN). The range of the tides, based on the difference between the mean high spring tides (MHWS) and spring lows (MLWS) is about 1.9 metres. The highest predicted astronomical tide (HAT) of the year is 2.00 metres CD, this also being the full tidal range for Napier. Having these tidal ranges, the Hawke Bay tides are classified as "microtides" by Davies (1964), only just reaching the "mesoscale" range at their maximum. Therefore, the ranges of tides experienced in Hawke Bay are modest compared with the tides on most other coasts.

Table 4-1 Predicted astronomical tides for Hawke Bay.

<i>Tidal Level</i>	<i>LINZ (metres)</i>	<i>Chart Datum (metres)</i>
HAT	1.05	2.00
MHWS	0.96	1.91
MHWN	0.61	1.56
MSL	0	0.95
MLWN	-0.56	0.39
MLWS	-0.93	0.02
Chart Datum	-0.95	0

The tide statistics in Table 4-1 for Napier are the predicted astronomical tides. The general experience is that the actual measured tides on any give day are somewhat different, sometimes significantly so, being either higher or lower than predicted. Of concern for coastal erosion and flooding are occurrences when the measured tides are substantially higher than predicted. This can happen in particular at the time of a storm, when the elevated water is created by the winds and low atmospheric pressures at the center of the storm, which can combine to pile water up along the coast as a storm surge. The surge usually reaches significant levels for only a day or two at the height of the storm, but can persist for several days depending on the duration of the low pressures and winds, and the rate at which the storm passes through the area.

On average, 50% of the storm surge elevations experienced along the New Zealand coast are produced by the lowered atmospheric pressures of the storm's center, the other 50% being caused by the strong winds of the storm (de Lange, 1996). The atmospheric pressure component is generally termed the "inverse barometer effect", wherein the sea surface elevation increases by 0.01 metre for a decrease in atmospheric pressure of 1 millibar. This correlation is based on a static response of the sea level to the reduced atmospheric pressure at the center of the storm's cyclonic rotation. However, the dynamic effects of a moving storm system can alter this correlation, shown by Goring (1995) in his analyses of storm surges recorded on tide gauges around the coasts of New Zealand; included in his analysis were tides measured by the Port of Napier's gauge from September 1986 through December 1988. In general, Goring found that the storm surge response depends on the exposure of the site to the predominant westerly winds, such that along the west coast the response was higher than the inverse barometer static correlation, whereas along the more sheltered east coast the response was generally smaller. However, during some events on the east coast, Goring found that the response could be greater. To further complicate matters, cases were found where the storm surge occurred in advance of the arrival of the storm itself, and in a few cases the storm surge displayed a secondary peak following the passage of the low-pressure system. Such unusual responses have been interpreted as resulting from the generation of coastal-trapped waves, apparently produced by the alongshore-directed winds of the storm. Such a coastal-trapped wave is in effect a long period bulge in the level of the sea that is held against the coast by refraction over the sloping continental shelf, and its movement is also affected by the Earth's rotation (the Coriolis force). Such surges have been observed along both the east and west coasts of New Zealand, moving southward along the west coast and northward along the east coast (Heath, 1979; Stanton, 1995). If they correspond to the path of the storm that generates them, they can amplify the rise in the water level directly associated with the low atmospheric pressure and winds of the storm, but the trapped wave can also travel along the coast independently of the storm.

It has been found that when the measured tides are averaged each month, thereby removing the variations due to the predicted tides, there are changes in the resulting averages from month to month amounting to about 0.2 metre, with the pattern of change generally following the seasons (Bell et al., 2000). These variations can be attributed in large part to the heating and cooling of the shallow water along the coast through the year, the higher temperature of the water during

the summer resulting in its thermal expansion so the water level is locally raised by some 0.2 metre above the colder water of the winter. Analyses of storm surges are generally taken as the difference between the measured and predicted tides, and therefore include this seasonal variation as well as the direct effects of the storm's winds and atmospheric pressures.

Analyses by de Lange (1996) of measured storm surges found that the maximum expected elevations for the New Zealand coast are in the range 0.8 to 1.0 metre, achieving those levels with return periods of 100 years or longer. Therefore, a value of 0.9 metre is commonly added to the MHWS tidal elevation to provide an estimate of potential storm surge elevations having a 1% probability of occurrence during a year. This is significant on the coast of Hawke's Bay where the predicted high tides are relatively modest, about 1 metre above mean sea level (Table 4-1), significant to the extent that the measured high tide elevated by a storm surge could be doubled to on the order of 2 metres above mean sea level. The effect on a typical Hawke's Bay beach is that the mean-water shoreline is advanced landward by some 15 to 20 metres, which at high tide brings the water much closer to shore-front properties so that the swash runoff on the beach of the waves generated by the storm are more likely to result in property erosion and flooding.

Detailed analyses by de Lange and Gibb (2000) of occurrences of storm surges measured between 1960 and 1998 by tide gauges in Tauranga Harbour on the Bay of Plenty have demonstrated decadal variations in response to cycles in the Earth's climate. In particular, they found that there was a marked shift in the magnitudes and frequencies of storm surges in about 1976; the period 1960-1976 showed a greater occurrence of storm surges compared with 1976-1998. They suggested that this change was a response to a shift in the Inter-decadal Pacific Oscillation (IPO), which reversed its phase in about 1976. A phase shift in the IPO includes a coherent change in sea-surface temperatures spanning the entire Pacific Ocean, affecting the paths of tropical cyclones in the southwest Pacific, and also represents a shift in the dominance of El Niños versus La Niñas between the separate phases; the 1960-1976 phase was dominated by La Niñas whereas El Niños prevailed during 1976-1998, with a return of La Niñas since 1998. Thus, there is an association between storm surges that are both more frequent and achieve higher elevations, and the IPO La Niña phase when there are more frequent storms. In discussing these results, de Lange and Gibb (2000) pointed out that the assessments of coastal hazards due to occurrences of storm surges have been largely based on measurements obtained from tide gauges during the post-1976 phase of the IPO when the magnitudes and frequencies of surges were reduced, so the results can be expected to under-predict the hazards during the opposite IPO phase. This distinction is significant in that climatologists have concluded that the IPO has again shifted its phase, so we have returned to a condition comparable to that in 1960-1976 with more frequent La Niñas, and once again can expect more frequent storms and occurrences of higher storm surges than experienced during the past 25 years.

The magnitudes of storm surges in Hawke Bay and the climate effects on their frequencies and magnitudes have received little attention by coastal scientists and engineers due to the availability of only a short record of tide measurements. Tide-level data have been collected by the Port of Napier with their Geddis Wharf tide gauge only since 1986, with electronic records available since February 1998. There are problems in the data prior to November 1998, having been recorded to only 1-centimetre resolution, with frequent spurious values, yielding trends that do not correspond to those found in the later improved measurements. Therefore, analyses of the Napier tide-gauge records are generally restricted to data collected since November 1998. Foremost of these analyses is that of Worley (2002a), which included measurements during the 4-year period from 1 November 1998 to 31 October 2002. The objective was to establish the process criteria to be used in the design of port facilities, with their analyses having included assessments of extreme waves and tides. The mean water level was calculated for each year from the measured tides, and was found to vary from 0.87 to 0.95 metre CD, which is reasonably consistent with the mean sea level of 0.95 metre CD for this site (Table 4-1). A tidal constituent analysis was undertaken of the same type employed to derive the predicted tides in Table 4-1, but the Worley analyses were limited to the one year, 27 May 2001 to 3 June 2002, the longest set of continuous measurements without missing data. However, of particular interest in this

analysis were the "tidal residuals", the portion of the water-level variation that is not accounted for by the astronomical tides, having resulted mainly from occurrences of storm surges. Eighteen storm surges were identified in that 1-year record when measured tidal elevations reached at least 0.75 metre higher than the predicted tide. The results of an extreme-value analysis of the residuals are listed in Table 4-2, showing that they are on the order of 0.9 metre, which is consistent with the results of de Lange (1996) based on his analyses of storm surges along the entire coast of New Zealand. As noted above, this value is commonly added to the predicted MHWS tide elevation (Table 4-1) to provide an estimate of potential storm surge elevations having a 1% probability of occurrence each year; for Hawke Bay this would yield 2.86 metres CD or 1.91 metres LINZ, that is, nearly 2 metres above mean sea level. As an alternative to provide a less conservative estimate of total water levels, Worley (2002a) undertook a joint probability analysis that combined the astronomical tides and tidal residuals. Based on 18,000 Monte Carlo simulations, effectively representing 1,000 years of simulated tides, the results in Table 4-2 were obtained for the Extreme Water Levels. Here the 100-year extreme is 2.70 metres CD (1.75 metres LINZ). Beyond that, Worley (2002a) also added 0.2 to 0.4 metre as the potential rise in sea level during the next 50 years, to obtain water levels in the range 2.9 to 3.1 metres CD (2.0 to 2.9 metres LINZ) used in their applications for the design of the Port of Napier facilities. These results are also applicable to analyses of potential extreme water levels on the Hawke's Bay beaches, important in assessments of the possible coastal erosion and flooding for the establishment of hazard zones (Section 7).

Table 4-2 Extreme-value assessments of tidal residuals (storm surges) and total water levels from a Monte Carlo simulation (*from* Worley, 2002a).

<i>Return Period</i>	<i>Residual (metres)</i>	<i>Extreme Water Levels (metres)</i>
5 years	0.87	2.58
10 years	0.89	2.62
25 years	0.91	2.65
50 years	0.93	2.68
100 years	0.95	2.70

4.3 GLOBAL AND LOCAL CHANGES IN SEA LEVELS

It is well recognized that important to the long-term evolution of the coast and to ongoing erosion problems is the global (eustatic) rise in sea level associated with the melting of glaciers and the thermal expansion of the ocean's water due to small increases in water temperatures. Related is the concern that global warming will produce an accelerated rate of sea-level rise during this century, greatly increasing the degrees of coastal erosion and flooding. These issues are important to Hawke's Bay, but are further complicated by land elevation changes produced by its tectonic setting. With respect to the coastal response, ultimately of significance is the "relative" sea-level change, the combination of the eustatic rise in sea level compared with the elevation change of the land. This variation in the relative sea level is generally determined for a site from long-term tide gauge records that respond to both the eustatic rise in sea level and the change in elevation of the land upon which the gauge is mounted. It is usually considered that at least 40 to 50 years of tidal records are required to establish an acceptable assessment of the local relative sea-level change. Unfortunately, as discussed above, tide-level data have been collected by the Port of Napier's tide gauge only since 1986, with higher quality electronic records available since February 1998, far short of that needed to establish the relative sea-level change. Lacking records of sufficient length, we can only look to studies elsewhere in New Zealand for assessments of sea-level change, which may be suggestive of its importance to erosion problems

in Hawke's Bay. We are interested in both the progressive changes in sea level spanning a century to thousands of years, as well as the year-to-year variations in mean sea levels that have been measured by New Zealand tide gauges.

Gibb (1986) has investigated the changes in sea levels along the New Zealand coast spanning the past 10,000 years. This time period reflects the global rise in sea level that began about 18,000 years B.P. (before the present) when the glaciers that had covered large areas of the continents during the Ice Age began to melt, returning water to the oceans. Data from throughout the world document that the sea level rose at a rapid rate up to about 7,000 to 5,000 years B.P., after which the rate of rise was much slower. This is also seen in the data collected by Gibb (1986) for the New Zealand coast, Figure 4-2, consisting of 82 radiocarbon dated sea-level indicators found on both the North and South Islands, though not specifically in the Hawke's Bay area. These sea-level indicators included beach-ridge elevations, shell beds deposited in estuaries, brackish carbonaceous mud, and peat layers. Gibb (1986) analyzed this data to separate out the eustatic world-wide component of sea-level rise from the local tectonic induced portion. The resulting sea-level graph for the regional eustatic sea-level change for New Zealand as a whole is presented in Figure 4-2. It shows that the eustatic sea level rose from about -34 metres below its present level 10,000 years ago, to about -9 metres at 7,500 years before the present. About 6,500 years B.P. the eustatic sea level approximately attained its present elevation, and according to Gibb's (1986) data has remained at that level with only small variations up to the present. His analyses also provided assessments of local tectonic uplift or subsidence; these are given in Figure 4-2 for the individual sites, and ranged from 0.1 to 0.3 metre per 1,000 years for the tectonic uplift, to -0.05 to -0.1 metre per 1,000 years for areas of subsidence. In general, these effects on the local relative change in sea level are in accord with the tectonic settings of the sites where Gibb (1986) obtained his data.

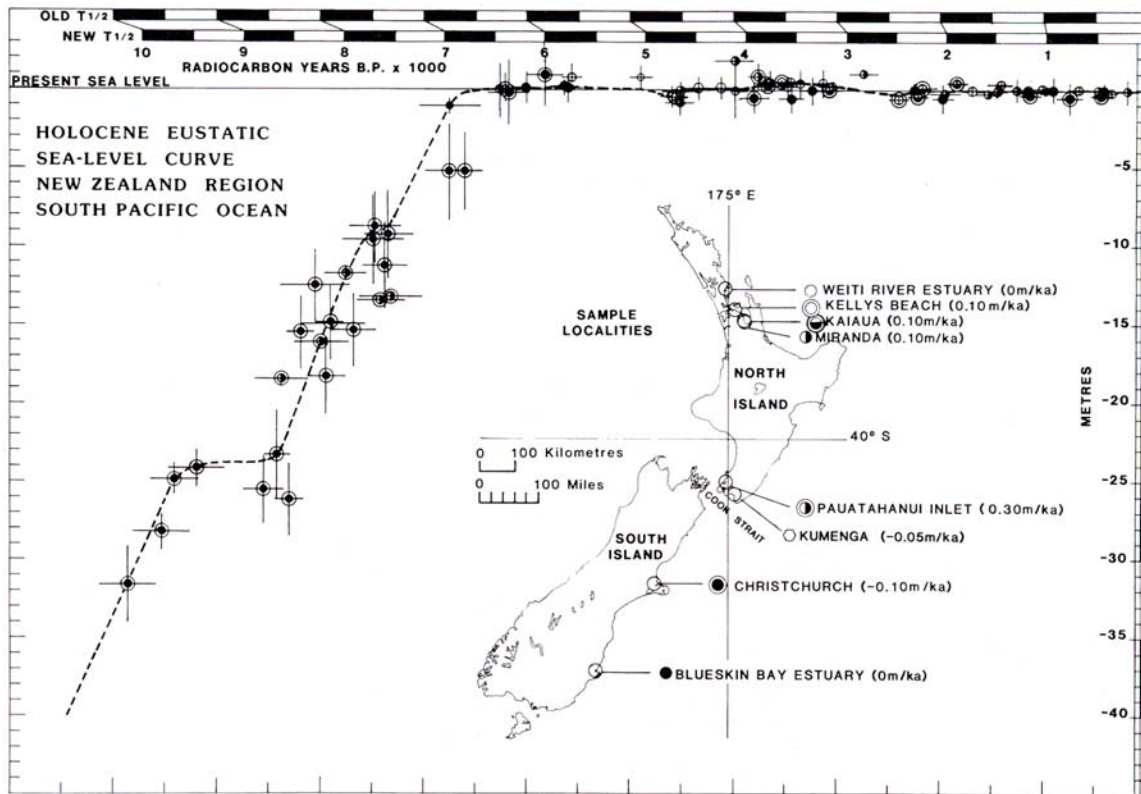


Figure 4-2 The regional Holocene eustatic sea-level curve for New Zealand, relative to its present level, compiled with data from the sites identified on the map. [from Gibb (1986)]

None of the sites included in the data analyzed by Gibb (1986) were on the east coast of the North Island. In contrast to the relatively stable sites he analyzed, it is likely that there has been some rise in the relative level of the sea along those portions of the Hawke's Bay coast that have generally experienced subsidence, particularly during the 3,500 years B.P. to 1,750 years B.P. time period identified by Hull (1986) in his study of peat layers on the western shore of the Ahuriri Lagoon (Section 2). A rise in relative sea level is also suggested by occurrences of waves having overtopped of the beach barrier ridges lining the shores of Hawke Bay, having occurred at times of storms prior to the 1931 earthquake, subsequent to which the uplift of the land has prevented further overtopping along most of the coast. Considering both the general trend of land subsidence and then its uplift by on the order of 2 metres during the earthquake, the relative sea level along the Hawke's Bay shore would have experienced major changes during the past 6,500 years when the eustatic level was otherwise relatively constant (Figure 4-2).

Gibb's (1986) sea-level curve indicates that about 10,000 years B.P. the level would have been about 30 metres lower than at present, and at that time the shoreline of Hawke's Bay would have been several kilometres to the east of its present position. There likely would have been a mixed sand-and-gravel beach at that time since the sediment sources would not have been significantly different from the present. However, the beach ridge 10,000 years B.P. would have been low in relief such that waves were able to overtop it during storms, carrying the beach gravel from the shore to the landward side of the ridge. This is the "rollover" response typical of beaches, particularly of coarse-grained beach ridges, resulting in their landward migration in response to the rise in sea level. That migration would have slowed with the cessation in the rapid rise in eustatic sea level 6,500 years B.P., but would have continued at a slow rate due to any long-term subsidence of the coast. It is probable that the barrier gravel beach ridge seen today along the shore of Hawke's Bay was effectively in place about 6,500 years ago, having experienced only a small landward shift in its position since that time. Boreholes sunk through the barrier between Napier and Ahuriri reveal that the gravel deposit is 25 to 27 metres thick, with an estimated 320 to 350 million cubic metres of gravel contained in the entire barrier along the length of Hawke's Bay (Gibb, 1996). Assuming that this volume accumulated in 7,000 to 7,500 years, Gibb calculated a net accumulation rate of 43,000 to 50,000 m³/year, representing an annual accumulation of 1.0 to 1.2 m³/year per metre of barrier length, a very low rate of net accretion of the beach barrier. As will be reviewed in Section 7 when we examine the sediment budgets that have been developed for the Hawke's Bay beaches, there are many complicating factors in this assessment such as the abrasion losses of the beach gravel.

In the shorter term, of greatest significance to the immediate problems with coastal erosion is the present-day rate of relative sea-level change, which has the potential of differing significantly from site to site due to their tectonic settings and related land elevation changes. The variation in relative sea levels spanning approximately the past century is generally determined from tide-gauge records, but this is not possible for Hawke's Bay due to the short span of available tide measurements. Such analyses have been undertaken by Hannah (1990, 2004) for tide gauges around the coasts of New Zealand, but there were only four gauges that yielded measurements of sufficient duration and quality: Auckland, Wellington, Lyttelton (Christchurch) and Dunedin. The resulting histories of mean annual sea levels since 1900 for those sites are graphed in Figure 4-3 from Hannah's 1990 paper. The Auckland data are significantly less "noisy" than collected at the other sites, which Hannah attributes in large part to the better maintenance history of that gauge. Hannah (2004) updated the analyses with the measurements extended to include the period 1989-2000, and also used improved analysis methodologies. His revised assessments for the rates of rise in relative sea levels from the four tide gauges are:

Auckland	1.30 mm/year
Wellington	1.78 mm/year
Lyttelton	2.08 mm/year
Dunedin	0.94 mm/year

The higher value for Lyttelton is attributed to the lack of data from very early in the century rather than being due to some localized tectonic effect. It is seen in the graphs of Figure 4-3 that the data for all gauges reveal higher trends of sea-level rise during the post-1930 era than found earlier, so lacking that early data for the Lyttelton gauge could account for its higher long-term average rate. The low rate of sea-level rise for the Dunedin gauge is attributed to its having suffered severe neglect in maintenance during the 1990s.

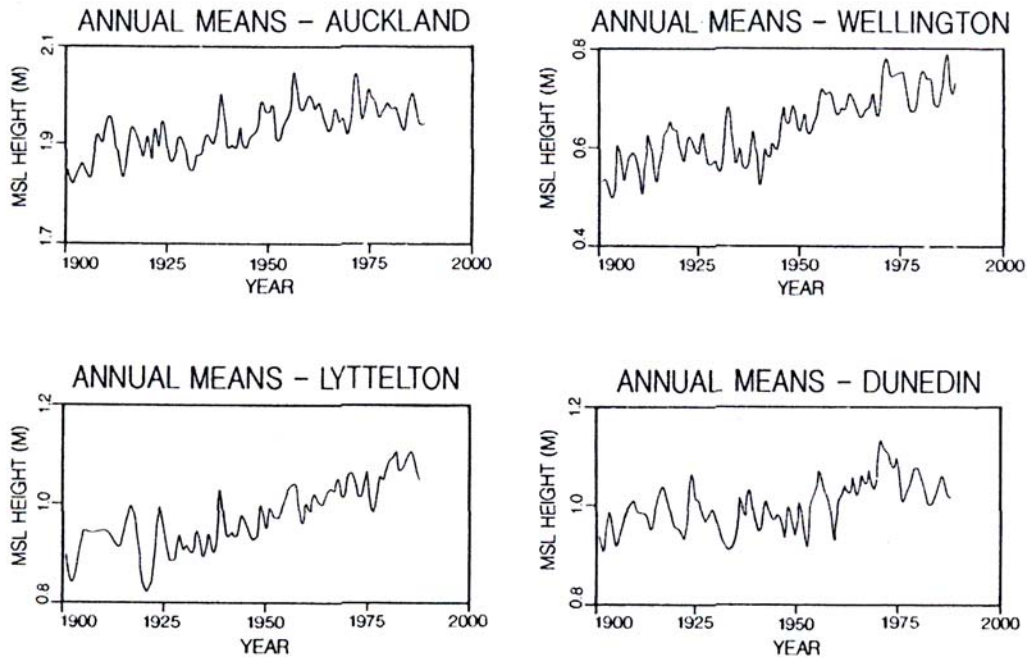


Figure 4-3 Annual mean sea levels derived from tide-gauge records. [from Hannah (1990)]

A simple average of the values for the four gauges yields a rate of relative sea-level rise of 1.53 ± 0.25 mm/year, but if less weight is given to the questionable results from Dunedin, a value of 1.61 ± 0.24 mm/year is obtained as best representing the average relative sea-level rise for New Zealand (Hannah, 2004). This rate falls close to the 1.43 mm/year "global" trend given by Barnett (1984) for the eustatic rise in sea level, based on analyses of tide gauges throughout the world. The reasonable uniformity of the results for the four sites in New Zealand is somewhat surprising, considering the complex tectonics of New Zealand. However, Auckland, Lyttelton and Dunedin are all located on relatively stable portions of the Australian and Pacific tectonic plates, with only Wellington expected to have experienced some effects of plate subduction on its land elevations. In that not even Wellington departs from the values for the other gauges, Hannah (1990) suggested that for at least the past century there has been a greater degree of vertical structural stability and lack of significant land elevation changes compared with the long term geologic record. It is doubtful, however, that this conclusion applies to Hawke's Bay, where during the past century there was the dramatic change in land elevation that took place during the 1931 earthquake. More of a question is what has happened to the land elevations and mean sea levels during the decades since that earthquake. As discussed in Section 2, land elevation changes are generally associated with subduction zones due to cycles between the aseismic periods of stress accumulation when the plates are temporarily locked together, and then the release of that stress at the time of a subduction earthquake. It is unfortunate that we do not have a sufficiently long record of tide-gauge measurements for Hawke Bay that could serve to analyze its change in relative sea level, permitting an inference of the long-term land elevation changes.

Results from the most recent research concerned with changing mean sea levels along the coast of New Zealand are of particular interest (and somewhat alarming) in that they connect the rate of rise to cycles in the Earth's global climate [Bell et al. (2000); also see the summary provided by Goring and Bell (2001)]. It is well recognized that are the differences between El Niños and La Niñas in their effects on a great number of atmospheric and oceanic processes, including annual mean sea levels along the shores of the Pacific Ocean. In order to investigate such effects on New Zealand's sea levels, NIWA has installed ten open-coast sea-level measurement sites constituting their Sea-Level Network. Important is that the gauges are located on the open coast, not in harbours where they can be affected by changes in the environment from port construction, dredging, etc. Nine of these sites were installed between 1994 and 1998; this includes their Riverdale gauge south of Hawke's Bay, which began operation in August 1997. The tenth site, Moturiki Island near Mt Maunganui in the Bay of Plenty, has the longest record, having yielded good quality data since June 1973. Thus far most of the recent NIWA research on interannual variations in mean sea levels have been carried out with the Moturiki data. One key finding has been the important roles of El Niños and La Niñas in producing interannual fluctuations in mean sea levels, demonstrating that La Niñas are accompanied by a rise in the annual mean sea level whereas El Niños result in a drop (Bell et al., 2000, Fig. 2). Although based on shorter records, results from the east coast gauges along the Canterbury coast (Sumner Head and Kaikoura) indicate similar responses, with elevated mean sea levels occurring during La Niñas.

Longer-term cycles in the Earth's climate are also recognized, including the Inter-decadal Pacific Oscillation (IPO) that has a periodicity on the order of 25 years. The alternate phases of the cycle are a "warm" period when El Niño occurrences dominate, versus the "cool" phase with more La Niñas. The control of the IPO climate index on New Zealand's annual sea levels was also investigated by Bell et al. (2000), with the results shown in Figure 4-4 where the IPO cycles since 1900 are compared with the annual mean sea levels derived from the Port of Auckland's tide gauge. Although it is apparent that there is a great deal of variability in mean sea levels from year to year, a pattern emerges wherein decades of rapid sea level rise occur during the cool IPO phases with La Niñas, while there is little or no net increase in the sea level spanning the decades during the warm phases with El Niños. Prior to about 1975 the IPO had been in its cool phase since 1948, during which there was a rapid rise in sea level. During the twenty-five years from 1975 to 1998 the warm phase produced essentially no additional net increase in the sea level. Climatologists concluded that in about 1998-99 the IPO again reverted to its cold phase, and Bell et al. (2000) accordingly predicted that there would be a return to the rapid rise in sea level such as occurred from 1948 to 1975. Although only limited subsequent sea-level data have become available since this shift in 1998-99, it suggests that the prediction made by Bell et al. (2000) is correct and that the coasts of New Zealand will once again experience a rapid rise in sea level, potentially with the accompanying enhanced impacts of coastal erosion and flooding. Rob Bell (pers. communication) is now updating these analyses to determine the most recent changes in sea levels experienced along the New Zealand coast, including gauges in addition to that in Auckland, so there will be a better documentation of what has occurred on the east coast, and presumable in Hawke's Bay.

Looming over the horizon is also the threat of an accelerated rate of global (eustatic) sea-level rise associated with global warming, attributed to human activities such as the burning of fossil fuels that have added greenhouse gases to the atmosphere. There is strong evidence for a marked warming of the Earth in recent decades, which has resulted in the more rapid melting of glaciers and increased temperatures of the ocean's surface water. In their 2001 report, IPCC projected the global impacts of this climate change into the future, including an assessment of the resulting rise in sea level during the 21st century. These projections are diagrammed in Figure 4-5, extending the sea-level measurement record derived from the Auckland tide gauge. There is a high degree of uncertainty in this projection, in part due to its inclusion of assessments of the future releases of greenhouse gases that depend on the global economy, with the projected rise also depending on our scientific understanding of how the atmospheric and oceanic processes will respond and translate into a rise in sea level. The "most likely" scenario predicts an accelerated rate of sea level rise becoming noticeable during the time frame 2020 to 2040; the

total increase in sea level during the 21st century is predicted to be on the order of 40 centimetres, more than twice as much as the 10- to 20-centimetre increase experienced during the 20th century.

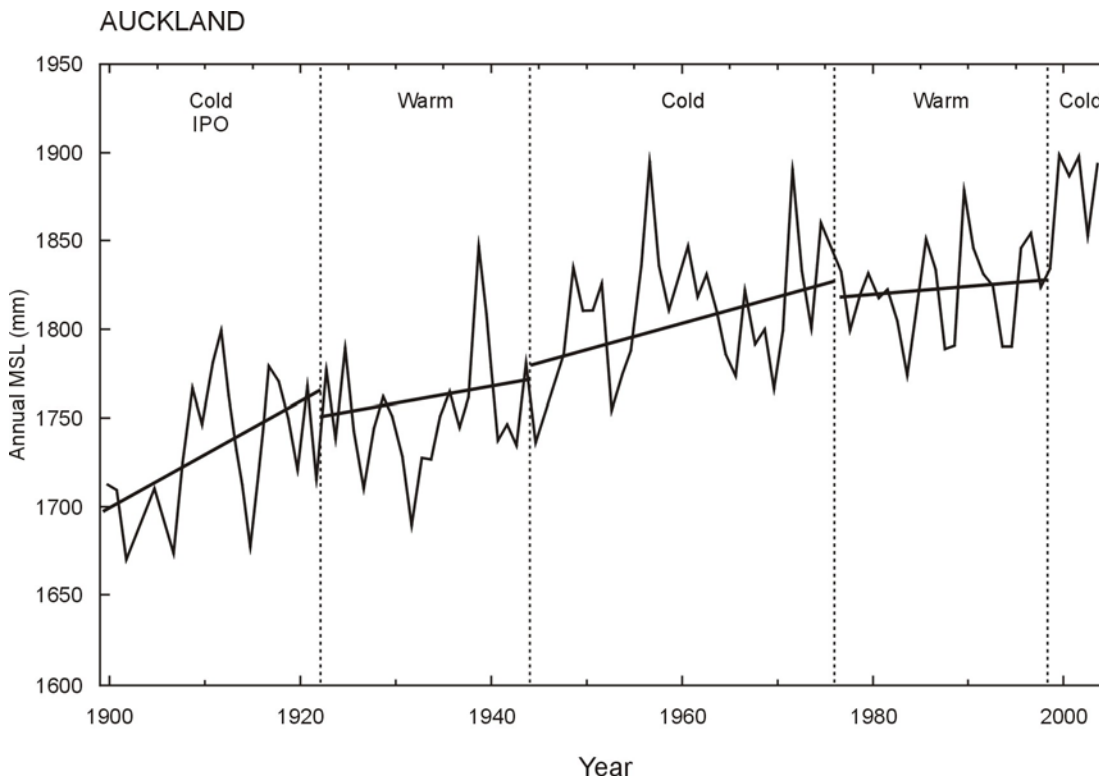


Figure 4-4 Annual mean sea levels derived from analyses of tide-gauge records from the Port of Auckland, compared with the warm (W) and cold (C) phases of the IPO climate cycle. [graph courtesy of Rob Bell, NIWA; also see Goring and Bell (2001)]

In summary, because there is only a relatively short record of tide measurements from the Port of Napier's gauge, it has not been possible to undertake analyses such as those reviewed above to determine the long-term rate of relative sea-level change underway in Hawke Bay. This is unfortunate in that changes in sea levels are recognized as being important to the evolution of the coast, and to occurrences of beach and property erosion. Specifically important to the Hawke Bay sea-level change is its tectonic setting within a subduction zone, and its history of associated land-elevation changes such as those that occurred at the time of the 1931 earthquake. However, we cannot be certain as to the direction of the land elevation changes subsequent to that earthquake, it not even being clear whether the land is presently rising or subsiding, such that the relative sea-level change represents a net rise or fall. This documentation should improve in the not-too-distant future, with the direct measurements of land elevation changes derived from the network of GPS sensors established throughout the Hawke's Bay region, described in Section 2, and as the lengths of tide records by the Port's gauge in the harbour and by NIWA's open-ocean Sea-Level Network increase and permit improved assessments of changing sea levels. Based on what is presently known, it can reasonably be assumed that the annual mean sea levels in Hawke Bay increase during La Niñas, and with the shift in 1998-99 of the IPO to the "cold" phase with more La Niñas there will be more frequent years with higher water levels. Furthermore, it is also probable that as shown in Figure 4-4 for Auckland, there will be a marked increase in the rate of sea-level rise during roughly the next 25 years of that IPO cold phase. Within that time frame, the IPCC projected accelerated rates of sea-level rise may also become a factor, contributing to occurrences of higher mean sea levels along the shores of

Hawke's Bay. The prospect therefore is that increasing sea levels will become a more important factor in coastal change and in the occurrence of erosion problems during the 21st century.

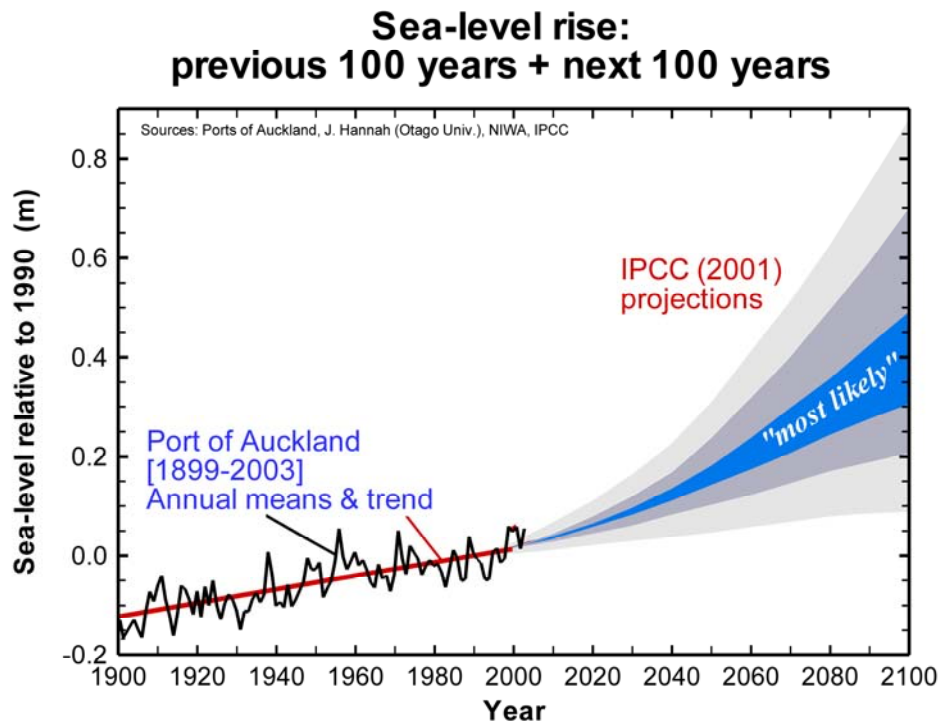


Figure 4-5 The IPCC predicted accelerated rates of sea-level rise during the 21st century, extending the 0.13 metre per century rise measured by the Port of Auckland gauge during the 20th century. [after Bell et al. (2001)]

4.4 THE WAVE CLIMATE OF HAWKE BAY

Waves along the coasts of New Zealand are generated in part by the westerly winds that in the Southern Hemisphere dominate the Earth's atmospheric circulation between 30°S and 70°S. New Zealand extends from 34°S to 47°S, with Hawke Bay centered at about 39°S, within this zone of westerly winds but with the strongest winds occurring over the Southern Ocean between New Zealand and Antarctica. In the winter the belt of strongest westerly winds shifts to the north and then lies across southern New Zealand. Being on the east coast places Hawke Bay on the lee shore, and as expected the wave heights are significantly smaller than occur along the west coast. However, due to the alignment of the country in a northeast-southwest direction, waves generated in the Southern Ocean turn northward and travel up the east coast, reaching Hawke Bay from the south to southeast. Superimposed on the westerly winds of the atmosphere are weather systems, storms that cross New Zealand from west to east. The clockwise pattern of winds surrounding the atmospheric lows of these storms produce onshore winds to their south sides as they cross the east coast, which can locally generate high waves. In addition, tropical cyclones originating to the north of New Zealand during the summer generate waves that tend to reach Hawke Bay from the northeast.

Few direct measurements of wave heights and periods have been collected at Hawke Bay spanning an extended period of time, which is true for the entire coast of New Zealand. For this

reason, wave hindcasts have been derived from meteorological records to serve as the primary assessment of the country's wave climate. The hindcasts completed by Gorman et al. (2003a, 2003b) for the period 1979-1998 provide the best long-term assessment of the wave climate, including that of Hawke Bay, while daily measurements of waves have been measured in Hawke Bay by a wave-rider buoy installed in August 2000 by the Port of Napier, having now provided five years of data. Fortunately, these two data sets generally agree as to the wave climate for Hawke Bay, and therefore compliment one another in respectively representing the deep-water wave climate and the near-coast wave conditions.

Prior to those recent undertakings to document the wave climate of Hawke Bay, only limited information was available. The Ministry of Works and Development collected visual observations of wave heights, periods and directions from 1975 to 1980, obtained at the Marine Parade shore. Similarly, under the direction of the Hawke's Bay Regional Council visual observations of waves have been obtained at the Marine Parade and at the Westshore Surf Club since August 1998. Being visual estimates, the heights can be taken as approximately the "significant wave height", the average of the highest one-third of the waves. The 1975-1980 data have been analyzed showing that 55% of all waves approached the beach from the east to east-southeast, and 42% approached from the east to east-northeast (Smith, 1986). Wave heights ranged from 0.1 to 3.5 metres, with 50% of all waves falling between 0.5 and 1.0 metre. On average there were 27 days per year when the waves were over 2 metres in height. Based on this data, Smith (1986) calculated that extreme waves having 6-metre heights would have a return period of about 50 years. The 1975-1980 data were also analyzed by Pickrill and Mitchell (1979), together with limited visual measurements (25 Nov. 1975 to 12 Jan. 1976) obtained from the *Glomar Tasman* in 57-metres water depth mid-way along Hawke Bay, as part of their summary of the wave conditions along the coasts of New Zealand. The mean significant wave heights were respectively 1.22 and 1.25 metres from the shoreline and offshore measurements, but their mean wave periods differed, being 11.0 sec for the Marine Parade data and 7.8 sec for the *Glomar Tasman* data.

The primary definition of the New Zealand wave climate used today, including that in deep water offshore from Hawke Bay, is derived from the hindcast analyses of Gorman et al. (2003a, 2003b). The hindcasts were made using the wave generation model WAM (WAVE Model) based on data for the daily winds across the ocean's expanse. In their analyses they included the latitudes from 10°S near the Equator southward to the coast of Antarctica, and 100°E to 220°E in longitude, New Zealand being positioned approximately at the center of this area. The hindcasts were made at 3-hour intervals for the 20-year period from 1979 through 1998. In the first of their pair of companion papers, Gorman et al. (2003a) presented the hindcast results and compared them with wave-buoy data at eight representative sites around the New Zealand coast (Gisborne being that closest to Hawke Bay). When the comparison was with a buoy that is well offshore and fully exposed to the waves, good agreement was found, whereas when the comparison was with an inshore buoy (e.g., Gisborne) there was poorer agreement due to the effects of wave refraction and sheltering by the land. The significance of these inshore effects was further demonstrated for a buoy at Mangawhai in the outer Hauraki Gulf east of Auckland, where the inclusion of wave refraction to transform the deep-water hindcast waves into shallow water resulted in considerably better agreement with the buoy data. In their second paper, Gorman et al. (2003b) compared the WAM wave hindcasts to satellite data of deep-water wave heights and periods measured with altimeters from satellites. The satellite data in the region surrounding New Zealand had been analyzed by Laing (2000), demonstrating that they can be useful in defining the wave climate except that the data collection is limited to those days when the satellite's orbit crosses the region. It was found by Gorman et al. (2003b) in the comparison that the long-term mean significant wave heights from the hindcasts were generally 0.3 to 0.5 metre lower than wave heights from the satellite altimeter; the distributions of the hindcast significant wave heights matched the satellite data reasonably well, but tended to underestimate the occurrences of the largest wave events. It is uncertain whether this disagreement represents an error in the satellite measurements or in the hindcast results (A. Laing, personal communication, 10/2004).

The wave hindcasts of Gorman et al. (2003a, 2003b) show the expected pattern of wave conditions along the New Zealand coast. The largest mean significant wave heights (3.6 metres) were found in the Southern Ocean where the westerlies are strongest and have long fetches around Antarctica. North of that band the waves propagate to the northeast along both the west and east coasts, with diminishing mean wave heights to the north, especially along the east coast due to the blocking effect of the land mass. Figure 4-6 from Gorman et al. (2003b) shows the distributions of significant wave heights derived from the 20-year hindcasts at six selected deep-water sites, while Figure 4-7 contains the corresponding graphs of significant wave heights versus wave periods. The site to the east of the North Island is at latitude 34.875°S, longitude 168.750°N, and its distribution of hindcast wave heights shows the mode of maximum occurrence at about 2 metres significant wave height, while the mean is 2.4 metres and the maximum significant wave height during the 20 years hindcast is 10.7 metres. Figure 4-7 shows that the highest storm wave heights correspond to wave periods centered at about 12 to 13 seconds.

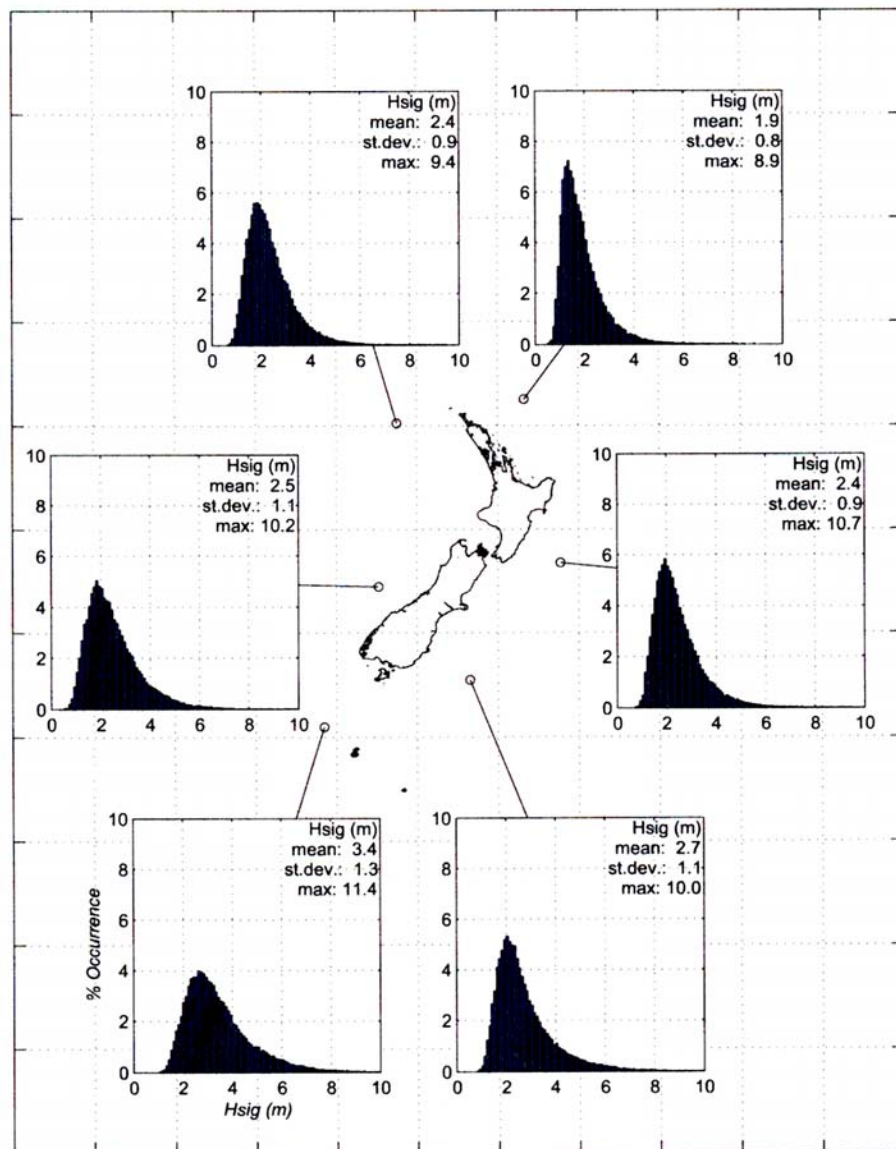


Figure 4-6 Distributions of significant wave heights at six sites around the coast of New Zealand, derived from 20-year WAM hindcasts. [from Gorman et al. (2003b)]

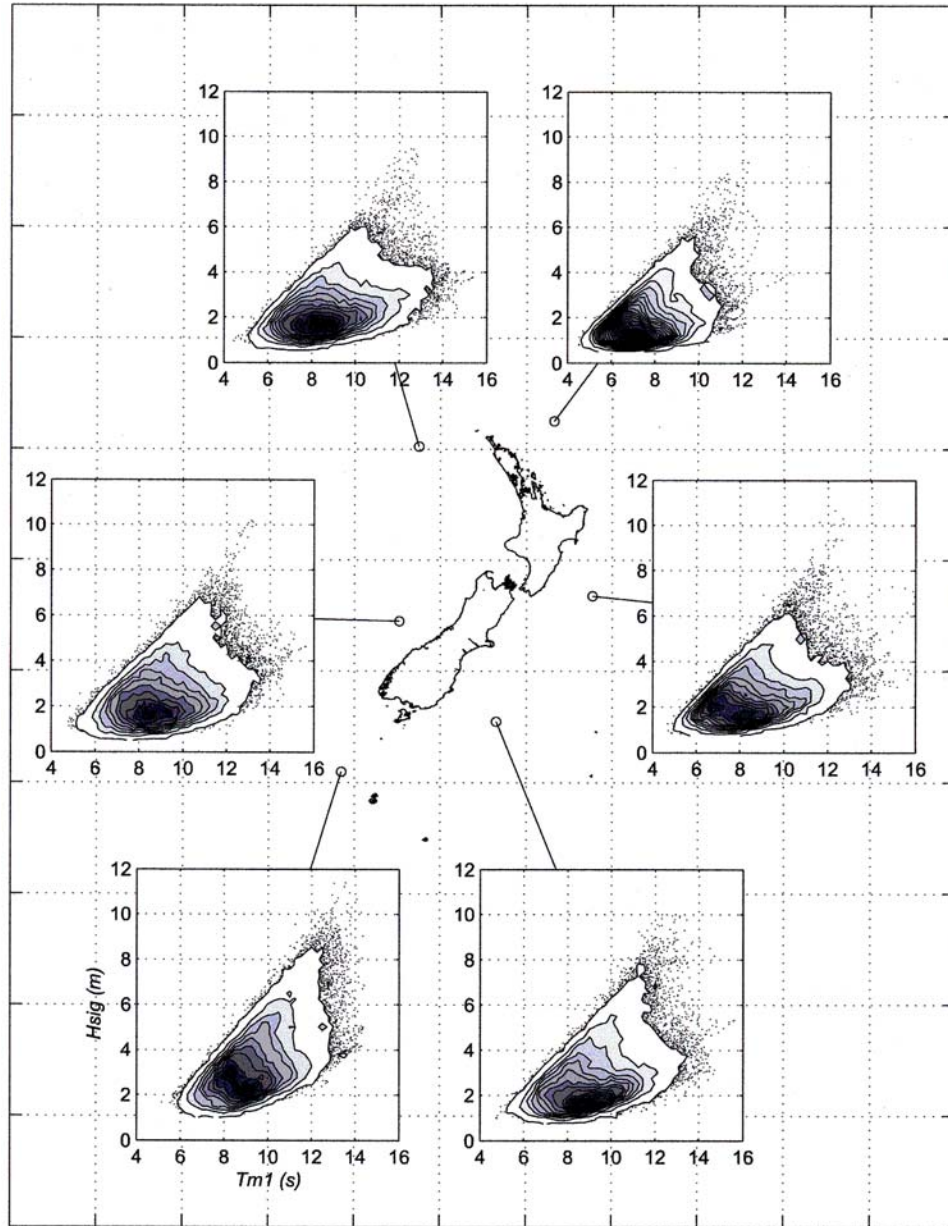


Figure 4-7 Graphs of significant wave heights versus periods around the coast of New Zealand based on the WAM hindcasts. [from Gorman et al. (2003b)]

Tonkin and Taylor (2003) employed the WAM hindcast data of Gorman et al. (2003a) to develop nearshore wave climates for Hawke Bay that include the effects of wave refraction; their study results for those nearshore wave conditions will be reviewed later in this Section. The WAM hindcasts were first evaluated at the 200 metres CD depth directly seaward from Hawke Bay, just beyond Lachlan Bank, to serve as the local deep-water wave climate in their analyses of the nearshore waves. This deep-water wave climate is given in Figure 4-8 in terms of the distributions of significant wave heights and spectral-peak wave periods. The mean significant wave height is 1.76 metres, the maximum significant wave height is 8.56 metres, and the mean period is 10.4 seconds. As noted above, the study of Gorman et al. (2003a, 2003b) found that the WAM hindcasts may have predicted lower wave heights generated by major storms, so this

8.56 metres maximum for Hawke Bay may be too low, and accordingly Tonkin & Taylor (2003) recommended that it be used with caution in engineering design analyses.

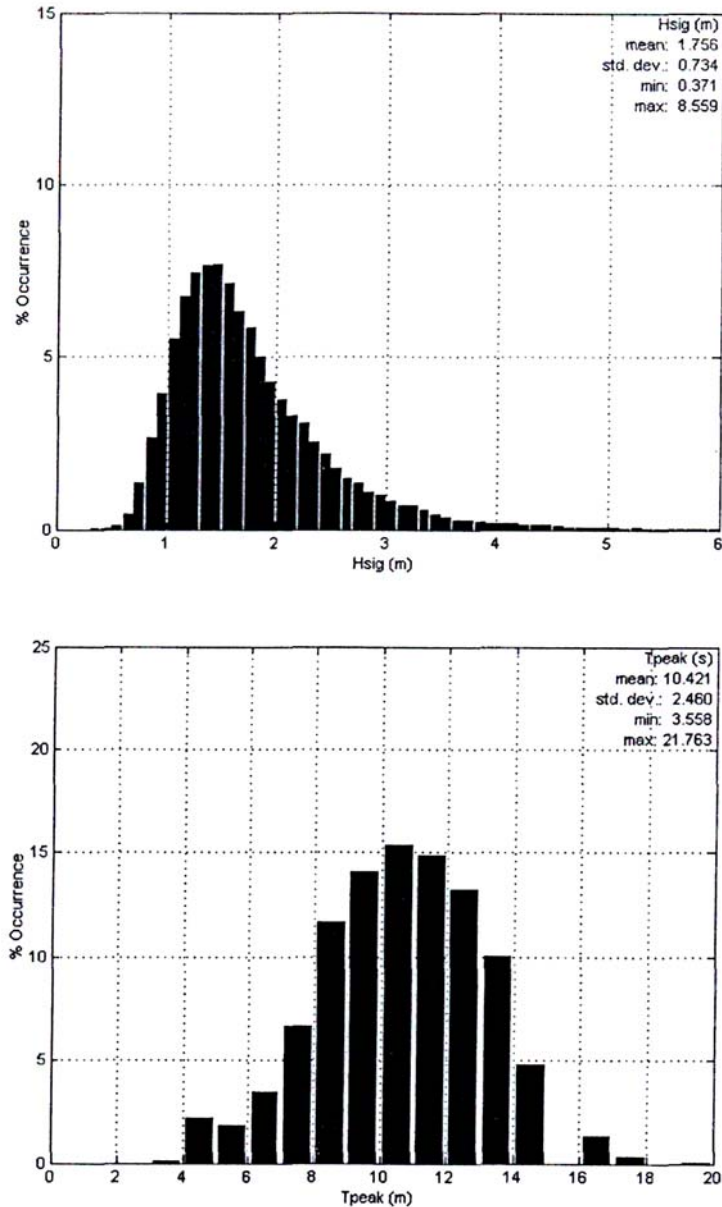


Figure 4-8 The WAM hindcast deep-water wave climate directly offshore from Hawke Bay. [from Tonkin & Taylor (2003)]

Analyses of the hindcast data demonstrate the existence of a seasonality to the wave conditions, with the WAM analyzed site east of the North Island having the highest waves during the winter months of May through August, when the monthly averages of the significant wave heights are on the order of 2.75 metres, reduced to about 2.0 metres during the summer (Gorman et al., 2003b, fig. 8). Trends in the wave climate were also examined, in particular showing some dependence on the range of climate events from El Niños to La Niñas. There is a response in the winds to that range of climate events, with an El Niño generating more southwesterly winds while a La Niña produces northeasterly winds. As a result, correlations were found between the wave

heights around the New Zealand coast with these climate events, El Niños tending to enhance the wave heights along much of the coast since that event reinforces the effects of the prevailing westerlies, while to the north in the Bay of Plenty the winds and waves increased during La Niñas. According to the analysis results of Gorman et al. (2003b, fig. 12), Hawke Bay is positioned within the zone of transition so its wave climate can be expected to have only a small influence from occurrences of El Niños or La Niñas. This is further indicated by the nearshore wave climate analyses of Tonkin & Taylor (2003) for Hawke Bay, having found no difference between El Niño and La Niña years, concluding that due to the importance of wave refraction within the Bay the waves in the nearshore are aligned nearly parallel with the shore irrespective of their directions offshore. They did note, however, that locally generated waves that were not included in the analyses might be affected by the change in mean wind directions between El Niños and La Niñas.

The hindcasts of Gorman et al. (2003a, 2003b) for the period 1979 through 1998 are important to defining the wave climate for Hawke Bay, and have seen applications in analyses of nearshore wave conditions and the establishment of hazard zones along the coast to protect developments from erosion and flooding (Tonkin & Taylor, 2003, 2004). The main unresolved short coming in that hindcast data is that it may under predict the wave heights of the most extreme events, and this represents something of a limitation in the assessments of the coastal hazards as those extreme events are of greatest interest; this limitation can be resolved only by additional research that improves either the data derived from the satellite measurements or from the wave hindcasts, so they eventually agree. It is also unfortunate that there was no overlap between the hindcast period analyzed by Gorman et al. (2003a, 2003b), which ended in 1998, and the initiation of wave measurements in 2000 with the buoy installed by the Port of Napier. A period of overlap would have been helpful in permitting direct comparisons between the two data sets, both for the waves generated by individual storms and in assessments of the overall wave climate for Hawke Bay.

The Port of Napier installed a Triaxys directional wave-rider buoy in August 2000, positioned in 16-metres CD water depth offshore from the Port, at 39°27'27"S and 176°56'3"E. The buoy records 20 minutes of water surface elevations, and then calculates a number of wave parameters including the significant wave height (H_s), the 10% exceedence wave height, the maximum wave height (H_{max}), the wave period at the peak of the energy-density spectrum (T_p), and the average wave direction and range of directions. For the first three years of operation the buoy collected these measurements once each hour, but in 2004 it began to collect data twice per hour. The buoy data have been analyzed and presented in a series of reports by Worley, prepared for the Port of Napier, with the most recent analyses having been for the data collected from August 2002 to September 2004, which was then integrated with the earlier data to derive wave statistics for the entire period of wave-data collection (Worley, 2004).

Monthly mean significant wave heights and periods are listed in Table 4-3 for the entire period of wave-data collection, August 2000 through September 2004. The results show the highest wave conditions occurring on average during July and August, being on the order of 1.2 metres, with the lowest in the summer months of November through January, averaging about 0.7 metres. This general pattern is found each year, but with maximum wave heights of the most severe storms variously occurring in June through September. Included in Table 4-3 are the numbers of storm events each month, defined as occurrences when $H_s > 2$ metres, and mean values of the maximum significant wave heights of these storms measured since August 2000. These columns reinforce the general pattern of July and August being the months having the greatest numbers of storms, but in terms of the maximum wave heights it is seen that high wave conditions can occur during essentially any month. Each of the Worley reports tabulates the individual storms, which shows that individually they have maximum significant wave heights generally between 2 and 4 metres, with a 4.68-metres significant wave height on 2-4 April 2002 having been the largest measured thus far. Table 4-4 compares the extent of storm conditions between the four years of buoy measurements, demonstrating that there can be significant differences from year to year; the record is too short, however, to establish any climate controls such as El Niños versus La

Niñas. Based on these measured storm wave heights, Worley (2004) undertook an extreme-value analysis, with the results given in Table 4-5 where it is seen that the 50- and 100-year projected significant wave heights are respectively 5.8 and 6.2 metres. They caution that these values should not be used for design applications without careful consideration, in view of their having been based on only three years of wave data (the general "rule of thumb" is that the prediction of the 50-year extreme wave height requires about 15 years of wave measurements, while the 100-year projection needs 33 years of data).

Table 4-3 Monthly-mean significant wave heights and periods, the numbers of storm events each month defined as occurrences when $H_s > 2$ metres, and mean values of the maximum significant wave heights for the period of wave measurements by the Port of Napier buoy, August 2000 through September 2004 [from Worley (2004)].

<i>Month</i>	<i>Ave. Significant Wave Height (m)</i>	<i>Wave Period (s)</i>	<i>Number of Storms</i>	<i>Ave. Maximum Wave Heights (m)</i>
January	0.73	11.4	3	2.25
February	0.74	10.0	2	2.35
March	0.87	11.4	6	2.47
April	0.85	11.6	3	3.15
May	0.86	11.6	5	2.25
June	0.83	11.9	4	2.80
July	1.12	11.7	9	2.73
August	1.22	11.9	11	2.90
September	0.8	11.9	5	2.71
October	0.78	10.7	1	2.35
November	0.68	10.2	0	0
December	0.64	10.9	1	2.13
Mean	0.86	11.4	50	2.65

Table 4-4 The numbers of storm events each year and numbers of hours during which $H_s > 2$ metres, and the average maximum H_s values for those events each year [from Worley (2004)].

<i>Year</i>	<i>Number of Storm Events</i>	<i>Mean Number of hours $H_s > 2$ m</i>	<i>Ave. Maximum H_s (m)</i>
Aug 2000-July 2001	12	14	2.55
Aug 2001-July 2002	9	30	3.18
Aug 2002-July 2003	13	23	2.57
Aug 2003-July 2004	11	11	2.39

The mean peak-energy wave period for the 4-years of wave measurements is 11.4 seconds (Table 4-3), while averages for the stormiest months, July and August, give values of 11.7 and 11.9 seconds. A scatter diagram of wave periods versus significant wave heights prepared by Worley (2004) demonstrates that while $H_s > 3.5$ metres can correspond to a wide range of periods above 8 seconds, the primary occurrences of waves when $H_s > 4$ metres had periods of 14 to 16 seconds. Specifically, the highest wave event in April 2000 with $H_s = 4.68$ metres had a period of 15 seconds. In that the wave power depends on both the height and period, as do runup elevations of the wave swash on beaches (Section 5), this combination of high wave heights and long periods for the most severe Hawke Bay storms is important to coastal erosion and flooding.

Table 4-5 Extreme-value analysis of waves measured by the Port of Napier buoy [from Worley (2004)].

<i>Return Period</i>	<i>Significant Wave Height (m)</i>
2 years	4.0
5 years	4.5
10 years	4.9
25 years	5.4
50 years	5.8
100 years	6.2

The Triaxys wave-rider buoy installed by the Port of Napier also measures the direction of the peak wave energy. Table 4-6 from Worley (2004) is the joint-frequency diagram of the directions versus the range of measured significant wave heights. It shows a strong dominance of the largest waves arriving from the directions 90 to 120°, that is east-southeast, representing 71.9% of the measured waves; the largest waves, those with $H_s > 4$ metres, arrived from 105 to 120°. It is also seen that only a small portion of the waves arrive from northeasterly directions, a total of 12.64% from 0 to 90°, with 7.74% arriving from 75 to 90°. As expected, this pattern is also seen in the joint-frequency diagram of the wave periods and directions, the longest period waves arriving from the 90° to 120° directions. Waves having periods greater than 8 seconds are limited to the range of directions from 60° to 150°, the lower period locally-generated waves having more extreme angles from the north and south.

Direct comparisons between the WAM hindcasted wave heights from the analyses by Gorman et al. (2003a, 2003b) and those measured by the Port of Napier's buoy are not possible. Most important, the data sets differ in their time periods, with the WAM hindcasts representing the period 1979 through 1998, while the Port's measurements began in August 2000, leaving a two-year gap without any overlap that would have permitted direct comparisons. However, indirect comparisons have been undertaken. Tonkin and Taylor (2003) employed the WAM hindcast data, evaluated at the 200 metres CD depth directly seaward from Hawke Bay (Figure 4-8), to serve as the local deep-water wave climate in their analyses of the nearshore waves. At that site the mean significant wave height is 1.76 metres while the maximum hindcast significant wave height is 8.56 metres, with this maximum possibly being too low according to the comparisons with satellite measurements of deep-water wave heights. Thus far the highest wave heights measured by the Port's buoy was during the April 2000 storm, yielding a significant wave height of 4.68 metres with a period of 15 seconds. As listed in Table 4-5, the projected 100-year event based on the Port's data is only 6.2 metres, some 2 metres lower than the maximum WAM hindcasted significant wave height. These comparatively lower heights based on the Port's measurements result in large part from the limited period of time covered by that data set, thus far having been only five years. There is also the problem that the WAM estimates represent deep-water wave conditions, while the Port's measurements are from a buoy in 16 metres CD water depth, that is, about 15 metres depth below mean sea level. For a wave period of 15 seconds, the deep-water wave length is calculated to be 350 metres and the ratio of the 15-metre water depth to that length is 0.043 or 1/23; this places the Port's buoy just into shallow water for that wave period, with the resulting ratio of the local wave height to its deep-water equivalent being about 1.1 (but not having included the effects of refraction). For a wave period of 10 seconds the wave length is decreased to 156 metres, and this places the buoy in an intermediate water depth with the ratio of the local wave height to its deep-water equivalent being 0.9. Thus, for this common range of wave periods experienced in Hawke Bay there is little difference between the deep-water values and those measured by the buoy closer to the shore, according to this simple calculation of the wave transformation during shoaling.

However, this calculation does not account for changes in wave heights brought about by refraction and energy losses due to bottom friction, which would depend on the direction of wave approach as well as the wave period. An indication of the degree of importance of refraction and frictional losses is provided by the study of Tonkin and Taylor (2003) in their analyses of the nearshore wave climates, employing the SWAN model to calculate the passage of the deep-water waves into Hawke Bay. They tested the performance of the SWAN model results, based on the WAM hindcast, against the Port's buoy measurements; this calibration in effect represented a comparison between the WAM waves refracted to the location of the Port's buoy, and waves measured by the buoy. Direct comparisons could not be made due to the lack of overlap in the two data sets that would have provided simultaneous assessments of the wave heights and periods, so Tonkin and Taylor (2003) instead compared the patterns and trends in scatter diagrams of wave directions versus wave heights, respectively measured by the buoy and those derived from refraction of the WAM hindcast data; the resulting good agreement supported the validity of the SWAN model. Furthermore, the SWAN analysis yielded a general reduction in WAM wave heights from their deep-water values to a mean height of 0.7 metres at the buoy position, ranging in heights up to about 4 metres at the buoy site, illustrating the significance of refraction and bottom friction in reducing the wave heights and energy levels from their values in deep water. As will be seen in the following section, these processes combine to reduce the wave heights and energy levels to even a greater degree along the Hawke Bay shore, especially in the sheltered region north of Bluff Hill and the Port's breakwater.

Table 4-6 The joint-frequency diagram of the wave directions versus the range of significant wave heights measured by the Port of Napier buoy. (Note: The * entries represent values that are less than 0.005% but greater than 0.) [from Worley (2004)]

<i>Dir/H_s</i>	<i>0-0.5</i>	<i>0.5-1</i>	<i>1-1.5</i>	<i>1.5-2</i>	<i>2-2.5</i>	<i>2.5-3</i>	<i>3-3.5</i>	<i>3.5-4</i>	<i>4-4.5</i>	<i>Total</i>
0-15	0.20	0.19	0	0	0	0	0	0	0	0.39
15-30	0.38	0.21	0	0	0	0	0	0	0	0.59
30-45	0.52	0.27	0	0	0	0	0	0	0	0.79
45-60	0.62	0.50	0.01	0	0	0	0	0	0	1.13
60-75	1.01	0.97	0.01	*	0	0	0	0	0	2.00
75-90	2.03	3.77	1.34	0.32	0.17	0.09	0.01	0.01	0	7.74
90-105	5.64	14.59	8.36	3.79	1.49	0.46	0.11	0.03	0	34.49
105-120	5.71	20.38	7.97	2.19	0.54	0.19	0.10	0.02	0.02	37.11
120-135	1.65	6.14	1.72	0.30	0.07	0.04	0.02	*	0	9.96
135-150	0.47	0.84	0.15	0.03	0.01	0	0	0	0	1.50
150-165	0.22	0.34	*	0	0	0	0	0	0	0.56
165-180	0.16	0.16	0	0	0	0	0	0	0	0.32
180-195	0.11	0.09	0	0	0	0	0	0	0	0.20
195-210	0.13	0.13	0	0	0	0	0	0	0	0.26
210-225	0.13	0.13	0	0	0	0	0	0	0	0.26
225-240	0.18	0.12	0	0	0	0	0	0	0	0.30
240-255	0.24	0.27	*	0	0	0	0	0	0	0.52
255-270	0.18	0.29	0.01	*	0	0	0	0	0	0.48
270-285	0.09	0.10	0.01	0	0	0	0	0	0	0.21
285-300	0.12	0.09	0	0	0	0	0	0	0	0.21
300-315	0.10	0.06	*	0	0	0	0	0	0	0.17
315-330	0.04	0.08	0	0	0	0	0	0	0	0.12
330-345	0.10	0.13	0	0	0	0	0	0	0	0.23
345-360	0.28	0.20	0	0	0	0	0	0	0	0.49
Total	20.31	50.07	19.59	6.64	2.29	0.79	0.24	0.06	0.02	100.00

It is evident from this review that while the WAM hindcast wave data for 1979 through 1998 and measurements by the Port's wave-rider buoy since August 2000 compliment one another in generally establishing a wave climate for Hawke Bay, both data sets have limitations that restrict their use in assessments of extreme values such as the 50- and 100-year wave heights. The maximum WAM hindcasted significant wave height of 8.56 metres potentially could be well below the 100-year event due to a systematic under prediction for extreme storms by the hindcast techniques employed in that study; as indicated above, additional research is needed to resolve this uncertainty. The 6.2 metres height given in Table 4-5 projected from the buoy data to represent the 100-year event is based on only three years of data, so is not a valid projection; furthermore, it represents that event at the position of the buoy in 15-metres water depth where the wave heights have been substantially altered by wave refraction, not the desired deep-water wave climate, or the extreme conditions along the shores of Hawke's Bay. Based on the existing wave data, it is possible that the 100-year storm for Hawke Bay is represented by a deep-water significant wave height on the order of 10 metres and a period of 15 to 20 seconds. It is important to better establish these extreme-storm conditions for Hawke Bay, required in engineering design and in coastal management applications such as the establishment of hazard zones for shore-front properties.

There is evidence for the existence of long-term variations in the wave conditions in Hawke Bay, perhaps with stronger storms and much higher wave heights having occurred in the past. This is indicated in the book *Port and People* (Stevenson, 1977) through its historic accounts of ship losses during major storms, the damage by storm waves to the Port's breakwater when it was being constructed between 1887 and 1890, and occurrences of surf inundation and flooding along the shores of Hawke's Bay. From this compilation, major storms occurred in March and November 1890, February 1891, April 1894, April 1907, July 1925, and in June and August 1974. These accounts of storms in the past also reinforce the observation that they can occur at any time during the year, not being limited to the winter months when the average wave conditions are highest.

4.5 WAVE REFRACTION AND ENERGY LEVELS ALONG THE HAWKE BAY SHORE

As indicated above, there can be a substantial reduction in the wave heights and energies from their deep-water values when the waves reach the shallow water of Hawke Bay and undergo refraction as they approach the shore. This reduction is greatest along the sheltered shorelines north of Cape Kidnappers and north of Bluff Hill (Scinde Island) in Napier, illustrated in Figure 4-9 from the study of Smith (1968) who made visual estimates of the average wave heights on the beaches during the five occasions when he surveyed beach profiles at 19 sites along the full length of shore from Te Awanga in the south to Tangoio in the north. The effects of wave refraction and sheltering are most apparent at times of storms with high waves reaching the coast from the south-southeast, during the 2nd and 5th surveys in Smith's (1968) series. Most apparent is the reduction in wave heights at Te Awanga due to the sheltering offered by Cape Kidnappers, and particularly at profile sites 8 and 9 along the Ahuriri and Westshore beaches due to the combined protection by Bluff Hill and the Port's breakwater. The result is both a reduction in the wave heights at the shore and marked changes in the directions of wave advance compared with their deep-water conditions. These changes can have significant impacts on the movement of the beach gravel along the shore, and also on the extent of beach erosion and coastal flooding. Because of this importance to the nearshore processes, several studies have analyzed the wave refraction patterns for Hawke Bay.

The earliest of these studies of wave refraction in Hawke Bay was that of Gibb (1962), who constructed wave refraction diagrams for the ranges of wave periods and directions experienced in the Bay. While the waves are still in deep water their velocity of advance is governed by the wave period, the longer the wave period the faster they advance, but once the waves cross the

continental shelf it is the combination of wave period and local water depth that governs the speed of advance. Depending on the direction of wave approach to the coast, different portions along the crests of the waves will be in different water depths and thus advancing at different speeds, the portion of the wave in deeper water moving faster than the portion in shallow water; the result is that the wave crest rotates and changes its direction of advance by refraction (Komar, 1998, pp. 189-196). The water depth contours of Hawke Bay are approximately parallel to the shore, and this causes the waves to alter their directions so their crests become more nearly parallel with the depth contours, and eventually with the shoreline. This is readily seen in Figure 4-10 for examples of the wave refraction diagrams prepared by Gibb (1962). Due to the dependence of the wave speed on the period, a different pattern of wave refraction is found for each combination of wave period and initial direction of wave approach in deep water.

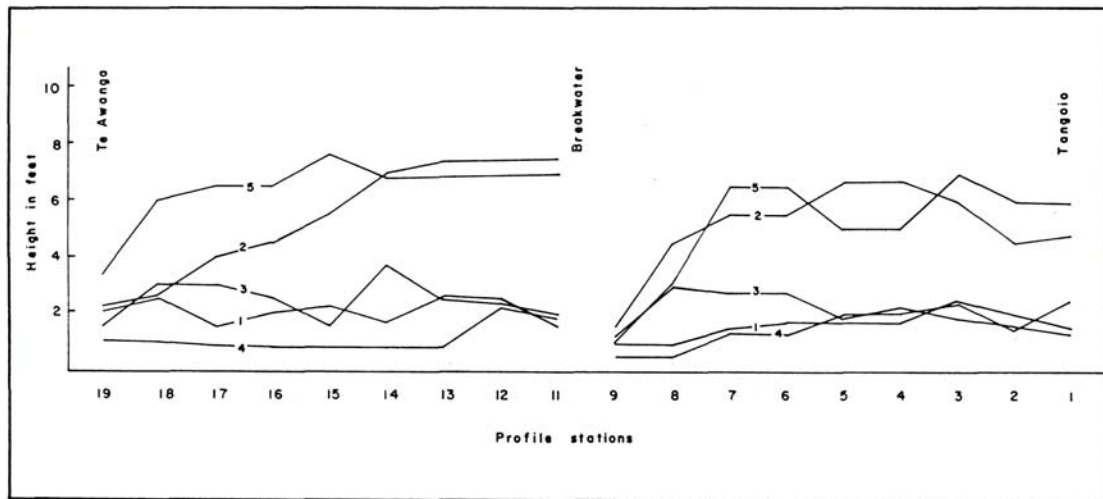


Figure 4-9 Alongcoast variations in average wave heights measured at the 19 profile stations by Smith (1968) during five survey times. [from Smith (1968)]

Irregularities in the offshore depths can affect the refraction patterns, and in the case of Hawke Bay the shallow depths of the Lachlan Ridge and Banks and the Pania Rock shoals offshore from the Port's breakwater influence to a small degree the wave refraction patterns. Due to the long periods of the waves approaching Hawke Bay, wave refraction begins well offshore so that substantial reorientations of the wave directions occur. The result is that most waves are nearly congruent with the shape of the Bay's shoreline when they finally reach the nearshore and break on the beaches. According to the analyses of Gibb (1962), waves arriving from the south to southeast, the predominant wave directions, still have breaker angles at the shore that would produce northward flowing longshore currents and a drift of gravel along the beaches. On the other hand, there is a prediction of southward flowing longshore currents and some degree of return movement of the gravel to the south whenever waves arrive from the north to northeast.

Because of the significance of wave refraction in Hawke Bay, altering the wave heights and directions from those in deep water, it is important to undertake analyses to account for these transformations. This was the objective of the study by Tonkin & Taylor (2003), which through wave refraction analyses transformed the deep-water wave climate obtained in the WAM analyses of Gorman et al. (2003a, 2003b) to nearshore wave climates along the length of the Hawke Bay shore. Their refraction analyses began at the deep-water location in 200 metres water depth, based on the WAM hindcast wave climate given in Figure 4-8. They employed the SWAN (Simulating WAVes Nearshore) model to transform the offshore deep-water WAM data to 19 nearshore sites along the 10-metre depth contour of Hawke Bay, accounting for both the wave refraction and bottom friction. As reviewed above, the SWAN analysis results were calibrated

through comparisons with measurements from the Port's wave-rider buoy. Spectral wave information as well as significant wave heights, periods and mean wave directions were determined at 3-hour intervals for the 19 locations, providing the desired nearshore wave climates for each of those sites. The results are given in Table 4-7 for the mean significant wave heights, maximum significant wave heights, mean periods, and mean directions. Sites 2 through 5 are located to the south of Cape Kidnappers, Site 2 being just south of Blackhead Point and site 5 is immediately south of Cape Kidnappers. Sites 6 through 10 are located between Cape Kidnappers and the Port of Napier, and 11 to 20 from Westshore to the Mahia Peninsula. The values listed in Table 4-7 are for the 10-metre CD depth contour (9 metres below mean sea level), so are still well offshore from the beaches.

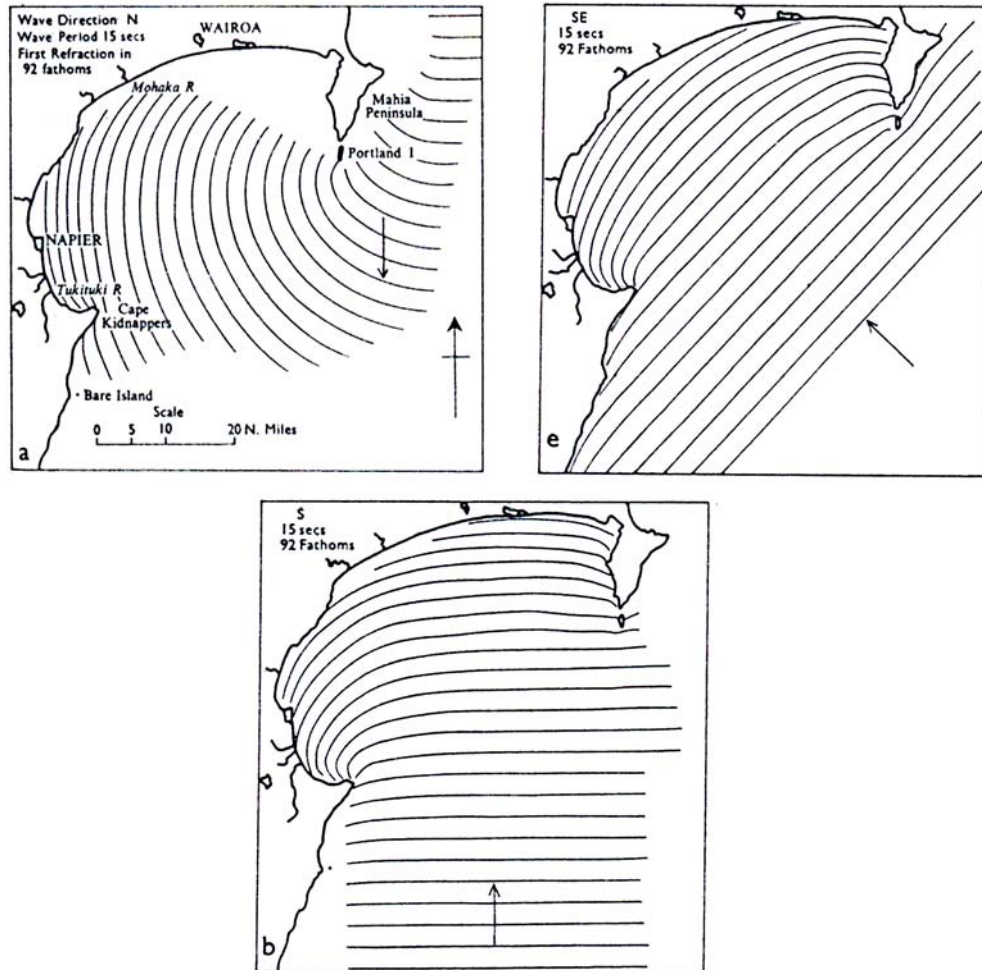


Figure 4-10 Examples of wave refraction diagrams for Hawke Bay. [from Gibb (1962)].

The wave climates from the Tonkin & Taylor (2003) analysis south of Cape Kidnappers have mean significant wave heights on the order of 1.4 to 1.5 metres, a slight reduction from the 1.76 metre mean deep-water value, with there having been only a small degree of wave refraction along that stretch of open coast. Along the beach from Cape Kidnappers to the Port of Napier the wave climates are fairly uniform, with a mean significant wave height on the order of 0.60 metre and period of 10 seconds, there having been more wave refraction than to the south, resulting in a greater reduction in wave heights compared with those in deep water. A still greater reduction in wave heights occurs at Westshore due to the sheltering effects of Bluff Hill, the analysis

yielding a mean significant wave height of 0.46 metre (Table 4-7). From Westshore northward to the Mahia Peninsula there is a progressive decrease in sheltering and in the degree of refraction, so there is a gradual increase in mean wave heights from 0.46 to 0.97 metre, and also a parallel increase in mean wave periods from 10.7 to 11.6 seconds. It is noteworthy that at all of the Hawke Bay nearshore sites analyzed by Tonkin & Taylor (2003), the wave heights are reduced from their deep-water values due to the combination of wave refraction and bottom friction having reduced the energy of the waves as they approach the coast. The resulting degrees of reduction produce marked longshore variations in wave climates, particularly in the stretch of shore north of Westshore, resulting in different potentials for beach erosion and flooding during major storms.

Table 4-7 Mean and maximum significant wave heights (metres), mean periods and directions of arrival (degrees clockwise from the north) at sites in 9-metres water depth along the coast of Hawke Bay. [from Tonkin & Taylor (2003)]

Site	Significant Wave Heights (m)		Wave Periods	Wave Arrival Directions
	Mean	Maximum		
Deep-Water Offshore				
1	1.76	8.56	10.4	
South of Cape Kidnappers				
2	1.53	7.81	10.6	
3	1.47	7.88	10.5	
4	1.50	8.00	10.4	
5	1.43	8.13	10.8	
Haumoana Littoral Cell (Cape Kidnappers to Napier)				
6	0.60	3.32	10.7	86.8
7	0.52	3.36	10.2	83.7
8	0.52	3.49	9.9	94.8
9	0.59	3.82	10.2	101.3
10	0.62	4.09	10.5	105.7
Bay View Littoral Cell (Ahuriri to Tangoio)				
11	0.46	3.35	10.7	99.4
12	0.58	3.93	10.7	108.8
13	0.64	4.15	10.7	113.4
14	0.69	4.44	10.8	116.2
15	0.70	4.26	10.9	120.0
Rocky Coast (Waipatiki Beach)				
16	0.74	4.25	10.5	131.2
Wairoa Littoral Cell (Waikari to 10km west of the Mahia Peninsula)				
17	0.87	4.66	10.7	148.7
18	0.97	4.77	11.0	163.1
19	1.16	4.88	11.4	182.9
20	0.97	5.31	11.6	191.9

Considering the potential under representation of extreme waves by the WAM data set, discussed above in reviewing the Gorman et al. (2003a, 2003b) wave hindcast study, the maximum wave heights in the nearshore derived from the SWAN analyses by Tonkin and Taylor (2003) may also too low; accordingly, Tonkin & Taylor (2003) noted that those values should be used with caution in engineering design and in assessments of coastal hazards. Furthermore, in

that the values listed in Table 4-7 are for the 10-metre CD water depth contour, they represent the wave climates well offshore from the beaches such that additional wave transformation and refraction will occur as the waves continue their advance to the shore, break, and swash up the beach. Generally this will result in some wave-height increase due to shoaling transformations, offset somewhat by the additional refraction of the waves that will also cause them to become more closely parallel to the shore when they finally break on the beaches.

Several of the Worley reports undertaken for the Port of Napier contain wave refraction analyses, but of more limited scope than the bay-wide analyses completed by Tonkin & Taylor (2003). The immediate interest of the Worley reports are the waves in proximity to the Port's breakwater, so their analyses include the diffraction of the waves in the area sheltered by the breakwater's arm, as well as the wave refraction. An interesting application is their analyses to investigate the effects of a proposed extension of the length of the breakwater that would further alter the patterns of wave refraction and diffraction (Worley, 2002b). To determine the degree of change, wave refraction analyses were undertaken for the existing Port configuration, and then for Stage 1 and Ultimate configurations that represent progressive increases in the breakwater's length. The analyses were based on wave measurements derived from the Port's wave-rider buoy located just seaward from the breakwater, with a Boussinesque wave model applied to analyze the wave transformations from the offshore to the nearshore, and a Danish model to analyze the refraction and diffraction of the waves as they move into the sheltered zone behind the breakwater and into the harbour itself. The analyses also include reflections of waves from the shoreline.

Of interest in the Worley (2002b) study are the wave transformation coefficients, the ratio of the wave heights along the shore to the wave heights offshore, with this ratio generally documenting the extent of wave-height reduction in the protected lee of Bluff Hill and the Port's breakwater. The wave input conditions for the model runs were for a wave period of 12 seconds and directions ranging from 75° to 120°, representing the dominant wave conditions measured by the buoy and those expected to be most affected by the proposed breakwater extension. The results of the analyses are presented in map view as the wave-transformation coefficients across the entire offshore region to about 3 kilometres north of the Port, and with tabulated results for 9 shoreline sites at 500-metre increments alongshore. Table 4-8 gives the results for the existing breakwater length, for the 90° and 120° wave directions, with Sites 1-2 representing the Hardinge Road shore, Sites 3-5 are Westshore, and with Sites 6-9 being progressively north of Westshore. All values represent the coefficients evaluated at the 3-metre CD depth contour, the ratio of the wave heights there to their heights offshore. With waves arriving directly from the east (90°), the offshore wave heights are reduced by half along Hardinge Road, and by a factor 0.6 to 0.7 along Westshore; the wave heights increase further to the north beyond the zone of direct sheltering, with the coefficients becoming greater than 1.0, likely increased by wave reflection from the beach. The pattern is similar for the 120° southeast wave arrival, but with a much higher degree of sheltering by Bluff Hill and the breakwater as indicated by the lower values of the wave transformation coefficients in Table 4-8. Of interest to the Worley study was the degree of additional wave-height reduction caused by the proposed extension of the breakwater. The Ultimate development is predicted to reduce the wave heights by up to 80 to 90% along Hardinge Road adjacent to the Port, and by 30 to 40% at Westshore compared with the existing wave heights. The effect of the extension is predicted to decrease to the north, and is negligible at approximately 2 kilometres north of Westshore.

4.6 SURF-ZONE PROCESSES ON THE HAWKE'S BAY BEACHES

While there has been an extensive program of monitoring the Hawke's Bay beaches through annual surveys of beach profiles and a few studies of the sediment compositions and grain sizes (to be reviewed in Section 5), there have been few studies directed toward a documentation of the nearshore processes of wave breaking, swash intensities and runup elevations. As reviewed

above, from 1975 to 1980 the Ministry of Works and Development collected visual observations of wave heights, periods and directions at the Marine Parade shore, and this program was renewed in August 1998 under the direction of the Hawke's Bay Regional Council with the visual wave observations being made at both the Marine Parade and Westshore Surf Club. While statistical analyses have been undertaken of the 1975-1980 data with respect to distributions of wave heights, periods and directions, similar analyses of the more recently collected data have not been completed.

Table 4-8 Wave transformation coefficients for the existing Port breakwater, the ratio of the wave heights along the shore at the 3-metre depth contour to the wave heights offshore, analyzed for the 90° and 120° wave directions. [from Worley (2002b)]

Site	Wave Transform Coefficients	
	90°	120°
Hardinge Road		
1	0.54	0.19
2	0.53	0.29
Westshore		
3	0.48	0.41
4	0.61	0.57
5	0.68	0.53
North of Westshore		
6	0.74	0.39
7	1.07	0.50
8	1.04	0.49
9	1.29	0.36

Studies have focused on evaluations of runup elevations of the waves on the beaches, this being of particular relevance to the potential erosion and flooding of back-shore properties whenever the runup of storm waves combines with the high water levels of the tide plus a storm surge, achieving a sufficient elevation to overtop the beach. Such analyses have been undertaken by Gibb (1996), Ganev (2000) and Tonkin & Taylor (2003), using different but complimentary approaches, with each study being interested in the potential hazards from property inundation (flooding) during extreme storm events.

In a study limited to the Napier City shore from Ahuriri to the mouth of the Esk River, Gibb (1996) followed an historic approach based on past occurrences of inundation during extreme storms, and assessed what must have been the total water levels of the astronomical tide plus the storm surge and wave runup, based on the elevation of the backshore area that had been inundated. For example, an account in Stevenson (1977) reported that on 13 February 1891, "seas swept right across the Marine Parade and through houses on the western side . . . Tons of shingle were lifted by the waves over the seawall and across the full width of road into the houses"; from this, Gibb (1996) concluded that the total water level during that storm must have reached 5 to 6 metres above mean sea level in order for it to have overtopped the elevation of the beach prior to its uplift by the 1931 earthquake. Through a number of such assessments, Gibb (1996) acquired a picture of the long-term potential for storm-induced extreme water levels that pose a threat to the Napier shore.

A more general approach was undertaken by Ganev (2000) using engineering analyses to calculate graphs of runup elevations for the range of beach slopes found along Hawke Bay and the potential range of wave heights. Two graphs were prepared, respectively for beach slopes of

1-in-8 and 1-in-9 (0.125 and 0.111), the slopes that are most common on the mixed sand-and-gravel beaches along the Hawke's Bay coast. Each graph is a plot of the "Wave Vertical Runup" versus the "Wave Height", the former being relative to mean sea level and the wave height being that measured at the shore, and with each graph containing three curves calculated for the wave periods 8, 10 and 12 seconds. Ganev (2000) does not explain how the wave runup levels were calculated, but the results correctly show an increase in runup levels with increases in wave heights and periods, and with an increase in beach slope, so it is likely that in the calculations he employed the conventional Hunt formula that contains those dependencies. The analyses further assumed a mean water level of 1.3 metres above mean sea level, to be added to the swash runup to obtain the total water level, one that however does not include a storm surge. At the highest wave height considered, 4.5 metres, the maximum runup elevations are achieved for the longest wave period, 12 seconds, reaching 4.0 metres and 3.5 metres respectively for the 1-in-8 and 1-in-9 beach slopes.

The study of Tonkin & Taylor (2004) had the objective of calculating coastal hazard zones for the entire shoreline length of Hawke's Bay. While the erosion hazards were assessed from the long-term beach profile surveys derived from the Hawke's Bay monitoring program (reviewed in Section 5), the hazards due to potential inundation were again evaluated by summing the astronomical tide, sea-level fluctuations due to water temperature changes (taken as 0.2 metre), a probable storm surge (0.9 metre), and the calculated wave setup and runup resulting from an assessed extreme wave height for that beach location. For example, at Westshore the wave height was found to be 3.9 metres from the refraction analyses, and the resulting wave setup plus runup was calculated to be 3.9 metres. Including a sea-level rise of 0.5 metre up to the year 2100, a potential inundation level of 14.9 to 15.3 metres above mean sea level was determined for the Westshore properties, increasing further to the north due to the higher wave conditions and swash runup levels on those more exposed beaches (Tonkin & Taylor, 2004, Table 7.3). The crest elevation of the backshore beach ridge at Westshore averages about 16 metres above sea level at Westshore, increasing to about 18 metres at Bay View; therefore, at present an extreme storm would not be expected to overtop the backshore ridge, but would have commonly done so prior to the 2 metres uplift of this area at the time of the 1931 earthquake.

It is seen from this review that while there have been calculations of beach processes such as wave-swash runup elevations and the total water levels, there have been few studies that have included direct measurements of those processes to document the conditions of wave breaking and the resulting swash runup elevations, yielding data that could be employed to test and validate the calculations of Tonkin & Taylor (2004) and others in their hazard assessments. As will be reviewed in Section 5, while there is a monitoring program to collect annual beach profiles at a large number of shoreline sites along the length of Hawke's Bay, that program has not established the responses of the profiles to major storm events, so we lack direct information and measurements to document both the surf-zone processes and beach responses during extreme events, information that is critical to assessments of coastal hazard zones for Hawke's Bay.

4.7 THE LONGSHORE MOVEMENT OF THE BEACH SEDIMENTS

The extreme degree of refraction of the swell waves as they cross Hawke Bay results in their crests being nearly parallel with the shoreline once they reach the nearshore and break. As a result, breaker angles of the swell are generally only a few degrees, although the short-period, locally generated waves can be observed to break with larger angles. As will be reviewed in Section 5, the rate at which sediment is carried along the beach by the waves is very sensitive to the angle of wave breaking, as well as depending on the height, energy or power of the breaking waves. This makes it difficult to calculate longshore sediment transport rates on the Hawke's Bay beaches, as even a small error in the assessment of the breaker angles after undergoing refraction can significantly affect the results. There is the additional problem that the beaches of Hawke's Bay are mixed sand and gravel. While a number of studies have collected data from

sand beaches to relate the sediment transport rates to the wave conditions, and a few studies have similarly focused on pure gravel beaches, as will be reviewed in Section 5, mixed sand-and-gravel beaches represent a more complex environment within which very few transport measurements have been obtained. Due to these multiple problems, few attempts have been made to calculate longshore transport rates of the sand and gravel on the Hawke's Bay beaches, and the resulting assessments have widely divergent magnitudes. It also needs to be recognized that in calculating the transport rates, the results obtained represent the potential transport rate assuming a ready availability of sediment on the beach of a grain size that could be transported; the actual transport could be much less if those volumes are not actually present on the beach. Because of such issues in calculating the longshore transport rates, the magnitudes of the transport along the Hawke's Bay shore have instead generally been inferred from the shoreline changes experienced when the sediment movement was blocked by the construction of groynes or other structures.

Inferences can be made regarding the transport directions of the beach sediments based on the locations of their sources [e.g., rivers and sea-cliff erosion], and it is also possible to make order-of-magnitude estimates of the transport volumes based on the quantities derived from those sources. In the Haumoana Littoral Cell it is clear that the primary sources of the gravel on the beach are the Tukituki River near the south end of the cell, and from the erosion of the sea cliff along Cape Kidnappers. Gibb (2003) and Tonkin & Taylor (2005) have made estimates of the volumes of sediments contributed by these sources as part of their development of sediment budgets for this littoral cell, as well as assessing the resulting northward sediment transport along this shore. Both studies estimated that the Tukituki River supplies on average approximately 28,000 m³/year of bedload (coarse sand and gravel) to the beaches. Tonkin & Taylor (2005) undertook a detailed analysis of the erosion of Cape Kidnappers and determined that it supplies on average 18,000 m³/year of gravel to the beach. To the north of Cape Kidnappers, but to the immediate south of the mouth of the Tukituki River, the construction of the Haumoana groyne in February 1999 temporarily blocked the northward transport of the beach sediment, impounding that transport on the south side until within a few months it filled to capacity and the continuing arrival of sediment from the south was able to spill over and bypass the groyne. This temporary impoundment made it possible to make an assessment of the net northward rate of the longshore sediment transport at Haumoana. In an analysis of the rate of sediment accumulation at the newly constructed groyne, Gibb (2003) found a northward transport of 110 m³/day or 40,000 m³/year. To that volume of sediment actually trapped by the 400-metre long groyne, Gibb (2003) added a rough assessment of the transport that is presumed to have occurred beyond its length, estimating that the total transport could be on the order of 70,000 to 80,000 m³/year. In a more detailed analysis of the sediment impoundment by the Haumoana groyne, Tonkin & Taylor (2005) evaluated the net northward transport to be about 62,400 m³/year. This rate of transport to the north at Haumoana is significantly greater than the 18,000 m³/year volume of gravel supplied to the beach by the erosion of Cape Kidnappers; the Tonkin & Taylor (2005) study showed that this difference was made up by the net erosion of the beach between the Cape and groyne, along the shores of Clifton, Te Awanga and Haumoana.

To the north of the Haumoana groyne the longshore transport is augmented by the volumes of gravel supplied by the Tukituki River, so the rates will be somewhat greater than assessed at the groyne position, but changeable from year to year depending on the occurrences of floods in the river which control the episodes of gravel delivery to the ocean beach. From approximately this location along the length of the shoreline of the Haumoana Littoral Cell, the continuing longshore sediment transport to the north progressively decreases, affected by the natural abrasion of the greywacke beach gravels and the commercial extraction of beach sediment at Awatoto that has average 47,800 m³/year. Due to those losses, the net northward transport of gravel along the beach is progressively reduced from its maximum in the south at the mouth of the Tukituki River, diminished to a very low value at Napier at the north end of this littoral cell, where there is some additional extraction of the gravel for use in the nourishment of the beach at Westshore. Therefore, one cannot think in terms of a single transport rate of sediment along the shore of the Haumoana Littoral Cell, but instead one has to consider a northward gradient of decreasing net

transport to the north. Furthermore, this gradient is not produced simply by the dominant waves arriving from the southeast, but instead is the result of the sum of the transport under waves arriving from a multitude of directions, including those from the northeast that produce some return transport back toward the south. The transport rate and direction at any specific shoreline site is therefore the net balance between the contributions of waves from multiple directions and having ranges of wave heights and periods.

Smith (1984) estimated a net northward transport rate of 57,000 m³/year near Awatoto, reduced to 6,000 m³/year south of the Port's breakwater, this latter transport rate having been derived from the analyses of Finch (1919) and Fisher (1976) of the volumes of sediment that had accumulated when the breakwater was constructed in 1887-1890; as will be discussed in Section 6, there is no evidence of gravel having bypassed the breakwater. This marked decrease in the net sediment transport to the north mainly reflects the sediment losses from the gravel abrasion and beach sediment mining. Tonkin & Taylor (2005) applied a numerical computer model (UNIBEST) to simulate the shoreline changes along the length of the Haumoana Cell in response to the abrasion losses of the gravel and its extraction, and an application of the model involves calculations of net longshore sediment transport rates at 100-metre increments along that length of the coast, providing the most detailed analyses that are consistent with the volumes of sediment added to the beach by its sources and its subsequent losses. The results of those model analyses will be reviewed at length in Section 7. As would be expected, the extraction at Awatoto has significantly reduced the quantities of the longshore sediment transport further to the north, and greatly reduced the beach accretion rates along that stretch of shore.

The directions and magnitudes of the longshore sediment transport within the Bay View Littoral Cell north of Bluff Hill are in some respects even more problematic, although to a degree the situation is basically simpler than found in the Haumoana Littoral Cell. This simplicity results because at present there are no significant sources of gravel to this cell, other than by the artificial nourishment at Westshore. Prior to the 1931 earthquake, the Tutaekuri River had entered the Ahuriri Lagoon near its inlet at Napier, and it may have delivered some gravel to the beach of the Bay View Cell; since its rerouting to the south in 1934, the Tutaekuri River now flows to the shore of the Haumoana Cell. The Esk River periodically contributes gravel, estimated by Gibb (2003) to be only 2,000 m³/year, a rather insignificant volume and with the last major flood having occurred back in 1988. Without significant sources of gravel to the beaches of the Bay View Cell, it can be expected that it would have adopted an equilibrium shoreline curvature that represents on average a net-zero transport condition along its entire length; that is, on a long-term basis there are equal volumes of beach sediment moving north and south under the changing wave directions. This net-zero transport condition is reflected in the near congruence between the shoreline and the refracted waves, as this condition is accomplished mainly by reducing the wave breaker angles to effectively zero.

A number of investigators have examined the shapes of such equilibrium, net-zero transport beach conditions, including comparisons by Yasso (1965) with the log-spiral geometric curve and especially by Silvester and colleagues with what they term the "crenulate shoreline" (Silvester and Ho, 1972; Hsu and Silvester, 1997). Qualitatively, the shoreline of the Bay View Littoral Cell has approximately adopted these arcuate geometric forms, supporting the notion that it has achieved an approximate condition of zero net sediment transport nearly everywhere along its length. Worley (2002b) has undertaken the most detailed comparison with the crenulate shoreline of Hsu and Silvester (1997), with the results shown in Figure 4-11. The near congruence between the existing shoreline and the crenulate shape is readily apparent, the main departure being found at Westshore where the existing shoreline has a greater curvature, placing it seaward of the equilibrium crenulate shore. The implication is that the beach along Westshore is not in complete equilibrium with the existing wave conditions, and therefore could be expected to experience a small degree of erosion until it is cut back and conforms with the crenulate shape. However, this should not be taken as a definitive explanation for the erosion experienced at Westshore; such comparisons between natural shorelines and these hypothetical geometric curves can be viewed as only suggestive of the equilibrium status of the coast, as the actual

equilibrium depends on the complex patterns of wave refraction that can be affected by irregularities in the offshore bathymetry.

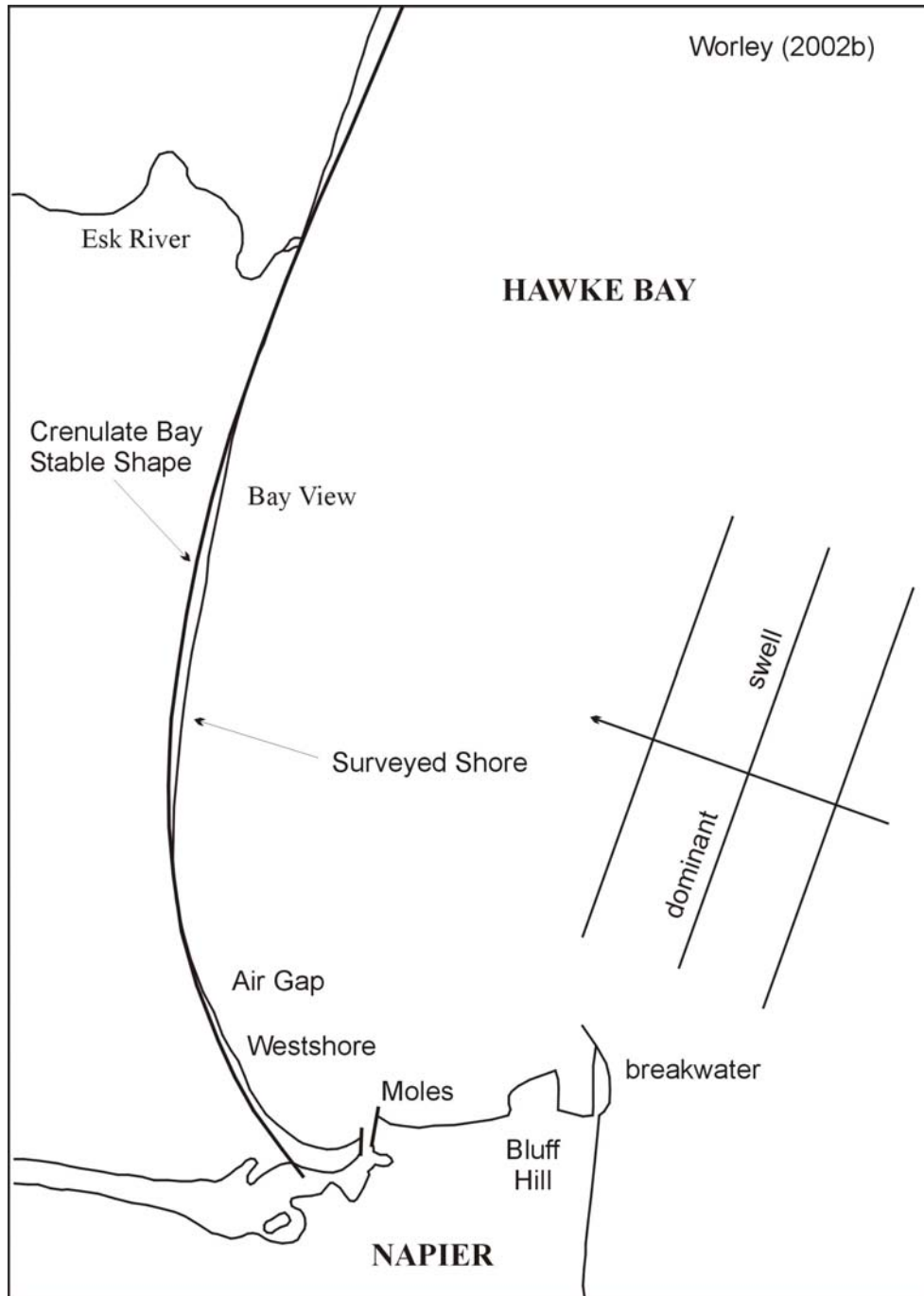


Figure 4-11 Comparison between the shoreline of the Bay View Littoral Cell and the geometric crenulate shoreline form of Silvester that approximates the condition of net zero longshore transport. [from Worley (2002b)]

Several attempts have been made to calculate the longshore sediment transport rates in the Bay View Littoral Cell. O'Callaghan (1986) undertook analyses of the transport as part of his

examination of the causes of the erosion at Westshore, and the potential use of beach nourishment to deal with that problem. However, his analyses can be viewed as having derived only approximate estimates of the longshore sediment transport. First, he completed hand-constructed refraction diagrams but for only two directions of waves reaching Westshore, one representing the predominant waves from the southeast and the second for waves arriving from the east-northeast, accounting respectively for the northward and southward components of the annual beach sediment transport, the difference being the net transport. Using a theoretical equation to calculate the sediment transport rates from the wave heights and breaker angles at the Air Gap, Westshore, O'Callaghan (1986) found that the waves arriving from the southeast would yield a northward transport of 39,000 m³/year, while waves from the northeast produce a return transport of 25,000 m³/year to the south; the difference is a calculated net northward sediment transport rate of 14,000 m³/year. Although this theoretical analysis is at best a rough approximation, O'Callaghan (1986) provides apparent confirmation through his analysis of the volume of beach erosion that occurred along Westshore from 1956 and 1984, concluding that if this loss is due entirely to the net northward transport at the Air Gap, it represents an annual average transport rate of 19,000 m³/year. However, as will be discussed below, such an assessment based on the erosion at Westshore is questionable, most likely incorrect.

The analyses undertaken by Worley (2002b) were more detailed in that they employed sophisticated models of the wave refraction and diffraction, the primary processes controlling the wave conditions in the Westshore area. Their interest was limited to the beach in the lee of the Port's breakwater and the potential effects on the shore by proposals to extend the length of the breakwater. The calculations of the longshore sediment transport were based on the empirical formula of Kamphuis (1990), equation 5-6 in Section 5, which depends on the beach sediment grain size and beach slope as well as on wave breaker heights and angles. As pointed out above, such calculations with a formula yield the potential sediment transport rather than the actual transport, with the latter depending on the availability of sediment to be transported. The calculations undertaken by Worley (2002b) were based on only two years of directional wave data from the Port's buoy, so cannot be taken as representative of the long-term net sediment movements. Along the Hardinge Road beach the calculated transport rates were on the order of 50,000 to 70,000 m³/year, directed westward toward the Ahuriri moles, but this would be the potential transport while the actual transport would certainly be much less due to the low availability of mobile sand and gravel on that beach; it is likely in fact that the actual transport along the Hardinge Road beach is now effectively zero. To the north of the Ahuriri moles Worley (2002b) calculated a net transport rate of about 20,000 m³/year, but directed southward toward the moles, the reverse of that normally accepted by other investigators.

With Westshore being located at the south end of the Bay View Littoral Cell, the transport directions and resulting patterns of beach erosion versus accretion can be expected to respond to subtle changes in the wave directions and heights from year to year, and perhaps to the Earth's varying climate in the longer term (e.g., El Niños versus La Niñas). While a long-term condition of net-zero sediment transport may prevail along the shore of the Bay View Cell, during the span of a year to even a decade there could be shifts in storm paths and wind directions, resulting in a slight shift in the directions of wave approach and perhaps in the energy levels of the waves. For example, with slightly more waves reaching Hawke Bay from the north to northeast, more beach sediment would be transported to the south, resulting in a temporary accumulation of sand and gravel north of the Ahuriri moles and along Westshore; in contrast, more frequent wave arrivals or higher storm waves from the southeast would produce a northward transport and erosion at Westshore. Thus, the probable long-term condition of a net-zero transport of sand and gravel along the Bay View Cell shoreline should be viewed as a "quasi-equilibrium", with the potential for significant departures and changing transport directions from year to year and decade to decade, in turn resulting in oscillations between beach accretion and erosion, with the cycles being most noticeable at the south and north ends of the littoral cell.

With this recognition of the potential oscillations from year to year in the directions of transport at Westshore, it is possible that the assessment by Worley (2002b) of there having been a 20,000

m³/year transport to the south during the two years involved in their calculations may in fact be correct. On the other hand, during other years it can be expected that there might be comparable rates of gravel transport to the north. This reversal in the transport directions and resulting cycles between prevailing erosion versus accretion of the beach along Westshore has in fact been demonstrated in the analyses undertaken by Smith (1993) of the beach profiles surveyed there between 1916 and 1984; this would have been the natural changes prior to the implementation of the beach nourishment program along Westshore. The results of Smith's analyses are given in Table 4-9 in terms of the total changes in beach volumes along that approximately 4-kilometre stretch of shore, and then the average changes in volumes per unit shoreline length. Note that due to the varying time periods between successive profile surveys, the series of entries in the table range from 1 to 23 years, although the majority involved 1 or 2 years between surveys.

Table 4-9 Average annual changes in beach erosion (negative values) or accretion (positive values) along a 4 kilometre length of Westshore based on profile surveys, and the equivalent changes per unit shoreline length. [from Smith (1993)]

<i>Survey Dates</i>	<i>Volume Change m³/year</i>	<i>Volume Change per unit shoreline length, m³/year.m</i>
1916 – 1925	-19,500	-4.88
1925 – 1927	-17,400	-4.35
1927 – 1929	7,500	1.88
1929 – 1937	19,400	4.85
1937 – 1946	3,300	0.82
1946 – 1948	32,000	8.00
1948 – 1950	-26,100	6.52
1950 – 1952	33,600	8.40
1952 – 1954	-27,400	-6.85
1954 – 1955	-8,800	-2.20
1955 – 1956	40,000	10.00
1956 – 1957	-40,100	-10.02
1957 – 1961	3,600	0.90
1961 – 1984	-9,400	-2.35

Of particular interest in Table 4-9 are the major shifts between net beach erosion (negative values) versus net accretion (positive values) along this stretch of shore; for example, between 1955 and 1956 there was 40,000 m³/year of accretion, but in the following year this was reversed to -40,100 m³/year of erosion, the net between the two years having been a loss of 100 cubic meters of beach sediment (0.02 m³ per meter of shoreline length). Such shifts occurred throughout the extent of the 68 years of surveys included in Table 4-9, and can be attributed to periodic reversals in the directions and rates of longshore sediment transport as described above. For the entire length of record, 68 years, the net beach volume change found by Smith (1993) amounted to -9,300 m³/year, in balance an erosion that he took to represent the net long-term transport of beach sediment toward the north. This conclusion is uncertain in that, as seen in the tabulation in Table 4-9, during almost any year either the northward or southward transport can be significantly higher, making this net of -9,300 m³/year statistically insupportable. This is even more so for the case of the similar analyses completed by O'Callaghan (1986), reviewed above, who had concluded that there is a net northward transport rate of 19,000 m³/year based on profiles collected from 1956 to 1984; as seen in Table 4-9 from Smith (1993), it is apparent that having been based on only those few specific years, O'Callaghan's assessment would have been governed entirely by the -40,100 m³/year erosion between 1956 and 1957, not having recognized that a comparable amount of accretion had occurred during the preceding year.

It would be reasonable to conclude based on the documentation in Table 4-9 of cycles between erosion and accretion at Westshore, that a condition exists having an essentially zero net longshore transport of sediment along that shore, which was to be expected when there were no sources of beach gravel prior to the initiation of the beach nourishment program. That program began in response to the erosion experienced at Westshore, but from the results in Table 4-9 it appears that the erosion problems would have occurred during the periodic episodes of beach volume losses within the cycles between accretion versus erosion that otherwise nearly balance. In that the volumes of beach sediment losses per unit shoreline have ranged up to 10 m³/year per metre of shoreline length, the loss would have resulted in a dramatic retreat of the shoreline, perceived as an erosion problem. This will be discussed at greater length in Section 7, where we consider both the threat to this area from erosion and the management responses.

In summary, while the patterns of sediment movement along the beaches of Hawke's Bay have been reasonably deciphered, the magnitudes of the transport rates are poorly established. In the Haumoana Littoral Cell there is clearly a net northward transport of gravel and sand along the beach, resulting from the sources of the sediment being at the south end of the cell, but with a progressively decreasing transport to the north as gravel is abraded and reduced to fine sand and silt which is lost offshore, and due to the commercial extraction at Awatoto. The assessments of the transport rates at the south end of this cell are highly uncertain due to problems in evaluating the volumes of sediment contributed by the sources, principally sea-cliff erosion at Cape Kidnappers and contributions from the Tukituki River; at the north end of the cell, the transport is apparently reduced to only a few thousand cubic meters per year, just sufficient to supply the extraction of gravel for the nourishment program at Westshore. In the Bay View Littoral Cell it appears that the shoreline has taken on a shape that yields effectively a net-zero transport of sediment along its length, a condition that is expected in the absence of significant natural contributions of gravel to this beach. The only stretch of shore apparently experiencing a net longshore sediment transport might be that at Westshore, perhaps because that stretch of shore locally extends seaward from the equilibrium zero-transport shape, but now maintained also by the beach nourishment program that provides an artificial source of gravel. Even if a net sediment transport does exist along Westshore it can be expected to be very small, and far more important is that the transport apparently reverses from year to year and decade to decade under the changing wave conditions, perhaps in response to subtle shifts in the climate such as the range from El Niños to La Niñas.

4.8 TSUNAMI

In the review of the wave climate for Hawke Bay completed earlier in this Section, we considered only the waves that are generated by storms, those that represent the most important form of energy reaching the coast and are normally responsible for beach and property erosion. However, also of concern to the Hawke's Bay coast is the potential for a destructive tsunami, waves that are produced by a displacement of the sea floor at the time of an earthquake, an underwater landslide, or an explosive volcanic eruption at sea. The sudden upward or downward movement of a portion of the seabed momentarily raises or lowers the overlying water surface, and this disruption of the sea surface then travels outward as a series of tsunami waves. In the deep ocean the heights of these waves are small, typically less than a metre, but they have long periods, the time between successive waves in a series typically being some 10 to 20 minutes. One significance of their long periods is that they are in effect shallow-water waves even in the deepest part of the ocean, so their rates of movement across the ocean are determined by the water depths. Calculations and measurements both document that they can travel at speeds on the order of 200 m/sec or 17,000 kilometres in a day, the speed of a jet airplane, so they can travel from their source to distance shores in the span of a day. When the tsunami waves reach the continental shelf their rates of movement slow considerably due to the shallower water depths, and this in turn causes their heights to significantly increase. At the shore they have been observed to achieve heights of 10 to 20 metres, with their runup over the land being more

akin to a flash flood, carrying water well beyond the normal reach of the wind-generated ocean waves.

The most-common sources of large tsunami are earthquakes that occur in the plate subduction zones that ring the Pacific Ocean; major tsunami have been generated by subduction earthquakes in the Aleutian Trench (1946 and 1957), offshore from Kamchatka on the east coast of Russia (1952), and from Chile (1960) as the Nazca plate is subducted in the Peru-Chile trench. Being located centrally in the Pacific, the Hawaiian Islands have been impacted by tsunami arriving from all quarters, including by those events listed above. Waves during the 1946 tsunami arriving from Alaska exceeded 10 metres in Hilo, flooding much of that city and killing 150 people. The 1960 earthquake in Chile, magnitude 9.5, is the largest quake on record; it generated a tsunami that killed more than 1,000 people in Chile, 61 in Hawaii, and 199 in Japan. It is apparent that the occurrence of tsunami pose a hazard to any nation that has a coast fronting onto the Pacific Ocean. The December 2004 Sumatran subduction earthquake and tsunami in the Indian Ocean served as a reminder of the potential severity of such an event, particularly for the coast immediately adjacent to the subduction zone, but also to those shores in the path of the generated tsunami even though they are many kilometres distant.

New Zealand has a history of its coast being impacted by tsunami, generated by earthquakes on the distant subduction zones, but has the potential of experiencing much greater impacts should a tsunami be generated by a subduction earthquake on the Hikurangi Trough, close offshore (Section 2). Details of past tsunami occurrences and impacts on the New Zealand coast are limited to written European records, so the quality of those records depends on the date of occurrence. These records have been compiled by de Lange and Healy (1986) to document tsunami occurrences and impacts from 1840 to 1982, listing 32 tsunami events including their sources, estimates of their maximum runup heights, and recorded impacts; Fraser (1998) provides an updated tsunami database for New Zealand. While tsunami have impacted both the east and west coasts of New Zealand, a significantly greater number have been recorded on the east coast due to its facing the open Pacific so it is affected by distantly-generated tsunami, and also because of the more active tectonics of the east coast, particularly that of the North Island. In their compilation, de Lange and Healy (1986) reported 5 tsunami for Hawke's Bay, 5 for Gisborne, and 9 for Wellington.

Several factors render Hawke's Bay particularly susceptible to the hazards of destructive tsunami. The Bay faces directly into the Pacific so it can be impacted by distantly-generated tsunami, most notably those produced by subduction earthquakes off the coast of Chile. Three historic tsunami generated off the coast of Chile have reached the shores of Hawke's Bay, in 1868, 1877 and 1960 (de Lange and Healy, 1986). The best documented was that in 1960, when 40 metres of a footbridge over the Ahuriri Lagoon was destroyed, and a number of pleasure boats were damaged and swept out to sea. Buildings were flooded and shifted by the forces of the tsunami waves. That tsunami produced a 4-metre water-level fluctuation, and 3 to 5 metres reported runup levels on the beaches. Although such distantly-generated tsunami pose a hazard to Hawke's Bay, more important is its tectonic setting with plate subduction occurring along the Hikurangi Trough immediately offshore, and with a number of faults and folds beneath the bay produced by the deformation of the Australian Plate (Section 2). An earthquake on either this local subduction zone or along a fault crossing the bay has the potential for generating a much larger and more destructive tsunami than the distant sources. Even though the 1931 Hawke's Bay earthquake occurred along a fault that is on land, it still generated a tsunami along the coast. The highest was a very localized 15.3-metre high wave caused by a landslide in the Waikari River estuary. A co-seismic tsunami with a maximum height in the range 3.0 to 5.5 metres washed fish and shellfish up the beach in Waikokopu at the base of the Mahia Peninsula; a large rock was also thrown on a train. A 3-metre surge wave was observed to travel up the Wairoa River shortly following the earthquake. It can be expected that tsunami generated by earthquakes in the immediate offshore, for example on the Lachlan fault and anticline that has caused the uplift of the Mahia Peninsula (Section 2), would be considerably higher and destructive than those experienced during the 1931 event.

The potential for such a major tsunami on the Hawke's Bay coast has been substantiated in investigations by geologists who have found layers of sand and gravel carried long distances inland from the beaches by pre-historic events. Specifically, the study by Chagué-Goff et al. (2002) identified the occurrence of a tsunami that occurred in about 6,300 years B.P. along the coast east of Wairoa, having swept nearly 2 kilometres inland. This documentation came from a series of cores into the sediments collected to the immediate west of the Te Paeroa Lagoon, several kilometres to the east of Wairoa. The most immediate evidence for the tsunami was a layer of coarse-grained sediment 3.0 to 3.5 metres down into the core, which otherwise consisted primarily of lagoonal mud and marsh deposits. Furthermore, this coarse-sediment layer graded from its being composed of gravel in the core closest to the ocean, to sand in the landward cores, with the thickness of the layer also decreasing in the landward direction. There were several lines of evidence for this event having involved the flow of seawater over the land, into environments that were otherwise more commonly fresh to brackish water. For example, Chagué-Goff et al. (2002) found marine diatoms (microfossils) within this sediment layer, and limited to that layer; the valves ("shells") of many of these diatoms were broken and fragmented, evidence that they has been carried there by a high-energy flow. This evidence collectively documents the occurrence of what must have been a very major tsunami event on the Hawke's Bay coast 6,300 years ago, one that would be particularly destructive were it to occur today. Chagué-Goff et al. (2002) tentatively conclude that it was most likely was generated by an active fault on the outer shelf of Hawke's Bay, and suggested specifically that it may have been the Lachlan fault. This is but one pre-historic tsunami event that being investigated by geologists, events that impacted the Hawke's Bay coast; Dr. James Goff of NIWA and colleagues have identified 5 other possible comparable events that range in ages from 7,100 years B.P. to some time in the early 15th century (J. Goff, personal communication). Further investigations such as these that document the past occurrences of extreme tsunami will be important to better establishing the degree of hazard to the Hawke's Bay coast from another such event in the future, which can be considered as a certainty.

Important to the susceptibility of Hawke's Bay to future tsunami impacts is that shallow bays and harbours tend to focus the tsunami energy and can set up oscillations as the waves reflect back and forth between its shores. With Hawke Bay being both wide and shallow, there is a greater potential for the magnification of the tsunami wave heights. Furthermore, the coast of Hawke's Bay is locally low-lying in elevations, and ultimately this determines the potential for significant property inundation; these low areas are also the most densely populated.

The potential hazards for the coast of New Zealand from tsunami have been examined first in terms of the probable occurrences of wave heights reaching this coast, and then evaluations made of inundation elevations and landward distances for specific coastal sites. de Lange and Fraser (1999) found that tsunami from South America have heights on the order of 1 metre, but project that those having a 1% probability of occurring (the 100-year event) could have a height of 2.5 metres. The potential for extreme tsunami heights reaching Hawke Bay from both distant and locally generating sources have been further analyzed at the Institute of Geological and Nuclear Science, with partial results contained in the report by Van Dissen et al. (1994). The analyses were undertaken for a range of return periods: 10% probability of occurrence in 15 years, 10% probability in 50 years, and with 1% probability in 50 years being the most extreme. According to past tsunami occurrences recorded in the database of Fraser (1998), a 2.5-metre height can be expected in 100 years as reported by de Lange and Fraser (1999), while a 10-metres height would have a recurrence interval of about 1500 years. The Institute of Geological and Nuclear Science also performed a probabilistic analysis using data from the UK Tsunami Initiative, a much longer record of tsunami measurements from throughout the Pacific, with the results yielding significantly higher predictions when applied specifically to Hawke Bay. Those projections yielded 8 metres wave heights with 10% probability of exceedence in 15 years, and 20 metres with 1% probability of exceedence in 50 years (Lifelines, 2001). These values are much higher than those inferred from the actual historical records for New Zealand, and it was concluded that this is due to the UK Tsunami Initiative having included tsunami generated by underwater

landslides throughout the Pacific basin. The Institute of Geological and Nuclear Science decided to adopt these higher tsunami heights as representing the potential hazard for the Hawke's Bay coast, in view of the fact that Hawke's Bay is very close to the Hikurangi Trough so potentially could be impacted by a tsunami generated by an underwater landslide. This appears to be justified as massive submarine landslides have been found by Lewis et al. (1999) in seafloor surveys off the New Zealand coast.

Having selected potential tsunami wave heights of 8, 11 or 20 metres, the Institute of Geological and Nuclear Science undertook numerical analyses of the possible extent of inundation of the Hawke's Bay coastal zone. The results show the greatest inland distances of tsunami inundation in the Westshore area and extending about 5 kilometres to its north, due to the low elevations of that area. Significant inundation is also predicted along the shore in the vicinity of the mouths of the Tukituki River and combined Ngaruroro and Tutaekuri Rivers, again due to the low elevations. The results of their analyses, therefore, clearly indicate that tsunami can pose a major hazard to Hawke's Bay, much greater than experienced during any historic events.

4.9 SUMMARY AND DISCUSSION

The collection and analysis of data for the range of ocean processes in Hawke Bay is critical to an understanding of the long-term evolution of this coast, in determining the causes of erosion problems, and in the establishment of hazard zones that will maintain homes and other developments safe from future occurrences of potentially extreme erosion and flooding. The objective of this Section has been to review the data for Hawke Bay to assess whether the programs of process measurements have been sufficient to meet those goals, or whether gaps remain that limit our ability to properly manage the coast of Hawke's Bay.

Based on this review, several conclusions can be offered with respect to the sufficiency of the process data that have been collected, where the critical gaps are, and with suggestions for future investigations. Following the order of the ocean processes considered in this Section:

- Tide-level data have been collected by the Port of Napier's tide gauge since 1986, with higher quality electronic records available only since February 1998; while this length of data record has been sufficient for the harmonic analyses of the astronomical tides, it is too short for the confident prediction of extreme measured tides that are affected by atmospheric and oceanic processes;
- Analyses have been undertaken by Worley (2002a) of the extreme measured tides at the Port to derive the 5 through 100-year statistical projections, but the analyses were based on only 4 years of data so that at best one can project with confidence only about the 15-year event; as a result of this limitation, applications such as the development of coastal hazard zones have had to rely on studies of storm surges measured elsewhere along the coast of New Zealand, with the assumption being that they will be comparable in Hawke Bay even though it is a much larger and shallower bay than found elsewhere, resulting in the potential for higher surges;
- Tide-gauge records have been important throughout the world to determine the local relative change in sea level during the past 50 to 100 years, affected by both the global rise in sea level and any local land-elevation changes; this approach is not possible for Hawke's Bay due to the short span of available tide measurements, and at minimum it will be another 25 years before sufficient tide records are available to determine with confidence the relative change in sea level at Napier;
- The wave climate for Hawke Bay is based on a combination of deep-water hindcasts of wave heights, periods and directions analyzed by Gorman et al. (2003a, 2003b) for the years 1979-1998, and from measurements in 15 metres water depth seaward from the Port's breakwater by a wave-rider buoy installed in August 2000; the combination of the hindcasts and buoy-measured wave

- parameters provides a good documentation as to the seasonality of the wave climate in terms of changing wave heights, periods and directions, but the data are uncertain for the projection of extreme events, it having been demonstrated that the hindcast techniques may under predict the wave heights generated by major storms, while the Port's program of wave data collection spans only 4 years so that at best one can statistically only project the 10- to 15-year potential extreme waves;
- Due to the shallow nature and geometry of Hawke Bay, with the shelter provided by Bluff Hill in Napier together with the Port's breakwater, the refraction of the waves as they travel from deep water and approach the bay's beaches is an extremely important processes, reducing wave energy levels along the shore; the recently completed study by Tonkin & Taylor (2003) has made a significant contribution in analyzing this process, but the refraction analyses were terminated at a water depth of 10 metres rather than continuing to the nearshore to establish the climates of the surf zone wave processes;
 - While considerable effort has been directed toward a monitoring program of the beaches that includes periodic surveys of beach profiles (Section 5), there has been minimal parallel effort to document the processes of wave breaking and swash runup on the Hawke's Bay beaches, the processes that produce the observed changes in the surveyed profiles and are fundamental to process-based assessments of coastal hazard zones including the potential for property erosion and inundation during storms;
 - While the directions of the longshore transport by waves of the gravel on the Hawke's Bay beaches can be established by the locations of the gravel sources (e.g., the Tukituki River and erosion of Cape Kidnappers), it is difficult to evaluate the quantities of gravel transported on average each year, and the few attempts to do so have yielded divergent results;
 - Hawke's Bay has been impacted by at least five tsunami since 1840, with that on 22 May 1960 generated by a subduction earthquake off the coast of Chile having resulted in some coastal inundation and property damage; locally-generated tsunami potentially pose a much greater threat, with a projection of an estimated 8-metre high tsunami wave having a 10% exceedence probability of occurrence in 15 years; however, such projections remain highly uncertain, but investigations by geologists of the sediment deposits from pre-historic extreme tsunami can be expected to improve the documentation of this potential threat to the coast.

Some of the gaps noted above in the collection of process data for Hawke Bay can be filled only with the passage of time, so that a sufficiently long record becomes available to satisfactorily define the potential for extreme measured tides and the highest potential waves generated by the most severe storm that might be expected during a 100-year time frame. In the mean time there is the possibility for improved analysis procedures, for example, improvements in our ability to satisfactorily hindcast storm wave heights for major storms so the results are in better agreement with the measured wave heights. Steps can also be made specific to Hawke Bay. For example, procedures could be developed for the reverse refraction of the waves, taking them from shallow water back out into deep water, so that the waves measured by the Port's buoy in 15-metres water depth can be expressed as their equivalent wave heights, periods and directions in deep water prior to having been modified by wave refraction. Numerical model analyses could also be undertaken of storm surges in Hawke Bay to supplement the limited measurements obtained by the tide gauge, to determine the effects of the wide expanse and shallow depths of the bay which could be expected to produced higher surges, and also to examine the along-coast variability in expected surge elevations.

Quality tide-level data have been collected by the Port of Napier's tide gauge only since 1998, and as noted above it may require at least another 25 years of data collection before we can confidently establish the rate of relative sea-level rise. It may be, however, that as reviewed in Section 2, the on-going program of measuring the horizontal and vertical changes in crustal positions using the Global Position System (GPS) network throughout the entire area will provide

measurements of land elevation changes for the Hawke's Bay region, which can then be combined with the tide-gauge record to arrive at a definition of the relative sea-level trends for this coast, important to assessments of coastal hazards.

Significant missing components in the understanding of the Hawke Bay ocean processes are those occurring in the nearshore, the processes of wave breaking and particularly of the swash runup intensities and levels on beaches. As will be reviewed in Section 5, predictions of wave runup on mixed sand-and-gravel beaches are problematic due to the effects of the proportions of gravel and sand on the overall permeability of the beach deposit. Since predictions of wave runup levels are important to both analyses of beach erosion and backshore inundation during storms, future efforts need to be directed toward the collection of field measurements of these processes as an additional aspect of the beach monitoring program of the Hawke's Bay coast.

The suggestions offered here for the collection of additional process data for Hawke Bay to fill the missing gaps, or for additional analyses of existing data, will be discussed again Section 8, providing further details regarding the objectives and scope of those studies considered to be most important.

4.10 REFERENCES

- Barnett, T. P. (1984) The estimation of "global" sea level change: a problem of uniqueness: *Journal of Geophysical Research*, 89 (C5): 7980-7988.
- Bell, R. G., D. G. Goring and W. P. de Lange (2000) Sea-level change and storm surges in the context of climate change: *IPENZ Transactions*, v. 27, no. 1/Gen, p. 1-10.
- Bell, R. G., T. M. Hume and D. M. Hicks (2001) *Planning for Climate Change: Effects on Coastal Margins*: New Zealand Climate Change Programme, Ministry for the Environment, Wellington, 100 pp.
- Chagué-Goff, C., and others (2002) A tsunami (ca. 6300 years BP) and other Holocene environmental changes, northern Hawke's Bay, New Zealand: *Sedimentary Geology*, v. 150, p. 89-102.
- Davies, J. L. (1964) A morphogenic approach to world shorelines: *Zeitschrift für Geomorphologie*, v. 8, p. 127-142.
- de Lange, W. P. (1996) Storm surges on the New Zealand coast: *Tephra*, v. 15, no. 1, p. 24-31.
- de Lange, W. P., and R. Fraser (1999) Overview of tsunami hazard in New Zealand: *Tephra*, v. 17, p. 3-9.
- de Lange, W. P., and T. R. Healy (1986) New Zealand tsunami 1840-1982: *New Zealand Journal of Geology and Geophysics*, v. 29, p. 115-134.
- de Lange, W. P., and J. G. Gibb (2000) Seasonal, interannual, and decadal variability of storm surges at Tauranga, New Zealand: *New Zealand Journal of Marine and Freshwater Research*, v. 34, p. 419-434.
- Fraser, R. J. (1998) *Historical Tsunami Database for New Zealand*: Unpublished MSc. thesis, Waikato University, Hamilton.
- Ganev, K. (2000) *Sea Inundation - Heavy Swells Wave Run-Up*: Technical Report for the Hawke's Bay Regional Council, 5 pp + diagrams and tables.

- Gibb, J. G. (1962) Wave refraction patterns in Hawkes Bay: *New Zealand Journal of Marine and Freshwater Research*, 5: 435-444.
- Gibb, J. G. (1986) A New Zealand regional Holocene eustatic sea-level curve and its application for determination of vertical tectonic movement: *Royal Society of New Zealand Bulletin*, v. 24, p. 377-395.
- Gibb, J. G. (1996) *Coastal Hazard Zone Assessment for the Napier City Coastline between the Ahuriri Entrance and Esk River Mouth*: Report for the Napier City Council, 80 pp + Appendices.
- Gibb, J. G. (2003) *Review of the Westshore Nourishment Scheme — Napier City*: Report prepared for Napier City Council, 40 pp + diagrams.
- Goring, D. G. (1995) Short-term variations in sea level (2-15 days) in the New Zealand region: *New Zealand Journal of Marine and Freshwater Research*, v. 29, p. 69-82.
- Goring, D. G. (1997) Tides around New Zealand: a pictorial essay: *Water & Atmosphere, NIWA*, v. 5, n. 1, p. 13-16.
- Goring, D. G., and R. Bell (2001) Sea level on the move?: *Water & Atmosphere, NIWA*, v. 9, n. 4, p. 20-22..
- Gorman, R. M., K. R. Bryan and A. K. Laing (2003a) A wave hindcast for the New Zealand region: Nearshore validation and coastal wave climate: *New Zealand Journal of Marine and Freshwater Research*, v. 37, p. 567-588.
- Gorman, R. M., K. R. Bryan and A. K. Laing (2003b) A wave hindcast for the New Zealand region — Deep water wave climate: *New Zealand Journal of Marine and Freshwater Research*, v. 37, p. 589-611.
- Hannah, J. (1990) Analysis of mean sea level data from New Zealand for the period 1899-1988: *Journal of Geophysical Research*, v. 95 (B8), p. 12,399-12,405.
- Hannah, J. (2004) An updated analysis of long-term sea level change in New Zealand: *Geophysical Research Letters*, v. 31, L03307, doi: 10.1029/2003GL019166.
- Heath, R. A. (1979) Significance of storm surges on the New Zealand coast: *New Zealand Journal of Geology and Geophysics*, v. 22, p. 259-266.
- Hsu, J. R. C. and R. Silvester (1997) *Coastal Stabilisation: Advanced Series on Ocean Engineering*, v. 14, World Scientific Publishing Co.
- Hull, A. G. (1986) Pre-AD 1931 Tectonic subsidence at Ahuriri Lagoon, Napier, Hawkes Bay, New Zealand: *New Zealand Journal of Geology and Geophysics*: c. 29, p. 75-82.
- IPCC (2001) *Climate Change 2001: The Scientific Basis*: Edited by Houghton, J. T., and others, Cambridge University Press, Cambridge, UK.
- Kamphuis, J.W. (1990) Littoral sediment transport rate: *Proceedings of the 22nd Coastal Engineering Conference, Amer. Soc. Civil Engineers*, pp. 2402-2415.
- Komar, P. D. (1998) *Beach Processes and Sedimentation*: 2nd edition, Prentice Hall, Upper Saddle River, New Jersey, 544 p.

- Laing, A. K. (2000) New Zealand wave climate from satellite observations: *New Zealand Journal of Marine and Freshwater Research*, v. 34, p. 727-744.
- Lewis, K., J. V. Collot and D. Goring (1999) Huge submarine avalanches: Is there a risk of giant waves and if so, where?: *Tephra*, v. 17, p. 22-30.
- Lifelines (2001) Facing the Risks: Chapter 8, Tsunami Hazards, published by the Hawke's Bay Engineering Lifelines Group
- O'Callaghan, R. B. (1986) *Report on the Coastal Protection of Westshore Beach, Napier*. 11 pp + diagrams.
- Pickrill, R. A., and J. S. Mitchell (1979) Ocean wave characteristics around New Zealand: *New Zealand Journal of Marine & Freshwater Research*, v. 13, p. 501-520.
- Silvester, R., and S. K. Ho (1972) Use of crenulate-shaped bays to stabilize coasts: *Proceedings of the 13th Coastal Engineering Conference*, Amer. Soc. Civil Engrs., p. 1347-1365.
- Smith, R. K. (1968) *South Hawke Bay Beaches: Sediments and Morphology*. M.A. thesis, University of Canterbury, Christchurch.
- Smith, R. K. (1984) *Beach Changes Between Napier and Clifton, Southern Hawke Bay*: Water Quality Centre Publication No. 5, Water Quality Centre, DSIR, Hamilton, 63 pp.
- Smith, R. K. (1986) *Coastal Erosion at Westshore, Hawke Bay*: Ministry of Works and Development, Water Quality Centre, Hamilton, Internal Report No. IR/85/11.
- Smith, R. K. (1993) *Westshore Beach Erosion Review*. prepared for Napier City Council, Consultancy Report No. NAP004, National Institute of Water and Atmospheric Research, 17 pp.
- Stanton, B. R. (1995) Sea level variability along the west coast of New Zealand: *Journal of Physical Oceanography*, v.25, p. 1265-1272.
- Stevenson, H.K. (1977) *Port and People: Century at the Port of Napier*. published by the Hawke's Bay Harbour Board, 352 pp.
- Tonkin & Taylor (2003) *Hawke's Bay Nearshore Wave Climate*: report to the Hawke's Bay Regional Council, 13 pp + Appendices.
- Tonkin & Taylor (2004) *Regional Coastal Hazard Assessment*. report to the Hawke's Bay Regional Council, 92 pp + Appendices.
- Tonkin & Taylor (2005) *Shoreline Modelling Report*. report to the Hawke's Bay Regional Council.
- Van Dissen, R. J., R. Lester and A. G. Barnett (1994) *Tsunami Hazard Study for the Hawke's Bay Region*: report prepared for the Hawke's Bay Regional Council, Institute of Geological & Nuclear Sciences.
- Walters, R. A., D. G. Goring and R. G. Bell (2001) Ocean tides around New Zealand: *New Zealand Journal of Marine and Freshwater Research*, v. 35, p. 567-579.
- Worley (2002a) *Port of Napier: Design Criteria Report for Outer Breakwater Extension*: 20 December 2002 report to the Port of Napier, Worley Infrastructure Pty Ltd, Perth, Australia.

Worley (2002b) *Port of Napier: Shoreline Effects of Stage 1 and Ultimate Development*. 28 November 2002 report to the Port of Napier, Worley Infrastructure Pty Ltd, Perth, Australia.

Worley (2004) *Wave Data Report, August 2003 - September 2004*: 2 November 2004 report to the Port of Napier, Worley Infrastructure Pty Ltd, Perth, Australia.

Yasso, W.E. (1965) Plan geometry of headland bay beaches: *Journal of Geology*, v. 73, p. 702-714.