Summary Report

HAWKE'S BAY, NEW ZEALAND: GLOBAL CLIMATE CHANGE AND BARRIER-BEACH RESPONSES

Paul D. Komar and Erica Harris

Consulting Oceanographers
3520 NW Elmwood Drive
Corvallis, Oregon 97330 USA
pdkomar@gmail.com

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SUMMARY: Elevations of the Hawke's Bay beaches and backshore properties were altered by a major earthquake in 1931, tilted in the longshore direction such that at the north end of this shore they were raised by 2 metres, while elevations dropped by about 1 metre at its south end. Along the shore that had been elevated, the morphology was altered from a low-lying spit that had experienced frequent overwash occurrences during storms, into a gravel barrier ridge where the increased stability permitted the construction of homes, forming the communities of Westshore, Bay View and Whirinaki. The shore to the immediate south of Napier, which had experienced only a small degree of uplift, has remained susceptible to wave overtopping during major storms, while properties at the far south where subsidence occurred have experienced significant erosion impacts over the decades (the communities of South Haumoana, Te Awanga and Clifton). With projections of future accelerated rates of rising sea levels and increased storm intensities due to Earth's changing climate, concerns are that the tectonically elevated stretch of the developed barrier gravel ridge will experience enhanced shorefront erosion, and potentially a return of wave overtopping during major storms, while the impacts where erosion problems already exist will experience still greater losses of properties and possibly the flooding of low-lying areas well inland from the barrier ridge. The objective of this study has been to undertake assessments of the future stability of the barrier gravel ridges, and the potential enhanced hazards to developed properties. Analyses have been undertaken of the ocean processes, including the hourly measured tides, waves, and calculated swash runup levels on the beaches, combined to yield the hourly total water levels at the shore. The extremes in water levels during storms were then compared with the morphologies and elevations of the surveyed beaches and properties atop the gravel ridges. In that little more than a decade of combined measured waves and tides were available for our analyses, and in recognition of the uncertainties in calculations of the refraction of the waves as they travel from deep water to the shores of Hawke's Bay, our working hypothesis has been that the morphologies of the surveyed beach and ridge profiles provide the best evidence for past severe storm events, the extremes in total water levels that have occurred subsequent to the land-elevation changes at the time of the 1931 earthquake. Assessments of future hazards from erosion and storm-wave overwash through the 21st century have been based on projections of rising sea levels beyond the present-day local rate of rise in the relative sea-level, and evidence for increasing wave heights and their swash runup levels on the beaches. However, complicating future hazard assessments and quantitative determinations of setback lines for

development are changes in the sediment budgets, with the future erosion of the gravel ridges expected to become significant sources of sediments to the beaches, altering the patterns of longshore sediment transport and producing alongcoast variations in the net erosion versus accretion of individual properties.

INTRODUCTION

Located on the Pacific coast of New Zealand's North Island, Hawke's Bay experiences hazards governed by multiple factors, most extreme being those related to its tectonic setting with subduction earthquakes and tsunami having occurred in the prehistoric past. An important control on the existing susceptibilities of this shore to erosion and flooding are the land-elevation changes that occurred at the time of the Hawke's Bay Earthquake in 1931, generated by a fault within the continental tectonic plate. While most of this shore experienced uplift of 1 to 2 metres, increasing its stability, subsidence along its southern-most shore has to a significant degree been responsible for continuing erosion problems that threaten a number of homes. Contributing to this erosion, the beach-sediment budgets are in the "red", exacerbated by a commercial mining operation that has removed large volumes of beach sand and gravel. Beyond those underlying controls on the Hawke's Bay hazards, the extreme waves and surge of storms have played the primary role in producing episodic beach and property erosion, while in the longer term rising sea levels and evidence for increasing storm-generated wave heights are contributing to the enhancement of this coast's hazards.

The focus of our investigations have been on the stretch of coast from Tangoio in the north to Cape Kidnappers in the south, Figure 1, the mixed sand-and-gravel beaches of the Bay View and Haumoana Littoral Cells, separated by the Bluff Hill headland within the city of Napier. This stretch of shore is the most heavily developed within Hawke's Bay, including from north to south the communities of Whirinaki, Bay View, Napier, Awatoto, East Clive, Haumoana, Te Awanga and Clifton. An earlier report and publication from this study was concerned with the present-day erosion problems and their causes, having been based in part on a review of the considerable number of previous studies and reports concerned with these littoral cells (Komar, 2005, 2010). The present investigation expanded our analyses of the erosion processes to include considerations of the future hazards, those enhanced by Earth's changing climate, being the consequence of global warming with projections of accelerated rates of rising sea levels and increased storm intensities. The results of this investigation, including details of our analyses of the waves and tides, have been presented in the our March 2014 report (Komar and Harris, 2014); the present *Summary Report* offers a condensed account of the main analysis results, together with a summary of our conclusions and discussions of the management implications.
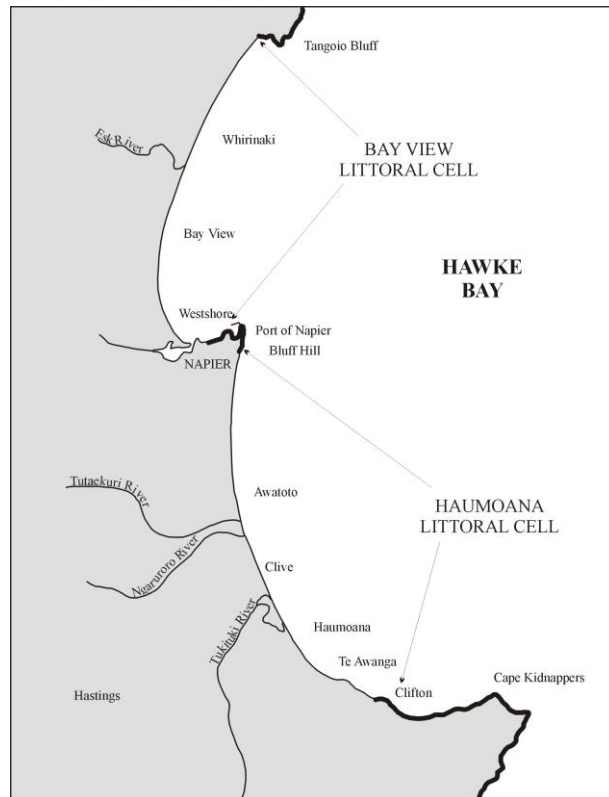
**Figure 1:** The Bay View and Haumoana Littoral Cells.

This investigation of the Hawke's Bay ocean processes, hazards, and management implications is similar to those completed or underway globally along other ocean shores, including those we have been involved in on the coasts of Washington and Oregon in the U.S. Pacific Northwest (Allan and Komar, 2006; Komar et al. 2011, 2013; Ruggiero et al., 2010; Baron et al., 2014). However, similar analyses of the Hawke's Bay erosion processes and projecting their future extremes have proved to be more challenging, primarily due to the limited data availability, there being little more than a decade of hourly measurements of waves and tides. On the other hand, there has been a long-term monitoring program that has included annual beach surveys, available to document the trends and extremes in the coastal responses, most important being evidence for past erosion events and net rates of property erosion.

The analyses completed in this study provide comparisons between the morphologies of the surveyed barrier beach ridges and magnitudes of the ocean processes — the hourly measured tides, waves, and calculated swash runup levels on the beaches, combined to yield a decade of hourly assessments of the total water levels at the shore. In that we are working with limited data for the waves and tides, and in recognition of the uncertainties in analyses of refraction of the waves as they travel to the shores of Hawke's Bay, and also in calculations of swash runup levels on the mixed sand-and-gravel beaches, our methodology has been based on the hypothesis that the morphologies of the surveyed beach profiles generally provide the best evidence for past extreme storms and total water levels, those that have occurred subsequent to the land-elevation changes at the time of the 1931 earthquake, prior to the measured data sets of waves and tides. This profile evidence is accordingly important to the hazard assessments, to which the analyzed total water levels have been compared. Such a joint consideration of the ocean processes and beach morphologies supports an improved understanding of the present-day erosion and flooding hazards, while analyses of the trends of increasing relative sea levels and wave heights, based the Port of Napier's tide gauge and wave-buoy records, support assessments of increasing hazards through the 21st century.

The ultimate concern of this study is an assessment of the future stability of the barrier gravel beach ridges along this coast, their existing stability largely having been acquired by the 1- to 2-metres uplift at the time of the 1931 earthquake, our analyses being directed toward determining whether the barrier gravel ridges will continue to protect this coast's developed properties through the 21st century.

EARTHQUAKES AND ALTERED LAND ELEVATIONS

New Zealand straddles two of Earth's major tectonic plates, Figure 2, the oceanic Pacific Plate that collides with and is being subducted beneath the Australian Plate along the Hikurangi Margin, the eastern shore of the North Island. With the subduction trough being only 160 km offshore, this tectonic setting is important to the Hawke's Bay natural hazards, the collision of the plates in the past several thousand years having generated multiple destructive earthquakes and tsunami. While the Hikurangi Margin exhibits the features typical of subduction zones that edge the Pacific Ocean, few details of its tectonics and associated hazards were known until research investigations completed during the past decade. The publications by Wallace et al. (2009, 2010) in particular documented the geometry of the subduction zone as it descends westward inland beneath the North Island, defined by the epicenters of low-magnitude quakes at depth below the Earth's crust, contrasting with earthquakes of magnitudes up to 7 and 8 that have occurred historically at shallow depths within the body of the Australian Plate, caused by the tectonic compression that results in the folding and faulting of its rocks.
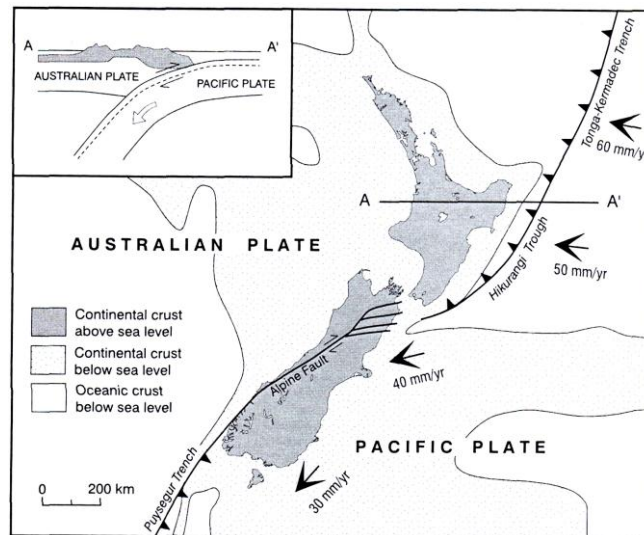
Figure 2: The tectonics of New Zealand, the collision of the Australian and Pacific plates, with plate subduction occurring at the Hikurangi Trough along the Hawke's Bay coast. [*From* Atkin (1999)]

Included in these recent investigations has been a search for geologic evidence within the coastal sediments of prehistoric subduction earthquakes and tsunami that have occurred along the Hawke's Bay coast (Cochran et al., 2006; Hayward et al., 2006). Those investigations focused on stretches of shore that generally have experienced subsidence during tectonic events, including the Bay View and Haumoana Cells, contrasting with shores that have experienced long-term net uplift (e.g., the Mahia Peninsula), these different responses being associated with the folding of the rocks within the Australian Plate respectively into synclines and anticlines. Several major earthquake events have been identified ranging in ages from about 7,000 years BP to as recent as 500 years ago. Figure 3 from the study of Cochran et al. (2006) shows the sediment stratigraphy and interpreted paleoenvironments identified in a core from the Te Paeroa Lagoon, an area of subsidence to the immediate south of the Mahia Peninsula; this core contains two layers of coarse sediments (labeled "marine influx") that are interpreted to having

been deposited by tsunami that washed well inland, each overlain by "Chaotic Deposition", sediments that had accumulated due to the abrupt subsidence at the times of the earthquakes. Uncertain is whether these major earthquakes were generated by movement limited to the subduction interface between the tectonic plates, by earthquakes within the Australian Plate whose epicenters are on the continental shelf, or possibly by both with the subduction earthquake having triggered movement on faults and folding within the Australian Plate.
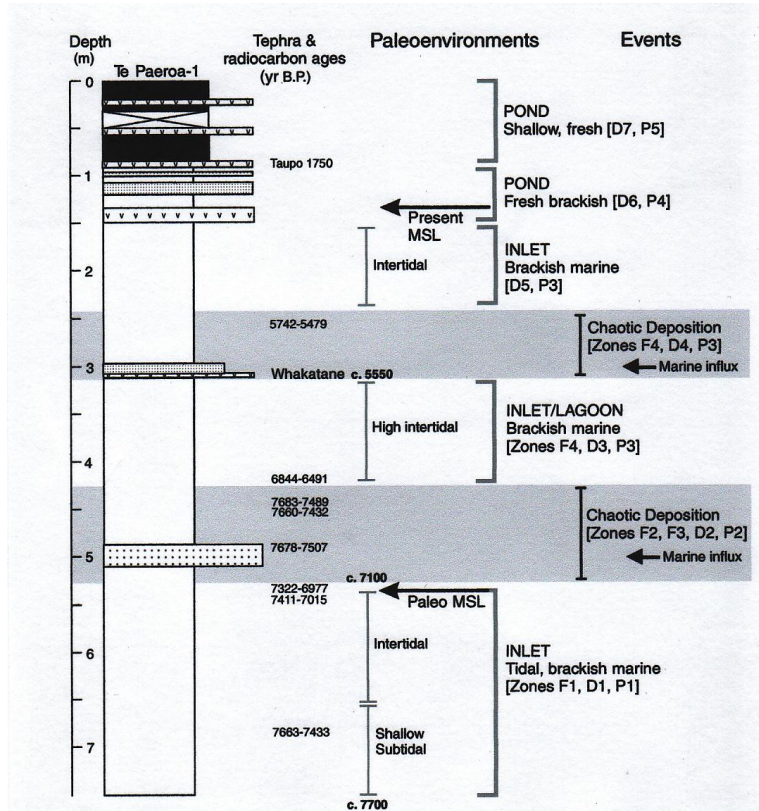
Figure 3: The sediment stratigraphy in a core from the Te Paeroa Lagoon, containing two layers of coarse sediments (labeled "marine influx") that are interpreted to having been deposited by major, locally generated tsunami. [*From* Cochran et al. (2006)]

The Hawke's Bay tectonic setting is also important in producing changes in its land elevations, progressive and episodic, combining with the global rise in sea levels to yield a trend in relative sea levels over the decades, being a major control on the resulting coastal erosion impacts. It can be expected that the "stick-slip" Hikurangi Margin experiences the general pattern of land elevation changes found in other subduction zones, a slow progressive trend over the decades to centuries when the plates were locked together (as they are now), with a sudden reversal in the direction of land-level changes expected at the time of a subduction earthquake. Evidence for this pattern along the Hikurangi Margin is supported by records from GPS units placed to measure trends of change in land elevations, having been analyzed in the report by Beavan and Litchfield (2009) to determine the directions and rates of change. In total there are six active units in close proximity to the Hawke's Bay shore, including stretches of coast that have experienced a long-term net uplift (the Mahia Peninsula), versus others that have been dominated by subsidence, including the Bay View and Haumoana Littoral Cells. Of interest, all of these units demonstrate ongoing subsidence, which conforms to the plates being locked, the interpretation being that the edge of the overlying Australian Plate is being "dragged down" by the descending Pacific Plate. Due to the shortness of the GPS records, only 3 to 4 years at the time of the Beavan and Litchfield (2009) analyses, the magnitudes of their rates of subsidence were not statistically significant (and still are not). It follows from these results that the occurrence of a subduction earthquake in the future would be expected

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to produce an abrupt uplift along the Hawke's Bay shore, assuming it is the reversal of the aseismic trend of subsidence now being measured. This uplift could possibly amount to as much as 1 or 2 metres, similar to experienced along other subduction zones.

It is uncertain, however, what the net change in land elevations might actually be, if one considers the full cycle of movement on this "stick-slip" margin, its ongoing subsidence followed by uplift during the next subduction earthquake. Furthermore, while the alongcoast variations in the net displacement of the land elevations attributable to this subduction cycle would make a direct contribution to the observed differences between long-term uplifted shores versus those that have subsided, more important have been earthquakes within the body of the Australian plate, that could occur either during faulting and folding at the same time as a subduction earthquake, or being an isolated occurrence as during the 1931 Hawke's Bay Earthquake.

The primary record for episodic earthquakes within the Australian Plate is the series of marine terraces on the flanks of the Mahia Peninsula, located at the northern boundary of Hawke's Bay, the Peninsula being within a stretch of coast that has experienced a net tectonic uplift spanning thousand of years (Berryman, 1998). Their formation is generally attributed to movement on the Lachlan Fault, located close by offshore on the continental shelf, a major fault that extends along much of the length of Hawke's Bay. The Peninsula is interpreted as being positioned on an anticline formed by the compression within the Australian Plate, raised during faulting events, while at the same time the elevations of the Bay View and Haumoana Littoral Cells to the south were lowered, its stretch of shore being within an adjacent syncline, presumably having experienced episodes of subsidence that correspond to the uplift events recorded by the terraces on the Mahia Peninsula.

The stretch of shore containing the Bay View and Haumoana Cells has been dominated by net subsidence spanning thousands of years (Hull, 1990). However, that long-term trend was reversed by the 1931 Hawke's Bay Earthquake, with most of this shore having experienced uplift. Immediately evident on the day of the event was the rise of the Ahuriri Lagoon to the north of Napier, inland from the Bay View Littoral Cell, a major portion of the Lagoon having rapidly drained into the sea, converting its area to land that now contains wineries and the region's commercial airport. The most recent analysis of the land elevation changes at the time of the Earthquake, including this entire region, has been undertaken by Hull (1990), having determined that the maximum uplift of 2.7 metres occurred on the coast about 5 km north of Tangoio, in the rocky stretch of shore leading to the Mahia Peninsula. The shore of the Bay View Littoral Cell was raised by about 2 metres, with the tide gauge in the Port of Napier's harbour constructed seaward from the Bluff Hill headland having recorded an uplift of 1.8 metres. Along the shore of the Haumoana Cell to the south of Bluff Hill, the amount of uplift progressively decreased with distance alongshore, becoming 0 at about Awatoto midway within that embayed shore, while the communities of Haumoana, Te Awanga and Clifton further to the south subsided by about 1.0 metre. This alongshore variation in land-elevation changes close to the shore is graphed in Figure 4, based on a resurvey of the railway line soon after the quake, while the solid curve is based on surveys completed by Single (1985) of profiles across the elevated beaches, documenting the increased elevations of the gravel ridges along the stretch of shore that had been raised; the divergent result at Whirinaki is attributed to local alterations in the morphology due to its proximity to the mouth of the Esk River.
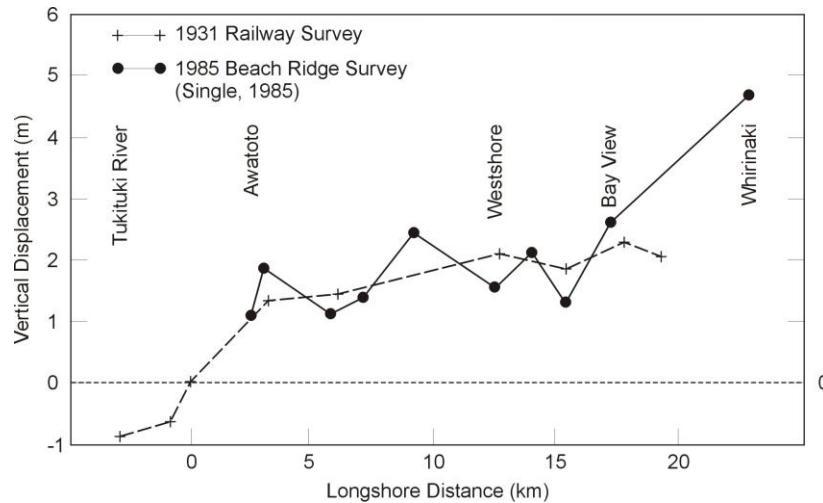
Figure 4: Land elevation changes produced by the 1931 earthquake, the dashed line being based on a resurvey of the railway line close by to the shore, while the solid curve is derived from surveys of profiles across the raised beaches.   [*After* Single (1985)]

COASTAL MORPHOLOGIES AND BEACH SEDIMENTS

The increased land elevations produced by the 1931 earthquake significantly altered the morphology of the Hawke's Bay shore, important in changing the susceptibilities of its properties to erosion and flooding. Uplift of the Bay View Cell by 2 metres shifted its shoreline seaward by about 20 metres, changing this stretch of coast from a low-lying spit that had experienced frequent overwash occurrences during storms, into an elevated gravel barrier ridge that now fronts a large expanse of land that formerly had been the Ahuriri Lagoon. Its backshore properties no longer experience wave overtopping during storms, having permitted their development with expensive homes. During the decades since the earthquake the waves and tides have cut a low scarp at the back of the beach, eroded into the uplifted gravel ridge, evident in the photograph of Figure 5 in the community of Whirinaki, representative of the beach/backshore transition along the north-central stretch of this cell's shore. However, examinations of surveyed beach profiles dating back to the 1970s show that there has been little to no erosional retreat of this scarp in recent years, its morphology having been acquired primarily during the earlier decades following its tectonic uplift (Komar and Harris, 2014). Evident from the scarp's morphology and its elevations above mean sea level is that during the early period of erosion it had been cut back by storm events that generated high waves and swash runup levels on the beaches, together with tides that would also have been raised by the storm's surge. The beachface/scarp junction elevations therefore presumably represent comparatively extreme but rare storm events, their antiquity being further evident from the vegetation cover that has grown on the face of the scarp. Also noteworthy in Figure 5 is the existence of a wide undeveloped Reserve backing the eroded scarp, a substantial setback adopted along this shore to insure the relative safety of the constructed homes.

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Figure 5: Beach and backshore gravel ridge in the community of Whirinaki, the Bay View Littoral Cell.

An exception to this stability of the beach/ridge junction within the Bay View Cell has been occurrences during the 1970s and 80s of episodes of erosion in the Westshore development within the city of Napier, located at the southern end of this cell's shore. This local occurrence of erosion has been attributed to this cell in effect being a pocket-beach shore that in the long term essentially has a net-zero longshore transport of its beach sediments, but with climate controlled decadal reversals so that its south and north ends (respectively Westshore and Tangoio) experience opposite cycles between periods of beach erosion and accretion, in the case of Westshore having also been responsible for the occasional erosional impacts to its Reserve (Komar, 2005, 2010).

The changes in land elevations at the time of the 1931 earthquake also affected the stabilities of the gravel barrier ridge within the Haumoana Littoral Cell. With the northern-most stretch this cell's shore having experienced uplift, though somewhat less than occurred along the Bay View Cell, overtopping events of its barrier-beach gravel ridge during storms have been significantly reduced. Prior to its increased elevation in 1931, the downtown area of Napier had experienced frequent flooding. Its 1.8-metre uplift produced by the earthquake greatly reduced this hazard, which was then eliminated by infill of the backshore area by placement of the ruined remains of the city's buildings, followed by construction of a seawall to fully protect its shore.

The small community of East Clive midway along the shore of the Haumoana Cell, close by to the north of the Tukituki River, is essentially at the node in the shift of land-elevation changes, it having experienced essentially no change at the time of the earthquake (Figure 4), representing the transition from the uplifted shore to its north, subsidence to its south. A portion of the sparsely developed East Clive shore is shown in Figure 6, containing the natural barrier gravel ridge with a series of small ponds to its landward side. The ridge along this shore can be overtopped by combinations of high tides and wave swash runup during storms, evident in the morphology of the ridge seen in Figure 6 (Daykin, 2010). Figure 7 provides a comparison between the earliest profile surveyed at this site in 1989 and that in 2011, demonstrating the net erosion of the beach and a significant accumulation of gravel on the landward side of the ridge, but with only a small retreat in the location and elevation of its crest. In the most recent analysis of the profile surveys collected by the Hawke's Bay monitoring program, Edmonson et al. (2011) derived a rate of -0.33 m/year for the net retreat of its ocean-beach shore.

Figure 6: The south-central shore of the Haumoana Littoral Cell, the barrier beach ridge in East Clive where overwash events have occurred during significant storms and high tides.
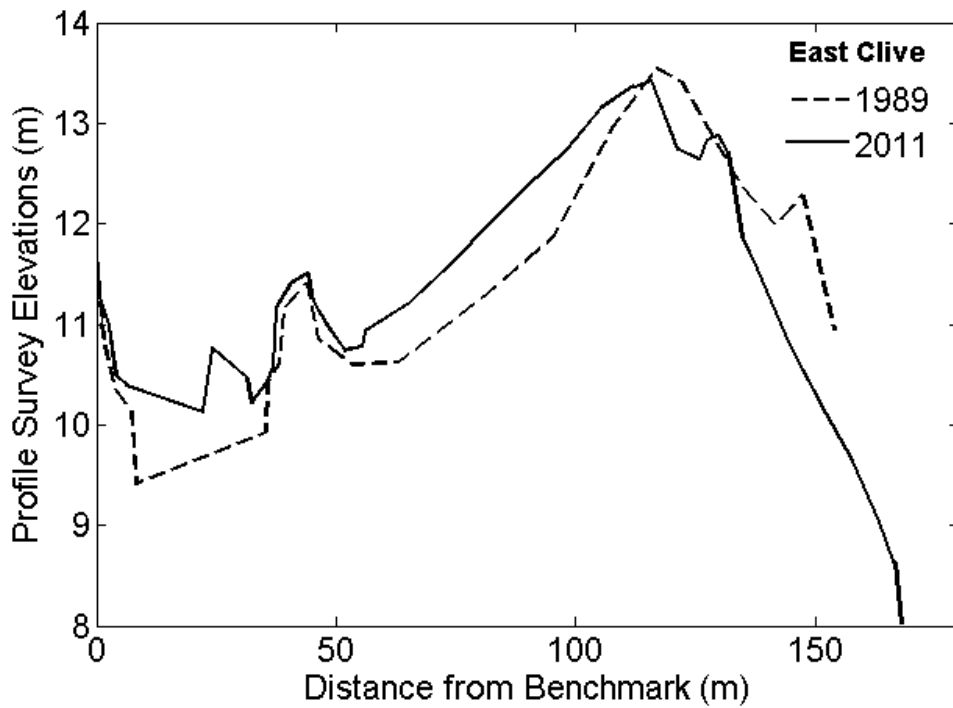
Figure 7: Comparison between the earliest surveyed (1989) and recent (2011) beach profiles of the barrier gravel ridge at East Clive, documenting erosion of the ocean beach and accumulation of gravel on the landward side of the ridge, produced by wave overtopping during storms.

The southern stretch of the Haumoana Cell has experienced the most extreme problems with erosion along the coast of Hawke's Bay, impacting ocean-front properties in the communities of Haumoana, Te Awanga, and Clifton, illustrated by the photos in Figure 8 showing a recent storm event and the remains of failed concrete sea walls that had been constructed to protect the homes. Investigations have concluded that this chronic erosion may in part still be a response to this shore's 1-metre subsidence at the time of the 1931 earthquake, although the main cause has been that the balance in the sediment budget for this shore south of the Tukituki River is substantially "in the red", that is the rate of sediment loss to its being transported alongshore by waves to the north exceeds that being acquired from the Tukituki River and erosion of Cape Kidnappers (Tonkin & Taylor, 2003; Komar, 2005, 2010).

The sediments, processes and morphologies of the Bay View and Haumoana Cell's beaches have been examined in detail in our previous report and publication (Komar, 2005, 2010); only a brief summary is presented here. The beaches are composed of gravel and sand, categorized as "mixed sand-and-gravel" in the classification by Jennings and Schulmeister (2002), being common along the east coasts of New Zealand's North and South Islands (Kirk, 1980). The gravel in the Hawke's Bay beaches is derived from the erosion of Mesozoic rocks found within the inland Front Range of mountains, a greywacke that originated in the deep ocean as deposits of silt and fine-grained sand, later metamorphosed by heat and pressure during mountain building, yielding the most resistant rocks in the Hawke's Bay mountains.

Figure 8: Storm-wave impacts and property damage in the south Haumoana Cell. [Photos from Daykin (2010).]

Although the greywacke gravel found in the rivers and beaches has the appearance of being extremely resistant, the cobbles and pebbles are actually susceptible to comparatively rapid rates of abrasion when transported by waves and currents. This was first demonstrated in the laboratory "tumbler" experiments undertaken by Marshall (1927), which served as the basis for his interpretations of the abrasion of the gravel found in the Hawke's Bay beaches, and the resulting changes in grain sizes and shapes as they are transported alongshore within the Haumoana Cell. His laboratory experiments demonstrated that the abrasion of the greywacke gravel yields sand, which initially is quite coarse as it is the product of collisions between pebbles and cobbles. This coarse sand is able to temporarily remain on the beaches, accounting for their being mixed sand-and-gravel, but eventually that coarse sand is ground down into the silt and very fine particles of sand that originally were deposited in the ocean. The recent field investigation by Dickson et al. (2011) is of interest in that it again focused on the Haumoana Littoral Cell, having employed the technique of tagging individual pebbles implanted with Radio Frequency Identification tags, permitting them to be followed for several months as they were transported by the waves northward along that shore, providing measurements of their transport rates and the extent of abrasion based on the decreasing particle weights.

With the gravel having originated by erosion of the inland mountains, they are then transported to the Hawke's Bay beaches by large rivers, there being three major rivers that reach the shore of the Haumoana Cell — the Tukituki, Ngaruroro, and Tutaekuri Rivers (Figure 1). However, only the Tukituki River now represents a significant source of gravel to this shore, the lower reaches of the channels of the other rivers to the north having been raised by the Hawke's Bay Earthquake, having cut off their delivery of gravel to the ocean beach. With the gravel now being contributed only to this southern-most stretch of the Haumoana Cell's shore, by the Tukituki River together with some from the erosion of Cape Kidnappers, the dominant waves reaching this shore from the southeast produce a net northward longshore transport, redistributing it along the length of this cell's shore. However, significant quantities are commercially extracted from the beach at Awatoto, it being the principal "debit" in this cell's sediment budget (Tonkin & Taylor, 2005; Komar, 2005, 2010). Detailed shoreline modeling analyses undertaken by Tonkin & Taylor demonstrated that the downdrift shore to the north of Awatoto still experiences some accretion, but at much reduced rates compared with prior to the inception of beach sediment extraction. According to the model analysis, this extraction at Awatoto has also produced negative impacts along the updrift shores, south of Awatoto to at least the mouth of the Tukituki River, of concern due to the low elevations of that shore, not having been raised by the 1931 earthquake. The models also indicated that beach and property erosion in the communities of Haumoana, Te Awanga

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and Clifton, south of the Tukituki River, was already occurring prior to the mining operation, its sediment budget already having had a negative balance, the extraction at Awatoto having little impact on the southern-most shore.

The Bluff Hill headland in Napier forms the northern boundary of the Haumoana Littoral Cell, separating it from the Bay View Cell (Figure 1). There is strong evidence that the beach gravel has not been carried by waves and currents past this headland, prior to the construction of the Port of Napier's breakwater in the late 19th century, or subsequent to its construction (Komar, 2005, 2010). However, since 1986 gravel and sand has been extracted from Pacific Beach, the Napier shore immediately south of Bluff Hill, carried by truck to Westshore north of Bluff Hill to nourish its recreational beach, this addition now representing the largest input of sediment into the Bay View Cell, amounting on average to 12,800 m^3/year as a "credit" in its sediment budget.

The Bay View Littoral Cell differs from the Haumoana Cell in there essentially being no natural sources of gravel to it beaches, the only river reaching its shore being the comparatively small Esk River, supplying minor quantities of sediment, mostly sand. The loss of gravel due to its abrasion results in a "debit" that has a comparable magnitude to the "credit" derived from nourishment at Westshore, but with the rate of abrasion being sufficiently uncertain it is unclear whether the resulting balance in the sediment budget is in the "red" or "black". Lacking significant natural sources of gravel and with a nearly zero net balance in its budget, the Bay View Cell is in effect a large pocket beach that over the long term must experience a net zero longshore transport, although there is evidence for seasonal and climate controlled reversals that account for cycles between periods of shoreline erosion versus accretion at the ends of this cell's shore, in the immediate proximity to the bounding headlands at Westshore in the south, and at Tangoio in the north (Komar, 2005, 2010). This quasi-equilibrium zero net transport of the beach sediments is explained by the orientation this cell's shoreline, seen in Figure 1, facing directly toward the southeast and the arrival of the dominant waves from that direction. This contrast in orientations between the Bay View and Haumoana Cells is significant to hazard assessments in that the waves reaching the Bay View shore on average undergo less refraction and energy losses than do those impacting the Haumoana shore.

OCEAN PROCESSES AND HAZARDS

With the objective of this study being to assess the erosion and flooding hazards along the coast of Hawke's Bay, most important are analyses of its causative ocean processes, the measured tides and waves, including a determination of the local trend in the relative sea level and an examination of whether there is evidence for increasing waves heights produced by greater storm intensities. The methodology applied to derive the resulting hazard assessments for shore-front properties includes the model developed by Ruggiero et al. (2001) in which the measured tides plus the wave-swash runup on the beaches are combined to yield the hourly total water levels (TWLs) at the shore, which can then be compared with the morphologies and elevations of the beach and backshore properties to assess their potential erosion or overwash occurrences during extreme storm events. This application to Hawke's Bay includes analyses of available data sets of measured tides and waves collected by the Port of Napier, with the deep-water wave heights utilized to calculate breaking wave heights and swash runup levels on the beaches. Beyond analyses of those individual ocean processes, important are their combinations that account for extremes in TWLs at the shore, being the ultimate factor important to the potential erosion and flooding of oceanfront properties. The results of these process analyses are summarized in this section, with the full account presented in our complete report (Komar and Harris, 2014).

Tides and Extreme Measured Water Levels

The changing levels and extreme elevations of the tides are a major factor in causing beach and property erosion, determining the elevations of the water atop which the waves break and swash up the sloping beaches. Important is the degree to which the levels of the measured tides are raised above their predicted (astronomical) elevations, in particular caused by storm surges that accompany extremes in the

storm-generated wave heights. Accordingly, our analyses were directed toward hourly measurements collected by the Port of Napier's tide gauge to document the frequency distribution of its water-level elevations. Unfortunately, this documentation is limited by the shortness of this gauge's record, hourly measurements having begun in 1989. Considering this limitation, our goal has primarily been to determine the general distribution of the measured water elevations, yielding an indication of their potential extremes, while relying on previous investigations by others that have been directed specifically toward assessments of the magnitudes of storm surge levels measured around the coasts of New Zealand, applied in our analyses to project the potential extremes in the Hawke's Bay tides.

The predicted astronomical tides are the most significant factor that accounts for variations in mean water levels along New Zealand's shores, overall being responsible for 96% of the measured variations, while the remaining 4% are the hourly effects of storm surges that can raise the measured tides by on the order of a metre above the predicted levels (Goring, 1997). For Hawke's Bay that magnitude of increase caused by a storm surge is particularly significant in that the range of predicted tides is only 1.9 metres. New Zealand's tides are relative to a Chart Datum (CD) that corresponds to the predicted Lowest Astronomical Tide (LAT) for that gauge, this choice having the result that all predicted tides would be expected to have positive values. However, according to the Land Information Agency of the New Zealand government, the CD datum for the Napier gauge is more precisely 0.06 metre CD (www.linz.govt.nz), so that extreme low predicted tides can in rare instances have small negative values. The predicted mean high water level at the time of spring tides (MHWS) for Hawke's Bay is 1.91 metres CD, on average 0.35 metre higher than the 1.56-metre level during neap tides (MHWN). The highest predicted astronomical tide (HAT) of the year is 2.00 metre CD, this essentially being the full tidal range of predicted water levels for Hawke's Bay. Its tides are therefore classified as "microtides" by Davies (1964), only just reaching the "mesoscale" range at their maximum, modest in comparison with tides on most coasts.

A peculiarity of the tides on New Zealand's east coast is that while there is a spring versus neap cycle, it does not correspond to the astronomical alignments of the Moon and Sun; the highest tides of the month do not occur during full and new Moon when their forces combine. Its monthly variation is instead produced by the changing distance of the Moon from the Earth, being greatest when the Moon is closest to the Earth at perigee in its monthly orbit, resulting in the highest tidal range of the month (Goring, 1997). 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.

Hourly tide data have been collected by the Port of Napier's Geddis Wharf gauge since 1989, but having a 3-year gap from 1995 to 1999. Furthermore, the pre-1995 data were recorded to only 1-cm resolution. As a result, while tide predictions have been available for Hawke's Bay and its harbour for more than a century, quality measurements are limited to little more than a decade. From an inspection of the raw data it is evident that beginning in about 2008 there have been occurrences of unusually high measured tides, including the highest water levels since 1989 (Komar and Harris, 2014). This grouping of high water levels in recent years is likely due to occurrences of more intense storms and their surges, the trend for the rise in sea level based on the Port's tide-gauge record having been only 1.9 mm/year, amounting to only a 2-cm increase during the decade of measurements, not having been a factor in causing these recent elevated water levels.

Of importance to occurrences of erosion and flooding events on the Hawke's Bay coast is the distribution of measured tides, in particular the most extreme high tides. Histograms for the frequency distribution of the hourly-measured tides during the year 2010 are presented in Figure 9, graphed using both linear and log scales for the numbers of observations. The linear-scale plot, shown in gray, is the conventional form generally used in graphing distributions, whereas the log plot in red is more informative in applications to hazard assessments in that it emphasizes the few occurrences of rare but extreme measured tides (Komar and Allan, 2007). Based on this distribution using the log scale, it is seen that the most extreme measured tides are on the order of 2.25 metres CD (5 occurrences); 0.25 metre above the predicted Highest Astronomical Tide (HAT), but with the surge magnitudes that produced these extremes undoubtedly having been substantially greater since these high water levels

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did not actually occur during the maximum HAT predicted level, or necessarily even during a spring tide. Although the histogram of Figure 9 is based on only a single year of data, 2010, the complete 21-year record shows that the highest measured tides in fact occurred that year.
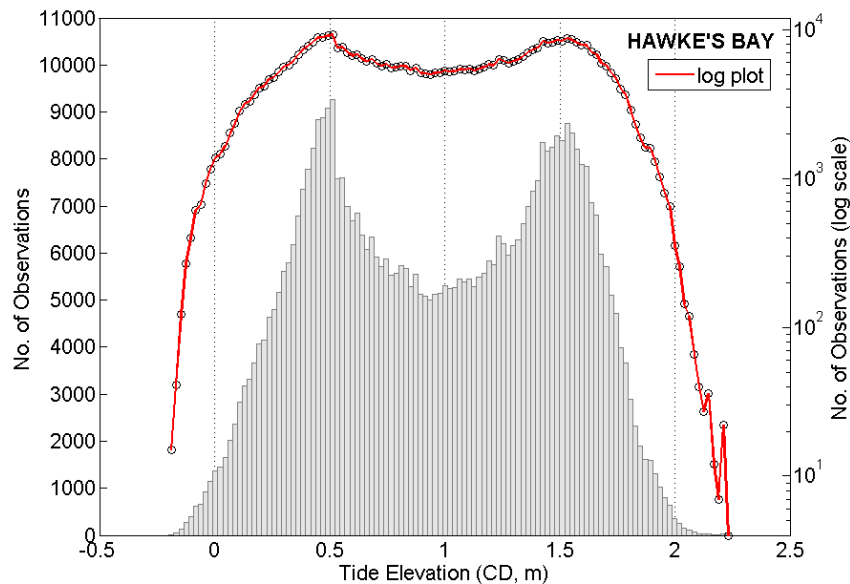
Figure 9: Frequency distributions of hourly measured tidal elevations during the year 2010, the numbers of observations graphed on both linear and log-scale axes.

The mean value of all measured tidal elevations during 2010 is 0.95 metre CD, which corresponds to that obtained when analyzing the predicted astronomical tides over a number of decades, effectively being the mean sea level (MSL) from 1989 to 2010. The modes of most frequent occurrences in Figure 9 are at approximately 0.5 and 1.5 metre CD, which respectively depend on the ranges of the daily low and high tides, although these modes differ somewhat from the predicted mean low tides and mean high tides. An overall asymmetry is evident in the distribution, with the maximum water elevation (2.25 metres CD) being 1.30 metres above MSL, whereas the lowest measured tide is 1.10 metres below MSL. This skewness toward higher measured tides has for the most part been produced by storm surges that enhanced the high water levels, amounting to 10s of centimeters above the predicted tides and accounting for the most extreme measured high water levels.

Bell et al. (2000) has analyzed the records from a number of New Zealand tide gauges, including their seasonal cycles in mean water levels, his results showing the common cycle with the highest levels occurring during the Southern Hemisphere summer (November through February), the variation amounting to about 0.2 metre. We similarly analyzed the Hawke's Bay tide gauge record, 1999-2010, but found an inverted pattern with the highest water levels on average having occurred during the winter (March to June), reaching a low in September. However, its change from winter to summer amounted to only 0.1 metre, our conclusion having been that its elevated levels during the winter are produced by storms, their low atmospheric pressures and generated surges, with seasonal variations due to changing water temperatures apparently being a minor factor (Komar and Harris, 2014).

Investigations of storm surges around the coasts of New Zealand have demonstrated their significance to erosion and flooding in that their levels are of the same order-of-magnitude as the ranges of tides, and in the case of Hawke's Bay are also of comparable importance to the wave–swash runup levels. Analyses by de Lange (1996) of measured storm surges found that the maximum expected levels for the New Zealand coast are in the range 0.8 to 1.0 metre, achieved with return periods of 100 years or longer.

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The magnitudes of storm surges that specifically occurred on the coast of Hawke's Bay have received comparatively little attention, due to the availability of only a short record of tide measurements. One significant study is the report by the engineering firm Worley (2002), which analyzed measurements during the 4-year period, November 1998 through October 2002. A tidal constituent analysis was undertaken, but was limited to one year (May 2001 to June 2002), at that time the longest set of continuous measurements without missing data. Of particular interest in their 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 surges were identified in that 1-year record, when measured tidal elevations reached at least 0.75 metre above the predicted tide. The result of an extreme-value analysis of the residuals showed that the extremes 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. In applications this value is commonly added to the predicted MHWS tide elevation to provide an estimate of potential extreme water elevations having a 1% probability of occurrence each year; for Hawke's Bay this would yield an elevation of 2.86 metres CD, that is, nearly 2 metres above MSL.

As an alternative assessment of extreme measured tides for Hawke's Bay, one that provides a less conservative estimate of the water levels, Worley (2002) also undertook a joint probability analysis that combined the astronomical tides and the measured tidal residuals. Based on 18,000 Monte Carlo simulations, effectively representing 1,000 years of simulated tides, the result was that the 100-year extreme is 2.70 metres CD.

An extreme water level with the predicted tide increased by a significant storm surge could clearly be a major factor in erosion and flooding hazards along the Hawke's Bay coast. In terms of the distribution of measured tides graphed in Figure 9, an extreme surge with a 1% probability could reach an elevation of 3 metres CD, some 0.75 metre higher than the highest measured tides during 2010. The effect on a typical Hawke's Bay beach having a slope of 1-in-10 is that the mean-water shoreline would advance landward by some 15 to 20 metres, which at high tide brings the water much closer to shore-front properties such that the wave swash runup on the beach, also generated by the storm, could forcefully impact and erode ocean-front properties.

The Deep-Water Wave Climate

Waves along the coasts of New Zealand are generated mainly by the prevailing westerly winds and superimposed extratropical storms that occur in the Southern Hemisphere between 30°S and 70°S. New Zealand itself extends from 34°S to 47°S, with Hawke's Bay centered at about 39°S, within this zone of westerly winds but with the strongest storms occurring over the Southern Ocean between New Zealand and Antarctica. During the winter the belt of westerly winds and storms shift to the north, extending across New Zealand with the storms crossing the land from west to east. Located on the east coast on the North Island, Hawke's Bay is therefore on the lee shore relative to the storm tracks, and as expected the wave heights are on average smaller than occur along the west coast. However, due to the alignment of New Zealand in a northeast-southwest direction, waves generated in the Southern Ocean by the strongest storms can progress northward and travel up the east coast, reaching Hawke's Bay predominantly from the south to southeast (Gorman et al., 2003a).

The development of a deep-water wave climate is critical to hazard assessments for Hawke's Bay, but like the tides is limited by the availability of direct measurements, the Port of Napier's wave buoy having been in operation only since August 2000. Representing an additional complication, the buoy is located in only 16-metres water depth, the measured waves therefore having been altered by shoaling and in particular by wave refraction that alters their heights and directions from those in deep water. Earlier investigations have developed deep-water wave climates based on hindcast methodologies, around the coasts of New Zealand and specifically for Hawke's Bay (Gorman et al. 2003a, 2003b; Tonkin & Taylor, 2003; MetOceans 2008, 2011). A goal in our analyses has been to develop a unified deep-water wave climate in which there is basic agreement between the Port's wave measurements and the hindcast analyses as to ranges and extremes in magnitudes of the significant wave heights (SWHs) in deep water, results that can be applied in our hazard assessments.

The wave hindcast analyses by Gorman et al. (2003a, 2003b) included the 20-year period 1979-1998, the results of which provide the most detailed assessments of wave climates around the coasts of New Zealand. Their hindcasts were derived using the wave generation model WAM (WAve Model), based on the daily winds across the ocean's expanse, 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 approximately at the center of that area. The hindcasts were made at 3-hour intervals. 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 closest to Hawke's Bay). In their second paper, Gorman et al. (2003b) compared the hindcast assessments of deep-water wave heights and periods with those measured by altimeters from satellites. It was found that the long-term mean SWHs from the hindcasts were generally 0.3- to 0.5-metre lower than wave heights from the satellite altimeter; the distributions of the hindcast SWHs matched the satellite data reasonably well, but tended to underestimate the magnitudes of more extreme wave events.

Tonkin & Taylor (2003) employed the hindcast data of Gorman et al. (2003a) to evaluate the SWHs and periods at the 200-metre water depth directly seaward from Hawke's Bay, serving as the local deep-water wave climate in their analyses of waves in shallow water along this coast. A histogram of its SWHs in deep water shows a mode of 1.4 metres for the most frequent occurrence, a mean of 1.76 metres, with the maximum SWH being 8.56 metres. The mean period of the waves was 10.4 seconds.

The deep-water wave hindcast by Gorman et al. (2003a, 2003b) has been complemented in similar analyses undertaken by MetOceans (2008, 2011) specifically for Hawke's Bay, covering the 12-year period from 1997 through 2010. While their hindcasts included the deep-water wave conditions, the primary objective of their 2008 report was to document the shallow-water waves in the Westshore area of Napier, and how they might be altered by the construction of a seawall/breakwater proposed to provide improved property protection, while the 2011 report expanded the analysis to provide inshore wave climates at intervals along the entire Hawke's Bay coast.

The Port of Napier installed a Triaxys directional wave-rider buoy in August 2000, positioned in 16-metes CD water depth offshore and to the north of the Port's breakwater (39°27'27"S and 176°56'3"E). At that depth the dominant waves are in intermediate to shallow water, depending on their period, only the locally generated waves with small heights and periods representing deep-water conditions. The buoy records 20 minutes of water surface elevations, and then calculates a number of wave parameters including the SWH, the 10% exceedence wave height, the maximum wave height, the wave period at the peak of the energy-density spectrum, and the average and range of wave directions. For the first three years of operation the buoy obtained measurements once each hour, but since 2004 it has collected data twice per hour. The buoy data have been analyzed in a series of engineering reports by Worley, directed toward the design and management of the Port.

In developing a wave climate for Hawke's Bay to be applied in our coastal hazard assessments, the decision was to utilize the Port's buoy data, representing the only direct measurements of the waves. This choice was in part governed by the ready availability of its hourly-collected data, provided to us by the Hawke's Bay Regional Council. It was recognized, however, that this reliance on the buoy measurements results in complications for the analyses in that the buoy is located in only 16-metres water depth, not representing the desired deep-water wave parameters for a wave climate, the measurements having been affected by shoaling and wave refraction. Those complications were overridden by the desire to integrate its measurements with the hindcast wave climates, yielding a unified deep-water wave climate that is in reasonable agreement as to the ranges and extremes of the Bay's SWHs and periods.

In our analyses we first developed a wave climate based directly on the wave-buoy data, representing its 16-metres water depth, the results being of potential interest to the Port and community of Westshore (Komar and Harris, 2014). Our methodology then proceeded to reverse calculate the equivalent deep-water SWHs from the hourly buoy measurements, this accounting for the shoaling transformations the waves had experienced while travelling from deep-water to the buoy depth, but

neglecting changes in the *SWH*s caused by wave refraction and energy losses due to bottom friction. This procedure initially produced a histogram of deep-water *SWH*s, which were then further corrected to include the effects of refraction, by insuring that the heights correspond in magnitudes to the histogram of deep-water *SWH*s derived by Tonkin & Taylor (2003), based on the hindcasts of Gorman et al. (2003a). The measurements by the Port's buoy are graphed in Figure 10, with the *SWH*s again being presented as a pair of histograms, having included a log scale to emphasize the extreme but rare *SWH*s generated by the most severe storms. The convergence of the Port's buoy data with the deep-water hindcast values involved the correction of the former, increasing its mean *SWH* of 0.92 metre by a factor of 1.91 so it agrees with the 1.76-metre mean *SWH* from the hindcast analyses. This 1.91 ratio in the mean *SWH*s was then used as an empirical "correction factor" for the entire histogram in Figure 10, in effect increasing the entire range of buoy measured *SWH*s, a uniform shift that is accomplished by the upper axis in the diagram, the Corrected Significant Wave Heights. With this empirically corrected axis, there is now reasonable agreement between the magnitudes of the deep-water *SWH*s derived from the Port's buoy and those based on the wave hindcast analyses, the modes of most-frequent occurrence respectively being 1.2 and 1.4 metres, with maximum *SWH* magnitudes of 9.9 and 8.6 metres (Komar and Harris, 2014). This extent of agreement for the extreme *SWH*s is perhaps surprising considering the different methodologies followed, hindcasts versus buoy measurements, and also the different time periods represented by these analyses.
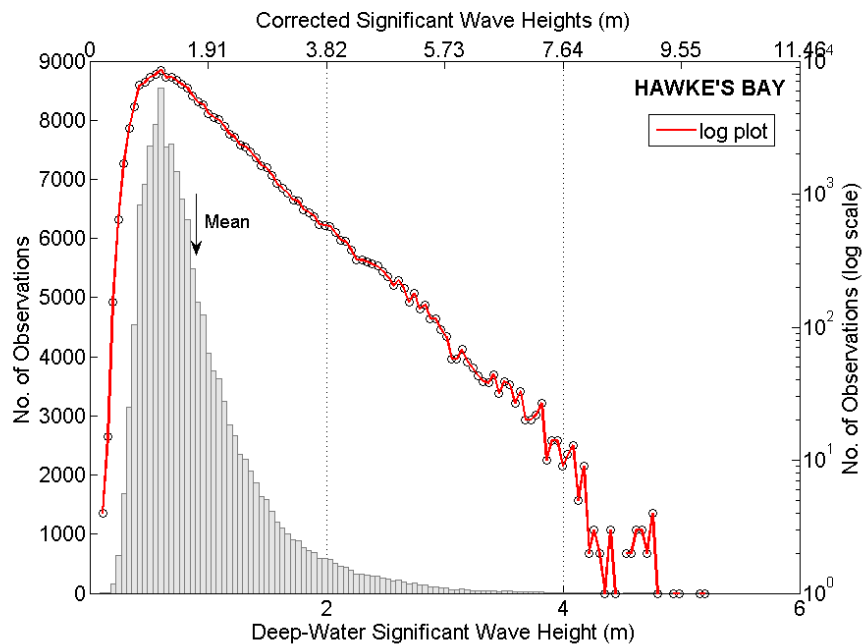

Figure 10: Histograms of deep-water *SWH*s calculated from the Port's hourly buoy measurements. The bottom axis accounts for shoaling transformations but not refraction, while the top axis for the "Corrected" magnitudes empirically accounts for wave height reductions due to refraction, yielding reasonable agreement with the *SWH*s derived from hindcast analyses.

This empirical 1.91 correction factor employed to account for wave refraction is in approximate agreement with Snell's Law for the dominant waves arriving in deep water from the southeast, compared with their directions measured by the buoy, the remaining difference likely being attributable to energy losses produced by bottom friction plus wave-wave interactions and instabilities leading to breaking in the offshore (Komar and Harris, 2014). Direct analyses of the wave refraction in Hawke's Bay were first developed by Gibb (1962), demonstrating the degree to which the crests of the dominant waves in deep water arriving from the southeast quadrant rotate counter-clockwise as they approach the shores of Hawke's Bay. This is further substantiated by refraction analyses undertaken by Tonkin & Taylor (2003) and MetOceans (2008, 2011), yielding wave climates in shallow water along these

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shores, providing direct assessments of the degrees of wave-height reductions caused by refraction, important in our hazard assessments.

The resulting deep-water wave climate based on the Port's measurements modified to their deep-water equivalents is shown in the "scatter diagram" of Figure 11, a graph of the hourly-measured SWHs versus their periods. The blue Xs are the mean SWHs for each band of reported periods, which range from about 2 to 25 seconds, with the highest SWHs occurring within the 9- to about 17-second range of periods. With the buoy being in 16-metres water depth, "deep-water" waves are limited to periods less than 6.5 seconds, while "shallow-water" waves have periods greater than 14.5 seconds, "intermediate" being waves between those periods. The density of points in Figure 11 is misleading in suggesting that deep-water waves dominate the occurrences, more so than the intermediate waves, but a simple histogram of the periods demonstrates that the reverse is true, with periods from 8 through 15 seconds having the most frequent occurrences, corresponding to the maximum SWHs (Komar and Harris, 2014).
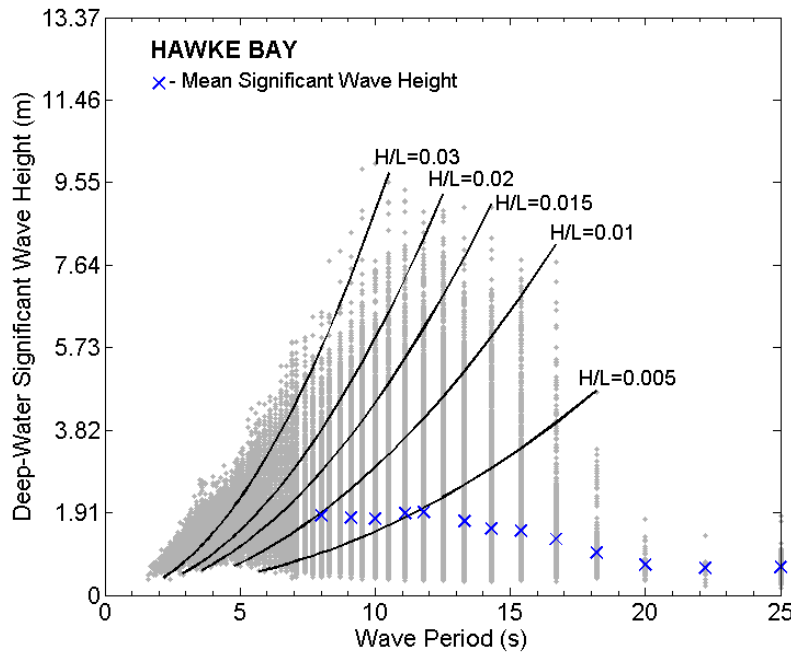
Figure 11: Scatter diagram of the "corrected" deep-water SWHs versus periods, derived from hourly measurements by the Port's buoy.

This graph for the Hawke's Bay waves is fairly typical of wave-scatter diagrams, the waves having the shortest periods, less than about 5 to 6 seconds, for the most part having been locally generated by winds not necessarily associated with storms, having lower heights due to the smaller fetch areas and insufficient time to have grown larger, and because short-period waves are stable only if their heights are small. All of the waves with periods greater than 20 seconds are seen in Figure 11 to have heights that are less than about 1 metre, representing low-steepness swell presumably generated by distant storms, likely the forerunners of the 10- to 12-second waves with higher SWHs that arrive hours to days later. Thus, the overall scatter of the SWHs versus periods follows the expected pattern of waves that had been generated by distant storms, presumably those in the Southern Ocean or crossing New Zealand to the south of Hawke's Bay.

Wave Swash Runup Levels on the Hawke's Bay Beaches

Of direct relevance to occurrences of ocean-front property erosion and flooding are the processes that operate on the beaches, components of what is termed the "nearshore processes climate", analogous to and dependent on the deep-water wave climate (Komar and Allan, 2002). Detailed analyses are presented in our full report for the ranges of calculated wave breaker heights and the levels to which the

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wave swash runs up the Hawke's Bay beaches (Komar and Harris, 2014), but here only the resulting distribution of runup levels will be presented, it being a critical component in the Ruggiero et al. (2001) model to calculate the total water levels at the shore, the sum of the measured tides and wave runup.

Values of the wave-swash runup levels (their vertical components) were calculated from the hourly deep-water wave heights and periods, the magnitudes of the runup elevations thereby being directly dependent on the Hawke's Bay wave climate. A formula derived by Stockdon et al. (2006) was applied in our calculations, based on time series of water-level measurements derived from ten field investigations, representing diverse beach morphologies. Their resulting formula is dependent on the combination of parameters, $\left(gSH_\infty T^2\right)^{1/2}$, where S is the beach slope, H_∞ is the deep-water SWH, and T is the wave period. Of importance, the swash runup level has a stronger dependence on the wave period than on the wave heights, the reverse being true in calculations of the wave breaker heights, which furthermore do not depend on the beach slope. The resulting swash runup formula of Stockdon et al. (2006) is therefore based on an empirical correlation with measured runup levels, yielding $R_{2\%}$ that represents the 2% exceedance value within the distribution of individual swash maxima, an extreme in the distribution but one that occurs sufficiently often during an hour that it represents a meaningful factor to the resulting impacts experienced by shore-front properties.

The slopes of the mixed sand-and-gravel beaches analyzed in our study, those within the Bay View and Haumoana Littoral Cells, are consistently close to about S = 0.1 (1-in-10), a value that has been used throughout our analyses. As a result, the horizontal distances of runup are simply 10 times the calculated $R_{2\%}$ vertical components.

Important in calculations of wave breaker heights and swash runup levels on the Hawke's Bay beaches is the extent of refraction of the waves as they cross the continental shelf from deep water to the shore. While the deep-water wave climate in Figures 10 and 11 is essentially the same for the entire coast of interest in this study, the Bay View and Haumoana Littoral Cells, the breaker heights and swash runup levels will vary systematically along the lengths of those shores, depending on the extent of refraction and sheltering by headlands. As will be seen in later analyses, there are parallel changes in the elevations of the junction between the beach and the toe of the wave-eroded scarp cut into the gravel ridges, a morphologic feature that provides evidence for the total water levels experienced during past major storms, important to projections of future hazards faced by developed properties.

The significance of wave refraction in Hawke's Bay has already been discussed, important being the analyses undertaken in the reports by Tonkin & Taylor (2003) and MetOceans (2008, 2011) that in effect calculated climates of SWHs for the immediate offshore from the beaches, at water depths of 5 and 10 metres, closer to shore than the 16-metres depth of the Port's buoy so that additional refraction of the waves has occurred. Their results for the coastal wave climates have been important in our analyses, providing guidance to evaluate both the wave breaker heights and to serve as a guide in the evaluation of swash runup levels. However, the effects of refraction will differ for these respective nearshore processes, due to the wave-breaker heights depending mainly on the offshore wave heights, while the runup primarily depends on the wave periods that do not experience significant changes during shoaling, the reduction in the runup therefore expected to be less than experienced by waves breaking on the beaches.

The runup levels derived from the Stockdon et al. (2006) formula need to be reduced from their original calculated magnitudes in order to account for the effects of refraction and energy losses due to bottom friction. Accordingly, the resulting decreased runup at the shore is expressed as $C_r R_{2\%}$ where C_r is simply a correction factor, in many respects an inverse of the 1.91 factor that was used in deriving the deep-water SWHs from those measured by the Port's buoy. However, this C_r correction factor for the reduction of the runup will vary from site to site along the shore, depending on the extent of refraction and sheltering, and could be expect to range from 1.0 where refraction is negligible, to on the order of 0.1 within sheltered shores where significant refraction has occurred.

An example of a calculated distribution of wave-swash runup levels is presented in Figure 12, based on the hourly pairs of deep-water wave heights and periods derived from the Port's buoy measurements, the results consisting of 11 years of hourly calculated runup magnitudes. In the analysis the beach slope was set at 0.1, typical for the Hawke's Bay beaches, and the correction factor to account for wave refraction was arbitrarily taken in this example as C_r = 0.3, representing an average shoreline site within the Haumoana Littoral Cell. The original calculated $R_{2\%}$ values, applying the Stockdon et al. (2006) formula, are graphed as the lower axis in Figure 12, this in effect being the magnitudes when C_r = 1.0, a fully exposed shore with no reduction by refraction. The magnitude of most-frequent occurrence is about $R_{2\%}$ = 1.3 metres, representing a horizontal runup distance of some 13 metres for moderate wave conditions, while the most extreme storms would result in $R_{2\%}$ = 5 metres, the horizontal distance being some 50 metres. The upper axis in Figure 12 is the runup that accounts for the reduction due to wave refraction, the factor C_r = 0.3 applied in this example yielding the more reasonable magnitude $C_r R_{2\%}$ = 0.4 metre, a 4-metre horizontal swash distance for the mode of most frequent occurrence, increasing to about 15 metres during major storms.
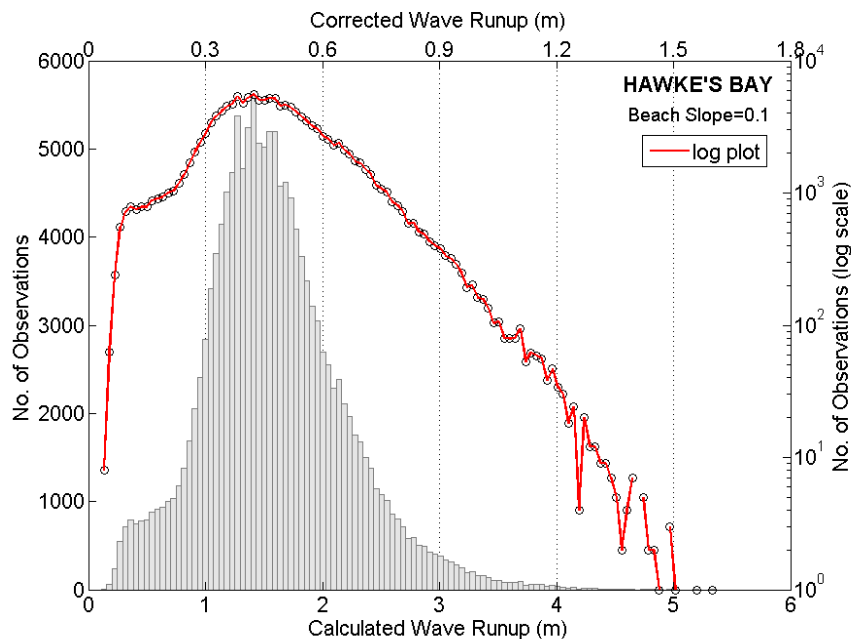
Figure 12: Linear and log graphs of wave swash runup levels (the vertical component), calculated from the deep-water wave climate. The upper axis includes a C_r = 0.3 factor to account for reduction by wave refraction.

Total Water Levels at the Shore

The present-day erosion and flooding hazards along the shores of Hawke's Bay depend on the total water levels ($TWLs$) achieved by the summation of the measured tides and wave-swash runup levels on the beaches. Particularly significant are their combinations during major storms when the generation of a surge elevates the tides, atop which the runup of the storm waves reach and impact backshore properties. This is the basis for the model developed by Ruggiero et al. (2001) that calculates the hour-to-hour combinations, our interest primarily being the distributions of the TWL elevations, particularly their extremes that pose hazards to shorefront properties, depending on their elevations. The resulting TWL distribution will vary from site to site, depending on the shore's exposure to the waves and the extent to which refraction has reduced the swash runup contribution. Accordingly, the total water level is calculated as

$$TWL = E_T + C_r R_{2\%} \tag{1}$$

where E_T is the elevation of the measured tide, which includes the effects of storm surges and climate controls such as the range of El Niño/La Niña events that can result in extremes in the monthly-mean sea levels, while $C_r R_{2\%}$ represents the hourly calculated swash runup with C_r accounting for the extent of reduction produced by refraction of the waves. Here it is noted that the $C_r R_{2\%}$ "level" has no datum reference, which however is derived by the addition of the measured tide, E_T, which initially is relative to the Chart Datum (CD) but is then altered to the Reference Level (RL) used in Hawke's Bay land surveys, including in the beach profiles that later will be compared with the TWLs determined here.

Our analyses of the TWLs for Hawke's Bay were again limited to the 11 years during which there were simultaneous hourly measurements of waves and tides. Distributions were calculated at 0.1 increments for the range C_r = 0.1 through 1.0, representing sites that are well sheltered to those that are fully exposed to the waves without reduction in the runup caused by refraction. To a degree these extreme distributions are respectively those of Figures 9 and 12, for the tides alone and the swash runup alone, the distributions blending at intermediate stages where both tides and waves are important contributors to the TWLs. For the range C_r = 0.1 through 0.3, the tides continue to dominate, the resulting TWL distributions being markedly bimodal, just as seen for the tides alone in Figure 9, although there is a shift in the TWLs to somewhat higher magnitudes as a result of some runup having been added. Figure 13 includes three representative examples where the wave runup comes to dominate the TWLs, calculated with C_r = 0.4, 0.7 and 1.0. The top-most graph for C_r = 0.4 still shows a small degree of bimodality, but is lost in the next distribution for C_r = 0.7, there being a broad mode of most-frequent occurrence ranging from about 10.5 to 11.5 metres RL. The final distribution for C_r = 1.0 represents a shore that is fully exposed to the waves, but even here the mode is noticeably broader than that for the runup alone as graphed in Figure 12, its width in Figure 13 having been produced by the tidal contributions to the TWLs.

As expected, the ranges of TWL magnitudes in this series of histograms systematically shift to higher values as C_r increases from 0.1 to 1.0, there progressively being higher wave-swash runup levels superimposed on the measured tides that otherwise have remained the same for all sites along this shore. This increase is most evident in the maximum TWL values, which are graphed in Figure 14, together with the mean values of the distributions that are close to their modes of most-frequent occurrences. The TWL maximums are seen to increase at a greater rate than the means, a consequence of the asymmetries of the runup and TWL histograms. The maximum TWL magnitudes range from about 11.5 to 15 metres RL, the implication being that the beach/backshore junction elevations found in surveyed profiles at monitoring sites along the lengths of the littoral cells potentially should have comparable elevations, the lowest elevations being found in sheltered areas such as Westshore, the highest on exposed shores where wave swash runup makes it greatest contribution to the TWLs. These parallel alongshore trends between the TWLs and elevations of the beach and backshore profiles will be compared later.
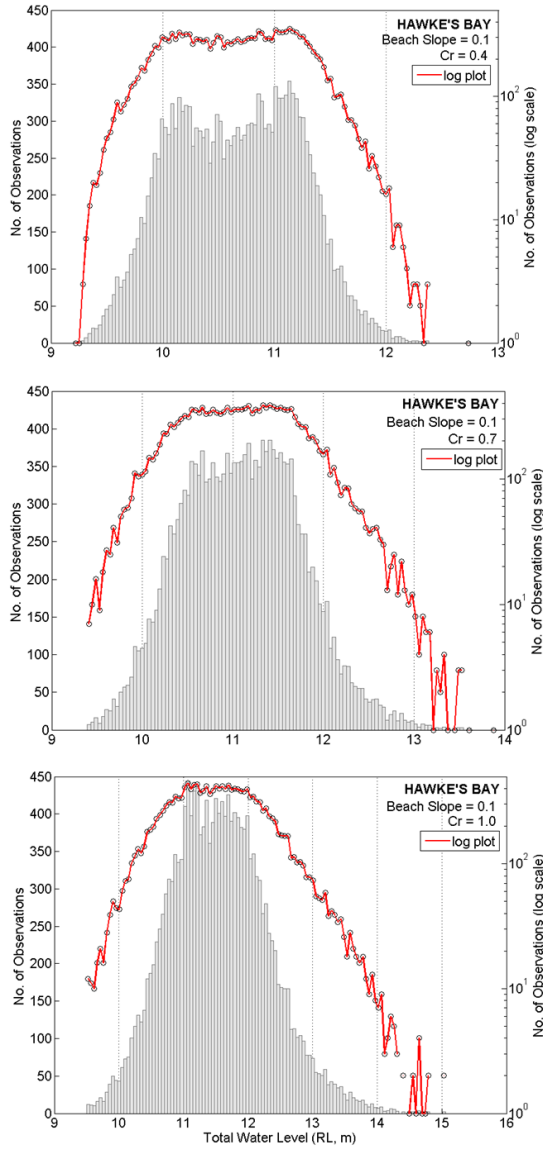
Figure 13: Representative examples of TWL distributions based on the Hawke's Bay hourly measured waves and tides, for a series of C_r values in equation (1) representing increased nearshore waves and swash runup levels, governed by the extent of wave refraction.
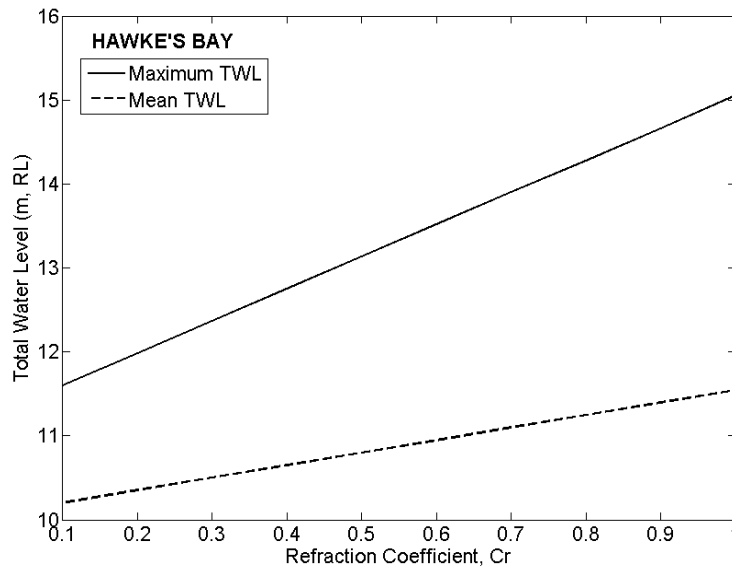
Figure 14: Means and maximums in the series of TWL histograms for C_r values ranging from 0.1 to 1.0, representing increasing wave runup contributions.

Analyses of Individual Storm Events

In our analyses of the Hawke's Bay erosion hazards we are also interested in the impacts of individual storms that result from combinations of the ocean processes. Applications of the Ruggiero et al. (2001) model to calculate the TWLs at the shore can similarly be directed toward the hour-to-hour variations in waves and tides during the storm, yielding detailed analyses of its hourly TWLs that account for the timing and extent of the resulting erosion and flooding impacts. Such analyses have been undertaken for the coast of the U.S. Pacific Northwest (Allan and Komar, 2002), for several storms during the El Niño winter of 1997-98 when tides were elevated by 10s of centimetres, and also for the following winter of 1998-98 when tide levels returned to normal but unusually severe storms generated the most extreme waves in recent decades. We have undertaken similar analyses in application to Hawke's Bay, for the strongest storms that occurred during 2010, which included the most extreme in the 11-year record of available measurements (Komar and Harris, 2014).

In an investigation of the erosion and flooding impacts in recent decades along the shore of the Haumoana Littoral Cell, Daykin (2010) included analyses of the hourly variations in wave heights and tides during major storm events, directly applying the measurements derived from the Port of Napier's buoy and tide gauge. Our corresponding analyses extend the calculations to include the hourly wave-swash runup ($R_{2\%}$) and total water levels (TWL), with the results for a March 2010 storm graphed in Figure 15, when the deep-water SWHs reached 7 metres. The upper panel includes the hourly measured SWHs and calculated $R_{2\%}$ runup levels, while the lower panel shows the hourly varying tides and resulting TWLs, the addition of the graphs for the tides and swash runup. The results provide a good example of how the ocean processes vary though the duration of a storm, in this case lasting for 4 to 5 days.

Of interest, the maximum values of the $R_{2\%}$ runup lag by nearly half a day behind the magnitudes of the SWHs, caused by the strong dependence of the runup on the periods of the waves, as well as their heights. Figure 15 also illustrates how the TWL responds on an hourly basis to the summation of the wave runup and the cycle of the tides, with the maximum level from their combination having reached nearly 15 metres RL. As will be seen in the following section, the beach/backshore gravel-ridge junction

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elevations in the Haumoana Littoral Cell range from 12 to 13.5 metres RL, it being evident that erosion of the foredunes potentially could have been continuous for 3 to 4 days, while the gravel ridge at East Clive with a crest elevation of 13.5 metres (Figure 3) could have experienced wave overtopping during three successive high tides, having been most extreme on 8 March 2010 when the calculated TWL potentially could have exceeded its elevation by more than 1 metre. However, the impacts during this March 2010 storm were less than this potential, in that the analyses graphed in Figure 15 did not include a reduction in the runup elevations produced by wave refraction, that is, in equation (1) the refraction coefficient had been set to C_r = 1 in order to evaluate the potential extreme $TWLs$ that might have occurred. With the storm having actually been well to the south and with its waves reaching the Hawke's Bay coast from the southeast, the magnitudes of these processes and impacts were reduced, but the results analyzed here in Figure 15 represent the potential for what might have occurred had the storm had been closer in proximity to this shore, the analysis having represented the potential extreme hazard.
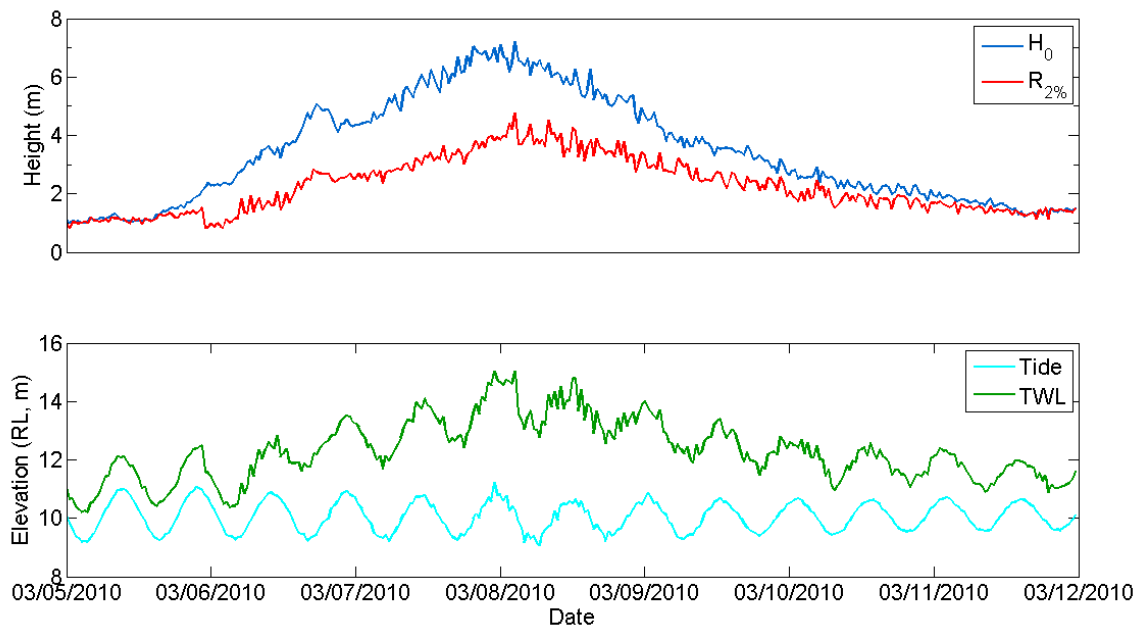
Figure 15: Analysis of the March 2010 storm, including the deep-water SWHs derived from the buoy data, the calculated swash runup at the shore ($R_{2\%}$), the measured tides, and the resulting hour-to-hour variations in total water levels (TWL).

An example analysis for a storm that was closer to this coast is illustrated in Figure 16, which impacted this shore from 31 August through 3 September 2010. Noteworthy is the abrupt increases in the SWHs and runup levels, resulting in a corresponding TWL increase within a few hours to a maximum 14-metre RL elevation, the subsequent decrease having spanned several days. This pattern presumably reflects the passage of a storm moving from west to east as it crossed New Zealand, probably close by to the south of Hawke's Bay; the sharp increase in measured wave heights would have recorded the first arrival of the storm over the ocean, having crossed the eastern shore of the North Island. In this instance the combined tides and swash runup would have reached the Haumoana Cell's beach/gravel ridge junction elevation of 12 to 13.5 metres RL for 1 to 2 days, resulting in some erosion, or not at all if refraction of the waves had been significant.
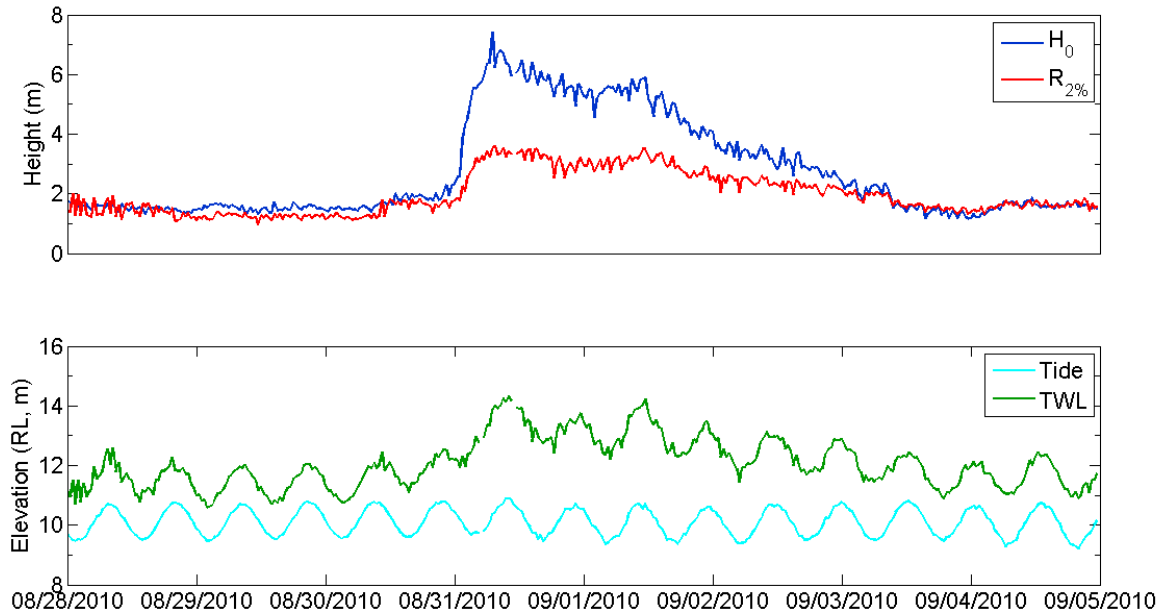
Figure 16: Measured waves and tides, calculated runup levels, and total water levels ($TWLs$) during the August-September 2010 storm.

BEACH MORPHOLOGY AND WATER LEVEL COMPARISONS

Having completed analyses of the Hawke's Bay ocean processes important to coastal impacts, including evaluations of the TWLs that combine those processes, comparisons can now be made with the morphologies of the surveyed profiles of the beaches and backshore barrier gravel ridges. This includes assessments of the junction elevations between the beach and base of the ridge scarp that has been cut back by waves during past major storms, and locally the maximum crest elevations where wave overtopping has occurred. Each of these morphologic features provides direct evidence for exceptional TWLs that have occurred under major storms in the decades since the 1931 Hawke's Bay Earthquake altered the gravel-ridge elevations. A reliance on this evidence is important to the hazard assessments in that as seen in the previous sections, uncertainties exist in evaluating the extremes in deep-water wave heights, the extent of wave shoaling and refraction from deep water to the shore, and in the calculations of swash runup levels on the mixed sand-and-gravel beaches. The morphologies of the ridges potentially provide longer-term evidence of past major storms and their TWLs than did our process analyses based on limited data spanning little more than a decade. Comparisons are undertaken in this section between the surveyed profiles and TWLs, first for the present-day conditions and then projected into the future by including a projected rise in sea levels plus a potential climate-induced increase in storm-generated wave heights and swash runup levels at the shore.

Surveyed Beach Profiles and Evidence for Past TWL Extremes

Important to the management of the Hawke's Bay beaches, particularly assessments of their multidecadal trends of erosion versus accretion, has been a monitoring program by the Hawke's Bay Regional Council with its emphasis placed on the collection and analysis of annual surveys of beach profiles at a large number of stations along the shores of the Bay View and Haumoana Littoral Cells, the sites identified in Figure 17 [reviewed in Komar (2005, 2010)]. The report by Edmondson et al. (2011) provides the most recent analyses of the surveyed profiles, ranging in dates from the 1970s to December 2010, the actual numbers of profiles depending on the site. In order to assess the extent of the erosion or accretion over the decades, analyses were undertaken by Edmondson et al. (2011) of the horizontal movement of the shoreline at the 1.5-metre elevation above mean sea level (not at the base of the eroded ridge scarp),

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and also included assessments of the volumes of beach sediment per metre of shoreline length above that elevation.

To meet the objectives of this study, six representative sites were selected for analyses, three from each of these littoral cells. In order from south to north the sites are (Figure 17):

HB03:   Representing the Hawke's Bay shore that has experienced the greatest impacts from erosion, affecting the communities of South Haumoana and Te Awanga;

HB06:   Located in the community of East Clive, approximately midway along the shore of the Haumoana Littoral Cell, an undeveloped barrier gravel ridge that has low elevations and is susceptible to overwash occurrences during storms;

HB10:   The southern edge of the city of Napier, in the vicinity of the Aquarium, with its parking lot having experienced minor flooding during storms;

HB14:   Westshore, at the south end of the Bay View Littoral Cell, sheltered by Bluff Hill and the Port's breakwater from the dominant waves that arrive from the southeast, this profile site being north of the stretch of shore where sand and gravel is placed in the nourishment program;

HB17:   Located in the community of Bay View, approximately midway along the length of this littoral cell, a site that has experienced erosion of the barrier ridge following its uplift during the 1931 earthquake, but has been comparatively stable in recent decades;

HB20:   The community of Whirinaki, representing the northern one-third of the Bay View Cell's shore, characterized by a higher scarp cut into the uplifted gravel ridge.

Table 1 lists the rates of shoreline change evaluated by Edmondson et al. (2011) for each of these sites, together with elevations that have been derived from the surveyed profile morphologies, including the beach/scarp junction levels that provide evidence of past toe erosion during major storms and high tides, and backshore ridge elevations that are of interest in terms of present-day and potential future overtopping that could flood properties during extreme storm events.

Figure 17: Locations of beach profile sites surveyed as part of the Hawke's Bay Regional Council's monitoring program. [*From* Edmondson et al. (2011)]

Table 1: Trends of shoreline change (Edmonson et al., 2011) and elevations of the beach/scarp junctions and crests of the backshore gravel ridge.

	Shoreline Trend (metres/year)	Beach/Scarp Elev. (metres RL)	Backshore Ridge Elevation (metres RL)
Bay View Cell			
HB20 (Whirinaki)	-0.288	16.5	20.0
HB17 (Bay View)	+0.062	16.5	18.0
HB14 (North Westshore)	+0.045	12.5-13.5	15.8
Haumoana Littoral Cell			
HB10 (South Napier)	+0.561	13.7	15.7
HB06 (East Clive)	-0.333	12-13	13.5
HB03 (South Haumoana)	-0.607	13.0	14.2

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Considering first the Bay View Littoral Cell, it is noteworthy in Table 1 that its ridge elevations are higher than those in the Haumoana Cell, expected due to its uplift during the Hawke's Bay Earthquake, but likely also in part because the Bay View ridge was higher even prior to its uplift, produced by the exposure of its northern shore to waves that had not been significantly reduced by refraction. The ridge elevation is lower along the sheltered south end of that cell, at Westshore, and is still lower in the southern half of the Haumoana Cell where subsidence occurred in 1931. While the beach/scarp junction elevations in general follow this same alongshore variation, tending to decrease to the south, their elevations are governed by the TWLs experienced during past storms, when combinations of elevated tides and wave-swash runup were able to reach and cut back the gravel ridges, the changes in elevation during the 1931 Earthquake not having been a factor in determining those morphologic elevations.

Beach Morphologies and Present-Day TWL Extremes

The comparisons between the TWLs and surveyed profile morphologies involve a choice of the C_r dependent histogram such as those in Figure 13, or based on the correlation curves graphed in Figure 14, a selection that provides the best agreement between the maximum TWLs and evidence from the beach profiles for past water levels during major storms. This selection necessarily also considers the degree of exposure of that profile site to the waves, the expected extent of wave refraction that would have reduced the wave heights and their swash runup levels. However, considering that we had little more than a decade of measured waves and tides to analyze, the probability exists that the morphologic evidence for past TWLs could represent elevations for more extreme storms that had combinations of waves and tides higher than those based on our limited data, supporting the TWL histograms and their extremes used in these comparisons. Furthermore, even when there is a match between the beach/ridge junction elevation and the process-based evaluation of the TWL, it may be that the C_r value yielding this match simply represents a convenient empirical coefficient that links the processes with the morphology, although one that should reflect the alongcoast variations in wave refraction and swash runup levels.

The comparisons between the calculated TWLs and the profiles in the communities of Whirinaki (HB20) and Bay View (HB17) are graphed in Figure 18. Included are their 2010 surveyed profiles, which however are essentially congruent with those surveyed during the 1970s, demonstrating that there has been little if any ridge-scarp erosion at these sites in recent decades, even though the beach at Whirinaki has experienced a small rate of net retreat in recent years (-0.288 m/year), while there has been minor accretion at Bay View (+0.062 m/year). Included in the graph is the 0 CD tidal datum, the mean sea level at about the equivalent 10-metre RL survey elevation, and also the highest measured tide that occurred during the year 2010, about 2 metres higher than the MSL. With the storm waves potentially reaching this shore having experienced little refraction, the TWL magnitudes included in Figure 18 are for the $C_r = 1$ histogram, yielding a mean TWL of 11.6 metres RL and a maximum of 15.1 metres according to Figure 14, lower than the 16.5-metres RL beach/scarp junction elevations that are the same for both the HB20 and HB17 profile sites. The difference between the calculated TWLs and the junction elevation is therefore about 1.4 metres, the model-analyzed process-based water levels being lower even for this maximum analysis assuming no reduction produced by wave refraction. While there are uncertainties in the methodologies applied in calculating the TWLs, the most likely explanation for this difference is the limited data availability for the measured waves and tides, accounting for only a decade of storm events, insufficient to yield projections of the rare and most extreme combinations of waves and tides that could account for TWLs of 16 to 17 metres RL, required to match the surveyed beach junction elevations at these sites. A match between the processes and morphology can be achieved if C_r in equation (1) is increased to about 1.2, thereby providing empirical evidence from the beach morphology for TWL magnitudes and possible combinations of tides and waves that have been produced by extreme but rare storms, those that have occurred in the past but are not represented in our recent process measurements. Considering that the ridge scarp along the northern portion of the Bay View Cell has experienced almost no erosion since the monitoring program began, with surveyed profiles dating back to the 1970s, this evidence for past extreme storms and their TWLs most likely dates to the decades soon after uplift of the ridge in 1931 caused by the Hawke's Bay Earthquake.
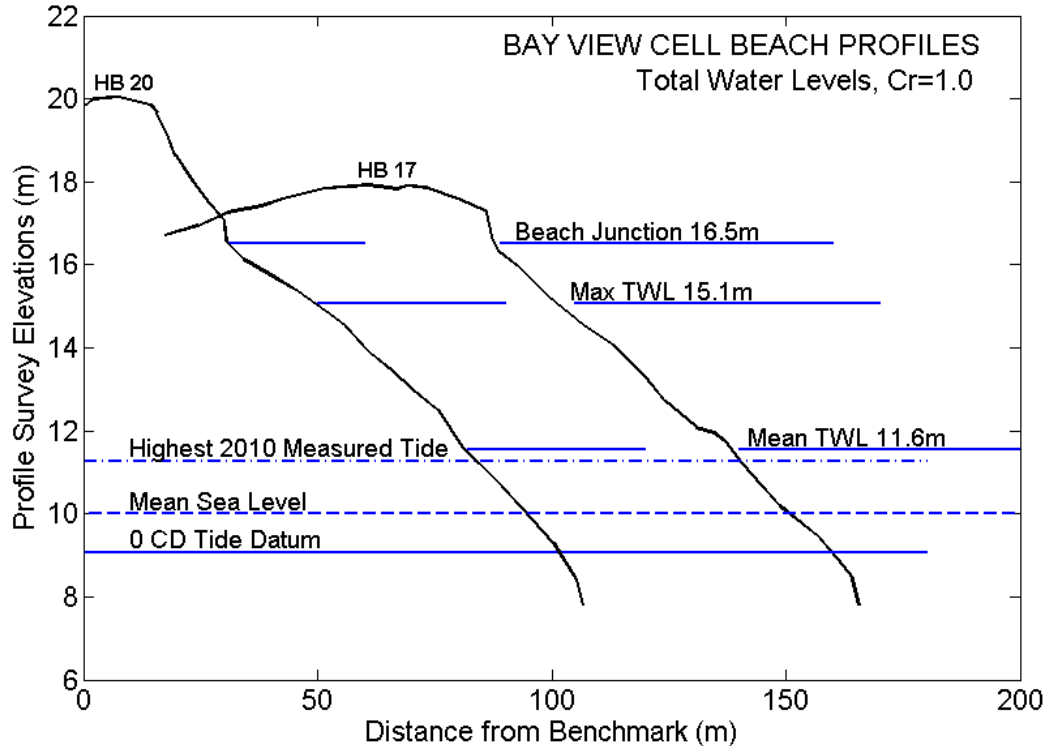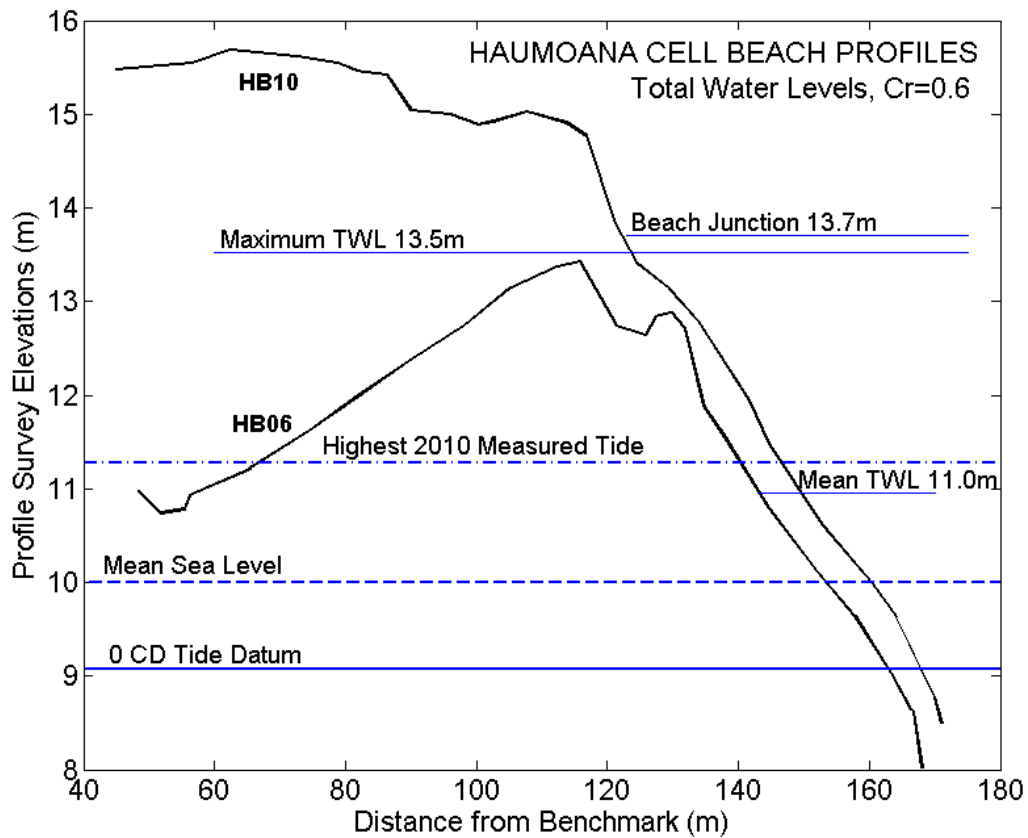
Figure 18: Comparisons between TWLs and morphologies of beach profiles surveyed at sites within the Bay View Littoral Cell.

With time and the collection of additional measurements of hourly waves and tides, and improvements in analysis methodologies applied to calculate the TWLs, the magnitudes of extreme events will be better established, supporting process-based matches. At this stage, however, it is necessary to basically treat C_r as a "matching coefficient", with the ridge morphology providing assessments of TWLs achieved during past extreme storms, thereby serving as the primary basis for our erosion and flooding hazard assessments, rather than being based purely on analyses of measured storm waves and high tides.

The Westshore development at the south end of the Bay View Cell has experienced occasional episodes of erosion, with the impacts to its undeveloped Reserve in the 1980s having led to the program of annual beach nourishment (Komar, 2005, 2010). Although the profile site (HB14) included in our analysis is located to the north of the gravel placement, there is not as distinct a beach/backshore junction elevation as found elsewhere within this Cell, likely due to the northward transport of the nourished sediments having covered the evidence for the past erosion and its TWLs. In Table 1 the elevation is placed approximately within the range 12.5-13.5 metres RL, on the order of 2 metres lower than the profiles to the north and analyzed in Figure 18, this result being expected in that Westshore is sheltered from the waves and experiences a greater degree of refraction, reducing the runup levels and potential TWLs. According to the results from the series of TWL histograms and the graph of their maximum elevations in Figure 14, a coefficient $C_r = 0.4$ yields a maximum water level of about $TWL = 13$ metres RL, providing a reasonable assessment for the toe of the eroded scarp in the Westshore profile, the erosion of which would have occurred during storms in the 1980s. This C_r value is reasonably consistent with the extent of wave refraction along this sheltered stretch of shore, and the reduced wave heights derived in the refraction analyses by Tonkin & Taylor (2003) and MetOceans (2008, 2011). However, it again has to be considered that this choice represents an empirical match, even though the result correctly reflects the alongcoast variations in wave heights and swash runup levels expected within this pocket-beach littoral cell.

Figure 19 presents a similar analysis for the HB06 and HB10 beach profiles within the Haumoana Littoral Cell, respectively from East Clive midway along the Cell's shoreline, and South Napier near the north end of this cell. While the beach slopes are essentially the same as those in the Bay View Cell ($S \approx 0.1$), the widths of the active beaches are smaller, and the elevations of the backshore are 1 to 2 metres lower than the profiles analyzed in Figure 18. It is evident that the undeveloped barrier beach ridge at East Clive (HB06) would be susceptible to wave overtopping during storms, and there are reports that the Aquarium located in proximity to the Napier profile (HB10) has occasionally experienced water washing into its parking lot during particularly severe storms and tides. As surveyed in 2010, Figure 19, the East Clive profile shows the presence of a small accretionary mound or ridge running along the length of its shore, probably formed by recent moderate to low wave conditions; during a storm that ridge would be quickly cut away, leaving an evenly sloped beach over which the wave runup could reach and possibly overtop the crest of this barrier ridge. There is a subtle beach/backshore junction in the Napier profile (HB10) that might represent an episode of beach erosion up to its 13.7-metre RL elevation, but of primary interest in this cell are the potential TWLs that could result in overtopping of the ridge crest at East Clive, or still higher flows over the 15.5-metre RL elevation of the South Napier backshore.

The TWL analysis presented in Figure 19 focuses on the water level that would result in overtopping the crest of the East Clive profile, with the C_r = 0.6 histogram having a maximum TWL = 13.7 metres RL matching that morphologic elevation. Of interest, it is evident that this water level also reasonably accounts for the beach/ridge junction elevation on the South Napier profile. This C_r value is consistent with the wave swash runup of the dominant storm waves that reach this shore from the southeast, the Haumoana Cell shore trending obliquely to their dominant arrival direction (Figure 1), a condition that accounts for the net northward longshore sediment transport within this Cell. The rare and mild overtopping of profile HB10 in South Napier, with a backshore elevation of about 15 metres, could be explained by storm waves that arrive more directly from the east, having experienced minimal refraction, the C_r = 1 model results yielding that elevation for the maximum $TWLs$.

Figure 19: Comparisons between the TWLs and beach junction elevations and ridge crests for beach profiles within the Haumoana Littoral Cell.

The southern portion of the Haumoana Cell's shoreline has experienced the greatest erosion and flooding impacts within Hawke's Bay (Figure 8), including from north to south the communities of East Clive, Haumoana, Te Awanga and Clifton. The report by Daykin (2010) documents the occurrences and extent of impacts during major storms from 1996 to 2010, including overtopping events in the area of profile HB06 on the East Clive shore, with extensive erosion to shorefront homes in Haumoana and Te Awanga. Included in our analysis has been profile HB03 for South Haumoana, representative of this erosion-impacted shore. Present in the surveyed profile is one of the many seawalls that have been constructed to protect the homes. The 13.0-metre RL elevation listed in Table 1 is the level at which the landward edge of the beach meets the seawall, and although this profile has experienced a high rate of retreat (-0.607 m/year) over the decades, reflecting the negative balance in its sediment budget, its junction elevation with the seawall remains essentially the same as those in the profiles to its north within the Haumoana Cell, attributed to this site in the community of Haumoana still being relatively central to the cell, experiencing much the same wave climate with minimal sheltering by Cape Kidnappers to its south, thereby producing the same extreme $TWLs$. In contrast, its junction elevation is a full 3.5 metres lower than the beach/ridge junction elevations in the northern Bay View Cell (Table 1), evidence for their contrasting exposures to the waves and the degrees to which wave refraction has been important in reducing the swash runup levels atop the tides.

Rising Sea Levels, Projected TWLs, and Increased Gravel-Ridge Impacts

The primary goal of this study has been to provide assessments of potential future erosion and flooding impacts along the coast of Hawke's Bay, enhanced by accelerated rates of rising sea levels and

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increased storm intensities, the result of global warming. Important is whether its barrier gravel ridge, most of it having been raised by up to 1 to 2 metres at the time of the 1931 earthquake, will continue to provide protection to shore-front properties and to low-lying inland areas. Having already documented the processes important to the present-day hazards, our analyses now turn to an inclusion of trends of rising sea levels and increasing wave heights, in part based on measurements by the Port of Napier's tide gauge and wave buoy, again recognizing the shortness of those records but with the data providing guidance for future projections.

The 20th century rise in sea levels along the coasts of New Zealand has been documented by Hannah (1990, 2004) based on data from four tide gauges in operation since 1900, located on relatively stable shores: Auckland and Wellington on the North Island, Lyttelton (Christchurch) and Dunedin on the South Island. Hannah and Bell (2012) have updated analyses of their trends, and also analyzed measurements from gauges that have records spanning only a few decades, applying improvised methodologies for short time series. Of the century-long records, most reliable are the results from Auckland (1.7 ± 0.14 mm/year) and Wellington (2.2 ± 0.13 mm/year), while the trends in relative sea levels for the six short-term gauges yielded an average rate of 1.7 ± 0.1 mm/year. These values for the relative rates of rise along the coasts of New Zealand are in reasonable agreement with the 1.74 mm/year global average for the 20th century found by Church and White (2006) and Holgate (2007), based on tide-gauge records throughout the world.

All of the New Zealand tide-gauges analyzed by Hannah and Bell (2012) are located on relatively stable shores, whereas the trend in measured sea levels on the tectonically-active Hawke's Bay could potentially differ due to changes in its land elevations. As reviewed in an earlier section, the shores of the Bay View and Haumoana Littoral Cells have experienced a net long-term trend of subsidence based on investigations of the stratigraphy of sediments deposited in the former Ahuriri Lagoon, the exception being its episode of uplift during the 1931 earthquake. At present there is again progressive subsidence of this coast, according to GPS land-elevation records analyzed by Beavan and Litchfield (2009).

We have analyzed the hourly Hawke's Bay tides measured by the Port's gauge since 1986, having determined the trends for both the monthly averages with the long-term seasonal cycle having been removed, and based simply on the annual averages (Komar and Harris, 2014), the results for the latter being graphed in Figure 20. A linear regression based on the monthly averages yielded a rate of 1.90 mm/year, while the trend for the annual average sea levels is 2.07 mm/year. Both analyses showed significant scatter in the data, and in view of the shortness of the tide-gauge record the resulting trends must necessarily be viewed as approximate. They are, however, consistent with the assessments of global trends of rising sea levels, and with those along the coasts of New Zealand where much longer records are available. This includes the 2.2 mm/year trend for the Wellington tide-gauge record, and furthermore, the variations (scatter) in the annual average sea levels in Hawke's Bay are almost identical to those found in an analysis by Beavan and Litchfield (2009) of the Wellington record, the implication being that the variations at both sites can be attributed in large part to climate controls that affect water temperatures and salinities along the shores of the North Island, combining to produce duplicate variations in water densities.

Based on our analyses of the Hawke's Bay tide-gauge measurements and its basic agreement with the global average and other New Zealand gauges, in our hazard analyses we adopted a present-day rate of 2.0 mm/year, slightly above the 20th century global average, in part accounting for a small local rate of subsidence along this shore.
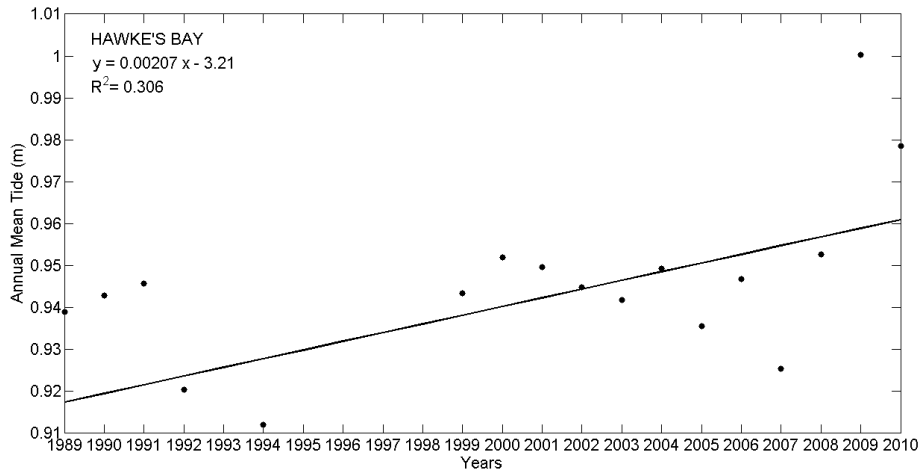
Figure 20: Trend in relative annual average sea levels for the Port's tide-gauge measurements, yielding 2.07 mm/year for the rate of rise.

Our inclusion of the future projected accelerating rates of rising sea levels through the 21th century and its elevation reached by the year 2100 have been based on considerations of the IPCC 2007 projections (Meehl et al., 2007), and the more extreme rates derived by Rahmstorf (2007) and other recent investigations. In relying on those assessments by climatologists, it is apparent that large uncertainties still exist in projecting future sea levels. The approach we have followed for Hawke's Bay is that applied to the coast of the U.S. Pacific Northwest, consisting of having derived a "consensus" projection based on curves published by several studies; for each of their projected curves of rising sea levels, values were extracted at decadal intervals through the 21st century to 2100, yielding "data" points to which quadratic curves were fitted to create an Average "consensus" projection, with similar analyses to represent a High and Low range in the estimates (Baron, 2011; Harris, 2011; Baron et al., 2014).

This "consensus" projection for the average global rise in sea level has been applied in our Hawke's Bay analysis by projecting its present-day 2.0 mm/year rate of rise, that presumably includes the effects of land subsidence (Komar and Harris, 2014). The results indicate that by the year 2050, the Average assessment is that the relative sea level could be expected to rise by about 30 cm above its elevation in 2000, and that by 2100 the rise could amount to on the order of 90 cm. These projections represent the most probable increases based on analyses by climatologists, while the more extreme potential future coastal hazards given by the High consensus indicate that the increase could amount to 50 cm by mid-century, as much as 130 cm by the end of this century. These projections applied to Hawke's Bay are consistent with those that are being used elsewhere in New Zealand and in Australia to derive assessments of future coastal erosion and flooding hazards.

Evidence also exists for there being climate-controlled increases in storm intensities and the heights of the waves they generate. This occurrence of globally increased storm winds and extremes of generated waves heights has been documented by Young et al. (2011), based on satellite measurements from 1985 through 2008. Their analysis results were presented in a graph for the trends of change in the 99th-percentile significant wave heights (SWHs), covering the world's oceans with the shores of New Zealand showing a net increase on the order of 1% per year. Assuming that the 9- to 10-metres maximum SWHs derived from the Port's buoy measurements (Figure 10) correspond approximately to this 99th percentile, its rate of increase would be on the order of 0.09 to 0.10 m/year. If this 1% rate is applied to the mean SWH in the distribution, 1.8 metres, the rate of increase would be on the order of 0.018 m/year.

Our results from an analysis of the annual averages of the hourly SWHs measured by the Port of Napier's wave buoy are graphed in Figure 21 (Komar and Harris, 2014). Although this includes only 11 years of data, the linear regression suggests that there has been an increase at roughly a rate of 0.008

m/year, amounting to about a 10-cm increase over that time scale of measurements. Relative to the 1.66-metres average deep-water SWH measured during the first year (2000) of buoy operation, this represents a 6% increase in the average SWHs, (0.06% per year). This rate for the annual average can be viewed as being approximately in agreement with the results found by Young et al. (2011) for the satellite data, considering that the increase in the average would be substantially less than for the 99th percentile extreme, this difference occurring when distributions of magnitudes are highly skewed, as apparent in Figure 10 for the Hawke's Bay SWHs.
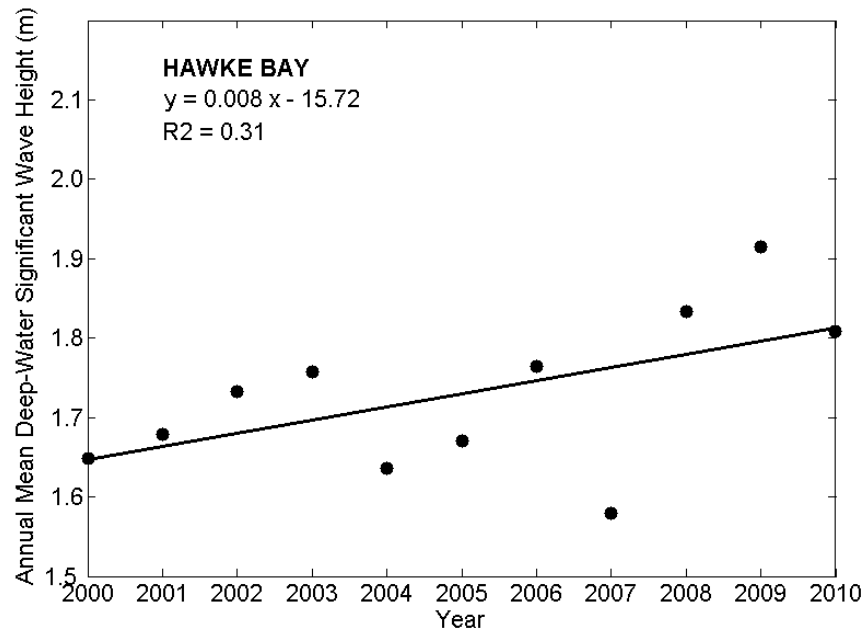
Figure 21: Trend of increasing annual average deep-water significant wave heights derived from the Port's buoy measurements.

With 25-years of satellite data analyzed by Young et al. (2011) showing trends of increasing extreme wind speeds and SWHs, and with approximate confirmation of increasing SWHs in the 11-year record of hourly measured waves by the Port of Napier's buoy, it was concluded that there is sufficient evidence for climate enhanced storm intensities and wave heights to warrant their inclusion in assessments of future hazards to the Hawke's Bay coast. The expectation is that there would be an accompanying increase in wave swash runup levels on the beaches, adding to the trend of rising sea levels. However, a problem exists in determining a rate of increase in the annual-average runup levels calculated from the buoy measurements (Komar and Harris, 2014). As discussed earlier, the formula of Stockton et al. (2006) applied to calculate the swash runup has a comparatively weak dependence on the hourly measured SWHs, depending mainly on the wave periods that show only a small net change within the 11-year data set. The result is that our calculations did not yield a definite trend of increasing swash runup levels, in spite of the increase in the deep-water SWHs; in contrast, an increase was found for the calculated wave-breaker heights on the beaches, which depend mainly on the deep-water SWHs, to a smaller degree on the wave periods.

Although our quantitative analysis of the trend of increasing swash runup levels has been inconclusive, the probability remains that there has been and will continue to be an increase in the Hawke's Bay wave heights during this century, producing higher swash runup levels by the year 2100, adding to the rising sea levels. In view of the importance of including this climate-controlled process in future hazard assessments, order-of-magnitude estimates have been added, assuming that there will be a 10% trend of increasing wave swash runup levels, a rate that approximately corresponds to the increase in the wave heights measured by the Port's buoy, and over a longer span of time by the satellite data (Young et al., 2011). However, in view of the uncertainties in the rate of increasing wave heights and the trend of swash runup levels on the Hawke's Bay beaches, it was decided that our initial assessments of the

future total water levels (TWLs) would account for only the projected rise in sea level, the assumption at that stage being that the wave climate will remain essentially the same as it is at present. A subsequent analysis then includes a potential increase in wave heights and swash runup levels, elevating to a still greater degree the future TWLs and their potential impacts.

Based on the above results, in our analyses directed toward future hazards projections, a rise of 1.1 metre has been adopted for the increased sea level, a value that is between the "consensus" Average and High projections for the year 2100. The result is that the Hawke's Bay mean sea level would be raised from its present elevation of 10.0 metes RL to 11.1 metres RL. This extent of sea-level rise relative to the beach and property elevations can be envisioned in Figures 18 and 19, respectively for the Bay View and Haumoana Littoral Cells, simply by raising the TWL lines in those graphs by 1.1 metre. As expected, the most dramatic consequence would occur on the low-elevation profile of survey site HB06 on the shore of East Clive, the rise in the Max TWL line relative to the crest elevation of the beach ridge in Figure 19 clearly expected to produce more frequent and intense overwash events than occur at present, undoubtedly resulting in a landward migration of the barrier ridge by 10s of metres. For the survey sites having higher backshore elevations (e.g., the Bay View Littoral Cell), applications of a geometric model (Komar et al., 2002) to evaluate the extent of erosional retreat of the wave-eroded escarpment (the beach/backshore junction) predict property losses on the order of 10 metres for this 1-in-10 beach slope, significant but not catastrophic considering there is a wide Reserve with homes set well back from the shore.

This projected 10-metre erosional retreat of the Hawke's Bay beach ridges, produced solely by rising sea levels, should be viewed as representing a minimum estimate for the potential future impacts, since the probability remains that there will be additional losses due to increasing wave heights and swash runup levels. Unlike the rise in sea level that would be essentially uniform along this coast, the inclusion to account for increasing wave heights and swash runup levels has alongshore variations due to wave refraction and partial sheltering by headlands. The magnitudes of the swash runup and hence the TWLs will depend on the shoreline site being analyzed, just as seen earlier in analyses of the present-day hazards, but in the analysis here with there also expected to be a coast-wide increase in the runup levels by the year 2100.

Our results that combine rising sea levels and increasing wave heights are summarized in Table 2 for the representative profile sites in the Bay View Littoral Cell (HB17 and HB20) and Haumoana Cell (HB06 and HB10), with the changes shown graphically in Figures 22 and 23. Comparisons are made between 2010 (the "present-day" conditions) and 2100, including the changes in mean sea-level elevations (SL), the swash runup (SRU) representing the levels of the highest combinations of tides and wave swash, and the resulting total water levels (TWL) that are the summation of the sea-level elevation SL and SRU for the waves and tides. It is seen that for both cells the difference in SL between 2010 and 2100 amounts to a water-level increase of 1.1 metres, their elevations being relative to the RL survey datum. The TWLs listed in Table 2 for 2010 are those analyzed earlier for the present-day hazards, while the maximum total water levels (MAX-TWLs) for 2100 have been increased by 1.5 to 2.0 metres. As discussed earlier, it is acknowledged that an assessment of these increased SRU values for the end of this century are the most uncertain component in this analysis, as it represents the potential increase in both the deep-water wave heights and computed swash runup levels. There is an additional unknown, the possible increase in the extreme storm-surge magnitudes, which could also raise elevations of the measured tides beyond those that occur at present. With both increases in deep-water wave heights and surge magnitudes being dependent on future storm intensities, the 2100 magnitudes listed in Table 2 for SRU represent a combined 10% increase, which is carried over into the 2100 values for the MAX TWLs that also include the 1.1-metre increase in mean sea levels.

Table 2: Analyses of sea levels (SL), wave swash runup levels (SRU), and total water levels based on wave and tide measurements. Also included is an Extreme Scenario that represents the potentially worst-case storm event.

Year	Sea Level (SL) (metres RL)	Swash Runup (SRU) (metres)	Max- TWL (SL + TWL)	Extreme Scenario TWL (metres RL)
BAY VIEW LITTORAL CELL (HB 17 and HB 20)				
2010	10.0	5.1	15	18
2100	11.1	6.0	17	19
HAUMOANA LITTORAL CELL (HB06 and HB10)				
2010	10.0	3.5	13.5	16
2100	11.1	4.0	15	17

The results from this analysis graphed in Figures 22 and 23 respectively compare the water levels with beach profiles within the Bay View and Haumoana Littoral Cells, representing the future projections of the present-day conditions to those at the end of this century (2100). The 1.1-metre increase in the sea level is reflected in the pair of graphed Mean Sea Level lines, while the increases in the total water levels MAX-TWL from 2010 to 2100 show greater differences since they include estimates of the increasing wave heights and swash runup levels on the beaches.
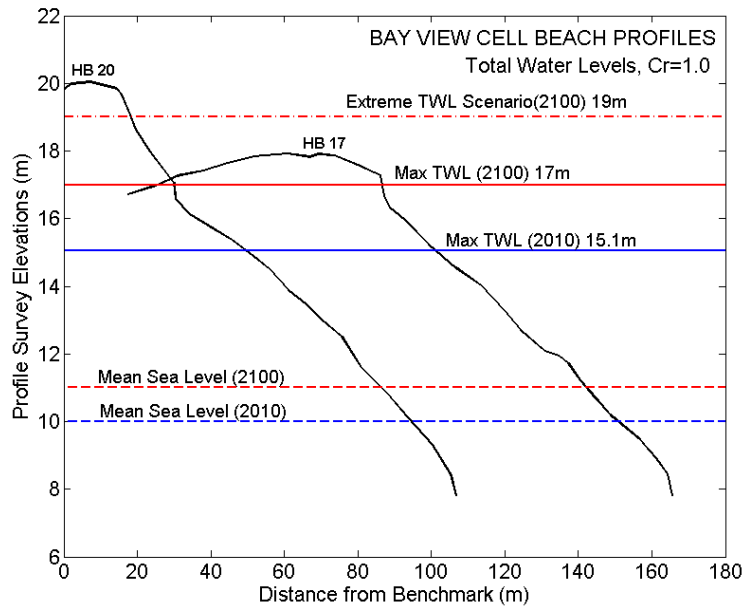
Figure 22: Future projections for the Bay View Littoral Cell, contrasting the present-day (2010) and end of century (2100) mean sea levels and maximum TWLs produced by both a rise in sea levels and an increase in wave swash runup during storms.
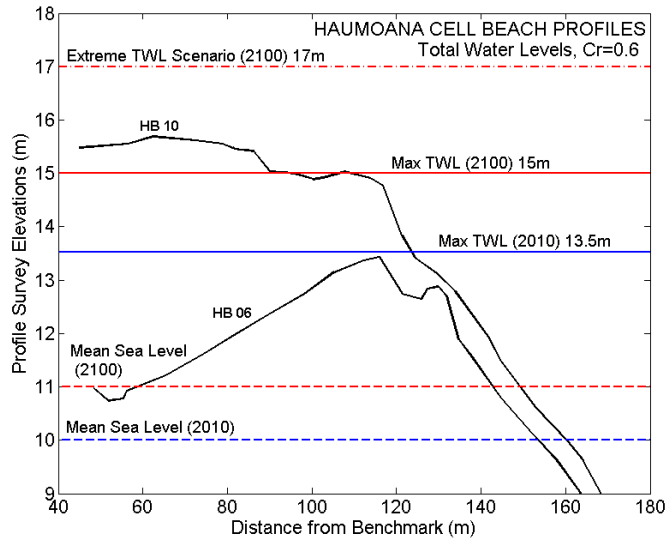
Figure 23: Analysis for the year 2100 TWLs due to rising sea levels and increased storm wave runup, compared with morphologies of beach profiles within the Haumoana Littoral Cell.

Having experienced up to 2-metres uplift during the 1931 Hawke's Bay Earthquake, the elevations of the barrier ridge crests within the Bay View Cell are again seen to range from about 18 metres RL at HB17 to 20 metres further to the north at HB20. Based on the MAX-TWL = 17-metres RL projected 2100 level for this cell's beach profiles, graphed in Figure 22, the extent of overwash and flooding during storms would continue to be rare to absent, but with the erosional losses of the ocean-front portions of the properties expected to be on the order to 15 to 20 metres according to geometric erosion models (Komar et al., 2002). In terms of increased hazards, the change is again significantly more dramatic in the Haumoana Cell, Figure 23, where the projected MAX-TWL = 15 metres RL would completely overwash the beach ridge on the East Clive profile site HB06, exceeding it by an estimated 1.5 metres, an expected result in that even now this site is susceptible to overtopping during storms. Based on the field observations by Orford et al. (1995, 1996) of major overwash events on gravel ridges in Nova Scotia and France, and in view of the low elevations inland from the HB06 profile site, it is doubtful whether this stretch of barrier gravel ridge would remain stable and continue to protect inland properties and infrastructure. In contrast, with the higher elevations of the uplifted ridge at profile site HB10 on the Napier shore, Figure 23, the analysis results indicate that ridge flooding would extend inland some 30 metres from the present-day beach/backshore junction position, this potentially also being the approximate extent of erosion losses according to the geometric model, a degree of impact comparable to that in the Bay View Cell.

In summary, these process-based analyses that have included both projections of accelerated rates of rising sea levels and increased swash runup of storm waves on the beaches support approximate assessments of the potential future erosion and overwash flooding impacts along the Hawke's Bay gravel barrier ridges. As expected, the susceptibilities of these shores vary depending on the extent of land elevation changes produced by the 1931 earthquake. It is expected that there would an erosional cutback of the ridge within the uplifted Bay View Cell, but not overwash flooding, while projections are that both severe erosion and overwash can be expected within the Haumoana Cell due to its lower elevations, most extreme being at its south end that subsided in 1931, with its properties expected to becoming far more hazardous due to the destructive impacts of rising sea levels and increased storm intensities.

SCENARIOS FOR EXTREME STORMS, TWLS, AND PROPERTY IMPACTS

While the above process-based analyses documented through model applications the distributions of TWLs and the possible extent of future impacts to the Hawke's Bay shores as a result of Earth's changing climate, those results were limited in their projections of the potentially most extreme events due to having been based on only limited records of measured waves and tides. Likely missing are assessments of the rare most severe storms that have generated both extreme waves and a surge that significantly elevated the measured tides, this storm by chance also having occurred at the time of a high predicted astronomical tide. This limitation of our process-based analyses became evident in the comparisons between the evaluated TWLs and the morphologic evidence from the surveyed beaches and gravel ridges, seen specifically in Figure 18 for the Bay View Littoral Cell where the beach/ridge-scarp junction elevations exceeded the water levels calculated from the limited data sets, the erosion to that level having occurred during more severe undocumented storms in the distant past. It is therefore apparent that missing in our hazard analyses are rare storms that generated still higher waves and surge levels than recorded in our process data sets, potentially the 100-year event or longer that combines extremes in the waves and swash runup on the Hawke's Bay beaches, together with a high predicted astronomical tide and a surge that elevates still further the measured tide, such that the combined TWLs significantly exceed those based on the process analyses presented in the previous sections of this report.

In order to account for the limitations of our process assessments, and to at least approximately consider how extreme a major storm and its TWLs might impact these shores, we have also formulated "scenarios" that directly represent combinations of the processes and their individual extremes — the predicted tides, potential storm-surge levels, the extremes in storm generated wave heights and periods, and calculations of the wave swash runup levels on the beaches. The scenarios can also include "short-term" cycles such as the El Niño/La Niña range of climate events, and in the long term the rise in sea level and increasing storm intensities, to provide future extreme projections. Such "scenarios" have been developed to assess the extreme potential hazards on the U.S. Pacific Northwest Coast, which proved to be informative even though relatively long records exist on that coast of measured waves and tides (Komar et al., 2002). While it might not be possible to precisely assess the probabilities of joint occurrences in the development of scenarios, the chosen combinations could be such that they reasonably represent an extreme though rare storm event that occurs at a high tide, one that would be rare but is still possible, posing the ultimate greatest threat from erosion and flooding to the coastal developments and infrastructure, both prior to and following a future rise in sea levels and increased storm intensities.

Such a scenario that extends our process analyses for Hawke's Bay has been formulated by including considerations of the research results of other investigators on the coasts of New Zealand, in particular concerning the magnitudes of extreme storm surges. As reviewed earlier, predictions of the Hawke's Bay astronomical tides yield a 1.91-metres CD elevation for the Mean High Water Spring (MHWS), and a 2.00-metres CD elevation for the Highest Astronomical Tide (HAT), the maximum tidal range therefore being about 2.0 metres. However, analyses of the tides measured by the Port's gauge demonstrated that its distribution of magnitudes is skewed to higher values, the maximum measured elevation having been about 2.25 metres CD (Figure 9), nearly all of its enhancement being attributed to storm surges. Analyses of storm-surge levels by de Lange (1996) along the New Zealand coasts have documented a range up to 0.8 to 1.0 metre, levels that have return periods on the order of 100 years. Considering that the highest possible predicted tide (HAT) could achieve an elevation of 2.0 metres CD (11.1 meters RL), the addition of another 1 metre by a storm surge represents a substantial increase to a potential water level of 3.0 metres CD (12 metres RL), a 100-year projection arrived at by de Lange (1996), and also by Worley (2002) specifically for Hawke's Bay. On a typical Hawke's Bay mixed sand-and-gravel beach having a slope of 0.1 (1-in-10), this 1-metre enhanced level due to a surge would shift the mean shoreline landward by 10 metres, and in terms of the 12.0-metres RL extreme the water could reach significant elevations even in the absence of waves; for example, the beaches along the southern portion of the Haumoana Littoral Cell (profiles HB03 and HB06) and at Westshore (HB14) would be nearly inundated by the elevated tide, while the higher elevation beaches and backshores toward the north ends of the littoral cells (HB10, HB17 and HB20) would have only about half of their profiles covered by water during extreme tides. Therefore, although it is evident that this degree of tide-level enhancement by storm surges represents an important component in the potential erosion and flooding

of Hawke's Bay shorefront properties, an equally important role must be the extreme waves generated by severe storms, their swash runup levels on the beaches combining with the high measured tides.

Based on data from the Port of Napier's wave buoy measured over an 11-year period (2000-2010), the histogram of equivalent deep-water SWHs (Figure 10) yielded a mean value of 1.76 metres, the maximum measured SWH having been about 10 metres, in reasonable agreement with the wave hindcast results based on 20 years of storm data (Tonkin & Taylor, 2003). From those assessments, a projected extreme for the 100-year SWH could be expected to be on the order of 11 to 12 metres. Based on the deep-water wave heights and periods, calculations were completed for the vertical components of the wave runup ($R_{2\%}$) on the Hawke's Bay mixed sand-and-gravel beaches, the results varying along the shores due to the changing degrees of wave refraction and sheltering by headlands. A representative example of the analysis results was presented as histograms in Figure 12, showing a mean swash runup level on the order of 1.7 metres, the maximum occurrences during those 11 years of wave measurements having been about 5.5 metres. Projected extremes could therefore be expected to be on the order of 6.0 to 6.5 metres. However, in the case of shores where reductions due to wave refraction are significant (e.g., Westshore), the mean runup level might be only on the order of 0.5 metre, the maximum runup about 1.6 metres, with the projected extremes roughly 1.8 to 2.0 metres. These results in terms of the wave runup levels demonstrate that on a sheltered beach such as Westshore, the runup is comparable to the storm surge in governing the total water levels, but on shores more exposed to the waves the runup is substantially greater than the surge enhancement of the measured tides. In that the tides enhanced by a storm surge will be effectively the same along the entire shore of the Hawke's Bay littoral cells, it is this alongcoast variation in the extreme magnitudes of the wave swash runup levels that produce different "scenarios" for shoreline sites that are exposed versus those that are sheltered from the waves arriving from deep water and experience a greater degree or refraction.

Our analyses of the TWLs based on the hourly combinations of measured tides plus the calculated swash runup levels, Figures 13 and 14, yielded a range of maximums from about 12 to 15-metres RL, depending on the potential extent of reduction caused by wave refraction (the value of the C_r coefficient). This range accounts for the general variation between fully exposed Hawke's Bay shores such as that at Bay Shore, compared with Westshore, but in terms of the potential possible extremes the TWLs experienced on any portion of this shore depend on the track of the storm as well as its intensity, for example whether the storm is far to the south, or its track takes it directly across the Hawke's Bay shore, having maximum impacts. The latter possibility to a degree serves as the basis for our analyses of "scenarios", thereby representing this coast's most extreme hazards.

The scenario for an extreme occurrence of erosion and flooding within the Hawke's Bay littoral cells is therefore one in which an extreme storm occurs at the time of a high predicted tide, the measured tide being further elevated by a 1-metre storm surge, with simultaneous extremes in the measured deep-water wave heights and swash runup levels on the beaches. It is reasonable to assume that the 100-year projections of the waves and surge are produced by the same major storm, and if they are combined to determine the extreme TWL the result could again approximate a 100-year event, but this also depends on the stage of the astronomic tide that would occur independently from the storm's occurrence.

As presented in Table 3 the resulting scenarios represent the present-day potentially most extreme total water levels (TWL), resulting from the occurrence of a storm that is on the order of a 100-year event; the assessments have not included a projected rise in sea levels or increased storm intensities, that would elevate the water levels still more in the 2100 projections. A pair of scenarios is presented, representing "Exposed" versus "Sheltered" shores along the Bay View and Haumoana Littoral Cells. An elevation of 12.0 metres RL is used in both scenarios for the extreme tides, which agrees with assessments by both de Lange (1996) and Worley (2002), having applied different analysis procedures to arrive at this value. The difference in this pair of scenarios appears in the extreme values of the swash runup levels, reflecting the different degrees of sheltering by headlands and in the case of Westshore by the Port's breakwater, and also the extent of refraction of the waves as they pass from deep-water to the shoreline sites. This difference is significant, the magnitudes of the swash runup extremes being 6 versus 2 metres respectively for the Exposed and Sheltered shores, resulting in a 4-metres difference in the

extremes for the TWLs, the results respectively being 18 and 14 meters RL. While this joint occurrence of the 100-year storm event at the same time as the HAT astronomical tide is highly improbable, in view of the low range of predicted Hawke's Bay tides with the Mean High Water Spring (MHWS) being only 0.1 metre lower than the HAT, whatever the high-water level of the predicted astronomical tide at the time of the 100-year storm event, the combination still represents a major hazard, producing an extreme TWL, an event that has a reasonable expectation of occurring.

Table 3: Scenarios of extremes in measured tides and wave swash runup levels, yielding extremes in the elevations of TWLs on Exposed versus Sheltered shores in Hawke's Bay.

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Exposed Shores

Extreme measured tides	12.0 m RL
Extreme swash runup level	<u>6.0 m</u>
Total Water Elevation	18.0 m RL

Sheltered Shores

Extreme measured tides	12.0 m RL
Extreme swash runup level	<u>2.0 m</u>
Total Water Elevation	14.0 m RL

_____

For an Exposed Shore the TWL extreme of 18 metres RL exceeds the 16.5-metres RL beach/scarp junction elevations on profiles HB17 and HB20 within the Bay View Littoral Cell, being well above the 15-metres maximum TWL derived from our process-based analysis graphed in Figure 18 for the present-day conditions. The expectation therefore is that significant erosion of the gravel ridge would occur during an extreme storm event, resulting in the retreat of the scarp, and this 18-metres water level in the scenario has the potential of overtopping the HB17 crest elevation of the ridge within the community of Bay View, but would be well short of the 28-metres elevation at Whirinaki (HB20). Profiles HB06 and HB10 in the Haumoana Cell, Figure 19, have lower elevations so that both could be expected to experience significant overtopping, with East Clive facing catastrophic overwash flows that likely would breach the ridge, leading to flooding of the low lying inland regions.

The analysis results in Figures 22 and 23 respectively for the Bay View and Haumoana Littoral Cells, containing the future projections of water levels for 2100, also include assessments for the Extreme TWL Scenarios, having added a 1-metre rise in sea level to the scenario assessments in Table 3, the result in effect representing a 100-year storm event (but not an increase in storm-wave heights) at the end of this century. With this combination of sea-level rise and an extreme storm event, it is evident that the TWL exceeds the crest elevation of the barrier ridges along essentially this entire coast, the exception being the northern-most shore of the Bay View Cell, as seen in profile HB20 from Whirinaki (Figure 22). A more detailed analysis, however, would be expected to show a gradual increase in the crest elevations in response to the progressive rise in sea levels over the decades, raised by overtopping events during moderate storms, such that the impacts of a 100-year storm occurrence would depend on the timing of such an extreme event during future decades, but in all cases the impacts would be near catastrophic as the barrier ridge would have lost most of its capacity to protect this shore.

The Sheltered Shore scenario in Table 3 should be viewed as representing only an approximate assessment to be compared with Westshore at the south end of the Bay View Cell, sheltered by Bluff Hill and the Port's breakwater, and possibly the south end of the Haumoana Cell protected by Cape Kidnappers (i.e., Clifton). The present-day scenario in Table 3 includes a 2.0-metre level for the extreme runup, accounting for the reduced heights of the waves, yielding a TWL extreme of 14.0 metres RL for those shores partially protected from storm waves arriving from the southeast. As listed in Table 2, the HB14 profile from Westshore has a backshore elevation of 15 to 16 metres RL, so that significant overwash events are doubtful at present, but a 14-metres water levels would reach well up onto the face of the scarp along the Reserve, with the expectation of significant erosion during a 100-year storm at a time of high tides. A future 1-metre rise in sea level together with this extreme storm event, would

elevate the TWL to 15 metres RL, resulting in some overtopping of the Reserve, but again most significant would be erosional retreat as the waves cut into the scarp.

The HB03 profile at South Haumoana has a backshore elevation of about 14 metres RL (Table 2), 13 metres at the toe of its vertical seawall, indicating that the Sheltered Shore scenario with reduced swash runup could be expected under present-day conditions to produce some overwash into the backshore properties. However, based on the frequent occurrence of property inundation occurrences during storms, which have been documented by Daykin (2010) for South Haumoana and Te Awanga, and the recent erosion impacts experienced at Clifton, the indication is that this stretch of shore is not sufficiently protected by Cape Kidnappers for it to actually be represented by our Sheltered Shore scenario, that it instead is intermediate between the Exposed and Sheltered scenarios, with the TWLs possibly being on the order of 16 to 17 metres RL according to Table 3, this extreme projection exceeding the property elevations by 2 to 3 metres. Considering the degrees of property impacts experienced along this shore to even moderate storm events occurring at times of high tides, it is apparent that the 100-year storm scenario would be expected to result in major damage to homes in these communities, and that a 1-metre future rise in sea levels would likely give rise to catastrophic losses.

Our motivation in developing these Extreme Scenarios for major storm events was not meant to be alarmist, its objective instead having been to provide an assessment of what might be the worst-case storm-induced impacts faced along the Hawke's Bay coast, one that is extreme but is still possible, posing the potentially greatest danger from erosion and flooding — the most extreme hazard short of the repeat occurrence of a subduction earthquake and tsunami, comparable to those that occurred in the distant past. This full range of potential hazards needs to be considered in formulating management plans for this coast.

SUMMARY AND DISCUSSION

The goal of this study has been to undertake analyses of the Hawke's Bay ocean processes that are important to its erosion and flooding hazards — its waves, tides and changing sea levels. The concern is that the magnitudes of these processes and the resulting hazards to shorefront properties will significantly increase during the 21st century due to continued global warming. Such concerns are warranted in that the shores of the Bay View and Haumoana Littoral Cells are composed of mixed sand-and-gravel beaches that experience dynamic changes during storms, and are backed by barrier gravel ridges on which homes have been constructed; furthermore, areas inland from those ridges have elevations that are barely above the present level of the sea. The stabilities and ultimate survival of these protective ridges under rising sea levels and increased storm intensities are of paramount importance in preventing future erosion and flooding impacts along this coast.

Accounting for the existing effectiveness of these backshore ridges as protective barriers is that most of this shore was tectonically raised by 1 to 2 metres at the time of the 1931 Hawke's Bay Earthquake. Prior to that event most of this shore could not have been developed with homes, since the beaches and backshore experienced frequent overwash flooding during storms, the water occasionally even inundating downtown Napier. In contrast, the southern-most stretch of this shore subsided by about 1 metre at the time of the earthquake, the result being that over the decades it has experienced extensive erosion, threatening a number of homes in the communities of Haumoana, Te Awanga and Clifton.

The tectonic setting of Hawke's Bay is an extremely important factor in the range of natural hazards faced along its shore, foremost being the potential future reoccurrence of a major earthquake and accompanying tsunami, events that prehistorically have impacted this coast. Their occurrence is the consequence of the collision of two of Earth's major tectonic plates, the ocean crust colliding with and being subducted beneath the continental plate, a tectonic setting that is identical to those along the coasts of Sumatra and Japan, both of which provide recent examples of the extreme hazards of subduction earthquakes and tsunami. Recent investigations by geologists and seismologists along the Hawke's Bay coast have found evidence for past occurrences of major earthquakes and tsunami, the

records of those events having been preserved in sediments deposited hundreds to thousands of years ago along this shore. The sediment records demonstrate that such seismic events were accompanied by an abrupt subsidence of the Bay View and Haumoana Littoral Cells, immediately followed by high tsunami waves that inundated this coast, washing far inland. Although rare in their occurrence, the repeat of an extreme earthquake and tsunami represents the ultimate and greatest future hazards to the Hawke's Bay coast.

In terms of this coast's present-day hazards from erosion and flooding during major storms, important is that plate subduction is causing this shore to slowly subside, combining with the global rise in the ocean's water levels to produce a net trend of rising annually-averaged sea levels. This rise in the sea levels on the Hawke's Bay coast has been analyzed based on the Port of Napier's tide-gauge record, yielding a net trend of increase at a rate of about 2.0 millimetres per year, which would amount to a rise of 20 centimetres in 100 years, close to the 17-centimetre globally averaged rise spanning the 20th century. If that 2.0 mm/year rate were to continue unchanged for the next 100 years, estimates are that the Hawke's Bay barrier gravel ridges would erode on average by about 2 metres, although in fact the local extent of erosion (or accretion) also depend on the budget of beach sediments, the net gains or losses in the total volumes of sand and gravel contained within that beach. However, projections by climatologists are that with continued global warming there will be an acceleration in the rate of rising sea levels, the consensus amongst climatologists being that it will amount to a rise of about 1 metre spanning this century. Our projection specifically for Hawke's Bay placed the net rise in sea level within the range 0.9 to 1.3 metres by the year 2100, in which case the potential erosional retreat of its gravel ridges would on average amount to roughly 10 to 15 metres. While the tectonically elevated stretches of the barrier ridges along this coast should continue to be reasonably stable even under that extent of rising sea levels, the southern shore of the Haumoana Cell that had subsided at the time of the 1931 earthquake can be expected to experience significantly enhanced erosion and flooding impacts, due to the low elevations of its shorefront properties and with its beach sediment budget being well "in the red", this loss of sediment reducing the capacity of the beach to serve as a buffer between the storm waves and properties.

While an increase in sea levels would undoubtedly bring about enhanced erosion and flooding impacts along the shores of Hawke's Bay, further impacts would occur if the changing climate also produces more intense storms, which in turn generate more extreme waves and surge elevations, combining with the rising sea levels to yield higher total water levels (TWLs) at the shore. There is evidence from buoys and satellites that storm-generated wave heights have been increasing over most of the world's oceans, with our analyses of measurements derived from the Port of Napier's wave buoy indicating a similar trend of increase along the Hawke's Bay coast. These increased wave heights would in turn result in greater wave breaker heights and swash runup levels on its beaches, with the enhanced runup combining with the increasing sea levels to produce elevated TWLs that are projected to be about 2 metres above the present-day levels on the shores of the Bay View Cell, with a 1.5-metre increase on the Haumoana Cell's shore, essentially doubling the increase contributed by the rise in sea levels acting alone.

Comparisons between these elevated TWLs projected for the end of this century and surveyed beach profiles demonstrate that the resulting erosion and flooding by overwash of the gravel ridges will become much greater than occur at present. The resulting erosional retreat of the barrier gravel ridge along the Bay View Cell's shoreline is estimated to potentially be on the order of 15 to 20 metres, while within the Haumoana Cell the erosion along its northern stretch of shore could reach 30 metres. Most destructive would be overwash events during major storms, with the total water levels expected to greatly exceed the low elevations of the gravel ridges along the southern shores of the Haumoana Cell, potentially resulting in catastrophic impacts from erosion and flooding, likely leading to the breaching of the barrier ridge and flooding of low-lying inland properties and infrastructure.

Although the above assessments of future erosion and flooding impacts along the Hawke's Bay coast have reasonably sound foundations by having been based on actual data for the wave heights measured by the Port's buoy, and of hourly water levels and sea-level trends derived from its tide gauge, those records of process measurements have been collected only for little more than a decade.

Although they supported analyses that yielded reasonable distributions for the measured significant waves heights and tides elevated by storm surges, providing guidance as to their potential extremes during major storms, those results and the corresponding evaluated maximum total water levels (*TWL*s) are unlikely to represent the potentially most-extreme but rare storms that have only a 1% probability of occurrence (the "100-year event"). In view of our process-based analyses possibly not having represented the most extreme storm event that could occur along this coast, our analyses also included the development of Extreme Scenarios in which the most severe event and hazard was based on a combination of the extreme measured tides that had been elevated by a 100-year surge, together with extremes in swash runup levels from the waves generated by severe storms, the result representing a rare occurrence that is extreme in its process components but one that is still possible, posing the greatest danger from erosion and flooding. With this Scenario having combined the extremes in the storm-generated processes, the result could approximately represent a 100-year storm event, but since it also includes the simultaneous occurrence of a high predicted astronomical tide that is independent of the storm itself, the Scenario more likely represents an event having a recurrence interval that is longer than 100 years, that it has a smaller probability of occurrence, possibly significantly so. It was found in the analysis that this Extreme Scenario produces *TWL* elevations that are some 2 metres higher than the *TWL* extremes based on the limited wave and tide measurements. Having this magnitude, such an extreme event could result in overwash of the barrier gravel ridges along the entire length of the Haumoana Cell's shore, and at least the southern half of the Bay View Cell's shore. Our motivation for developing this Extreme Scenario was not to be alarmist, but instead was offered to provide an assessment of what could be the <u>worst-case</u> storm event faced on this coast, posing its potentially greatest danger from erosion and flooding.

Beyond the analyses developed in this study, additional considerations need to be directed toward potential future changes in sediment budgets for the Haumoana and Bay View Littoral Cells produced by Earth's changing climate, including those altered by the erosion of their barrier ridges that become sources of gravel to the beaches. While we have derived estimates for this credit in the sediment budgets based on the projected erosion of the ridges, there are additional consequences that are more speculative and difficult to evaluate. For example, the rise in sea levels could act to flood the estuary of the Tukituki River, diminishing and possibly cutting off entirely its supply of gravel to the coast, representing a loss of the most significant present-day credit in the Haumoana Cell's budget. With its loss as a sediment source to the southern-most shore of the Haumoana Cell, in part replaced by the erosion of the barrier ridge that would supply gravel mainly to the northern half of this embayed shore, it can be expected that there would be substantial changes in the directions and magnitudes of the longshore transport of beach sediments by the waves, in turn locally affecting the beach widths and rates of erosion of backshore properties. With an awareness of such potential "feed-back" responses to rising sea levels and increased storm-generated waves, our assessments of the resulting alongcoast variations in erosion rates of shorefront properties largely became speculative, lacking firm quantitative evaluations for individual properties. It was suggested that a more detailed understanding of those future changes could be derived from numerical model analyses, similar to those undertaken by Tonkin & Taylor (2005) that examined the present-day shoreline changes and property impacts that have resulted from beach sediment mining at Awatoto. The objective of this recommended investigation would be to account for the future effects of Earth's changing climate on the altered sediment budgets — the quantities of gravel supplied to the beaches and the changed locations of those sources, and the possible loss of sediments contributed by the Tukituki River. Application of similar model analysis techniques could then be undertaken, leading to evaluations of changes in the sediment transport patterns, the resulting altered shorelines, and local assessments of property hazards, their rates of erosion or accretion. More robust analysis results would be expected, that could replace the speculation we offered in regard to the consequences of such feed-back effects, the model-based results providing greater details of the potential impacts to individual shore-front properties, supporting the establishment of scientifically-based hazard zones to protect developed properties.

Projected future sea levels, storm-wave heights, their combined total water levels, and resulting enhanced hazards from erosion and flooding will all occur gradually such that their consequences might not become particularly evident for another 25 years or longer, although each year there is the possibility for a storm that approaches the extreme 100-year event with its significant impacts. While

there may be time to wait for research advances and data collection that provide improved projections, there are measures that should be undertaken immediately to enhance the stability of this coast, the integrity of its barrier gravel ridges. Important is the "health" of its beaches that provide buffer protection to the barrier gravel ridges, with the present and future conditions depending in large part on the sediment budgets of the Haumoana and Bay View Littoral Cells. Efforts therefore need to be directed toward shifting their balances into the "black", with there being more sediment contributed to the beaches than is being lost. Most problematic is the Haumoana Cell where according to its present-day budget, each year the losses of sediment far exceed the gains from its sources, the expectation being that the balance could become worse in the future with rising sea levels. This improvement in the sediment budget requires that the primary loss of gravel and sand produced by commercial mining at Awatoto be phased out as soon as possible. Considerations should also be directed toward the rivers, with measures implemented that could enhance their delivery of sediments to the beaches, particularly important being the Tukituki River that might otherwise in the future cease to be a credit in the Haumoana sediment budget. Special consideration needs to be directed toward the fates of coastal properties such as those in the south Haumoana Cell, which are already experiencing problems with erosion, it being evident from the analyses in this study that with rising sea levels and increased storm intensities, the danger to homes along those shores will become significantly greater in the future, possibly catastrophic.

In conclusion, with the goal of this study having been to investigate the ocean processes and their climate controls, to assess the degrees to which they might intensify during the 21st century, our analyses were limited by the availability of measured waves and tides. Accordingly, our projections of future erosion and flooding impacts have at present unavoidable degrees of uncertainty. However, improvements in projections should be forthcoming in the near future with additional research and data collection, investigations by climatologists that better define future sea levels, and in particular as additional years of measurements of the Hawke's Bay waves and tides become available, permitting improved projections of their extremes and more confident trends of increase in storm-generated wave heights and sea levels along this shore. Management practices therefore need to remain flexible, amenable to future changes as we come to better understand the magnitudes of Earth's evolving climate, and how it is affecting the trends of rising sea levels and enhanced storm intensities.

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