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Shoreline Evolution and Management of Hawke's Bay, New Zealand: Tectonics, Coastal Processes, and Human Impacts

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ABSTRACT

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The evolution of the coast of Hawke's Bay, New Zealand, and its erosion problems have been governed by multiple factors, including its tectonic setting with an earthquake in 1931 that altered land elevations along its shore, ranging from a 2-m uplift at its north end to 1-m subsidence at its south. Human environmental impacts have also been important, including the deforestation of the watersheds of rivers and the mining of gravel and sand from their channels, having decreased the sediment supplies to the beaches. Significant erosion has occurred at the south end of the Hawke's Bay shore, attributed in part to its subsidence in 1931, together with the net northward longshore transport of the beach sediment that is greater than the volumes being supplied by the rivers, the beach-sediment budget being significantly "in the red." Midway along the Bay's shore, the construction of the Port of Napier's breakwater in 1887–90, extending seaward from the Buff Hill headland within that city, is interpreted by some investigators to have been the cause of the erosion experienced at Westshore, a development located immediately north of the breakwater. The assumption has been that this erosion was the result of the breakwater having blocked the northward longshore transport of sediment that formerly had bypassed Bluff Hill, this being an example of down-drift beach erosion. However, a reexamination of the history of the Port's development, the resulting shoreline changes, differences in beach gravels on the shores north and south of Bluff Hill, as well as other evidence, support the conclusion that the breakwater was not the cause of the erosion; instead, the impacts to Westshore at the time of the breakwater construction can be attributed primarily to a series of major storms, which produced erosion at a number of sites along the Hawke's Bay shore. There has been minimal erosion at Westshore since the completion of the breakwater a century ago, its northward extending arm acting to shelter the development from the waves of major storms. Investigations by coastal scientists and engineers of the Hawke's Bay coast, together with a comprehensive beach-survey monitoring program, support its sound management based on an understanding of the multiple factors that are important to its responses during storms, and to its long-term changes.

ADDITIONAL INDEX WORDS: *Sediment budgets, river watersheds, gravel beaches, jetties, breakwaters, wave climates.*

INTRODUCTION

The shore of Hawke's Bay extends along the east coast of New Zealand's North Island and contains three littoral cells, two of which are the focus of this article (Figure 1): the Bay View littoral cell, with its beach extending for 18 km from Tangoio in the north to the Bluff Hill headland and the Port of Napier's breakwater within the City of Napier; and the Haumoana littoral cell, the 23-km stretch of beach south from Napier to Cape Kidnappers. The City of Napier is the principal community located on this shore, whereas the smaller communities of Awatoto, Haumoana, and Te Awanga to its south (Figure 1) are of special interest because they have experienced significant erosion over the decades and continue to be of management concern.

This coast has experienced significant changes during the past two centuries since settlement by Europeans: induced by tectonic activity that produced a major earthquake in 1931, resulting in significant changes in land elevations; alterations in the environment produced by humans, which included the extensive mining of sand and gravel from the rivers and beaches; and changes associated with the construction of the Port of Napier's breakwater. The beaches are mixtures of gravel and sand, common along much of the east coast of New Zealand's North and South Islands (Kirk, 1980), but comparatively rare elsewhere along the world's coasts. Accordingly, they have received less research attention by coastal scientists and engineers than have sand beaches or those consisting entirely of gravel and cobbles, so their morphodynamic responses during storms are not as well documented (Mason and Coates, 2001). This history of coastal change and uncertainties regarding the ocean and beach processes has made it a challenge to manage the Hawke's Bay coast.

In 2003 I was hired to be the Independent Facilitator for Coastal Issues, to work with the Hawke's Bay Regional Coun-

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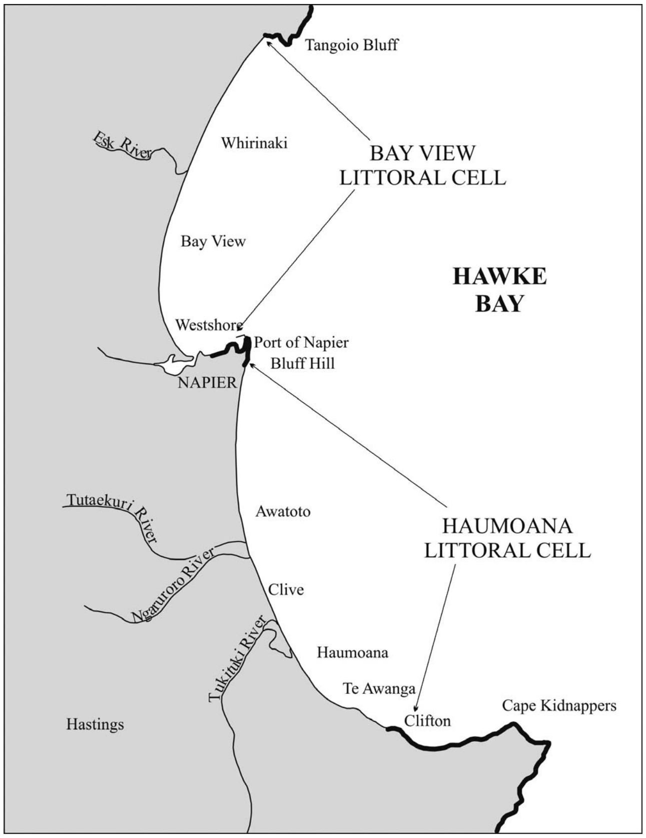

Figure 1. The Bay View and Haumoana littoral cells on the Hawke's Bay shore.

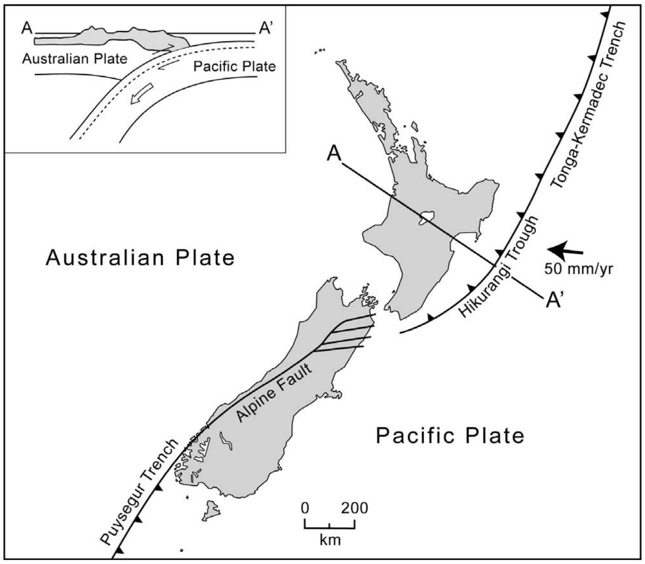

Figure 2. The tectonics of Hawke's Bay, showing the collision between the Australian and Pacific plates, with plate subduction along the Hikurangi Trough.

cil, the Napier City Council, and the Port of Napier Ltd, advising them on issues dealing with investigations of the Hawke's Bay coast and its management. This led to my preparing a report (Komar, 2005) that provided a comprehensive review of the region's tectonics and geology; the waves, tides and changing sea levels; and the consequences of human settlement and modifications of the region's environments that have affected this shore. Although there have been comparatively few publications in journals and conference proceedings that focused specifically on the Hawke's Bay coast, this is not due to a lack of investigations by coastal scientists and engineers—indeed, few stretches of coast worldwide have been the subject of so many studies that generated such a great number of unpublished reports (my compiled bibliography contains more than 80 entries, dated from 1882 to 2007). This number of reports is actually part of the problem in managing this coast because, at times, their conclusions are seemingly at odds, leading to confusion when decisions have to be made. This has particularly been the case for the perceived impacts of the construction of the Port of Napier's breakwater in the late 19th century, with many Hawke's Bay citizens still attributing their beach and property erosion to its presence.

This article provides a review of the multiple factors that are involved in the evolution of the Hawke's Bay coast and its erosion problems, providing a summary of my full report (Komar, 2005).

TECTONICS AND LAND-ELEVATION CHANGES

New Zealand straddles two of the earth's major tectonic plates, the Pacific and Australian plates (Figure 2), with their collision east of the North Island resulting in the subduction of the Pacific plate, forming the Hikurangi Trough, centered about 160 km offshore from Napier. The tectonics and geology of the Hawke's Bay region have been dominated by the collision of these plates, which occurs at a rate of about 50 mm/y. However, this convergence is not head on, instead taking place obliquely so there is also a horizontal sliding, with the Pacific plate moving to the south relative to the Australian plate in a motion that continues along the Alpine Fault, a strike–slip transform fault that crosses the South Island.

This combination of collision and horizontal movement in the Hikurangi Trough is transferred to the landmass of Hawke's Bay, the interior of the Australian plate, with the complex pattern of deformation having formed inland mountains, including the Ruahine Range that rises to more than 1700 m elevation. There are a number of faults on land and in the shallow offshore, which are imbricate thrust faults commonly found in zones of plate collision; however, although there is a degree of reverse movement on these faults in Hawke's Bay at times of earthquakes because of the regional compression, there is also a horizontal movement that is some five to six times greater than the vertical displacement. Although there has not been a major subduction earthquake during at least the past 200 years, there have been a number of earthquakes associated with movement on the faults within the Australian plate, this being one of the most earthquake-prone areas in the world. The most destructive was the

Hawke's Bay earthquake in 1931 (magnitude 7.8), generated by movement on a fault 30 km northwest of Napier.

This tectonic setting has determined the topography of the region, which is divided into an inland Frontal Range of mountains and an Accretionary Borderland that extends seaward from the foot of the mountains, across the shore, out to the submarine trench (Berryman, 1988; Cole and Lewis, 1981). The uplift of the Ruahine Mountains within the Frontal Range has taken place at an incredibly rapid rate, on the order of 2000 m during the past one million years, but with the uplift having been offset by erosion that is also rapid because of the high level of precipitation. Most important, the erosion has yielded large quantities of gravel and coarse sand, derived from the resistant Mesozoic greywacke rocks, which are then transported by rivers to the coast where they constitute the most important sediment components of the beaches.

The Accretionary Borderland seaward of the mountains is underlain by rock formations that are younger than those found in the mountains; this includes conglomerates, sandstones and mudstones, originally deposited as sediments in the ocean atop the Pacific plate during the past 10 million years, but then accreted to the Australian plate as the Pacific plate was subducted. The Heretaunga Plains within the Borderland is a tectonic depression that developed during the past 1.5 million years between the compressional folds of its rock formations; the changing courses of the Tukituki, Ngaruroro and Tutaekuri Rivers have deposited their loads of gravel and sand across the Plain, building up its level by as much as 1 km of accumulated sediment.

The earthquakes associated with the tectonic activity of this region have resulted in changes in the elevations of the Heretaunga Plains, with the evidence generally having documented its net subsidence spanning thousands to millions of years. In particular, the study by Hull (1986) of sediments deposited along the margin of the Ahuriri Lagoon, northwest of Napier (Figure 1), showed that their stratigraphic section is dominated by peat, which Hull interpreted as having been produced mainly by subsidence spanning at least the past 4000 years. However, that subsidence was reversed by the 1931 Hawke's Bay earthquake that resulted in the abrupt uplift of the Ahuriri Lagoon, which rapidly drained into the sea, reducing its area by about 12.8 km^2 (3,170 acres); Napier's airport is now located central to that area of the former lagoon.

A reconnaissance team of scientists was immediately dispatched to Hawke's Bay to investigate the impacts of the earthquake, with the investigations by Marshall (1933) having focused on the land-elevation changes and effects on the beaches. He reported that the Port of Napier's tide gauge had been raised by 1.8 m, which was confirmed by uplifted strandlines and levels of rocks covered by dead sea life. Marshall then extended his assessments along the remaining shore of Hawke's Bay, finding that the uplift progressively increased to the north from Napier, reaching 2.0 m at Tangoio, achieving a maximum uplift of 2.7 m along the rocky shore at Moeangiangi, 30 km north of Napier; still further to the north, the extent of uplift rapidly decreased. Henderson (1933) extended these observations by compiling earlier land surveys and comparing them with postquake resurveys, those undertaken in releveling the railway lines and resurveys of the levees (stopbanks) that had been constructed for flood control along the major rivers. This extended inland the documentation of the land-elevation changes beyond those found by Marshall (1933) along the shore, and also included the region to the south of Napier.

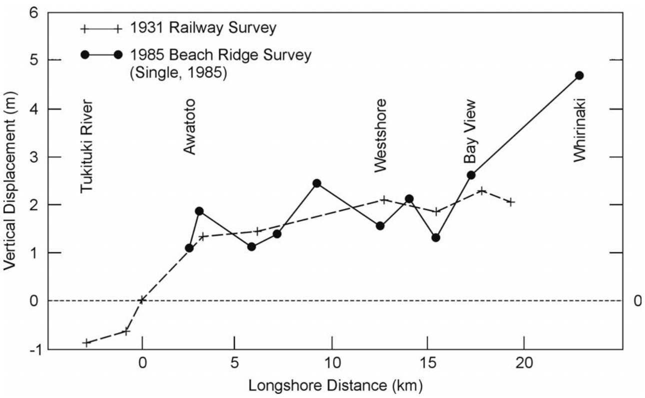

Figure 3. Land elevation changes along the Hawke's Bay shore caused by the 1931 earthquake, and the corresponding elevation changes documented by surveys of the gravel beach ridges (after Single [1985]).

The most recent analysis of this postearthquake survey data is that by Hull (1990). He confirmed the 1.8-m uplift at Napier, but found that further to the south along the shore the amount of uplift was progressively less, having been zero at Awatoto south of Napier (Figure 1), and with a zone of subsidence still further to the south, on the order of 1.0 m. The 1931 earthquake, therefore, resulted in a systematic along-coast change in land elevations at the shore; for the two littoral cells of interest in this study (Figure 1), the greatest degree of uplift occurred at Tangoio (2.0 m) at the north end of the Bay View cell, reduced to 1.8 m at Napier, and reduced still more to the south within the Haumoana cell. Of particular significance, the 1-m subsidence along the shores of Haumoana, Te Awanga and Clifton has certainly been a factor in the extensive property erosion there, continuing 75 years after the earthquake's occurrence (Single, 1985; Smith, 1977).

In contrast to the erosion at the south end of the Haumoana littoral cell due to its subsidence, the uplift of the shore to the north by about 2 m resulted in its having become significantly more stable. Prior to that change in 1931, a substantial portion of the land had very low elevations, and the beach consisted of a low gravel ridge that was frequently overtopped by storms; the city of Napier was commonly inundated by floods from this overtopping by the sea, and by floods in the rivers (Campbell, 1975). This changed with the uplift caused by the earthquake, with the vertical displacements of the beach ridge documented in Figure 3 from the profile surveys made by Single (1985), compared with the resurvey after the 1931 earthquake of the stretch of railway line that ran parallel to the shore just inland from the beach. The shore within the Bay View cell is now relatively stable

Figure 4. The mixed sand-and-gravel beach at Westshore.

and does not experience overtopping, even during the most extreme storms. The uplifted beach ridge behaves much like an artificial dynamic revetment (cobble berm), which are sometimes constructed on coasts to prevent erosion and flooding (Allan and Komar, 2004). Only after its uplift in 1931 was this shore along Hawke's Bay suitable for development, with homes now being found along much of the shore north of Napier.

This uplift also widened the fronting beach because of the seaward shift of the shore. The gravel beaches of Hawke's Bay have slopes that are typically on the order of one in nine, so the approximate 2-m uplift during the earthquake should immediately have produced an 18-m seaward shift in the shoreline and expansion of the beach width; this assessment is confirmed by surveys completed by Marshall (1933). Immediately offshore from the gravel beach the seafloor is covered by sand, and the uplift resulted in the creation of a sand beach fronting the gravel ridge at Westshore, the development within Napier to the immediate north of the inlet to the Ahuriri Lagoon (Figure 1). According to a historian (Campbell, 1975, p. 161), the uplift of that shore altered the beach from a "dangerous shingle bank to a placid sand expanse", and it became the community's principal recreational beach, which it continues to be today, although much of the sand has been lost over the decades, being essentially gone by the late 1950s or 1960s (Smith, 1986). As will be discussed later, the residents of Westshore have attributed this loss of their sand beach to the construction of the Port's breakwater, a view that has been supported by some coastal scientists, but challenged by others.

THE MIXED SAND-AND-GRAVEL BEACHES

The erosion of the mountains within the Frontal Range has yielded large quantities of coarse river gravel, derived from the Mesozoic greywacke that forms the higher elevations, accounting for the mixed sand-and gravel beaches characteristic of Hawke's Bay (Figure 4). However, at present, only the Tukituki River is supplying significant volumes of gravel to the beaches. Prior to European settlement, the Tutaekuri and Ngaruroro Rivers were also important sources of gravel to the Haumoana littoral cell, while the Esk River supplied smaller quantities to the Bay View cell; as will be recounted below, because of sediment extraction and the rerouting of their channels, these rivers now yield very little sediment, and that yield is primarily sand. The erosion of Cape Kidnappers also supplies greywacke gravel to the Haumoana cell, both it and the Tukituki River being sources to the beach at the south end of the cell, and with the sediment then being transported to the north by the waves that arrive predominantly from the southeast.

Although the particles of this greywacke gravel have the appearance of being highly resistant, they are susceptible to abrasion, so the angular particles derived from erosion and landslides in the mountains have their edges rapidly worn away as they are transported down the rivers, and by the time they reach the beaches they have become well rounded. This abrasion continues under the waves on the beaches, so the sizes of the gravel particles are progressively reduced, displaying size reductions and shape modifications to the north along the shore of the Haumoana cell as they are transported away from their sources. Marshall (1927) undertook detailed laboratory experiments on the rates of abrasion, with his results being of fundamental importance to an understanding of the processes in general, and of particular relevance to this study because he performed his experiments with particles collected from the Hawke's Bay beaches. He was the first to clearly distinguish between several forms of gravel "wearing", including abrasion (the effect of pebbles rubbing against one another), impacts (blows of relatively large pebbles on smaller pebbles), and grinding (the crushing of small grains, mainly sand, by the continued contact with pebbles). Hemmingsen (2004) has extended this research, mainly with experiments using gravel from South Island beaches, but also with Hawke's Bay samples.

Marshall (1929) applied the results of his experiments to interpretations of the wearing of the gravel on the Hawke's Bay beaches, and their resulting changes in grain-size distributions as they were transported alongshore north from the mouth of the Tukituki River. His experiments demonstrated that the wearing of the greywacke gravel yields sand, which initially is quite coarse because it is the product of the grinding and collisions of larger against smaller particles, with the smaller particles shattering into sand. Of importance, that coarse sand is able to temporarily remain on the beaches, accounting for their being mixed sand-and-gravel, but it is eventually ground down into the silt and very-fine particles of sand that originally were deposited in the ocean, later to be compressed to form the greywacke. On the ocean beaches, those fine sediments are quickly carried offshore, with some being deposited just seaward from the gravel beach. Marshall (1929) documented these abrasion processes and particle sorting on the Hawke's Bay beaches, while the more recent research on the mixed sand-and-gravel beaches of the South Island has extended our understanding of these processes (Hemmingsen, 2004; Kirk, 1980).

The thesis research of Smith (1968) of the Hawke's Bay beaches had many of the same objectives as Marshall's (1927) investigations, including a determination of how the sediment sources and the variation in wave energy along the shore control the gravel-size distributions and particle shapes. Smith (1968) expanded this research by collecting sediment samples and surveying beach profiles at 19 sites along the shore, attempting to correlate the variations in grain sizes with the profile morphologies. He concluded that on average the gravel size in the Haumoana cell is coarser and has an overall greater range of sizes than found in the Bay View cell, in agreement with Marshall's (1927) observations. Smith (1968) also analyzed the grain sphericity and roundness on pebbles in the 1.5- to 3.0-cm size fraction. In both littoral cells, the more-spherical particles were found in the south, whereas toward the north, the stones became flatter. There is a distinct offset at Bluff Hill, indicating that the trends are independent of one another between the two cells, rather than being continuous, which would be the case if there had been active bypassing of the beach gravel around Bluff Hill and the Port's breakwater. Smith's (1968) overall conclusion was that the differences in the sediments between the Haumoana and Bay View littoral cells demonstrated that the cells are separate entities and that, because the input of fresh greywacke gravel to the beach of the Bay View cell is minimal, the pebbles there must have nearly reached their optimum degrees of roundness, noting that they are both uniformly smaller and more polished than the gravel of the Haumoana cell. His conclusion was that the Bay View gravel must represent an "old" deposit, in contrast with the Haumoana cell, where gravel is being actively contributed by the sources, the Tukituki River and the erosion of Cape Kidnappers. As will be discussed later, Smith's (1968) conclusions are important to assessments of whether or not large quantities of beach gravel were able to bypass Bluff Hill prior to the construction of the Port's breakwater, and whether its construction has been the chief cause of erosion at Westshore, the community to the immediate north of Bluff Hill and the breakwater.

Offsetting the limited extent of research that has been undertaken on the processes and dynamics of mixed sand-and-gravel beaches (Mason and Coates, 2001), in general and specifically regarding those in Hawke's Bay, has been a monitoring program in existence for more than 30 years. Its principal emphasis has been directed toward the collection and analysis of periodic surveys of beach profiles at a large number of stations extending along the shores of both littoral cells (Gibb 1995a, 1995b). The earliest beach profiles date back to 1914, surveyed in response to the erosion and flooding problems. In 1916 the New Zealand Railways established 15 profile sites at Westshore to monitor the threat of erosion to their railway line, and surveyed them at regular intervals until 1961; Smith (1986) located and resurveyed 13 of these sites, updating the shoreline changes. The principal beach-profile monitoring program now underway was initiated in 1974, its objective being the collection of annual profile surveys at sites all along the shores of the two littoral cells. Those widely spaced profiles were soon thereafter (1977) supplemented by the establishment of 22 closely spaced profile sites at Westshore, in response to an episode of erosion; those profiles are now used to monitor the beach nourishment program that began at Westshore in 1985 (Gibb, 1995a).

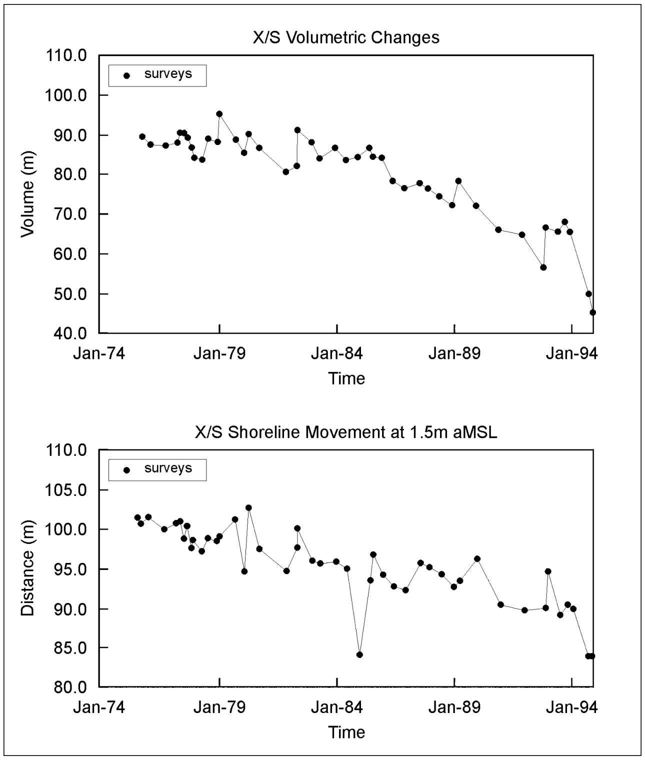

Figure 5. Analyses of a beach-profile monitoring site (K-10) on the Westshore beach in Napier, documenting the annual variations in sediment volumes and positions of a reference shoreline (after Gibb [1995a]).

The analysis procedures of the surveyed profiles have been developed primarily by Gibb (1995a, 1995b), with the profile changes presented both in terms of the variations between surveys in the sediment volumes (m^3/m of shoreline length), in effect the change in the cross-sectional area of the beach between surveys, and the horizontal displacement of a reference shoreline, selected as the 1.5-m contour above the mean sea-level Napier Datum, providing a representation of the progressive advance or retreat of the beaches. Figure 5 is an example of Gibb's (1995a, 1995b) analyses: on each graph, an upward displacement of the data from year to year represents net accretion during that year, whereas a downward displacement represents net erosion. The overall trends of the curves, therefore, depict whether there has been a prolonged period of accretion, erosion, or the occurrence of significant reversals. The rates of change documented by the monitoring results have been important in management applications, specifically in the establishment of hazard zones (development setbacks). The variations from year to year seen in Figure 5 have also been used to infer the responses of these mixed sand-and-gravel beaches to major storms. However, to improve our understanding of these beach responses, I recommended that the monitoring program be expanded to collect profile surveys immediately following storms, and furthermore to analyze the profiles in terms of the causative erosion processes, the elevated tides and swash run-up elevations of the storm waves (Komar, 2005).

WAVES, TIDES, AND WATER LEVELS

Direct measurements of the ocean waves and tides in Hawke Bay were initiated only recently, so the records are limited. In August 2000, the Port of Napier installed a Triaxys wave-rider buoy in 15-m of water depth, seaward from the breakwater, to provide hourly measurements of the waves (including their directions). The results have been analyzed in a series of annual reports that update the wave–climate assessments (*e.g.,* Worley, 2006). The results demonstrate that the highest wave conditions generally occur during July and August (winter in the Southern Hemisphere), when the average significant wave height (H_s) is on the order of 1.2 m. However, the highest waves generated by the stronger storms can occur from June through September, typically achieving significant wave heights on the order of 2.5 to 3.5 m. Extreme-value assessments place the 25-year return event as having a 5.4-m significant wave height, whereas the 100-year storm would be 6.2 m (Worley, 2006); however, with only a 5-year record, those projections are only approximate. The mean peak-energy wave period is 11.4 seconds, but a scatter diagram of wave periods *vs.* the significant wave heights showed that for $H_s > 4$ m the periods are in the range 14 to 16 seconds; the highest wave event in April 2000, with $H_s = 4.68$ m, had a period of 15 seconds. With the buoy being in only 15 m water depth, this represents intermediate to shallow water for that range of wave periods, and in approaching the coast from deep water the waves from most directions have undergone substantial degrees of refraction. These factors, as well as energy losses due to bottom friction, imply that in deep water the waves have greater heights than those measured by the Port's buoy. The main applications of this wave data derived from the buoy have been investigations of proposed expansions of the harbor sheltered by the Port's breakwater, including analyses of the wave refraction, diffraction, and the potential effects of the breakwater on the shore.

The primary definition of New Zealand's wave climate, including that in deep water offshore from Hawke Bay, is derived from hindcast analyses by Gorman, Bryan, and Laing (2003a, 2003b), employing the WAve Model (WAM) wave-generation model. Their analyses included the latitudes from 10°S, near the Equator, southward to the coast of Antarctica, and from 100°E to 220°E in longitude, with New Zealand being approximately at the center of this area. The hindcasts were made at 3-hour intervals for the 20 years from 1979 through 1998. The results show the expected pattern of wave conditions along the New Zealand coast, with the largest mean significant wave heights found in the Southern Ocean, between New Zealand and Antarctica, where the Westerlies are strongest and have long fetches. North of that band, the waves propagate to the northeast, along both the west and east coasts of New Zealand, with diminishing mean wave heights to the north, especially along the east coast because of the blocking effect of the land mass. Figure 6 is a histogram of significant wave heights for the deep-water eastern edge of Hawke Bay, based on the hindcast assessments. The most frequent occurrences are waves on the order of $H_s = 1.5$ m, but with the more extreme hindcast waves included in this graph reaching 6 m; the maximum H_s for that 20-year record achieved 8.6 m.

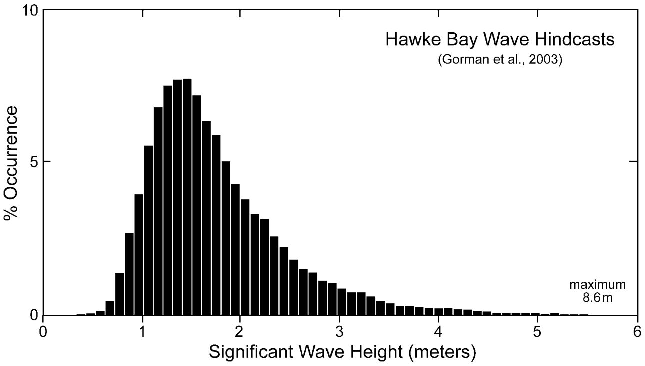

Figure 6. Hindcast deep-water significant wave heights from the study of Gorman, Bryan, and Laing (2003b) (after Tonkin and Taylor [2003]).

The hindcasts of Gorman, Bryan, and Laing (2003a) and the measurements by the Port's buoy are in basic agreement about the range of wave arrival directions, with the buoy showing a strong dominance of the largest waves from 90° to 120° relative to north, that is, from the east–southeast, representing 71.9% of the measured waves (Worley, 2006). This was to be expected, given the source being storms in the Southern Ocean. Only a small portion of the waves arrive from northeasterly directions, a total of 12.6% from 0° to 90°, with most of those arriving from 75° to 90°.

The waves reaching Hawke Bay undergo considerable refraction, beginning far offshore, having experienced significant changes in directions by the time they reach the shore. The earliest of the studies of wave refraction in the Bay was that by Gibb (1962), who constructed wave refraction diagrams for the ranges of wave periods and directions. The continental shelf is wide, with the depth contours approximately parallel to the shorelines of the littoral cells, and according to the refraction analyses by Gibb (1962) this alters the wave directions to the degree that their crests become nearly parallel with the shorelines. The exception is where the waves wrap around Cape Kidnappers in the south and the large Mahia Peninsula at the far north of Hawke Bay. Detailed analyses of the wave refraction and diffraction affected by Bluff Hill and the Port's breakwater have been undertaken by Worley (2002b), demonstrating that the extension of the breakwater beyond the natural headland provides a significant degree of sheltering of Westshore whenever storm waves arrive from the dominant east–southeast; the breakwater, on average, reduces the wave heights along that shore by half, compared with what they would have been in the absence of the breakwater.

Hawke's Bay provides an excellent example of how a coast adapts in its large-scale morphology to the imposed locations and volumes of sediment sources contributed to the beaches and to the wave climate that governs the longshore transport and redistributions of those sediments, the shoreline having achieved a quasi-equilibrium morphology. This is illustrated in Figure 7, modified from Smith (1968), comparing the ori-

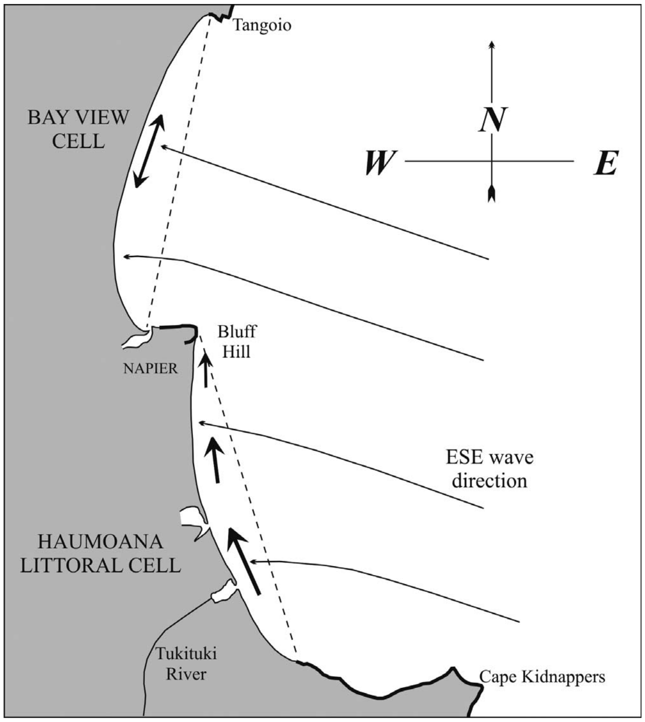

Figure 7. Orientations of the shores of the Bay View and Haumoana littoral cells, compared with the directions (wave rays) of the prevailing waves. The arrows denote the patterns of the longshore sediment transport (modified from Smith [1968]).

entations of the two littoral cells with the dominant southeast waves (shown by the wave rays). Of particular interest are the different orientations of the beaches, respectively in the Haumoana and Bay View littoral cells. Their deep-water wave climates, in terms of heights and periods, are effectively identical, but the main difference lies in their sources of beach sediment, with the Tukituki River and erosion of Cape Kidnappers supplying gravel to the Haumoana beach near its south end, whereas the Bay View cell has essentially no natural gravel sources. As a result, the shore of the Haumoana cell has become oriented so it faces toward the east–northeast, such that with the dominant waves arriving from the southeast, there is a prevailing (net) longshore sediment transport of the beach sediment to the north, carrying the gravel from its sources in the south and redistributing it along the shore up to Bluff Hill at the northern boundary of this cell. The details of this process are affected by the refraction of the waves and partial sheltering of Cape Kidnappers, but as seen in Figure 7, progressively to the north the shoreline systematically changes its orientation, facing more directly east at its north end, the result being that in general the wave-breaker angles systematically decrease, as does the resulting net northward longshore sediment transport rate. Tonkin and Taylor (2005) have undertaken numerical analyses of these processes, including the longshore sediment-transport rates, in the context of assessing the impacts of commercial beach-gravel extraction at Awatoto, midway along this length of shore. When the Haumoana Groyne was constructed just south of the mouth of the Tukituki River in 1999, it quickly filled to capacity with sediment from the northward longshore transport, which is now bypassed; this impoundment provided a direct assessment of the longshore transport at that position (White and Healy, 2000), which when added to the assessed gravel contribution by the river yields an assessment on the order of 46,000 m^3/y for the total longshore transport to the north. This is the maximum rate within the Haumoana cell, in that as the gravel is being transported to the north, a portion of it is progressively lost to abrasion as well as by its commercial extraction at Awatoto. On the Napier shore at the north end of the cell, the models developed by Tonkin and Taylor (2005) indicate that the longshore transport rate has been reduced to about 5000 m^3/y, an assessment that is supported by the build-out of the shore when the Port's breakwater was constructed.

In contrast to the Haumoana cell, it is seen in Figure 7 that the shoreline of the Bay View cell is rotated to face the east–southeast, corresponding to the arrival directions of the prevailing waves, again affected by refraction. Having achieved this orientation and curvature, the shoreline of this cell has acquired what must be close to a net-zero balance in the longshore sediment transport, in effect being a large pocket-beach bounded by headlands. A number of investigators have examined the shapes of equilibrium, net-zero transport beaches, including comparisons with the log-spiral geometric curve and especially with the crenulate shoreline (Hsu and Silvester, 1997; Silvester and Ho, 1972). Worley (2002b) compared the shape of the Bay View cell's shore with the crenulate shoreline and found a near-perfect congruence, which indicates that the curvature of the shore does represent effectively a net-zero equilibrium. The main departure from the crenulate form was a relatively small difference centered along Westshore, with the actual shore being seaward from that equilibrium shape, the implication being that Westshore is not presently in equilibrium with the existing wave conditions and might be expected to experience some erosion and shoreline retreat until it is cut back and conforms with the crenulate shore. This may be a factor in the small degree of erosion that has occurred at Westshore during the 20th century and the northward dispersal of gravel placed on that beach for its nourishment, discussed later in this article.

The tides of Hawke Bay, and of the east coast of New Zealand in general, are unusual in that they are semidiurnal, but unlike the normal pattern of monthly tidal variations corresponding with the astronomical alignment of the moon and sun, the highest tides do not occur during full and new moons, when their forces combine. The monthly variations are instead produced by the varying distance of the moon from the earth determining the force of attraction by the moon on the ocean water (Goring, 1997). Therefore, the highest tidal range of the month occurs when the moon is closest to the earth, at perigee in its monthly orbit; the lowest tidal range occurs at apogee. Every 7 months the full or new moon coincides with the moon's perigee, producing somewhat larger-than-normal perigean spring tides, the highest predicted astronomical tides of the year. The predicted tides for Hawke

Bay are relatively modest, with the full range being 2.0 m, generally classified as microtides (Davies, 1964).

Direct measurements of tides in Hawke Bay are limited, having begun only in 1986 with the installation of the Port's gauge, but until November 1998 the measurements were only to a 1-cm resolution, so analyses are generally limited to the later records. Worley (2002a) has analyzed the tidal residuals, the portion of the variation that is not accounted for by the astronomical tides, the portion attributed to storm surges. The results of an extreme-value analysis of the residuals showed that they are on the order of 0.9 m, which is consistent with the results of De Lange (1996) based on analyses of storm surges along the entire coast of New Zealand. In applications, as in assessments of property erosion hazards, this value is commonly added to the predicted mean high-tide elevation to provide an estimate of the total water elevation having a 1% probability of occurrence each year, which comes out to be about 2 m above mean sea level. As an alternative approach, Worley (2002a) undertook a joint probability analysis that combined the astronomical tides and tidal residuals, based on 18,000 Monte Carlo simulations, effectively representing 1000 years of simulated tides, and found the 100-year extreme to be 2.70 m. Beyond that, in their applications, Worley (2002a) added 0.2 to 0.4 m as the potential rise in sea level during the next 50 years. That sea-level addition is uncertain because of the very short record of tide measurements, too short to determine the trend in the relative sea-level rise, which can be expected to be affected by progressive land-elevation changes associated with plate subduction; at this stage, we are not even certain whether this region has been slowly rising or subsiding since the 1931 earthquake, but ultimately most important is the potential for another abrupt land-elevation change in the advent of a major earthquake, which could either raise or lower the elevations along the shore.

HUMAN ENVIRONMENTAL IMPACTS

Potentially important factors in the erosion of coasts are the environmental modifications by humans. These can occur far inland, as when deforestation or sediment extraction from rivers alters the volumes of sand and gravel delivered to the coast, affecting the budget of beach sediments. At the shore, the mining of sediment or the construction of jetties and breakwaters can result in major changes, inducing erosion problems. All of these modifications have occurred in the Hawke's Bay region, but their degrees of impact on the coast are difficult to assess and have been the most controversial in terms of the perceptions of people as to the causes of their property erosion.

People reached Hawke's Bay beginning with the Maori about 800 years ago, followed by Europeans in the 19th century, with each group having altered the environment as they established their settlements. Their greatest impacts initially affected the watersheds of the rivers and the quantities of sediment delivered to the coast. The Maori were active hunters, and there is evidence they burned areas of forest in their pursuit of game, and later to clear land for agricultural use. This clearing of the forests increased greatly with the arrival of Europeans, many of whom chose to settle inland to raise sheep and cattle. Deforestation, together with the use of the land for grazing, would have resulted in increased water runoff and soil erosion, adding greater quantities of sediment to the rivers, mostly silt and sand, but also gravel from the erosion of the rocks and landslides in the upper watersheds.

The early settlements were affected by major floods in the rivers that cross the Heretaunga Plain, and one response was the construction of levees (stopbanks) to confine the water to the channels. They were constructed of gravel and sand extracted from the channels, a practice that also had the benefit of deepening the channels, so they had an improved capacity to contain the flood discharges. Sand and gravel were also mined from the river channels to fill marshes across the Plain to improve the grazing lands, and were transported to the growing community of Napier to raise its elevation, which was prone to flooding. During the settlement period there was no regulation of this activity because it was viewed favorably for reducing the flooding. Even today, large volumes of gravel and sand are extracted, in part for the same reason.

Some alterations of the Hawke's Bay watersheds, therefore, acted to increase the quantities of gravel and sand that reached the ocean beaches, whereas others would have decreased those quantities. In balance, it is probable that the quantities have decreased, especially from the Tutaekuri and Ngaruroro Rivers because of diversions to their channels, such that at present they do not even supply the beaches with gravel, and it will be more than a century before they do so. Of the rivers, only the Tukituki now supplies significant volumes of gravel and coarse sand to the beaches, estimated to average about 28,000 m^3/y (Tonkin and Taylor, 2005). If all of the sediment extraction were halted in its watershed, the volume could potentially be increased to 75,000 m^3/y, but the resulting sediment accumulation in the channel would likely lead to flooding problems. Thus, there are trade-offs, with the sediment extraction from the rivers continuing to be a positive management strategy for reducing floods, but with the practice also having negative consequences for the Bay's beaches, it being one of the factors causing shoreline erosion and the inundation of low-lying backshore properties during storms.

There has also been a long history of mining gravel directly from the beaches of Hawke's Bay, beginning during the earliest period of settlement. In particular, large volumes were extracted during the construction of the railway to raise its bed. In recent years, the most significant mining has taken place at Awatoto in the Haumoana littoral cell (Figure 1), which has averaged 47,800 m^3/y, so that during the 30 years from 1973 to 2002, for which we have the best records, this extraction removed nearly 1.5 million m^3 of beach sediment. This commercial extraction is scheduled to be phased out within a decade. As will be reviewed later in the development of sediment budgets, this extraction at Awatoto has exceeded the quantities of gravel reaching this shore from the Tukituki River and sea cliff erosion along Cape Kidnappers. As a result, the total quantity of gravel and sand contained within the beach of the Haumoana littoral cell has significantly decreased over the years, making this stretch of shore more susceptible to property erosion and overtopping.

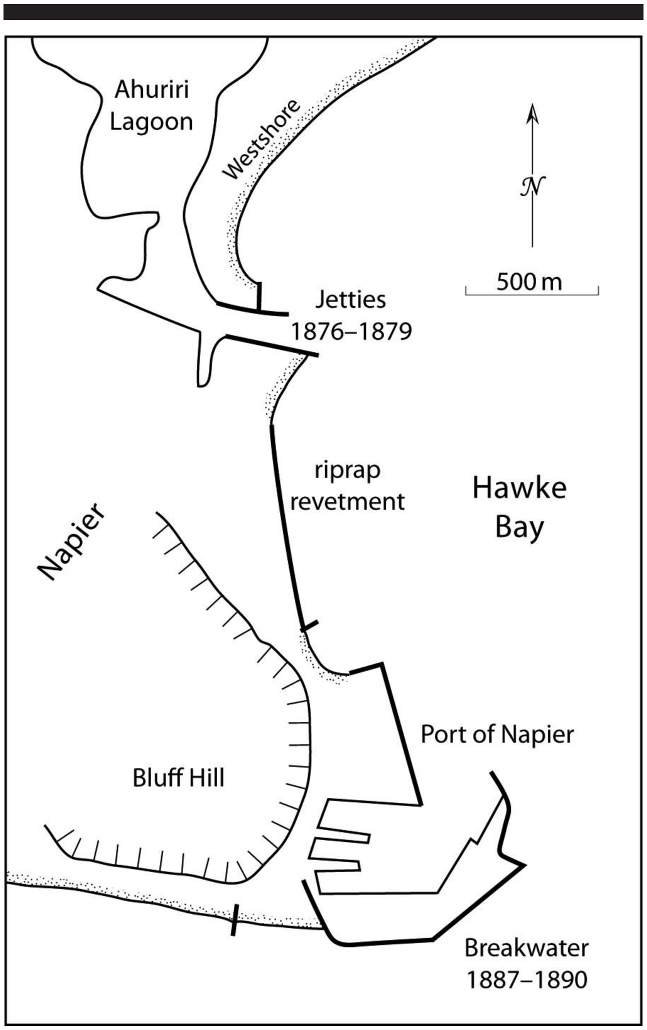

Figure 8. The Port of Napier, consisting of the Ahuriri Inner Harbour controlled by jetties, and the Outer Harbour breakwater.

The development of the Port of Napier potentially represented the greatest environmental change along the Hawke's Bay shore (Figure 8), and has resulted in a century of controversy as to whether it has been a major factor in the erosion of Westshore to its immediate north. In response to this controversy, my examination of the Hawke's Bay erosion problems required a detailed consideration of the Port's development and its possible impacts (Komar, 2005). Its development began in 1876–79 with the construction of a pair of jetties (moles) at the entrance to the Ahuriri Lagoon, which in its natural state had served as the region's harbor throughout the settlement period. However, even with jetties this small harbor proved inadequate for the growing community, so construction of the Port's breakwater was undertaken in 1887–90. It began as a groyne-like projection extending seaward from Bluff Hill, but then bent toward the north to follow a trend that is nearly parallel to the shore to its south (Figure 8); the length of this segment has progressively increased over the years to expand the Port's facilities. Having this form, the breakwater extends the area sheltered from the waves that predominantly arrive from the south to southeast, beyond that naturally provided by Bluff Hill for the shore to its north; as noted earlier, wave refraction analyses undertaken by Worley (2002b) demonstrated that the breakwater has decreased the heights of the waves reaching the Westshore beach by approximately half their natural values.

The controversy concerning the Port has focused on the breakwater and whether its construction blocked the beach gravel and sand assumed to have previously bypassed the Bluff Hill headland, transferring sediment from the north end of the Haumoana littoral cell to the south end of the Bay View cell. The initial indication was that this had occurred because sediment quickly accumulated to the south of the breakwater as it was being constructed, and erosion occurred on the beach along Westshore to its north. A few coastal scientists have interpreted this as being an example of the blockage of a longshore sediment transport by the construction of a breakwater, with the principal consequence being the downdrift erosion at Westshore (Gibb, 1996; Smith, 1968, 1993). However, others pointed to the importance of different causes of the erosion at the time of the breakwater's construction, including this having been a period of unusually intense storms, probably the most extreme during the period of European settlement up to the present (Kirk and Single, 1999). Of significance, those storms produced erosion all along the Hawke's Bay coast, not just at Westshore, including along the updrift side of the breakwater, resulting in the flooding of downtown Napier (Campbell, 1975). Another contributing factor to the erosion of Westshore was the decision to halt the practice of disposing sand on the Westshore beach that had been dredged from the Ahuriri Inner Harbour (lagoon), a practice that had formed a sand beach in front of the gravel ridge; that disposed sand rapidly dispersed with the retreat of the shoreline under the high waves of the extreme storms that coincided with the construction of the breakwater.

A significant argument offered against the breakwater having prevented the bypassing of beach gravel and sand around Bluff Hill is that although more than a century has passed since its completion, the updrift beach has not built out to the extent that gravel has bypassed the breakwater's arm and entered the channel leading into the harbor (Kirk and Single, 1999; Komar, 2005). When the breakwater was constructed, the gravel and coarse sand of the beach accumulated to its north at a rate of 6000 m^3/y, so one might have expected that soon thereafter this coarse sediment would have found its way into the channel. However, dredging records show that only the fine sand from the offshore of Hawke Bay reaches that channel. My interpretation is that the constructed breakwater in effect behaves as a headland, an extension of Bluff Hill, accounting for the advance of the shore at the time of construction, but now the beach gravel and coarse sand arriving from the south is consumed by abrasion, as found in the experiments of Marshall (1927), converting it to the fine sand and silt component of the greywacke, which only then is able to move offshore and around the breakwater's arm (Komar, 2005).

One aspect of my examination of the debate concerning the impacts of the Port's development was a consideration of whether the coarse beach sediment had been able to bypass Bluff Hill prior to any Port development. This in effect was a consideration of whether there had been a net northward longshore transport of gravel along Westshore, supported by that bypassing, which could have first been blocked by the construction of the jetties (moles) on the entrance to the Ahuriri Lagoon, a decade before the construction of the breakwater. I concluded that before any harbor development, it is likely that some beach gravel was able to bypass Bluff Hill, but this involved only relatively small volumes and its occurrences had been infrequent, with no bypassing during most years (Komar, 2005). Circumstantial evidence for the occurrence of some bypassing came from an 1873 chart that included the rocky shore of Bluff Hill, where there were two localized pockets containing "shingle," presumably greywacke gravel that had been trapped as it was bypassing this headland. Particularly informative were the differences in the gravels north and south of the headland found by Smith (1968), as reviewed earlier. Specifically, north of Bluff Hill in the Bay View cell, the beach gravel was smaller in size than that to the south, was generally less angular in its shapes, and had acquired a polished surface from having been acted upon by the waves for a long time. This led Smith (1968) to characterize the beach gravel to the north of Bluff Hill as being "old", in contrast to the comparatively young gravel to the south, where it had more recently reached the beach from the Tukituki River. Although the presence of the shingle (gravel) in the pockets along the rocky shore of Bluff Hill suggested that some bypassing had occurred, the differences in the gravels north and south of that headland provided evidence that the quantities must have been small and that bypassing had been infrequent.

The original historic records from the period of Port development were important, with recent summaries provided by historians (Campbell, 1975; Stevenson, 1977). Most informative from the Port's archives were the reports by Saunders (1882) and Carr (1893), successive Chief Engineers of the Napier Harbour Board, with Saunder's (1882) report coming immediately after completion of the Ahuriri jetties but before the breakwater's construction, and Carr's (1883) report having been written soon after the completion of the breakwater. Both examined the shoreline changes that had occurred along Westshore, and found that its shore had gradually eroded from 1854 to 1876, that is, during the two decades before the construction of the Ahuriri jetties. This erosion in itself suggests there must have been little, if any, bypassing of gravel around Bluff Hill during that period. The erosion appears to have been enhanced within the Ahuriri inlet by the removal of limestone boulders along its shore, to be used as ballast in departing ships. That erosion resulted in the widening and shoaling of the inlet, so it became a hazard to navigation; this was the primary inducement for having constructed the jetties with a spacing of 122 m, close to its original natural width.

Much of the focus of past investigators has been on the rapid accumulation of gravel on the beach to the south side of the constructed jetties, which was interpreted as evidence for there having been a net longshore sediment transport, supplied by bypassing Bluff Hill during the 3 years of jetty construction. According to Saunders (1882), the rate of gravel accumulation was so rapid it kept pace with the extension of the jetties and was equivalent to an annual longshore transport rate of 50,000 m^3/y. Such an extreme rate of gravel accumulation is totally unrealistic for the volumes of gravel that could have bypassed Bluff Hill since the estimated transport rates on the beach to its south were only on the order of 6000 m^3/y, and probably much less than that. Furthermore, Saunders (1882) reported that at the time of jetty construction the beach to the south of Bluff Hill was "much reduced" in its width and sediment volume, indicating that it was inadequate to support bypassing.

Also significant was the beach accretion that took place to the north of the jetties as they were being constructed on the inlet, on the beach of what has become Westshore; that is, there was no downdrift erosion, which would be expected if the jetties had blocked a net longshore transport of beach gravel. This accumulation was in part due to the disposal of sediments dredged from the Inner Harbour, but that disposal would mainly have been sand, whereas it appears that most of the accretion was gravel. The accumulation of gravel on the beaches to both the northwest and southeast sides of the constructed jetties is not consistent with their having blocked a net longshore transport, certainly not one involving 50,000 m^3/y. My interpretation is that the rapid accumulation of gravel adjacent to the Ahuriri jetties in response to their construction came instead from the onshore movement of the bay-mouth bar, a response that has been found on other coasts when jetties were constructed. Specifically, this was the pattern that occurred when jetties were constructed on the coast of Oregon (Komar, Lizarraga-Arciniega, and Terich, 1976), which is of added relevance because the beaches of the Oregon coast also have a zero net longshore sediment transport, consisting of a series of littoral cells bounded by headlands, much like the Bay View cell in Hawke's Bay.

My conclusion was that the Port of Napier's development—first the construction of jetties in 1876–79, followed by the breakwater in 1887–90—had not been the cause of the erosion at Westshore at the time of their construction, nor has it been a problem in the century since their construction. In fact, as discussed in the next section, there has been minimal additional erosion along Westshore during the past century. Instead, the presence of the breakwater has provided significant protection to the Westshore community by having sheltered it from the dominant storm waves from the southeast, in large part accounting for its stability. These conclusions have not been well received by the inhabitants of Westshore, particularly by politicians who over the years have campaigned using the issue of the Port being the cause of Westshore's perceived erosion problems.

SEDIMENT BUDGETS AND SHORELINE EROSION

Evident in the above review is that multiple factors have affected the Hawke's Bay shore and the locally induced beach and property erosion. Some factors directly affected the sediment budgets, including the environmental impacts that humans have had in altering the sediment contributions from the rivers and mining gravel and sand from the beach. The

Table 1. *The sediment budget for the Haumoana littoral cell.**

Budget Components	Estimated Annual Rates (m^3/y)
Sources (credits)	
Tukituki River	28,000
Cape Kidnappers erosion	18,000
Total	46,000
Losses (debits)	
Awatoto extraction	−47,800
Pacific Beach extraction	−12,800
Gravel abrasion	−30,400
Total	−91,000
Net balance of beach sediments	−45,000

* Modified from Tonkin and Taylor, 2005.

ocean processes are of course important, including the northward longshore transport of sediment on the beach within the Haumoana littoral cell, which in large part is responsible for the major property erosion experienced at the south end of that cell, where the sediment budget is significantly "in the red." The development of sediment budgets for the two littoral cells has been important in understanding the origin of the erosion and its potential solutions (Gibb, 2003; Komar, 2005; Tonkin and Taylor, 2005).

Haumoana Littoral Cell—The Sediment Budget and Property Erosion

The gravel and coarse sand on the beach in the Haumoana littoral cell is derived from the erosion of Cape Kidnappers and from floods in the Tukituki River. The long-term average contribution from these sources has been evaluated respectively as 18,000 and 28,000 m^3/y, for a total contribution of 46,000 m^3/y (Tonkin and Taylor, 2005); these values have been entered as the credits in the sediment budget for this cell (Table 1). The primary debit is the commercial extraction of gravel and sand from the beach at Awatoto, which on average has removed 47,800 m^3/y (Tonkin and Taylor, 2005). Sediment extraction has also taken place at Pacific Beach in Napier, the north end of the cell's shore, initiated in 1993 to serve as a source of gravel for the nourishment of the beach at Westshore. Between 1993 and 2002, a total volume of 146,300 m^3 was removed, with an average of about 12,800 m^3/y (Table 1). The third debit in the sediment budget is the natural loss of the greywacke gravel and coarse sand because of its abrasion, which reduces the sediment to fine sand and silt that is lost offshore. The research by Marshall (1927, 1929) of the abrasion rates of this gravel, together with the more recent laboratory measurements of Hemmingsen (2004), support assessments of this loss in the sediment budget, but the results remain uncertain. Instead, the debit resulting from sediment abrasion listed in Table 1 has been derived from the other values contained in the budget. Specifically, the net balance of −45,000 m^3/y has been obtained directly from the beach profiles collected over the years by the monitoring program, and as a result this value is one of the more confident assessments in the budget (Tonkin and Taylor, 2005). Working backward, the total of the debits must then be −91,000 m^3/y, and the loss from gravel abrasion would amount to −30,400 m^3/y; this value is reasonably consistent with the experiments of Marshall (1927, 1929) and Hemmingsen (2004).

Figure 9. Erosion at South Haumoana threatening several homes, with the failure of their shore-protection structures (2001 photo).

The debits in this sediment budget for the Haumoana cell are substantially greater than the credits, with the net balance being −45,000 m^3/y, so it can be expected that over the length of its shore there would be problems with beach erosion, threatening local shorefront properties. An examination of the credits and debits in Table 1 reveals the significance of the commercial extraction at Awatoto, which alone removes all of the sediment that, on average, is being supplied to the beach, the credits in the budget. It was in large part because of this evidence that a decision was recently made to gradually phase out that extraction, with its eventual cessation expected to bring the budget close to being in balance. This improvement will mainly affect the shore of Awatoto and to its north, including Napier, which is desirable because the beach elevations are low and experience some overtopping during storms, problems that could be expected to increase with the projected accelerated rates of sea-level rise. The hope is that the beach elevation will increase in response to the greater availability of gravel, once the mining operation has ended.

However, even when the sediment budget becomes more balanced, it will not halt the problems with beach and property erosion experienced along the southernmost stretch of shore within this cell, impacting the communities of South Haumoana, Te Awanga, and Clifton. That erosion has spanned at least several decades, and as seen in Figure 9, homes are in immediate danger and a variety of shore-protection structures have failed. As discussed earlier and documented in Figure 3, this stretch of shore subsided by up to 1 m at the time of the 1931 earthquake, and analyses applying a type of Bruun Rule for the expected extent of shoreline retreat suggest that part of the ongoing erosion could still be a result of that subsidence (Komar, 2005; Smith, 1977). However, of greater significance is the net longshore transport of beach sediment to the north, caused by the prevailing waves from the southeast, which carries the sediment from the southern half of this shore to its northern half. Analyses of the beach profiles acquired in the monitoring program show an average net sediment loss of $-48{,}800$ m^3/y along the shore south of the mouth of the Tukituki River (south of the groyne that has been constructed adjacent to its mouth), whereas there has been a small net accretion of the beaches to the north, with the monitoring profiles yielding an average of $+3800$ m^3/y; together, these values yield the net balance of $-45{,}000$ m^3/y for the cell as a whole, the value listed in Table 1 for its sediment budget. The local budget for this southernmost shore reveals that its balance is $-48{,}800$ m^3/y, so that the erosion being experienced there (Figure 9) is caused mainly by the longshore transport to the north being substantially greater than the rate at which the erosion of Cape Kidnappers supplies gravel and coarse sand to this beach.

The potential responses to this erosion are under consideration and include the range from hard structures, such as the construction of groynes, to the soft solution of beach nourishment, or to retreat and relocate. Beach nourishment would require the annual import of at least 48,800 m^3/y of gravel to balance the local sediment budget, but such an operation would be expensive, and the demand for such large volumes would not likely be sustainable. This could be an instance where the construction of groynes might be valid; a series of groynes spaced along this shore would act to retain part of the nourished gravel placed in front of the eroding properties. This option would also be an expensive undertaking, likely greater than the values of the homes, and not certain of success. Considering the level of threat, evident in Figure 9, retreat and relocate is probably the best option.

The Bay View Littoral Cell and Its Management

The budget of beach sediments for the Bay View littoral cell is simple to formulate, because of the limited natural supply of gravel and its loss to abrasion being the only debit. The one natural source of gravel is the Esk River, but studies have concluded it amounts to a mere 2000 m^3/y of pea-size gravel (Gibb, 2003). Its contribution again would have been somewhat greater in the past because it is now reduced by commercial extraction from the river's channel. The beach nourishment program at Westshore, begun in 1987, is now the primary sediment credit for this cell, with the total credit on average amounting to 12,000 m^3/y. The best estimate for the loss from gravel abrasion is $-27{,}000$ m^3/y, yielding a net balance of $-15{,}000$ m^3/y, so the sediment budget of the Bay View cell is also in the red, but not nearly to the degree as that for the Haumoana cell. Furthermore, there is a significant uncertainty in this balance because of the difficulty in assessing the rate of gravel abrasion; examinations of these uncertainties indicate that the net balance could be as great as $-16{,}800$ m^3/y, or could actually be close to being in balance (Komar, 2005). If the $-15{,}000$ m^3/y of net erosion is assumed to occur uniformly over the 18-km shoreline length of the cell, it amounts to a loss that is slightly less than 1 m^3/y of sediment for each meter of shoreline length.

With only small volumes of new sediments being contributed to this shore, the waves need to produce only minor longshore transport rates to distribute those sediments from their sources along the remaining stretch of shore. As discussed earlier and illustrated in Figure 7, the orientation and curvature of the Bay View cell's shoreline is close to being in an equilibrium zero-transport condition, accomplished by its having rotated to face into the direction of the predominant waves arriving from the east–southeast. However, at times, waves arriving from the northeast cause some sediment transport to the south, whereas waves that arrive more from the southeast than those depicted in Figure 7 transport sediment back to the north. Therefore, a reversing longshore transport of the sediment exists within this cell, which can result in alternating periods of beach erosion *vs.* accretion at the north and south ends in proximity to the headlands, including at Westshore. There is evidence that such cycles correspond with strong El Niños *vs.* La Niñas, with an El Niño tending to produce the southerly transport and beach accretion at Westshore, whereas the La Niñas cause erosion, but documentation of this climate control requires additional research.

Such cycles in sediment transport directions and end-effect beach erosion *vs.* accretion appear to have been important in the episodic erosion of Westshore during the 20th century, generally blamed on the Port's breakwater. These cycles are evident in the beach profiles analyzed by Smith (1993), surveyed on a nearly annual basis from 1916 to 1961 along a 4-km stretch of shore at the south end of the Bay View cell, including Westshore. The results revealed the occurrence of significant shifts between net erosion and accretion from year to year. The largest cycle occurred during the mid 1950s; between the surveys in 1955 and 1956 this beach gained 40,000 m^3 of sediment, but in the following year between 1956 and 1957 it lost 40,100 m^3. If this cycle occurred uniformly along the 4-km stretch of surveyed shore, it was equivalent to first gaining 10 m^3 of sediment *per* meter of shoreline length, and the next year losing that volume. This is an extreme example, with the cycle between erosion and accretion more commonly being on the order of 10,000 to 20,000 m^3/y, about 2.5 to 5 m^3 of beach sediment *per* meter of shoreline length.

This natural cycle at Westshore is now largely obscured by the annual beach nourishment program. However, such cycles are still visibly evident at the north end of the littoral cell, at Tangoio, where from year to year the beach width can vary, and the composition changes from being almost entirely gravel in one year to a mixture of sand and gravel the next year.

This cycle between the growth and loss of the beach fronting Westshore is important for the susceptibility of its backshore to erosion, the presence of the beach acting as a buffer between the waves and the low bluff backing the beach, the seaward edge of the uplifted gravel beach ridge (raised further by the importation of gravel). The actual episodes of erosion occur during storms, when the high tide augmented by a storm surge plus the swash run-up of the high waves cut back the beach, resulting in some erosion of the bluff. The most significant storms in recent years that produced erosion at Westshore occurred in 1978 and 1985. Smith (1986) analyzed the extent of the beach and bluff erosion using a set of 22 profile lines extending along a 1.1-km stretch of shore, finding that the sediment losses were some 5000 and 7600 m^3, respectively during those two storms (4.5 and 6.9 m^3 of sediment loss *per* meter of shoreline length). Those losses included the erosion of the bluff, which retreated by 2.1 m in 1978 and 3.1 m in 1985, with 6 years of stability between. This degree of erosion is comparatively small, in view of its episodic nature and the tendency for the beach to recover between erosion events. Furthermore, there is a wide, largely undeveloped Reserve between this shore affected by erosion and the homes in Westshore, so they have not been threatened. Accordingly, in analyzing the impacts of the 1985 storm, O'Callaghan (1986) concluded that the erosion at Westshore "has not been severe in coastal engineering terms" and is "relatively minor." Its occurrence apparently alarmed those living in Westshore because immediately thereafter a number of investigations and reports dealing with the problem were initiated, leading to a decision to undertake the beach nourishment program to replace the lost sediment. This began in February 1987, with the imported gravel in recent years amounting on average to 10,000 m^3/y, derived by extraction from the beach to the immediate south of Bluff Hill; this measure therefore in effect represents the artificial bypassing of beach gravel from the Haumoana cell to the Bay View cell, at a rate that certainly exceeds any natural bypassing that may have occurred before the construction of the Port's breakwater (Komar, 2005).

With the erosion and flooding hazards well under control along Westshore, the focus has turned to improvements that would support the increased recreational use of this beach, which at the same time could provide still greater protection from erosion. Interest in recreational improvements has centered primarily on the development of a sand beach, which ironically may be possible thanks in large part to the shelter provided by the Port's breakwater.

SUMMARY AND DISCUSSION

This article has provided a summary of the factors involved in the evolution of the Hawke's Bay coast and the causes of its erosion—the tectonics of the region, its ocean and beach processes, sediment budgets, and the environmental impacts of humans, including the potential consequences of having constructed the Port of Napier's breakwater. The elevation changes of the shore at the time of the 1931 Hawke's Bay earthquake have been particularly important, having elevated much of the shore by about 2 m to form a relatively stable gravel ridge; in contrast, the southernmost stretch of shore from South Haumoana to Clifton subsided by about 1 m, and 75 years later its erosion is still attributed in part to that subsidence. However, the most significant contributing factor to that erosion has been that the longshore transport of beach sediment to the north exceeds the volumes contributed by the sources, the Tutkituki River and erosion of Cape Kidnappers, so there is a substantial deficit in the budget of beach sediments.

In recent decades, the primary attention has been directed toward the erosion at Westshore, to the north of the Bluff Hill headland in Napier, even though the assessment has been that its erosion is relatively minor. The perception by some is that the construction of the Port's breakwater in 1887–90 has been the cause of Westshore's problems, but my reexamination of the evidence led me to conclude that, rather than having caused erosion, the sheltering of that shore by the breakwater's arm has protected it from the largest storm waves, acting to reduce the extent of any erosional impacts.

The considerable number of investigations by coastal scientists and engineers of the Hawke's Bay coast, and the monitoring program that has surveyed beach profiles for more than 30 years, support its sound management based on an understanding of these multiple factors important to coastal change. Hazard zones have been established to protect developments from the extremes expected from the ocean processes, and decisions have been made to discontinue beach-sediment mining at Awatoto in order to balance the sediment budget. Considerations of the beach at Westshore now wisely focus on improving its recreational potentials, rather than attempting to solve what has mistakenly been perceived as a significant erosion problem.

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