5 The Dynamics of Mixed Sand-and-Gravel Beaches and the Hawke's Bay Monitoring Programme

5.1 INTRODUCTION

The beaches within the Bay View and Haumoana Littoral Cells of Hawke's Bay are composed of mixed sand and gravel, the type of beach that is found along much of the east coast of the South Island but is otherwise comparatively rare on the world's coasts. Due to their significance on the coast of New Zealand, initially most of the scientific research investigating the compositions and processes on "mixed" beaches was conducted there. Until recently, mixed beaches have received much less research attention in other countries, the investigations instead having focused on sand beaches or on coarse-grained beaches consisting entirely of gravel (shingle) and cobbles. Only in the last decade have investigators outside of New Zealand taken particular interest in mixed beaches. While recognizing the important research that had been undertaken in New Zealand, Mason and Coates (2001) concluded in a recent review that from an international perspective: "Beaches containing a mixture of both sand and gravel have aroused only sporadic interest." The result is that much remains unknown about this type of beach to serve as the basis for their management.

The objective of this Section is to first provide a general review of mixed sand-and-gravel beaches, in particular examining their compositions, their observed range of morphologies that depend on the proportions of sand versus the coarse-grained component, and then to review processes such as the dynamics of wave breaking and swash runup. Of particular interest will be the morphological responses of these beaches to storms, as this aspect of their behavior is important to assessments of the erosion hazards. This review will also extend to the longshore transport of the mixed grain sizes, the abrasion and loss of the sediment particles from the beach, and finally how these beaches respond in the long term to a change in relative sea level, either a rise in the sea as is presently occurring globally, or a drop in the relative sea level as happened abruptly along much of the Hawke's Bay coast at the time of the 1931 earthquake. This review of research undertaken on mixed beaches is offered in lieu of scientific studies undertaken specifically on the Hawke's Bay beaches, which have been limited in numbers and in their scope. The attention of this Section then turns specifically to the few studies that have been completed of the Hawke's Bay beaches, in particular examining the procedures and products of the monitoring program that has been underway for a number of years, and has been important in assessments of erosion occurrences and the establishment of hazard zones.

5.2 MIXED SAND-AND-GRAVEL BEACHES: A REVIEW

As noted above, the earliest research on mixed sand-and-gravel beaches took place in New Zealand due to the importance of that beach type in this country; Kirk (1980) provides a good review of those investigations. Only in recent years have researchers in other countries become interested in mixed beaches, with those studies having been undertaken mainly in England, Wales, Ireland and Canada where coarse-grained beaches are common. Previously the research in those countries focused primarily on relatively pure gravel/shingle/cobble beaches, but it was found that the sand component could be significant in the dynamic responses of those otherwise coarse-grained beaches, even if the percentage of sand was relatively small. This was particularly found to be the case for beach nourishment projects undertaken in England, where the shingle used in the project was derived from dredging offshore on the continental shelf, so the material initially contained a high percentage of sand and silt, sometimes to the detriment of the project due to the effects of this fine material on the resulting stability of the nourished beach. Mason and Coates (2001), being UK investigators, provide a review of those research results. Between the investigations undertaken in New Zealand and later on other coasts, we have begun to understand the dynamics of mixed sand-and-gravel beaches, but as will be seen in this review, gaps remain in this coverage, some of which restrict our capability to manage mixed beaches, including those in Hawke's Bay.

5.2.1 The Compositions and Morphologies of Beaches

The composition of a beach depends on the sources of its sediment. The majority of beaches throughout the world consist primarily of quartz and feldspar sand, derived from the weathering and erosion of rocks such as granite and the range of metamorphic rocks, schist and gneiss. The sand can also have a biological origin, derived from mollusk shells or coral that have been washed up onto the beach and broken down by the waves. Other rock sources supply coarse-grained material to the beach, ranging from pebbles to cobbles, and even boulders. The shingle beaches of England are composed primarily of highly resistant pebble-size flint and chert, formerly concretions in limestone such as the White Cliffs of Dover. The mixed beaches of New Zealand, including those in Hawke's Bay, contain pebbles and cobbles derived from the erosion of greywacke rocks found in the Southern Alps of the South Island and the mountain range to the west of Hawke's Bay on the North Island: the greywacke was produced by the low-grade metamorphism of a fine-grained sandstone, the heat and pressure producing a highly compact rock, but whose erosion yields gravel and sand that is significantly more susceptible to abrasion. The classic form of a mixed sand-and-gravel beach contains significant proportions of both sand and the coarser particles, the proportion depending initially on that supplied by rivers or from sea-cliff erosion, but then altered by the processes of waves and currents, which may sort and separate these respective grain sizes due to their contrasting hydraulic properties.

Taking a broad perspective to consider the full range of beach types depending on their mixtures of grain sizes, they can be classified into the four categories that are illustrated in Figure 5-1 (Jennings and Shulmeister, 2002):

(a) *pure coarse-grained beaches*
   Beaches composed of particle sizes ranging from pebbles to cobbles and boulders, with minimal sand;
(b) *mixed sand-and-gravel beaches*
   Beaches consisting of high proportions of both coarse particles and sand, with there being an intimate mixing of the two size fractions in the beach deposit;
(c) composite beaches
   Beaches having a higher proportion of sand that has been sorted by the waves and nearshore currents, so the beach consists of an upper foreshore or backshore ridge composed of gravel and cobbles, and a lower foreshore of sand, generally with a distinct boundary between them; and
(d) *pure sand beaches*
   Beaches consisting almost entirely of sand, and if coarse particles are present the quantity is insignificant so it does not appreciably affect the morphology and dynamics of the beach.

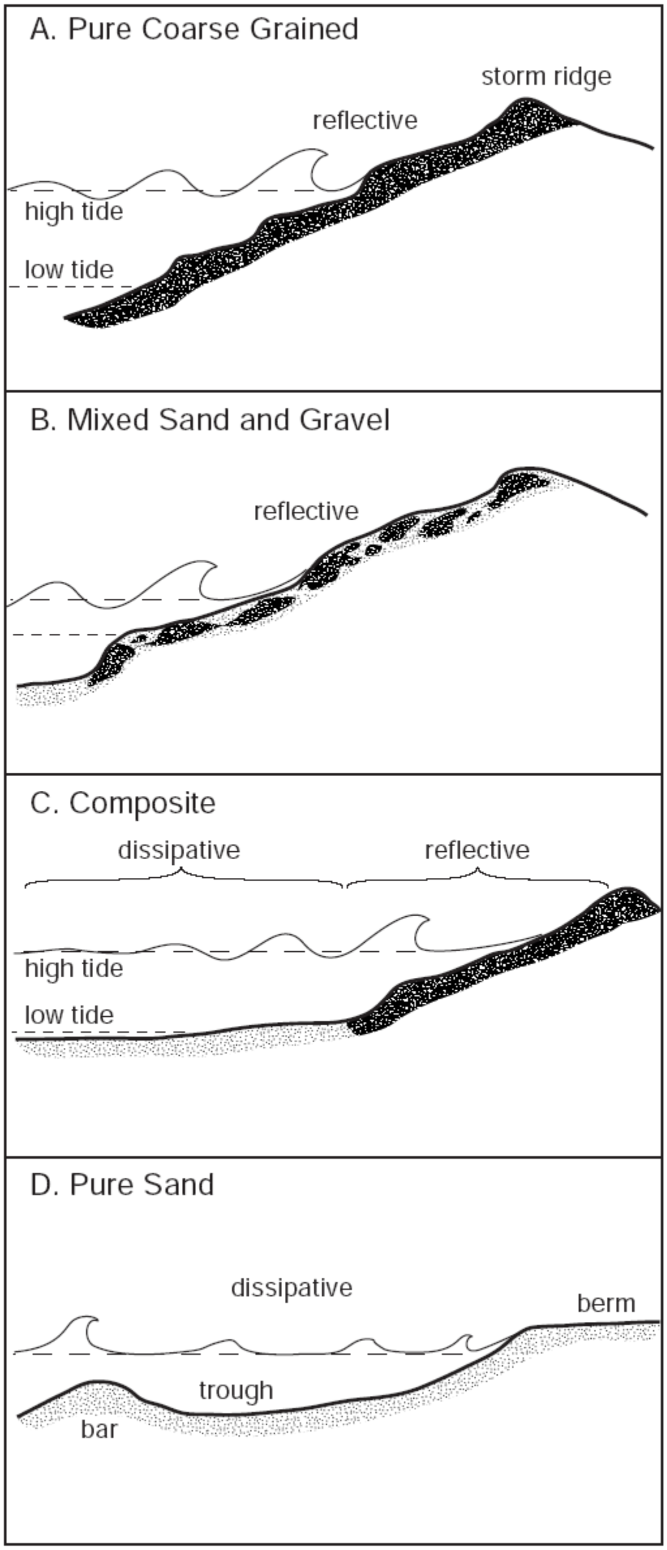


Figure 5-1 The classification of beaches based on their proportions of coarse sediments (gravel and cobbles) versus sand, with the resulting differences in their morphologies. [*extended from* Jennings and Shulmeister (2002)]

A "pure" coarse-grained beach typically does contain some sand in the voids between the particles of gravel and cobbles, but with an insufficient proportion to significantly affect the porosity and permeability of the deposit as a whole, which is important in that with enough sand it can alter the runup of the wave swash on the beach and the resulting mobility of the gravel particles. This critical proportion of sand is not well established, but can be taken as approximately 5 to 10% of the deposit as a whole.

The distinction between beach categories (b) and (c) is dependent on both the proportions of sand versus the coarse-grained component, and on the ability of the waves and currents to sort and separate those respective sizes. Generally, the classic form of a mixed sand-and-gravel beach is where there is still a relatively small portion of sand, sufficiently small that the volume can mainly reside within the voids between the coarser gravel and cobble clasts. In this sense the "mixed" beach is an intimate mixture of the full range of grain sizes. There may be a degree of sorting and separation of some of the sand so it is locally concentrated on the beach face or is carried by the waves to the immediate offshore, leaving a beach that can still be classified as mixed but with a sub-tidal offshore sand deposit. With increasing quantities of sand provided by the sediment sources to the coast, the volume of this offshore sand accumulation increases to the extent that it is exposed at times of low tide, at which point it would be classified as a category (c) composite beach, since there is a fronting sand beach at least during low tides. With a still greater quantity of sand, a well-established sand beach can form in front of the gravel ridge, with the sand beach visible at all tidal stages; the waves might then only reach the gravel ridge during storms that erode back and inundate the fronting sand beach.

This classification of beach types based on their compositions and morphologies is a minor extension of that developed by Jennings and Shulmeister (2002), a study of special interest in that their classification was based on 42 gravel beaches found on the South Island of New Zealand. Their resulting classification was limited to categories (a) through (c), those containing a significant coarse-grained component, not extrapolated to the category (d) pure sand beaches. The vast majority of beaches they investigated on the South Island were either category (a) or (b), that is, dominated by the gravel over the sand component. Important on the east coast of the South Island is the greywacke composition of the gravel, the abrasion of which ultimately yields very fine sand; as reviewed by Kirk (1980), this fine sand moves into the immediate offshore where it generally is not exposed even during the lowest tides, so the mixed coarse-grained beach is a distinctive entity from that offshore fine-sand deposit, this accounting for those beaches being either category (a) or (b). Jennings and Shulmeister (2002) did identified category (c) composite beaches on the west coast between Hokitika and north just beyond Greymouth, on the north shore of the South Island near Nelson, and near Timaru on the east coast at the south end of the Canterbury Bight Littoral Cell. As found in New Zealand and classified by Jennings and Shulmeister (2002), these composite beaches generally have only a small accumulation of coarse sand seaward of the otherwise dominant gravel ridge, the sand being exposed at low tides while otherwise being submerged. This is also true of the Hawke's Bay beaches, with intertidal sand deposits commonly seen at the base of the otherwise coarse-grained beach, with the most extensive sand accumulations found at Westshore, undoubtedly due to its protection from the waves by Bluff Hill and the Port's breakwater, and at Tangoio due to its local protection by the rocky headland to its north.

The extension of the classification presented here in Figure 5-1 is based in large part on beaches found along the west coast of the United States, where the proportion of sand relative to the gravel is significantly greater than found on the South Island of New Zealand, and generally even in the UK beaches. The result is that on the US west coast the composite beach type is generally a wide sandy beach backed by a gravel ridge, with the sand beach exposed at all tidal stages during the summer, only becoming submerged in the winter when storms occur and much of that sand moves to offshore bars, allowing the waves to reach the gravel ridge at mid- to high-tides (Everts et al., 2002; Allan and Komar, 2002, 2004).

This range of beach categories exhibits contrasting morphologies with different degrees of stability when assaulted by storms. This can be illustrated by placing the categories into the morphodynamics classification developed by Wright and Short (1983), illustrated in Figure 5-2.

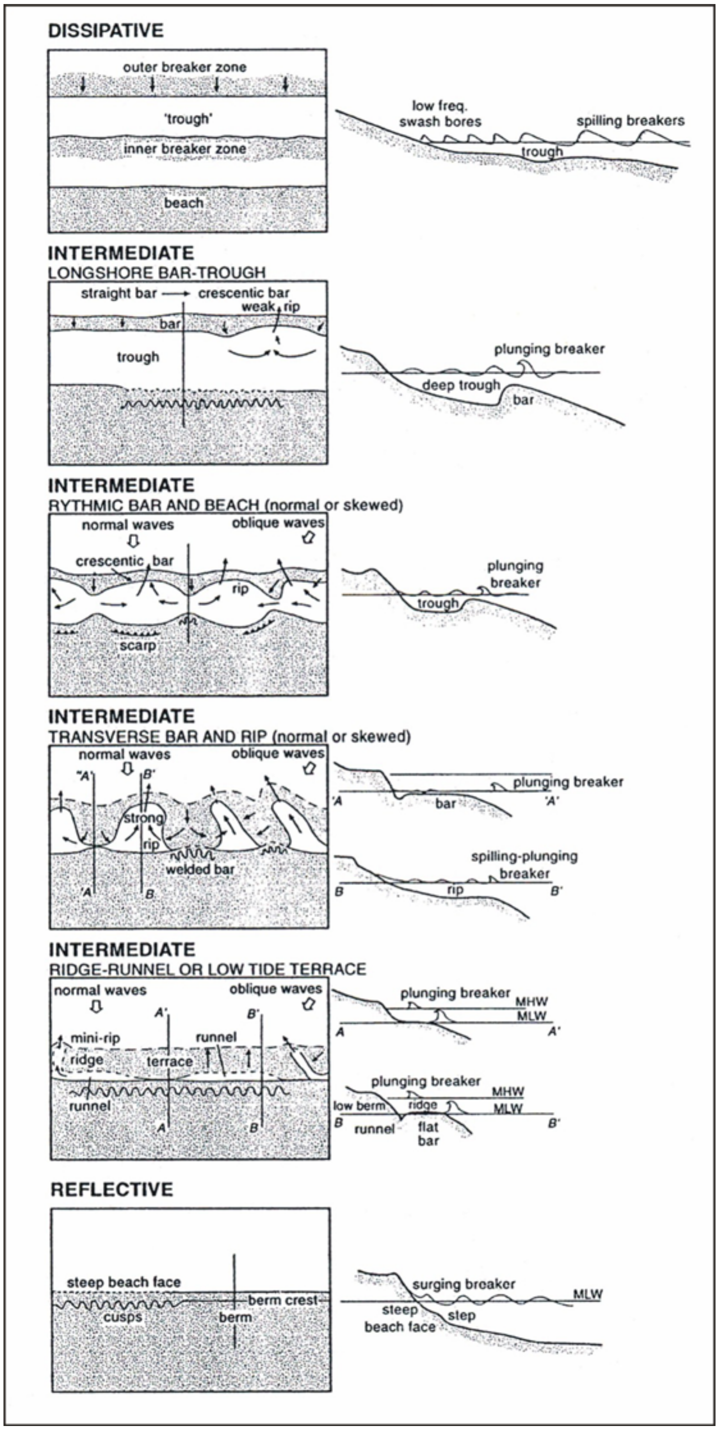


Figure 5-2 The morphodynamics classification of beaches. [*after* Wright and Short (1983)]

The "morpho" portion of this classification refers to the geometry of the beach, both in its two-dimensional profile and in the three-dimensional topography of bars and troughs, while the "dynamics" part refers to how that morphology changes in response to the varying wave conditions. It is seen in Figure 5-2 that at one end of the spectrum are Dissipative beaches, at the other end Reflective beaches, with four stages of Intermediate categories. The average beach slope is seen to progressively steepen from the Dissipative to the Reflective condition, with the profiles of the Intermediate categories tending to be more irregular due to the presence of offshore bars and troughs, or rip-current embayments. Dissipative beaches are so termed because they are effective in dissipating the energy of the waves, their low slopes causing the waves to break well offshore from the dry beach, with the bores formed from the broken waves crossing a wide surf zone and loosing most of their energy before they reach the shore and swash up the beach face. In the opposite extreme, on Reflective beaches the profile slope is steep so the waves reach close to shore before breaking, and immediately develop into a strong swash up the beach face, not having lost energy in first crossing a wide surf zone. These beaches are reflective in the sense that because of their steep slopes, they can reflect a significant portion of the wave energy, so one can often observe waves returning seaward after having been reflected from the beach.

The position of a specific beach within this morphodynamics classification depends on both its sediment grain size and the energy level of the waves (also affected to a degree by the range of tides). In general, the coarser the grain size the steeper the beach profile, so that gravel and cobble beaches are almost always Reflective. A pure sand beach tends to be Intermediate at times of low waves and Dissipative under high wave conditions, although a coarse sand beach may be sufficiently steep to become Reflective under low waves. As the heights of the waves increase during a storm, the sand on the beach is rapidly transported offshore where it is deposited as bars, so the slope is reduced and the morphology shifts very quickly toward the Dissipative end of the spectrum (Wright and Short, 1983; Lippman and Holman, 1990). This is an interesting natural response of sand beaches to storms, as their becoming Dissipative at the height of the storm helps to reduce the energy of the waves at the shore, thereby limiting the extent of the storm-induced erosion to the beach and backshore properties. After the storm, with a return of reduced waves energies, the sand moves back onshore and the beach morphology shifts from the Dissipative end into the Intermediate states, tending to follow in order the sequence of beach forms diagrammed in Figure 5-2, perhaps eventually reaching the Reflective condition; unlike the rapid shift of the beach category during the storm, this progression following the storm may take many days to weeks as the onshore transport of the sand under the low waves is slow.

Of particular significance, beaches that are at the extremes, either Dissipative or Reflective, tend to show the least variability in their three-dimensional morphologies or in a simple set of beach profiles; it is the Intermediate beaches that are most dynamic in their responses to storms, and therefore tend to be the most hazardous in terms of the potential erosion of shore-front properties (Wright and Short, 1983). For example, on the Oregon coast we have found by repeated beach profile surveys that the finer-grained Dissipative beaches change in elevations by only about 1 metre between the summer and winter, or at the time of a major storm, while the somewhat steeper, coarser-grained sand beaches that are Intermediate in the morphodynamics classification experience elevation changes that are on the order of 3 metres, typically with a much greater extent of property erosion in both foredunes and sea cliffs backing those beaches (Aguilar and Komar, 1978; Shih and Komar, 1994).

Pure coarse-grained beaches that consist of gravel and cobbles tend to always remain Reflective due to their persistent steep profile slopes. As shown by Wright and Short (1983), this imparts a degree of stability to the beach by virtue of the large sizes of the particles and perhaps also because a significant portion of the wave energy is reflected; they are less dynamic in profile changes during storms than are the Intermediate beaches. As will reviewed below, the stability of mixed sand-and-gravel beaches is uncertain and often unpredictable due to the added proportions of sand which can fill the voids between the gravel particles, reducing the extent of percolation of the wave-swash runup so it retains more of its energy, resulting in the cut back of the beach profile during storms. Composite beaches are interesting in that if the fronting sand deposit is sufficient, it in effect provides a Dissipative sand beach backed by a Reflective coarse-grained ridge, the two most stable end members in the morphodynamics classification of Wright and Short (1983). As will be discussed below, because of this relative stability of pure coarse-grained beaches, some mixed beaches, and particularly composite beaches that have both Dissipative and Reflective elements, it has been recognized that constructing a comparatively small ridge of cobbles at the back of a sand beach can provide the same degree of protection to shore-front properties as does a large volume of sand added in a beach nourishment project, and in some cases can even substitute for a hard structure such as a riprap revetment or seawall.

With the classification of beaches presented in Figure 5-1 having originally been formulated in New Zealand by Jennings and Shulmeister (2002), it can be expected that it has direct application to the Hawke's Bay beaches that differ little from the mixed beaches on the South Island. The research on the South Island beaches can also be expected to serve as the primary guide in understanding the dynamics of the Hawke's Bay beaches, and in their management. As noted above, the beaches of the Canterbury Bight are limited to categories (a) and (b) in the classification, Figure 5-1, depending on the proportions of gravel versus sand. This is a consequence of the susceptibility of the greywacke gravel to abrasion, which will be reviewed below. Experiments have shown that the gravel particles in the beaches can abrade relatively rapidly when they collide while being transported by the waves, and this abrasion yields sand. Even if the sand is sufficiently coarse to remain on the beach, it is susceptible to being crunched between colliding gravel particles, and is soon reduced further to fine sand and silt, which is too fine to remain on the high-energy beach so is quickly lost to the offshore. In his review of the Canterbury beaches, Kirk (1980) emphasized the significance of this two-part nature of the coastal sediments, and of the resulting morphology of the beaches as diagrammed in Figure 5-3, showing the steep slope of the gravel deposit with a marked step at its base, providing a transition to the offshore, sub-tidal fine-grained sand.

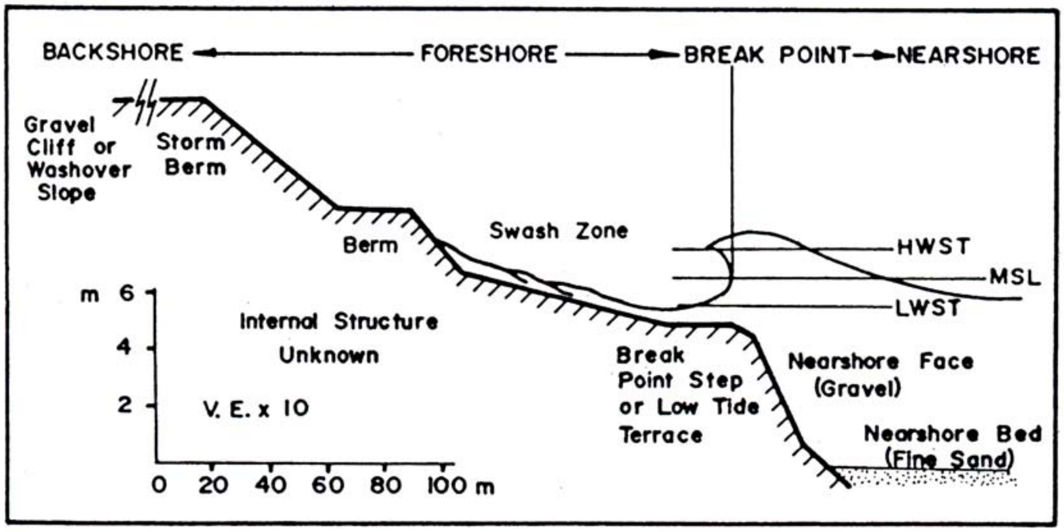


Figure 5-3 The generalized profile of a mixed sand-and-gravel beach as found on the South Island, New Zealand. [*from* Kirk (1969, 1980)]

As well as there being a distinct difference between the fine sand found in the offshore versus the gravel and coarser sand on the beach itself, there are differences in ocean processes and resulting sediment transport by those processes. As diagrammed in Figure 5-3, the wave breaking almost always occurs on the steep toe or “step” of the coarse-grained beach, with the breakers in turn generating a strong swash up the beach face, followed by a backwash weakened somewhat by the loss of water through its percolation into the coarse deposit of the beach. The transport and sorting of the gravel on the beach is therefore governed directly by the processes of wave breaking and swash. In contrast, in the immediate offshore the transport of the fine sand is determined by a combination of waves and currents, with the waves acting to suspend the sand above the seafloor while the currents cause that suspended sand to drift along, it being the superimposed current that determines the direction and rate of the transport of the fine sand. In that these offshore currents can be largely independent from the waves, often being driven by the coastal winds, the transport of the fine sand in the offshore can be effectively independent from the transport of the gravel and coarse sand on the beach; for example, the fine sand offshore may experience transport to the south along the coast, while the gravel and coarse sand on the beach are being transported by the waves to the north. This difference in the grain sizes of the sand, with coarse sand in the beach and fine sand in the offshore, restricts their exchange between those two environments. In this respect the Canterbury beaches may differ to some extent from those in Hawke's Bay, at least in well sheltered areas such as Westshore where significant quantities of sand can accumulate for prolonged periods of time, with a continuous gradation from the gravel upper beach, to an intertidal sand beach, which appears to continue uninterrupted into the offshore fine-grained sand deposits. In this respect, the Hawke's Bay beaches have similarities to the morphologies and dynamics of mixed sand-and-gravel beaches found elsewhere in the world where there is a more active exchange of the sand component in the beach with the offshore.

5.2.2 Ocean Processes on Mixed Beaches

When waves reach a beach and enter water that is approximately as deep as the waves are high, they become unstable and break with the crest thrown forward as the wave disintegrates into bubbles and foam. Three types of breakers are generally recognized, Figure 5-4: spilling, plunging, and surging (Komar, 1998). With spilling breakers each wave gradually peaks until the crest becomes unstable and cascades down as "white water". With plunging breakers the shoreward face of the wave becomes vertical, curls over, and plunges forward and downward as an intact mass of water. Surging breakers peak up as if to plunge, but then the base of the wave rushes up the beach face so the crest collapses and disappears. There is actually a continuum of breaker types grading from one to another, at times making it difficult to apply such classifications. Furthermore, on a given day at a beach it is common to see some waves break by plunging while others are spilling, depending on their individual heights and interactions with other waves and the sea floor. In general, spilling breakers tend to occur on beaches of very low slope with waves of high steepness values, the ratio of the wave height to wave length; plunging waves are associated with steeper beaches and waves of intermediate steepness; surging occurs on high-gradient beaches with waves of low steepness. Research has yielded predictions of the dominant breaker type depending on the grain size and steepness of the beach face, and on the height and period of the waves, which together determine the wave steepness (Komar, 1998, p. 208-211).

From this, plunging and surging breakers can be expected to dominate on Reflective beaches, including category (a) pure gravel and (b) mixed sand-and-gravel beaches. In that category (d) pure sand beaches can potentially range from Dissipative to Reflective depending on their grain sizes and slopes, as well on the wave conditions, any of the wave-breaker types might be observed. Wave breaking on category (c) composite beaches can yield a complex surf zone, especially when the Reflective gravel ridge is fronted by a Dissipative sand beach; in this case the waves arriving from deep water might initially break by spilling, then cross the surf zone over the sand beach as bores, and then break a second time on the steeper slope of the gravel beach by plunging or surging. The energy of the waves is in part dissipated by their initial breaking over the sand beach and as bores, so the second breaking and swash runup over the gravel beach is moderated compared to that of a mixed sand-and-gravel beach where the full impact of wave breaking occurs on the gravel beach. This range of breaker types can be observed on the Hawke's Bay beaches. For example, on one occasion when fairly high waves with long periods reached this coast, I noted that along the Marine Parade where the waves were high in the offshore due to their having experienced little loss of energy from refraction, and where the beach is uniformly steep, the arriving waves broke by surging with minimal swash runup, but with a high degree of reflection; at the same time, the waves reaching Westshore were reduced in their heights due to having undergone considerable refraction, while retaining their long periods, and therefore broke by plunging, much to the delight of the crowd of surfers. This example illustrates the considerable range of process dynamics experienced on the Hawke's Bay beaches, depending on their locations and degrees of exposure to the arriving waves.

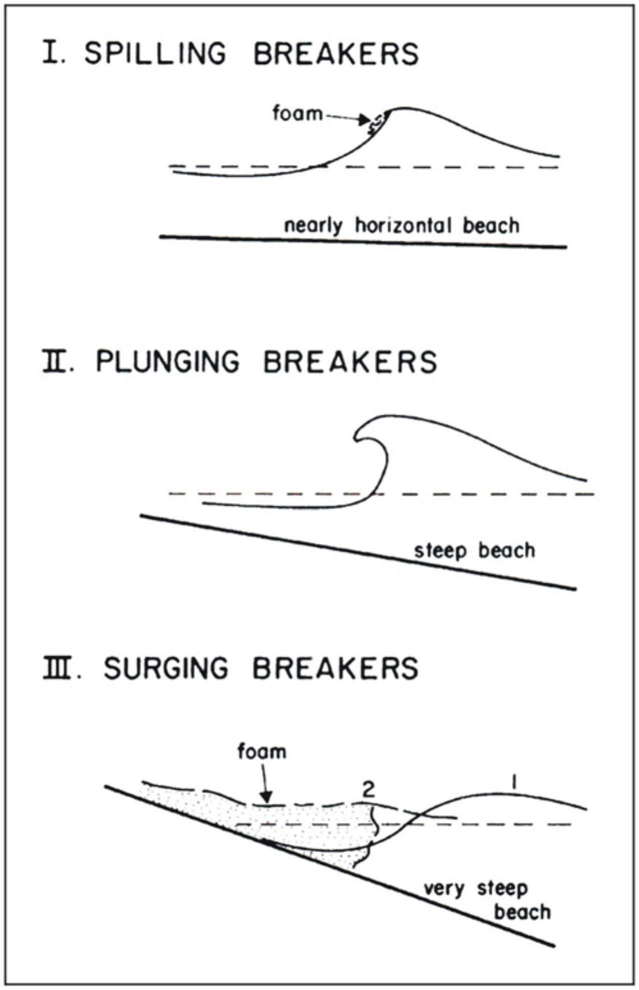


Figure 5-4 Three types of breaking waves on beaches, depending on the beach slope, and the wave height and period. [*from* Komar (1998)]

When waves break on a sloping beach they produce a rise in the mean water level at the shore, termed wave setup, as well as generate an oscillating swash runup and backwash (Komar, 1998, p. 232-248). Taken alone, the setup shifts the mean shoreline upward and landward, so it can be metres to tens of metres landward of the still-water shoreline that would exist if the waves were not present. The motions of the swash runup and backwash oscillate above and below the mean shoreline that is established by the level of the setup.

Laboratory wave-flume experiments and field studies on beaches have obtained measurements of the wave setup and runup levels to determine how they depend on the wave heights and periods, on the slope of the beach face, and on the grain size of the beach sediment as this can govern the amount of water lost from the runup by percolation into the beach. Having an ability to predict the total water levels due to the wave setup plus the runup is important in engineering and management applications, respectively in the design of shore-protection structures such as riprap revetments that may be impacted and potentially overtopped by the runup, or in the establishment of coastal hazard zones that include assessments of the backshore erosion and flooding produced by extreme total-water levels. The primary field studies on sand beaches to obtain such predictive relationships are those of Holman (1986) and Ruggiero et al. (2001). From measurements on an Intermediate type beach on the U.S. east coast over a range of wave conditions and beach slopes, Holman (1986) empirically derived the relationship

$$R_{2\%} = 0.36 g^{1/2} S H_{\infty}^{1/2} T \tag{5-1}$$

for the "total runup", the sum of the setup plus the swash level, which is seen to depend on the beach slope, *S*, the deep-water significant wave height, H_{∞}, and the wave period, *T*; *g* is the acceleration of gravity [as given here, Holman's relationship has been slightly modified by Komar (1998, p. 243)]. This equation is dimensionally homogeneous, so it can be used with any consistent sets of units (e.g., metres and seconds). The assessed total runup, $R_{2\%}$, is the 2% exceedence value, that is, it is exceeded in elevation by only 2% of the swash events; it was selected because, while being only slightly lower than the maximum runup level, it represents a number of elevated swash occurrences and therefore is relevant to the highest elevation to which wave-swash impacts might be expected to be significant to erosion or over-topping occurrences. The study of Ruggiero et al. (2001) collected additional swash measurements, but on a Dissipative beach, so the data set was extended to lower beach slopes. The main change from equation (5-1) was a reduction in the dependence on the beach slope, becoming proportional to $S^{1/2}$ rather than *S*. Of interest in either of the predictive relationships, the runup level increases with the deep-water wave height and period, both of which tend to increase during storms so the resulting increase in $R_{2\%}$ is influenced by both wave parameters. Note that this relationship does not include the effects of offshore wave refraction, which in general will decrease both the effective wave height and runup elevation. The equation also shows that the steeper the beach face, the higher the runup level. The field data upon which equation (5-1) is based come entirely from sand beaches, so it also does not include the effects of water percolation into the beach face as the swash runs up the slope, so this relationship might be expected to over predict the $R_{2\%}$ levels for pure gravel beaches and mixed sand-and-gravel beaches.

The dynamics of wave swash runup and backwash on gravel beaches is significantly more complicated than on sand beaches, due to the porosity and permeability of the coarser grained beaches which potentially can extract water from the swash, or add water during a falling tide if the reservoir of ground water within the beach is higher than the mean water level of the sea. A further complicating factor is the amount of sand within the gravel matrix; in the case of mixed sand-and-gravel beaches this quantity can be sufficient to reduce the loss of water to percolation, thereby increasing the velocity of the runup and the elevation it achieves on the beach.

The study that has come closest to providing predictions of swash runup elevations based on measurements on mixed sand-and-gravel beaches is that of Kirk (1975), undertaken on the beaches in the Canterbury Bight. The primary correlation found was between the measured breaker height and the length and elevation of the resulting swash runup. For breaker heights in the range 0.3 to 2.5 metres, swash lengths ranged from about 15 to 39 metres. The correlation is not as good for the runup elevations, and two lines are provided by Kirk (1975) for different wave-period events, demonstrating the dependence on the wave period as well as wave height as seen in equation (5-1). Kirk (1975) also obtained numerous measurements of swash and backwash velocities using an electro-mechanical force-plate dynamometer. The average maximum runup velocity was 1.68 m/sec with an average duration of 2.98 seconds at the mid-swash position, while the backwash velocities averaged 1.40 m/sec with a mean duration of 4.25 seconds. Kirk concluded from these measurements that only 20 to 60% of the incident wave energy is translated into runup and backwash velocities, the proportion decreasing as wave energies increase. Other researchers have investigated the dynamics of wave swash on gravel beaches, including the important role of percolation and the exchange of water with the groundwater reservoir that can either extract or add water to the runup and backwash [e.g., Kobayashi et al. (1991); Blewett et al. (2000); Horn and Ling Li (in press)]. That work is fundamental to an understanding of the movement of the gravel on the beach and the resulting profile responses, but has not been applied to the prediction of total runup elevations important to assessments of backshore erosion and flooding.

The capacity to establish coastal hazard zones on mixed sand-and-gravel beaches, including assessments of the potential for backshore erosion and flooding during extreme storms, requires techniques to satisfactorily calculate total-water elevations, which include the swash runup (the setup together with the swash level reached by individual waves) plus the water-level contribution of the tide and storm surge (Ruggiero et al., 2001). Equation (5-1) has been used in such applications for coasts having sand beaches. That relationship can also serve as a guide, until more research is completed, to assess runup elevations on coarse-grained beaches. It can be anticipated that there will be the same basic dependence as given in equation (5-1) on the beach slope, and on the wave height and period. It may simply come down to a modification of the proportionality coefficient from the 0.36 value derived from measurements on sand beaches (Holman, 1986). It can be expected that the value would decrease the most for pure gravel beaches due to their having the greatest permeability, but less so for mixed sand-and-gravel beaches which may in some cases not be significantly more permeable than a sand beach, though there would be the addition of the frictional drag by the gravel particles on the flow within the swash, reducing their runup elevations. Ultimately, most complex will be an evaluation of the runup on composite beaches, in that it depends on the degree of energy loss of the waves as they cross the dissipative sand beach, and only then re-break and swash up the gravel beach. This will require the application of numerical surf-zone models that can evaluate these multiple processes; such models have been developed for sand beaches (Komar, 1998, p. 217-231), but again need to be adapted for applications on composite beaches.

5.2.3 The Dynamic Responses of Beaches to Changing Wave Conditions

Of particular interest are the morphological responses of beaches to storms, as this behavior is important to assessments of erosion hazards, both of the beach itself and of backshore properties. Again, most of the coastal research has focused on the responses of sand beaches, documenting the changes due to individual storm events and seasonal variations in the beach morphology on coasts where there generally are higher wave conditions during the winter compared with the summer. These responses of sand beaches have been reviewed in detail by Komar (1998, Chapter 7); far less is know about the process-dynamics involved in the responses of mixed sand-and-gravel beaches to storms.

The early research concerned with the profile responses of sand beaches to changing wave conditions took place on the U.S. west coast, primarily in southern California (Shepard, 1950; Bascom, 1953). A seasonal variation was found, with the beach profiles having a wide, dry berm during the summer, which is eroded by storms during the winter with the berm sand being transported a short distance offshore where it is deposited to form sand bars. This change is depicted schematically in Figure 5-5, with the two types of profiles respectively termed "berm-type profiles" and "bar-type profiles", a terminology that is now preferred in that the change can occur during any time of the year (e.g., during a summer hurricane or cyclone), so does not necessarily correspond to the summer versus winter seasons. This shift in profile types has been related empirically to the wave steepness, which increases during a storm, and the beach sediment grain size or settling velocity (Komar, 1998, p. 308-311). The early research was limited to a two-dimensional view of the beach, its profile as depicted in Figure 5-5, whereas the later morphodynamics model of Wright and Short (1983), discussed earlier and presented in Figure 5-2, represents an expanded three-dimensional analysis but within which a single profile can behave much as shown in Figure 5-5. As previously discussed, with the occurrence of a storm the beach morphology shifts toward the Dissipative stage, with erosion of the berm and transport of sand to form an offshore bar, while following the storm the shift is in the opposite direction, first through the Intermediate stages and perhaps eventually reaching the steeper Reflective condition. Wright and Short (1983) and other studies have empirically related this shift to dimensionless numbers (e.g., the Iribarren Number) that are in effect the ratio of the wave steepness to the beach slope, the latter in turn depending on the beach sediment grain size.

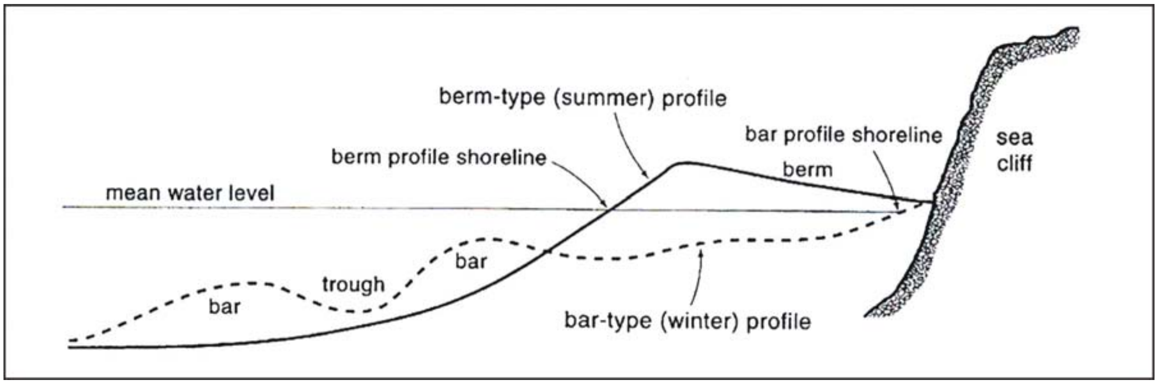


Figure 5-5 The bar-type profile that forms during a storm or prevails throughout the winter with higher wave conditions, versus the berm-type summer profile that forms by accretion at times of lower waves. [*from* Komar (1998)]

While the responses of sand beaches to storms have been thoroughly studied, our understanding of the comparable morphologic responses of coarse-grained beaches to changing wave energies is still rudimentary. Furthermore, different responses have been found in the several studies that have been undertaken. Some found that similar to sand beaches, high-energy waves erode back the beach face and berm of gravel beaches, transporting the gravel toward the offshore (Orford, 1975; Williams and Caldwell, 1988; Sherman, 1991); however, unlike sand beaches the gravel that is transported offshore is deposited at the base of the gravel deposit, but does not form a bar as generally is the case for sand beaches. For example, Sherman (1991) undertook his research on two gravel beaches on the northern coast of Ireland. Both are pocket beaches, with Pebble Strand being a mixed sand-and-gravel beach while Slievebane Beach is a composite beach, having an upper ridge of gravel with its lower limit being just above mean low water, and with a gently sloping sand deposit seaward of the gravel. At Pebble Strand the particle sizes range from 5 to 200 mm, while those at Slievebane range from 4 to 64 mm; both beaches show down-slope decreases in grain sizes. Repeated surveys of both beaches showed that their profiles are concave upward, with the smoothest profiles found following storms, at which time there is also a net offshore movement of gravel as reflected in the profile responses. During quiet periods between storms the gravel moves back up the beach face and forms small berms at mid-beach elevations, governed by the runup levels reached the waves. Multiple berms can develop under the changing wave conditions.

While storm waves may result in the offshore transport of much of the gravel, depositing it at the base of the beach face, it has also been observed that some of the gravel can be swept landward by the intense wave swash, to be deposited at the top of the beach face or carried over the top of a gravel ridge, elevating the level of the berm or depositing the gravel on the landward side of the ridge, resulting in its inland migration. This was noted, for example, by Bluck (1967) on the coast of Wales, a study that found a net landward movement of coarse particles and accretion of the upper beach during storms, so both the crest elevation and slope of the beach increased. Similar responses of gravel and cobble beaches have been found by Carter and Orford (1984, 1993) on the coast of Ireland, and by Everts et al. (2002) and Allan and Komar (2002, 2004) on the U.S. west coast. These U.S. west coast studies both involved composite beaches having a gravel and cobble ridge at the back of a wide sand beach, including an artificially constructed dynamic revetment/cobble berm for protection of a park. Typically, the average slope of the cobble beach is on the order of 0.3 (1 in 3.3), while the slope of the sand portion of the profile has slopes that are an order-of-magnitude lower, typically 0.02 to 0.04. In the winter with the return of high wave conditions, the fronting dissipative sand beach responds as expected, with erosion of the berm and the offshore transport of sand. With the reduction in the level of the fronting sand my 1 metre or more, the waves of mid-and late-winter storms are able to reach the gravel ridges. The response of the gravel-beach morphology generally is just the opposite to the sand, there being a net landward movement of the coarse particles during a storm so that both the crest elevation of the gravel deposit and its slope increase. While the fronting sand beach had become more dissipative in response to the storm waves, the gravel beach had become more reflective. This difference in responses was undoubtedly caused by their contrasting permeabilities and how that determines the balance between the swash runup of the waves and the backwash, with the competence of the landward-flowing swash able to transport cobbles up the beach face, but not necessarily back down the slope. With the return of low waves during the summer the sand moves from the offshore bars back to the dry part of the beach, partly covering the cobbles with a layer of sand; at some locations the cobble beach becomes completely covered throughout the summer. The result is that these U.S. west coast gravel beach ridges tend to have variable contents of sand with the seasons, a maximum in the summer and a minimum in the winter when the sand is winnowed from the gravel matrix by the storm-wave swash and is carried offshore. This variability in sand content has an effect on the porosity and permeability of the deposit, and hence on its morphologic responses to the waves. Engineers responsible for the construction of beach nourishment projects on the coast of England have observed that when sand and silt is included in the dredged shingle used in the project, the result is a decreased stability of the constructed beach; this is presumably due to the increased wave swash intensities that result from the decreased permeability of the shingle deposit when the fine-grained sediments are added. Similarly, on the composite beaches of southern California, Everts et al. (2002) concluded that the inclusion of sand in the gravel ridge resulted in its being less stable; in some instances this sand returned naturally to partially cover the gravel, while at a few locations the gravel was artificially covered with sand for the improved recreational use of the beach during the summer.

This effect of the sand content on the responses and morphologies of otherwise coarse-grained beaches is illustrated indirectly by differences in the resulting beach slopes. Figure 5-6 is a graph of the foreshore slopes of beaches ranging in mean grain sizes from medium sand through pebbles, based on the tabulation of Shepard (1963) for beaches in southern California and McLean and Kirk (1969) for mixed sand-and-gravel beaches in New Zealand. The California beaches show a uniform increase in slope, depending on the mean sediment grain size: the results show that the pebble beaches achieve slopes of 15°. In the extreme, on cobble beaches the slopes can reach 25°, which is close to the angle of repose (approximately 32°), the limit to which non-cohesive grains can usually be piled. The curve in Figure 5-6 from the study of McLean and Kirk (1969) of the New Zealand mixed sand-and-gravel beaches shows a distinctly different pattern. Due to the overall poorer sorting from the addition of sand, these mixed beaches have lower slopes than those measured by Shepard, even for the same median grain size. The wavy pattern of the New Zealand curve is due to the nature of the sources of sediments to those beaches, sources that yield beaches that consist of pebbles with diameters of 4 to 16 mm or of sand having a median diameter of 0.5 mm, or mixtures of the two. When the individual modes of pebbles or sand occur alone, the sediment sorting is good and the resulting beach is steeper; when the modes are mixed, the sorting is poorer so the water percolation is reduced, and the beach slope is lowered. Accordingly, the curve of McLean and Kirk (1969) in Figure 5-6 rises to higher slopes for sands of 0.5 mm and for pebbles, but with the slopes reduced for intermediate grain sizes due to the poorer sorting of the mixed sizes.

The importance of swash infiltration into the beach and how it determines the beach slope has been analyzed by Masseling and Ling Li (2001) in a series of numerical models. It was found that swash infiltration increases the onshore asymmetry in the swash flow, thereby enhancing onshore sediment transport and resulting in relatively steep beach-face gradients. However, this accretionary effect of swash infiltration is only evident when the rate of infiltration is sufficiently large, that is, when the total infiltration volume over a wave cycle exceeds about 2% of the uprush volume. This threshold is attained when the beach sediment grain size is coarser than about 1.5 mm, implying that the correlation between the beach-face slope and sediment size found for sandy beaches is not due to enhanced swash asymmetry caused by swash infiltration. For gravel beaches, however, swash infiltration was concluded to be the dominant factor in controlling the beach-face gradient, with the increased sediment size and permeability being responsible for the steeper beach slopes.

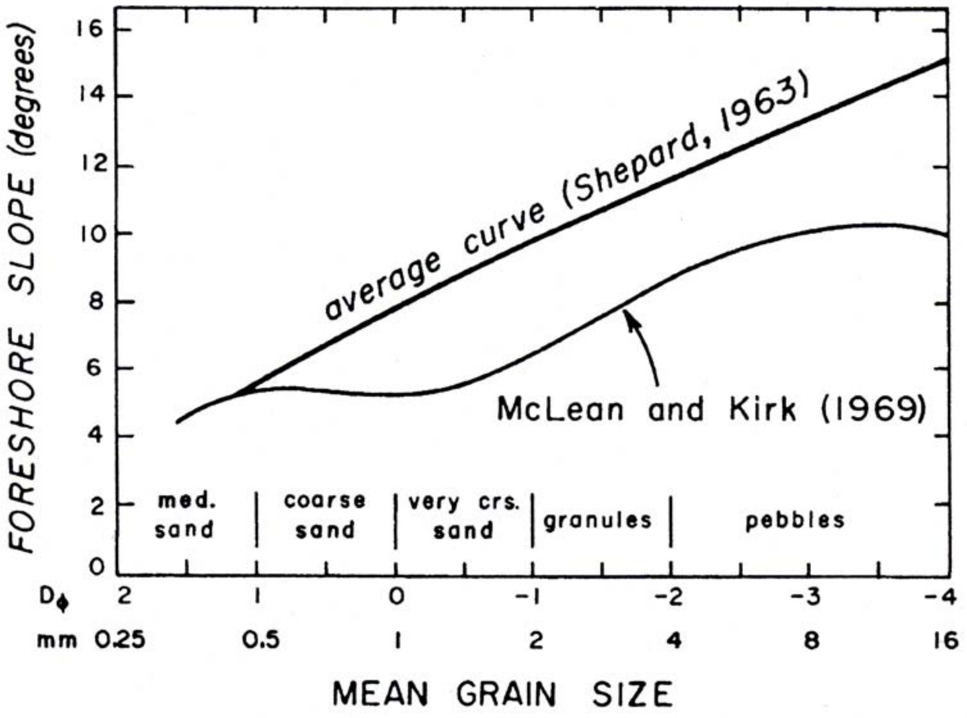


Figure 5-6 The beach-face slope versus mean grain size on sand to coarse-grained beaches, according to the data of Shepard (1963) for California beaches and McLean and Kirk (1969) for the mixed sand-and-gravel beaches of New Zealand. [*from* Komar (1998)]

There has been comparatively little research undertaken on the coarse-grained beaches of New Zealand regarding their morphologic responses to individual storms and seasonal variations in wave conditions. Kirk (1980) reported that on the mixed sand-and-gravel beaches of the Canterbury Bight, there is only a weakly developed seasonal cycle of profile change because storms can occur at any time of the year and their incidence is only slightly higher in the winter (May to August). The largest changes in beach profiles therefore occur at the time of an individual storm. Episodes of erosion produce a concave foreshore with a steep scoured face toward the landward extent of the profile and a low, flatter terrace to seaward. Intervals of time with smaller waves may produce one or more depositional berms within the concave storm-cut profile, so it becomes steeper and convex. This can be seen in the photograph of Figure 5-7 for a Canterbury Bight beach having two distinct elevated berms, with a third narrow berm in the process of being formed by the active surf. The presence of sea-cliff erosion at this site implies that during the most extreme storms this beach can be cut back entirely by the elevated wave swash, with the wide berms seen in the photo having formed during the subsequent prolonged period of reduced wave conditions.

Figure 5-7 A mixed sand-and-gravel beach in the Canterbury Bight north of Oamaru, showing the presence of two elevated berms, fronted by an active zone of wave swash in the process of forming a small third berm.

In spite of this apparent extent of profile changes in response to extreme storms, it has been noted by a number of researchers that the presence of a gravel to cobble beach can impart a degree of protection to backshore properties from the impacts of storms. With this recognition, "cobble berms" or "dynamic revetments" have been artificially constructed to provide shore protection (Ahrens, 1990). The latter name recognizes that they are dynamic, the expectation being that the gravel and cobbles will be moved by the waves, contrasted with conventional "static" riprap revetments constructed of sufficiently large stones to prevent movement. While dynamic revetments obviously provide a lesser degree of protection to a coast than do the conventional static revetments, to a degree their movement represents a natural adaptation of the deposit to the extreme wave conditions, whereas the movement of the large stones in a riprap revetment usually leads to its failure. Such unconventional shore-protection structures have been constructed on the U.S. west coast; the studies by Everts et al. (2002) and Allan and Komar (2002, 2004) reviewed above were undertaken to investigate natural cobble beaches to aid in their design, and then to monitor the constructed dynamic revetment. A short test section was constructed in Ventura, California, to enhance the protection provided by the already present natural cobble beach, and a full-scale cobble berm/dynamic revetment backed by an artificial sand dune was built on the Oregon coast in 1999 to protect a state park. Monitoring of this cobble berm in Oregon, as well as nearby natural cobble beaches, has demonstrated that they can provide substantial protection, reducing the erosion of sea cliffs and sand dunes (Allan and Komar, 2002, 2004).

5.2.4 *The Longshore Transport of Gravel on Mixed Beaches*

When waves break at an angle to the shoreline they can produce a longshore transport of the beach sand and gravel. This sediment movement may continue for 10s of kilometres along the coast, and manifests itself mainly where it is interrupted by the construction of groynes, moles (jetties) or a breakwater. When blocked by such structures, the transported sediment accumulates on the up-drift side and results in an advance of the shoreline, while erosion of the beach and eventually shore-front properties occurs in the down-drift direction due to the loss of beach sediment that had formerly reached that stretch of shore. Because of the importance of this process and at times the severe consequences of blocking the natural longshore movement of beach sediments, it has been the focus of considerable research by coastal scientists and engineers (Komar (1998, Chapter 9). In Section 4 the patterns of the longshore sediment transport in the Hawke's Bay littoral cells were discussed; here we will review in general the formulae that have been developed for the general evaluation of the longshore transport of beach gravel.

A major objective of coastal research has been to derive relationships that can predict the volumes of sediment being transported alongshore by the waves as a function of their heights, periods and breaker angles. The sediment transport rates are commonly correlated with the "longshore component of the wave power", given by:

$$P_\ell = (ECn)_b \sin\alpha_b \cos\alpha_b \tag{5-2}$$

where *E* is the energy of the waves, *Cn* is their group velocity, the rate at which the energy of the waves is propagated so that $(ECn)_b$ is the wave energy flux or power evaluated at the breaker zone. The wave breaker angle relative to the shoreline is denoted by α_b, and inclusion of the $\sin\alpha_b \cos\alpha_b$ angle dependence in equation (5-2) is such that P_ℓ becomes a maximum for a breaker angle of 45° and zero when α_b = 0, which is intuitively reasonable and borne out by field and laboratory data; its inclusion also makes P_ℓ the "longshore component" of $(ECn)_b$, the wave energy flux or power per unit shoreline length. The sediment transport rate can be expressed either as the volume transport rate, Q_ℓ (e.g., cubic metres of sediment transported per second), or as an immersed-weight transport rate, I_ℓ, defined as

$$I_\ell = (\rho_s - \rho) g a' Q_\ell \tag{5-3}$$

where ρ_s and ρ are respectively the sand and water densities, and *a'* is a pore-space factor such that $a'Q_\ell$ is the volume of solid sediment alone, eliminating the pore spaces included in the Q_ℓ volume transport rate (a' is usually taken as 0.6 for relatively well-sorted beach sediments). The correlation then becomes

$$I_\ell = KP_\ell = K(ECn)_b \sin\alpha_b \cos\alpha_b \tag{5-4}$$

where *K* is an empirical proportionality coefficient that needs to be evaluated through measurements of longshore sediment transport rates and how they relate to the wave parameters. The use of I_ℓ rather than Q_ℓ has several advantages, including the fact that I_ℓ accounts for the density of the sediment particles compared with water, and it has the same units as P_ℓ so that equation (5-4) is dimensionally homogeneous with *K* being dimensionless. Therefore, any consistent set of units can be used. Combining equations (5-3) and (5-4) yields

$$Q_s = \frac{K}{(\rho_s - \rho) g a'} (ECn)_b \sin\alpha_b \cos\alpha_b \tag{5-5}$$

for the volume transport rate, for example, the cubic metres of sediment transported alongshore per second.

Equation (5-5) shows the expected dependence of the transport rate on the wave parameters and on the density of the sediment particles, but not directly on the sediment's grain size. The dependence on the grain size will have to enter the relationship through the values of *K*, with the expectation that the coarser the sediment the lower the value of *K* so as to yield a reduced transport rate for gravel compared with sand. Such a dependence is indicated by the field and laboratory measurements of longshore sediment transport rates. Komar (1998, p. 390-393) has reviewed the available field data from sand beaches, and determined that *K* = 0.70 provides the best fit to the data. Within the narrow range of grain sizes found on sand beaches, it could not be clearly established how *K* varies with increasing grain size. Finding this dependence requires an inclusion of measurements obtained on gravel beaches, but unfortunately there is only limited data available.

One study that provides an indication of the reduction in *K* for gravel beaches is that of Nicholls and Wright (1991), undertaken on the shingle beaches of the south coast of England. Two experiments were completed on Hengistbury Long Beach near Bournemouth, with a third on Hurst Castle Spit. Hengistbury Long Beach is a composite beach, with a backshore and foreshore of shingle containing subsidiary sand, and with an offshore sand bed that is exposed at low tide; the median shingle size is about 32 mm. Hurst Castle Spit is formed entirely of shingle, including the offshore zone, with sand being a minor component, so it likely is a pure gravel beach in the classification of Figure 5-1; the median size of its shingle at the time of the experiment undertaken by Nicholls and Wright (1991) was about 16 mm.

The three experiments involved the use of aluminum pebbles as tracers to measure the longshore transport rates of the natural flint shingle (Wright et al., 1978). The aluminum pebbles were cast from natural pebbles so as to have the same sizes and shapes, and the density of aluminum is nearly the same as flint. With this correspondence in size, shape and density, it can be expected that the aluminum pebbles will trace the movements of the natural pebbles, and their magnetic detection permits an evaluation of the rate (velocity) of longshore transport. Each experiment involved a span of time of about two weeks, during which the causative waves were measured visually. With measurements of both the waves and the resulting longshore transport of the shingle, Nicholls and Wright (1991) were able to evaluate the *K* proportionality coefficient in equation (5-5). There are large uncertainties in the results, but in general the *K* values for the transport of the shingle on those English beaches were between 1% and 20% of the *K* = 0.70 value determined for sand beaches. This result is in order-of-magnitude agreement with the analysis results of Brampton and Motyka (1987) where the values of *K* were inferred on the basis of the agreement between numerical models of longshore transport compared with observed shoreline changes. One curious result in the tracer measurements of Nicholls and Wright (1991) is that the values of *K* tended to be higher for Hengistbury Long Beach than for Hurst Castle Spit, that is, *K* was higher for the coarser shingle beach, opposite to the expected result. The experiment on Hurst Castle Spit employed aluminum tracer pebbles having a range of sizes, and it was found that the coarser particles had higher advection rates so that the values of *K* increased with the grain-size fraction, the *K* value for the coarsest fraction being about double that of the finest. This agrees with the observation that Hurst Castle Spit has a natural longshore grading with a down-drift increase in shingle size. These results from the study of Nicholls and Wright (1991), although limited in the number of experiments, are informative in both providing approximate assessments of the reduction in *K* for gravel/shingle beaches compared with sand beaches, and also demonstrate that there can be significant sorting of the gravel particles in a beach according to their differences in sizes and shapes, which can affect the values of *K* so there may not be a simple decrease in *K* with increasing grain size.

The relationships presented above for the longshore sediment transport are based on sound analyses of the processes responsible for that transport, including the generation of a longshore current by waves breaking at an angle to the shoreline and the stresses exerted by the waves that are important to the initiation of movement of the sand or gravel. The details of those process-based derivations, as well as the verification of the relationships, are reviewed by Komar (1998, p. 390-393). An alternative approach is to base the predictive transport relationships purely on empirical correlations between the measured transport and the controlling parameters, the later including both the wave conditions and the beach sediment grain sizes. Noteworthy of the studies that have taken this approach are those of Kamphuis and co-workers, summarized by Kamphuis (1990). Their research included the collection of laboratory data from wave basins and its analysis together with the field data collected by others. The accumulated data were analyzed empirically using dimensionless ratios of the various parameters, rather than through considerations of the actual physical processes responsible for the transport, but the results might still be useful in applications as the relationships more explicitly express dependencies on the controlling parameters. For the field data alone, the dimensional analysis yielded the relationship

$$\frac{Q_\ell}{\left(\rho H_{bs}^3 / T\right)} = 0.0012 S^{1.0} \left(\frac{H_{bs}}{L_\infty}\right)^{-0.5} \left(\frac{H_{bs}}{D_{50}}\right)^{1.0} \sin\alpha_b \cos\alpha_b \tag{5-6}$$

where *T* and L_∞ are respectively the wave period and deep-water wave length, *S* is the beach slope, and D_{50} is the median diameter of the beach sediment (Kamphuis et al., 1986; Kamphuis, 1990). If this dimensionless form of the correlation is reduced to its dimensional equivalent, the basic proportionality becomes

$$Q_s \propto \frac{S}{D_{50}} H^{3.5} \sin\alpha_b \cos\alpha_b$$

in which the dependence on the wave period has dropped out. The empirical establishment of this relationship was based entirely on data from sand beaches, but the hope is that it can be extrapolated to gravel beaches. Only one comparison was made with a gravel beach, and that was in a laboratory wave basin at the Delft Hydraulics Laboratory in the Netherlands, yielding the conclusion that equation (5-6): ". . . slightly over-predicted the gravel sediment transport" (Kamphuis, 1990). Of interest is the proposed dependence on S/D_{50}, the ratio of the beach slope to the sediment's mean grain size. These tend to be off-setting parameters, with the beach slope increasing with the sediment diameter as seen in Figure 5-6, so the reality of this proposed dependence is to some degree uncertain.

The above equations have been reviewed to serve as examples of the types of relationships that are available to serve in calculations of longshore sediment transport rates from the wave conditions, with a dependence as well on the sediment grain sizes. Other relationships are available that see use in applications. It should also be apparent from this review that additional measurements of the transport rates of gravel/shingle on beaches are need to better establish these predictive relationships, to improve the selection of the *K* coefficient in equation (5-5) depending on the beach's sediment size, and to determine the extrapolation of the empirical equation (5-6) from sand to gravel beaches.

5.2.5 The Sorting of Sediment Particles on Coarse-Grained Beaches

As the waves and currents transport the beach sediment, they often produce a sorting of the individual particles according to their contrasting sizes, shapes and densities. This sorting can take place in the cross-shore direction under the variable velocities of the wave swash up the beach face, followed by the seaward return of the backwash. It can also occur in the longshore direction due to the different rates of movement of the particles under the action of the combined waves and longshore current. Grain sorting can take place on sand beaches, but it is more readily apparent on gravel and cobble beaches where the sizes and shapes of the individual particles are easily seen. There has been considerable research undertaken by coastal geologists to document these sorting patterns, and to explain them in terms of the variable velocities of the nearshore waves and currents. Only a brief review of this fairly extensive research can be presented here, sufficient only to indicate the general patterns of grain sorting that might represent a complicating factor in the analyses of mixed sand-and-gravel beaches.

The movement of pebbles and cobbles on beaches is particularly affected by their sizes and shapes; the importance of the size is readily apparent since it governs the threshold velocity of the flowing water required to initiate movement, while the shapes of the particles determine how easily they can be rolled about by the waves and currents. For example, Landon (1930) showed that spherical pebbles are less stable on a beach than are flat, disc-like forms, the spherical pebbles tending to roll down the sloping beach toward the offshore, while the flat particles preferentially remain on the beach. The classic study of the resulting cross-shore sorting of pebbles by sizes and shapes is that of Bluck (1967), who investigated pebble beaches on the south coast of Wales. He found that the beaches can be subdivided into four zones on the basis of differences in pebble shapes and sizes. Furthest shoreward on the gravel ridge is a large-disc zone, dominated by cobble-size discs. Next seaward is a zone composed mainly of imbricated disc-shaped pebbles, the discs being stacked on edge but dipping seaward. This offshore-dipping imbrication is enhanced on beaches where the backwash is weak. Where there is strong backwash or an impermeable layer of fine gravel and sand below the discs, the imbrication may be completely destroyed or even dip landward. Where there is a zone of sandy bottom seaward of the imbricated zone, the pebbles are able to move quickly across the sand and accumulate on its seaward side to form a band consisting of spherical and rod-shaped pebbles. The seaward-most zone consists of a framework of large cobbles containing an in-filling of rod-shaped pebbles. Thus, the beaches studied by Bluck (1967) showed a pronounced cross-shore sorting of pebbles by shape, which he attributed in part to the ability of the backwash of the waves to roll the more spherical grains down the beach face, as had been demonstrated by Landon (1930). Bluck further suggested that the sorting is partly produced during storms when all shapes are thrown forward by the waves, with the discoidal particles being most easily lifted above the sea floor and tending to have lower settling velocities, so they are thrown further up the beach than are the other shapes. This cross-shore pattern of grain sorting of pebble sizes and shapes found on the Welsh beaches by Bluck (1967) is by no means universal, however, as different patterns have been found on other beaches, in part due to different ranges of grain sizes and shapes, and perhaps also due to differences in the dynamics of the wave-swash motions affected by the permeability of the beach [e.g., Orford (1975), Williams and Caldwell (1988), and Sherman (1991)].

Sorting of the grains on a beach can also take place as they are being transported along the length of the shore as part of the total volume of longshore sediment transport reviewed above. It was noted in that review that in the study by Nicholls and Wright (1991), their shingle-tracer experiments on Hurst Castle Spit yielded the seemingly counter-intuitive result that the larger shingle particles are transported alongshore at faster rates than the smaller particles. It turns out that in many respects the longshore sorting of gravel particles according to their different sizes and shapes is more complex than the cross-shore sorting, so much so that one can be mislead by intuition. For example, an already established cross-shore sorting pattern can in turn affect the longshore sorting. If the cross-shore sorting pattern found by Bluck (1967) were to experience a longshore transport, it is likely that the coarser and more spherical to rod-shaped particles would have the greatest longshore transport rates and distances. This is because, as seen above from the study of Bluck (1969), the cross-shore sorting can concentrate those particles in the offshore position of the beach profile where the storm waves break and produce higher longshore transport rates. In contrast, the grains that have been swept to the top of the beach by the wave swash, possible being smaller and more disc-shaped, will be transported alongshore only under the individual wave swash events that reach this elevation on the beach profile, and will not be displaced as far even when they are moved. In the extreme, the particles that have come to reside at the highest elevations of the beach profile may remain stationary for months to years, before once again being transported during a particularly extreme storm event. There is a further complication that involves the potential abrasion of the particles as they are being transported alongshore, reviewed in the following section, such that a documented decrease in particle sizes in the direction of the net longshore sediment transport may in part be the product of their progressive abrasion and size reduction, not necessarily due entirely to hydraulic sorting by particle size and shape.

The patterns of grain sorting on beaches become even more extreme with the addition of sand to an otherwise gravel and cobble beach. In that the sand component is extremely mobile, and may come and go depending on the daily wave conditions, there can be major changes in the overall beach sediment composition and even in its morphology. This is illustrated by the study of Pontee et al. (2004) of the sand and shingle beaches of East Anglia on the North Sea coast of England. It was found that these beaches have high degrees of spatial and temporal variability in their sediment sorting patterns and overall beach morphologies. At a particular beach site remarkable changes were seen to occur from day to day, from a beach composed mainly of gravel during a day with large waves, to one that by the next day has become mainly sand with gravel arranged in shore-parallel bands at the back of the beach. At all sites the gravel was concentrated landward of the mean high water as a beach ridge, and at the low mean water elevation as a lower foreshore step. In between these gravel-dominated zones, the beach face was normally characterized by an intimate mixture of sand and gravel.

This variability can also be seen on New Zealand beaches. For example, Kirk (1980, Table 1) noted the extreme composition changes in a beach near Timaru between 1967 and 1977; in 1967 there were nearly equal proportions of pebbles (48.3%) and sand (41.4%) with granules forming 10.3%, while in 1977 there were more pebbles (73.0%) and much less sand (18.0%). This Timaru beach was one of the sites identified by Jennings and Shulmeister (2002) as being a composite beach in their classification system, summarized here in Figure 5-1, likely observed during one of the rare times when the sand locally exceeded the content of pebbles on a Canterbury beach. This local accumulation of sand at Timaru likely involved the coarser sand that is stable on the beach, having arrived by its longshore movement under the action of the wave swash, not being the fine sand that tends to remain in the offshore as documented by Kirk (1980). A still greater degree of variation can be seen on the beaches of Hawke’s Bay, with significant ranges in the proportions of sand versus gravel and in the resulting effect on the beach morphology. This occurs primarily on the beaches in close proximity to the headlands, and is readily seen in the variable contents of the sand on the beaches of Tangoio and Westshore, respectively at the north and south ends of the Bay View Littoral Cell. The sand tends to accumulate at the ends of the littoral cells in variable quantities, in large part due to the changing directions of the waves reaching this shore. With waves arriving from the southeast, the beach sediment is transported along the shore to the north, and in some circumstances this could involve the preferential transport of the sand component so it accumulates on the beach at Tangoio, having been blocked by that headland; in multiple visits to Tangoio, I have seen the beach face range from effectively 100% pea-size gravel to 100% coarse sand with the gravel then confined to the back-shore berm. In contrast, with waves arriving from the northeast, the sand could be preferentially transported alongshore to the south, accumulating at Westshore. Another important factor is the sheltering of these beaches by the headlands, and in the case of Westshore, also by the Port’s breakwater, such that once the sand is transported into those beaches it could remain there for long periods of time.

The amount of sand that accumulates at Westshore commonly reaches such an extent that it can be classified as a type (c) composite beach in Figure 5-1 from the classification of Jennings and Shulmeister (2002), although the sand accumulation at the toe of the gravel deposit is usually intertidal, visible only at low tides. Similarly at Tangoio, from one visit to the next the beach can be either a category (a) pure coarse-grained beach, (b) a mixed sand-and-gravel beach, or a category (c) composite beach with sand dominant on the beach face. This illustrates that the processes of grain sorting and beach variability can in some instances be so extreme that the beaches may shift categories in the classification of Jennings and Shulmeister (2002), Figure 5-1. On coasts where there are cross-shore movements of sand as well as alongshore as discussed here, it might not be unusual to have a category (a) pure gravel beach at the time of a storm that moves the sand into the offshore, becoming a category (b) mixed sand-and-gravel beach with a return of some sand a few days after the storm, and perhaps even achieving a category (c) composite beach status with the return of still more sand; this appears to be the case for the East Anglia, UK, beaches investigated by Pontee et al. (2004). It is also evident that this range of beach categories is most likely to be found in proximity to headlands, in part because the headland can provide partial sheltering from the waves that permits a greater accumulation of sand, or perhaps because the headland temporarily blocks the longshore movement of the sand.

5.2.6 Particle Abrasion

Sediment particles can be abraded as they undergo transport by waves and currents, progressively being reduced in size and with their shapes altered. This is most readily seen by the change in the "angularity" of the particle, in effect the sharpness of its edges that are worn off by abrasion. There may also be a change in the overall form of the particle, its "sphericity", defined by geologists as a measure of the degree to which the particle's shape departs from a perfect sphere. As seen above, differences in particle shapes in being defined as discs, rods or spheres can also be important, being in part the product of the history of abrasion but more apt to be inherited from the original fabric of the rock whose erosion yielded the particles.

Generally, gravel is more readily abraded than sand, and can more rapidly achieve a high degree of rounding. The rapid abrasion of pebbles was shown, for example, by the study of Grogan (1945) on a Lake Superior beach. He found that rhyolite (volcanic) pebbles are progressively rounded as they move alongshore away from their source. There is an outcrop of the parent rock at one end of a long stretch of beach that supplies angular block-shaped pebbles to the beach, with this shape being controlled by the jointing of the rhyolite. As the pebbles moved away from that source, carried alongshore by the waves, they progressively lost their sharp edges and eventually developed a high degree of roundness. The rounding initially progressed rapidly as the rough edges of the blocks were worn away, but with a subsequent decrease in the rate of additional rounding at greater distances from the source. Grogan (1945) found that the sphericity of the pebbles also increased in the direction of transport, but not markedly so. Therefore, there was relatively little modification of the overall shapes of the pebbles as their edges were rounded. This was further established by Sames (1966) who compared beach and river pebbles on the coast of Japan, composed of resistant chert and quartzite. He could find no tendency for the beach pebbles to change their overall shapes and sphericity; they instead retained the flatness inherited from their bedrock source. However, in a similar study of pebbles in the rivers and beaches of Tahiti, Dobkins and Folk (1970) concluded that abrasion yields more disc-like forms as well as higher degrees of roundness. It was found that the size of pebbles that achieved the most nearly disc-like shape depends on the wave energy and character of the beach surface. For each grain size there is an optimum intensity of wave action that best produces a sliding motion, and this is the wave intensity that develops the best discs. Any pebbles that are larger tend to remain stationary and are not abraded by sliding to form discs, while smaller pebbles are rolled and tossed randomly by the waves and thus are abraded on all sides so their shapes are not altered.

Some of the most important studies of gravel abrasion and rounding have been conducted in New Zealand. Most of this research focused on pebbles composed of greywacke, derived from the erosion of ancient rock formations in the Southern Alps of the South Island and in the uplands backing the Hawke's Bay region of the North Island. Erosion of the rocks yields a wide range of particles sizes, with the coarse fractions ranging from pebbles through cobbles, found in the rivers that drain to the east and contribute this material to form the mixed sand-and-gravel beaches of the Canterbury Bight and Hawke's Bay. Of importance, the rates of abrasion of these greywacke pebbles and cobbles on those beaches may be sufficiently high that it represents a significant loss of gravel from the littoral cells. This is indicated by the sediment budgets developed for those cells; in the Canterbury Bight the large rivers and extensive sea-cliff erosion contribute large quantities of greywacke pebbles and cobbles to the beaches, which apparently are then consumed by abrasion rather than resulting in a comparable increase in beach volume together with a net advance in the shoreline. The sediment budgets for the Hawke’s Bay beaches will be examined in Section 7, where it will be seen that gravel abrasion represents a significant loss of beach sediment.

Foremost in the New Zealand studies of beach gravel abrasion was that of Marshall (1927), of particular interest in that his experiments involved sediments from the Hawke's Bay beaches. He undertook a systematic series of laboratory experiments that included naturally graded gravel as well as artificial combinations of sieve fractions. All experiments were with naturally worn shingle from the beach at Napier, greywacke that is very uniform in character and composition, that had already achieved a fairly high degree of rounding by having been on the beach for a long period of time. In analyzing the results of his experiments, Marshall (1927) distinguished between several forms of gravel "wearing", including abrasion (the effect of pebbles rubbing against one another), impact (definite blows of relatively large pebbles on small grains), and grinding (the crushing of small grains, mainly sand, by the continued contact and pressure of pebbles of relatively large size). The experiments were conducted with a Deval Machine, an iron cylinder that is 34 cm long and 20 cm diameter, inclined at a 30-degree angle. In each experiment 5,000 grams of gravel were used, with two liters of water added. The average rate of rotation was 38 revolutions per minute. The pebbles had a fall of several centimetres every half revolution or 76 times per minute, and slid for a distance of about 29 metres every minute.

With the distribution of grain sizes actually found naturally on the beach, the proportions of the different size fractions remained nearly the same throughout the experiments as they were being abraded. In contrast, with an artificially uniform distribution of grain sizes the finer size fractions were reduced at a higher rate, leading Marshall (1927) to conclude: "... when a sample is not graded in proportions approximate to its dominant nature and to the conditions of abrasion, the wearing action at once tends to rectify those incongruities that exist." With a bimodal distribution, the loss of the fine material was considerably greater, amounting to nearly 10% in 24 hours. This led to a detailed series of experiments which established that the loss was due to impacts of the larger particles on the smaller, crushing them. This conclusion was reached by actually counting the numbers of pebbles in each size fraction and documenting their decrease with time in the experiments. Initially this crushing would have yielded sand-size grains, but another series of experiments demonstrated that the sand is very quickly reduced by grinding to silt and clay (Marshall, 1927, 1929). As a result, sand was seldom a significant product of the wearing process. It was further shown that the presence of material of intermediate grades tends to protect the small impactees from the larger pebbles, the impactors, so their wearing loss is much less than occurs with distinctly bimodal distributions of sizes. There was little effect on the shapes of the pebbles; they did become rounder, and the flat pebbles from the beach were clearly worn on their edges. Although the change was not great, Marshall (1927) concluded that the movement of the pebbles during the experiments involved a greater amount of throw and a relatively smaller amount of sliding compared with the natural conditions on the beach. In his second paper, Marshall (1929) applied the results of these laboratory experiments to the distributions of sizes and shapes of greywacke pebbles found on the Hawke's Bay beaches; the results of those analyses will be discussed later in this Section.

The recently completed Ph.D. thesis of Hemmingsen (2004) at the University of Canterbury in many respects represents a continuation of the experiments undertaken by Marshall (1927), with application mainly to the Canterbury Bight beaches. The term "reduction" is used, comparable to Marshall's (1927) "wearing", to include grain abrasion, impact and grinding, but also to include the decrease in particle size produced by chemical processes that can operate concurrently with those physical processes. In particular, it was shown by Hemmingsen (2004) in her experiments that the presence of a weathering rind on a gravel particle results in its more rapid reduction by the physical processes. Her series of tumbler experiments, undertaken in a concrete mixer, included beach sediments collected from multiple sites along the length of the Canterbury Bight shore, and also from Hawke's Bay. It was found that even though the gravel from the sites always consisted of greywacke, and were always derived from the Torlesse Supergroup of rocks, the experiments demonstrated distinct differences in their degrees of resistance to "reduction"; of interest, in the series, the gravel from the Hawke's Bay beach was the most resistant.

As well as yielding results on the effects of gravel size mixtures as a control on the rates of abrasion or "reduction" of the different size fractions, the experiments of Marshall (1927, 1929) and Hemmingsen (2004) yielded data on the overall rates of size reduction which can be used in applications to determine the losses of the greywacke gravel from the beaches contained within littoral cells; for example, Gibb (2003) and Hemmingsen (2004) have undertaken such analyses as part of sediment budgets developed respectively for the Hawke's Bay and Canterbury Bight beaches. However, questions remain as to the accuracy of those rates based on laboratory experiments using tumblers, the iron cylinder employed by Marshall (1927) and the cement mixer of Hemmingsen (2004). A basic question is how well those experiments simulate the movement of gravel under the oscillatory swash motions of waves on a beach. My impression is that while such experiments correctly yield conclusions regarding the effects of sediment-size mixing, etc., on the relative rates of "wearing" or "reduction" of the different size fractions, the actual magnitudes of the size reductions found in the experiments are probably not correct for natural beaches, with the rates on the natural beaches likely being lower than implied by the experimental results. This is suggested by the results of similar experiments undertaken with the highly-resistant flint shingle of English beaches, with the experiments yielding significant rates of abrasion which imply that the shingle would exist on those beaches for only on the order of a century, whereas the geologic evidence is that they persist with relatively little loss for thousands of years, in some cases having reached the beaches with the rise in sea level at the end of the Ice Age.

Experiments on grain abrasion have been conducted *in situ* on natural beaches, but this is generally difficult due to the slowness of the process and the necessity of tracking individual gravel particles over an extended period of time in order to measure their resulting size and weight reductions. One such study is that of Matthews (1983), undertaken on the beach within Palliser Bay east of Wellington. The natural beach sediments there are derived from the adjacent highlands of Mesozoic greywacke, argillite and some basic volcanic rocks. There is a progressive west-to-east decrease in wave energies along the shore, with the waves generally arriving from the southeast to produce a westward longshore sediment transport. At Ocean Beach at the west end of the bay the beach was found by Matthews (1983) to consist of 22.5% pebbles, 27.7% granules, and 49.5% sand. At Whangainmoana toward the east end the mixture was 9.6-14.0% pebbles, 26.6-52.8% granules and 33.1-63.8% sand. At Washpool on the bounding headland the beach was 36.7% pebbles, 45.8% granules and 17.3% sand. The roundness of the beach and river pebbles was estimated using a visual comparison scale, and it was found that there is not a significant difference in roundness between the several pebble-size fractions, while the granules are mostly less rounded than the pebbles at the same site. The pebbles show a gradual increase in roundness towards the center of the Bay, reflecting the northwest transport of gravel by the prevailing southerly waves. Matthews (1983) conducted tracer experiments using material not naturally present in the Palliser Bay beach, introducing a limestone gravel of small to large pebbles having grains that initially were very angular as they were the product of a crushing plant; 74 tons were introduced at Ocean Beach, and 22 tons each at Whangainmoana and Washpool. The subsequent development of roundness in the different pebble-size fractions was essentially the same, so Matthews (1983) examined the development of the average roundness of all pebbles. The rate of rounding was initially very rapid, but approached nearly constant values after about 5 months. The most rapid rounding occurred at Ocean Beach, also leading to the highest degree of rounding, clearly a function of the wave energy which is greatest at that western end of the Bay. The percentages of freshly broken pebbles ranged from 3.9 to 4.7%, but did not reflect the wave energy levels at the three beach sites.

Matthews (1983) also undertook laboratory experiments using a gemstone tumbler, comparing the limestone and greywacke pebbles. The greywacke proved to be between 5 and 8 times more resistant to attrition than the angular limestone, depending to some extent on the initial angularity. The tumbler results were used primarily to investigate the roundness versus weight loss relationships. The results showed that a large weight loss is required to produce well-rounded gravel. The initial rapid development of rounding involved little loss of weight because it was accomplished by the removal of the sharp corners and edges, but the subsequent more gradual increase in roundness required much greater losses of weight. Applying the results to Palliser Bay, Matthews (1983) made estimates of the times required for the observed grain rounding. The roundness of the river pebbles, the source of the natural beach gravel, was only 0.40-0.45 according to the visual scale, so they are essentially unrounded. At Washpool where the average roundness was 0.63, it was concluded that it would take between 3.5 and 7 years to achieve that degree of rounding.

This research undertaken by the several investigators has demonstrated that the abrasion ("wearing" or "reduction") of gravel particles on beaches can be significant, with the abrasion rates of greywacke being intermediate between the incredibly slow rates of resistant flint shingle and the fairly rapid abrasion of the limestone pebbles investigated by Matthews (1983). While the precise rates of size reduction and ultimate losses of greywacke pebbles from beaches remain uncertain, it is clear that they are sufficiently rapid to be important in assessments of sediment budgets, as for the Canterbury Bight and Hawke's Bay littoral cells, and can affect the longshore decrease in pebble sizes from their river or sea-cliff sources, so that the observed longshore grain-size variations may only in part be due to hydraulic sorting.

5.2.7 The Beach Responses to Long-Term Changes in the Relative Sea Level

The establishment of hazard zones for properties backing beaches typically consider time frames of 50 to 100 years, based on the expected lives of homes and other infrastructure that are to be constructed on those properties (Section 7). With that extent of projection into the future, there is the potential that a global rise in sea level, or the relative change in sea level at that site which also includes an increase or decrease in the elevation of the land, may have an impact on those properties. The average annual rate of global sea-level rise during the 20th century was about 2 mm/year, which means that in 100 years the sea rose by about 20 centimetres. It is not unusual for the relative sea-level increase to have been on the order of 50 to 100 centimetres on coasts that have experienced subsidence. Those increases in the level of the sea relative to the land are greatly amplified when viewed as the potential horizontal landward shift in the shoreline across the backshore properties, an amplification that depends on the average slope of the land. One can roughly expect an amplification on the order of 100, so that the 20-centimetre global rise in sea level during the 20th century potentially resulted in a 20 cm x 100 = 2000 centimetres = 20 metres landward shoreline migration, with the loss of shorefront properties. The higher relative rates of sea level rise of 50 to 100 centimetres during the 20th century, areas of land subsidence, would correspondingly have produced some 50 to 100 metres of shoreline retreat and property losses. These examples are offered only as order-of-magnitude assessments to illustrate that the seemingly slow rise in sea level during the span of 50 to 100 years can have a significant impact on coastal properties, and therefore needs to be included in the establishment of hazard zones. However, when one actually develops hazard zones for a specific stretch of shore, such analyses also need to include the budget of littoral sediments to determine the extent to which the sources of those sediments might offset the potential impact of sea-level rise if the sources are sufficient to produce a net accretion of the beach; on the other hand, along shorelines that are naturally retreating because the losses of beach sediments are greater than the volumes contributed by the sources, that erosion is compounded by the long-term rise in sea level. Furthermore, it is predicted that due to global warming, during the 21st century the rise in sea level will take place at substantially higher rates than during the 20th century. As reviewed in Section 4, a range of potential increases in sea levels has been offered, reflecting the uncertainties in the estimates, but if one accepts the "most likely" scenario (Figure 4-5) then on average the future shoreline recession rates will increase substantially, and obviously needs to be accounted for in the establishment of hazard zones.

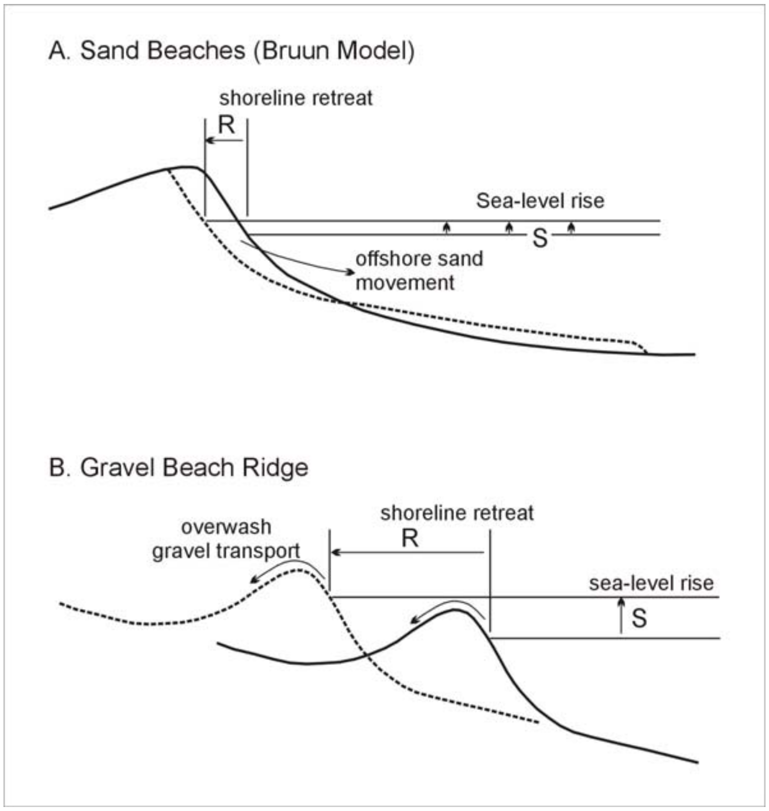


Figure 5-8 A. The model of Bruun (1962) for the retreat of a sand beach due to a rise in sea level, the response involving the erosion of the beach face and transport of that sand to the immediate offshore where it is deposited so the sea floor rises at the same rate as the water; B. The landward migration of a gravel beach ridge in response to a rise in sea level, with the gravel carried inland by overwash events.

With this concern about the effects of increasing sea levels on the potential retreat of the shoreline, analyses by coastal scientists and engineers have been directed toward the derivation and testing of models that can be used in the prediction of the future erosion and shifts in shorelines. A review of those models can be found in Komar et al. (1991) and Komar (1998, p. 121-129). Best known of the models developed to predict the retreat of the shoreline due to a rise in the mean level of the sea is that of Bruun (1962, 1988), a model that is widely used in coastal management applications. As depicted in Figure 5-8A above, Bruun's model simply involves the upward and landward translation of the equilibrium beach profile to match the rise in sea level, while conserving the sand volume. The analysis is two-dimensional and assumes: (1) the upper beach is eroded due to the landward translation of the profile; (2) the material eroded from the upper beach is transported immediately offshore and deposited, such that the volume eroded is equal to the volume deposited; and (3) the rise in the nearshore bottom as a result of this deposition is equal to the rise in sea level, thus maintaining a constant water depth in the shallow offshore. Following these assumptions, Bruun (1962) derived a relationship for the shoreline retreat rate, *R*, due to an increase in sea level, S; the simplified version of his more detailed relationship is

$$R = \frac{1}{\tan\theta} S \qquad (5\text{-}7)$$

where $\tan\theta$ is the average slope over which the beach migrates landward, taken to include the backshore, the beach itself, and some of the shallow offshore where the eroded sediment is assumed to accumulate. The factor $1/\tan\theta$ in this relationship is in effect the "amplification factor" between *R* and *S* used above to illustrate the order-of-magnitude impacts of the global rise in sea level during the 20th century. In that $\tan\theta \approx 0.01$ to 0.02 is the range of average slopes for many coastal sites having sand beaches, equation (5-7) yields $R = 50S$ to $100S$, proportionalities that are commonly used as a "rule of thumb" to calculate expected shoreline retreat rates or distances *R* from a rise in sea level *S*.

Bruun’s (1962) model in Figure 5-8A, with its assumption of the erosion of the beach and offshore transport and deposition of the eroded sediment, mainly depicts the response of a sand beach to a rise in sea level. The more common response of a gravel beach ridge is shown in Figure 5-8B, wherein the gravel ridge migrates inland and is shifted upward in response to the rise in the water level, the migration being accomplished by the gravel being carried landward over the crest of the ridge during overwash storm events, the ridge migrating landward until it achieves an elevation that prevents further overtopping. Although the responses of the sand and gravel beaches are therefore fundamentally different, Figure 5-8, the underlying geometry turns out to be basically the same, so that equation (5-7) can be applied to estimate the rate or distance of inland retreat of a gravel beach ridge in response to a rise in sea level. Dean and Maumeyer (1983) have developed a Bruun-type model that considers the landward migration of an entire barrier island, having a lagoon on its landward side, with its migration brought about by overwash storm events carrying sand from the ocean beach into the lagoon. In that the responses of gravel barriers or ridges are comparable to those composed of sand, their relationships are again applicable.

The elevation of the top of the beach ridge is controlled by occurrences of extreme total water levels during storms, as these result in the overtopping of the ridge, carrying gravel eroded from the beach side, with its deposition on top of and on the landward side of the ridge. In the short term the total water level controlling the migration is the sum of the astronomical tide, the magnitude of a storm surge or other processes that elevate the measured tide above the predicted, and the runup level of the swash of the storm waves on the beach. It is apparent that with a longer term rise in sea level, this total-water elevation will also progressively increase with the addition of this rise in sea level, and it is this additional component that in large part determines the landward rate of migration of the beach ridge, and the loss of developable property backing the beach.

Compared with the extensive research and models that have been developed to analyze the erosion produced by a rise in sea level, very little attention has been given to what happens to the beaches and shoreline positions with a reduction in the level of the sea, or as happened at the time of the 1931 Hawke's Bay earthquake when the land abruptly rises relative to the level of the ocean. This near absence of research is in large part a reflection of the view that this change does not represent a hazard to people living on the coast, as it generally results in a gain in the land over the ocean, not causing a loss of coastal properties. Therefore, such an occurrence is not generally included in coastal hazard assessments. The main consideration of the potential coastal changes due to a lowering of the relative sea level might be undertaken by geologists who are interested in the long-term evolution of the coast, irrespective of whether or not the change represents a hazard. In specific cases such as following the Hawke's Bay earthquake, it is of interest to better understand the subsequent changes in the coast that have included rearrangements of the beach by the gravel either moving in the cross-shore direction or alongshore, perhaps due to subtle shifts in the wave refraction patterns produced by even a small alteration in the offshore water depths. This was the focus of the thesis research of Single (1985), which was reviewed in Section 2 as part of an examination of the impacts of that major tectonic event on the Hawke's Bay coast. In particular, he wanted to determine the degree to which the present beach morphology and its erosion are still a lingering response to the vertical tectonic movement of the land that occurred during the earthquake. He concluded that the beach response has been markedly different for various sections of the coast, depending on the amount of uplift and the differing beach morphologies found in each section. This illustrates the fact that the prediction of the changes due to a drop in sea level is more complex than for a rise in sea level, as is the development of predictive models. There is no simple model available for the beach morphology changes and shifts in shoreline positions to account for a drop in the relative sea level, analogous to the Bruun (1962) model and his equation (5-7) for a rise in sea level. Instead, the analysis approach will more likely have to take the form of applying numerical beach-profile models that account for the processes of waves and tides, the cross-shore sediment transport, and including either an abrupt or prolonged downward shift in relative sea level, with the model hopefully yielding a depiction of how the morphology of the beach would evolve. Although 75 years have passed since the 1931 earthquake, undertaking such analyses would still be relevant to the Hawke's Bay beaches, particularly those in the central Bay View Littoral Cell where the gravel beach ridge was elevated by on the order of 2 metres. In some places that ridge is slowly being eroded at times of extreme swash runup levels of major storms, with the formation of a scarp at the back of the active beach. Of importance is how far into the future will this erosion reach the extent that storm waves will once again be able to overtop the lowered ridge and flow into backshore properties, causing their inundation and erosion. This prospect will be considered again in Section 7 where we examine these stretches of coast and their potential hazards.

5.3 THE BEACHES OF HAWKE'S BAY

There has been comparatively little research undertaken by coastal scientists and engineers specifically on the Hawke's Bay beaches. This was reason that the above review of mixed sand-and-gravel beaches was undertaken, to serve as a guide in evaluations of swash runup elevations, the longshore sediment transport, and the morphodynamic responses of the beaches to major storms. Such assessments can be important in management applications, including the development of sediment budgets and the establishment of hazard zones (Section 7). Most of the effort directed toward the beaches of Hawke's Bay has been through the establishment of monitoring programs that mainly have involved the surveying of beach profiles at intervals along the shore. For the most part those surveys have been obtained on an annual basis and applied to determinations of long-term shifts in shoreline positions, either a net erosion or accretion, which in turn have served as the foundation for the establishment of hazard zones for the safer development of this coast.

The objective of this section is to review the research that has been undertaken on the Hawke's Bay beaches to investigate their sediment compositions and morphologies. That review is followed by a summary of the monitoring program, examining its contributions to documenting changes in the shoreline positions.

5.3.1 Research Investigations of Hawke's Bay Beach Sediments and Morphodynamics

The primary research investigations into the sediments of the Hawke's Bay beaches were those undertaken by Marshall (1927, 1929) and Smith (1968). As reviewed above, Marshall's 1927 paper focused on his tumbler experiments to measure the abrasion ("wearing") rates of gravel collected from the beach at Napier, deriving data for the overall rates of abrasion as well as the effects of mixtures of sizes on their relative rates of size reduction. Those experimental results were applied by Marshall in his 1929 paper to an investigation of the gravel found on the Hawke's Bay beaches, their size and shape changes after having been contributed to the beach by the rivers and erosion of Cape Kidnappers, during their progressive longshore transport to the north by the waves. There was also an extended consideration of the sand and silt components found in the beaches and shallow offshore, its origin as a product of gravel abrasion and the processes that control the ranges of grain sizes and areas of accumulation within the Hawke's Bay littoral cells.

Marshall (1927, Table 4) presented results based on his "wearing" experiments of the expected numbers of days required to reduce the greywacke pebbles to the next smaller size fraction, and the days to reduce the pebble sizes by half. Both assessments show that the smaller the pebble size the longer the time required to reduce its size. For example, the tabulation shows that a pebble 44 mm in diameter will lose as much by abrasion during one yard (0.9 metre) of movement along the shore as a 4.7 mm diameter pebble loses in moving 20,000 yards (18,000 metres) or nearly 12 miles (19 kilometres). Most of Marshall's 1927 paper is a documentation of the distributions of beach sediment grain sizes along the Hawke's Bay shore, with an attempt to analyze their alongcoast variations in both sizes and shapes in the light of his laboratory experiments. Marshall observed in his field studies that after the gravel reaches the beach from the rivers, the larger sizes tend to be thrown high on the beach profile, to a level where they no longer experience transport except during rare major storms, while the smallest pebbles are eliminated through impacts by the medium-sized pebbles. The overall result is the production of a more-evenly graded gravel, one having a narrower range of grain sizes. Marshall's (1929) field study primarily included the collection of gravel samples at several sites spanning the length of Hawke's Bay, and also from 1 mile (1.6 kilometre) upriver from the mouth of the Tukituki River. Examinations of the grain-size distributions and degrees of particle rounding in the different size fractions demonstrated that in the river sample all of the larger pebbles had already been well rounded during transport down the river, those in the 12.7-6.3 mm size range were for the most part rounded, but those in the 6.3-3.4 mm grade were for the most part still angular. On the beach at the mouth of the river the larger pebbles are flatter than found in the river, the 6.3-3.4 mm grade being more rounded than in the river, and there is some degree of rounding of the 3.4-2.0 mm size fraction. This change in roundness of the intermediate pebble sizes corresponds to what Marshall (1927) had found in his tumbler experiments.

Marshall's (1929) beach sediment samples along the shores of the Haumoana and Bay View Littoral Cells documented the northward decrease in median grain sizes and ranges in sizes of the pebbles, and also showed the occurrence of subtle shifts in particle shapes. At Bay View well to the north of the potential sediment sources the average grade had been reduced to 19.0 to 4.5 mm, and particles in the 12.7-6.3 mm grade were found to be flatter than in samples to the south, but with the smaller stones in this grade clearly in the process of losing their flattened shapes due to impacts and breakage by larger stones. Pebbles in the grade 6.3-3.4 mm were more spherical as they had been formed by the impact breakage of larger pebbles. The grains in the 3.4-2.0 mm size fraction were interpreted as also having been formed by impact breakage, recently so as they still retained their angularity. At Tangoio the grade 3.4-2.0 mm is dominant and the few pebbles found there that are larger than 6 mm had been flattened and well rounded. From these patterns of size reduction and changes in shapes of the beach gravel documented by Marshall (1929), a picture emerged of the progressive abrasion ("wearing") and loss of gravel on the beaches in the Haumoana and Bay View Littoral Cells.

Marshall's (1929) analyses of the gravel on Mohaka Beach within the Wairoa Littoral Cell on the northern half of Hawke's Bay provided an even clearer picture of the longshore patterns of wearing and changing grain sizes, occurring over a shorter alongshore distance from the river source. That beach is fed at its western end with greywacke gravel supplied in large quantities by the Mohaka River. Table 6 in Marshall's paper gives the alongshore variations in gravel sizes at seven sites extending from the river mouth to 35 miles (56 km) north at Waitaniwha near the Mahia Peninsula. A greater alongshore degree of size reduction was found than in the southern littoral cells, which Marshall attributed to the slower rate of northward gravel movement by the waves so the gravel located at a certain longshore distance from its river source had been on the beach for a longer period of time than those in the southerly littoral cells at the same longshore distance, thereby having attained a higher degree of rounding.

Marshall (1929) also devoted considerable attention to the sand and silt found in the Hawke's Bay beaches and in the offshore deposits. He initiated this study by analyzing the grain sizes of sand on beaches throughout New Zealand, and found that beaches exposed to moderate to high wave energies had their maximum percentages in the 0.25-0.17 mm size fraction, while there is very little sand smaller than 0.15 mm and practically nothing finer than 0.074 mm. This is typical of sand beaches throughout the world (Komar, 1998). Marshall (1929) then collected sand samples offshore from Napier, from just south of the Port's breakwater to beyond the Ahuriri moles. The depths of the samples ranged from 18 to 37 feet (5.5 to 11 metres). All samples showed remarkably similar grain-size distributions, distinguished by their narrow grading (being well sorted), with the 0.149-0.074 mm fraction dominant, and with considerable material finer than 0.074 mm. Marshall (1929) concluded: "These sands are sharply graded and are quite distinct from all the samples of beach sand by their fine nature." Marshall also collected a series of samples along profiles extending offshore from the municipal baths on the Marine Parade, and from the outer end of the breakwater. The sand sizes normally found on beaches (0.250-0.177 mm) constituted only a small percentage of these offshore sands, while the 0.149-0.074 mm size generally rare on beaches increased toward the offshore until it formed 80% of the samples. Marshall found an interesting variation in particle rounding between the series of size fractions within the samples: all material coarser than 3.4 mm was well rounded, that between 3.4 and 0.84 mm was mostly angular, the small amount of sand between 0.84 and 0.42 mm was quite angular, from 0.42 to 0.25 mm the sand was fairly well rounded, and all sizes finer than 0.25 mm consisted of well rounded grains. Marshall (1929) concluded:

> It is at once apparent that it is precisely the condition that resulted from the experiments that were made in connection with gravel abrasion. The rounded form of the coarser matter is due to simple abrasion. The angular form of the intermediate grades is the result of impact which has been shown to act far more rapidly than abrasion with particles of these sizes. The rounded form of the smaller sizes is caused by grinding which supersedes impact when the grains are small though the action seems to decrease rather in speed when they have been reduced to a smaller size than 0.149 mm.

From these detailed investigations of both the gravel and sand within the Hawke's Bay littoral cells, both along the lengths of the beaches and into the shallow-water offshore, Marshall (1929) developed a consistent model for the abrasion ("wearing") and losses of gravel from the beaches, interpreted in light of the results of his laboratory tumbler experiments: sand is initially created by the impacts and crushing of small pebbles by the larger pebbles, yielding sand that initially is sufficiently coarse to remain on the beach, but with its continued crushing this coarser sand is reduced to silt-size particles that are carried offshore and deposited in deeper water.

The thesis research of Smith (1968) at the University of Canterbury had many of the same objectives as the Marshall (1927) study, including a determination of how the sediment sources and the variation in wave energy along the shore are reflected in the beach sediment characteristics, their grain-size distributions and particle shapes. Smith expanded those aspects of the research by collecting samples and surveying beach profiles at a greater number of sites along the Hawke's Bay shore than had Marshall (1929), and attempted to correlate the variations in beach sediment grain sizes with the profile morphologies. Smith also devoted more consideration to the sources of the beach gravel.

Marshall (1927) and Smith (1968) held different opinions as to the sources of the beach gravel on the Hawke’s Bay beaches. Marshall (1927, p. 334) maintained: "For the greater part the beach is fed with the gravel that is supplied by the Tukituki River; but two miles from this point there is an additional feed from the Ngaruroro River, and to a far less extent from the Tutaekuri River on the north side of the Ahuriri Bluff. A negligible amount is supplied by the Esk River." He was not diverted from this opinion by his comparisons between the sizes and shapes of the river gravel versus the beach gravel, concluding instead that they are consistent with results from his tumbler experiments. In contrast, Smith (1968) concluded that the rivers are not a significant source of beach gravel, a conclusion based on his assessment that only at times of floods are the rivers capable of transporting pebble-size particles as bedload and that on a per annum basis this contribution would be small. He instead suggested that the erosion of Cape Kidnappers is the primary source of the beach gravel. Smith (1968) further maintained that the construction in 1887-1890 of the Port's breakwater at Bluff Hill (Scinde Island) cut off the supply of gravel to the "North Beach" (the Bay View Littoral Cell); however, this opinion is offered as an *a priori* conclusion without providing any analyses or a discussion to justify this belief. Even today the relative importance of the rivers and the erosion of Cape Kidnappers as sources of gravel and sand to the beach to a degree remain uncertain, as do the impacts of the Port's breakwater; these topics will be reviewed at length in Sections 6 and 7 of this report.

A primary focus of Smith's (1968) study was his collection and analysis of beach sediment samples along the lengths of the Haumoana and Bay View Littoral Cells. He collected samples at 19 sites along the shore, and surveyed beach profiles at each. In total five survey sets were obtained during a period of two years. In the first sampling series, separate gravel samples were collected from several points along each beach profile, but in subsequent surveys only one sample was collected per profile from between the mid- and low-tide positions. No samples were collected offshore from the surf zone. Visual observations of wave heights, periods and breaker angles were also made at each beach study site during the sampling periods.

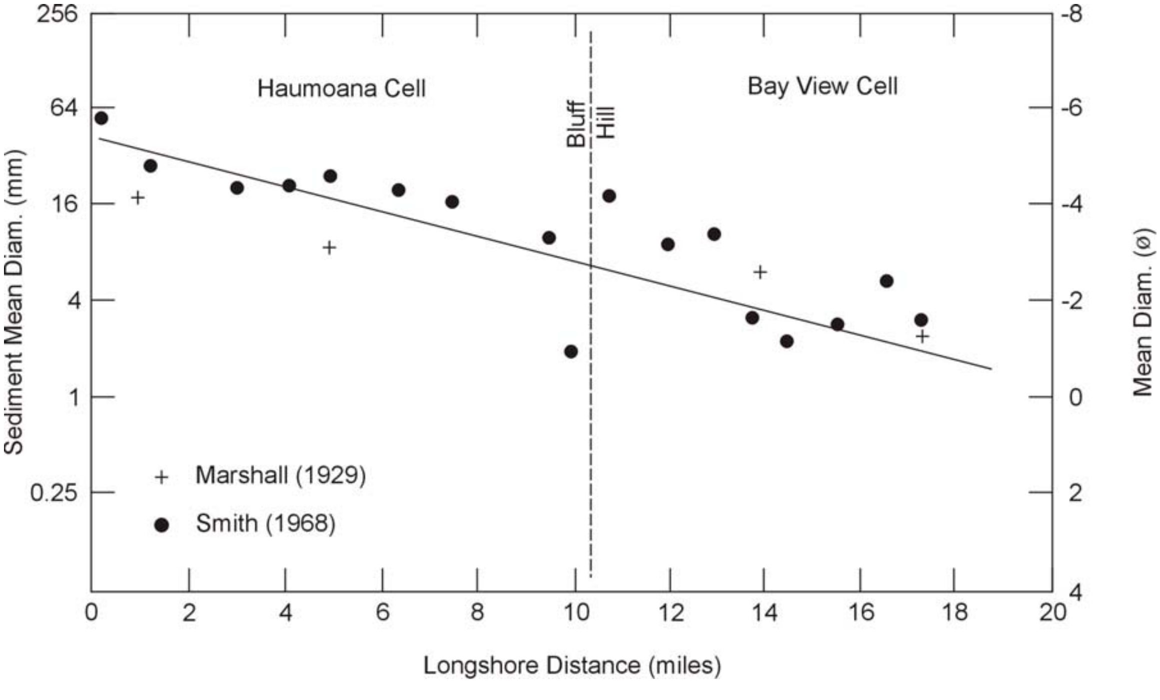


Figure 5-9 The longshore variations in mean grain sizes of beach sediments in the Haumoana and Bay View Littoral Cells as analyzed by Marshall (1929) and Smith (1968). [*after* Smith (1968)]

Figure 5-9 above is the graph from Smith (1968) of the longshore variations in mean grain sizes found in his sampling program, and also those from the analyses by Marshall (1929): the longshore distance is measured southward from Tangoio, while the Bluff Hill headland in Napier is located at about the 10.5-mile longshore distance south. Both data sets suggest a progressive northward decrease in mean sediment grain sizes on the beach, from about 45 mm in the south near Cape Kidnappers to about 5 mm at Tangoio. The differences in the two data sets, collected 40 years apart, may be due more to the different sediment sampling techniques used in the two studies than to an actual change with time: Marshall's (1929) results were based on composite samples collected along the profiles, while as noted above, Smith's (1968) were primarily for single samples from each profile collected approximately at the mid-beach position. The finest grained sample in this series was that collected immediately north of Bluff Hill (2.8 mm), attributed to wave sheltering by this headland and by the Port's breakwater, contrasting with a significantly coarser gravel size (25 mm) on the beach to the immediate south of the headland and breakwater.

While the graphical results in Figure 5-9 are certainly suggestive of a progressive decrease in mean sediment sizes to the north along the Hawke's Bay beaches, extending the full length of the two littoral cells from Cape Kidnappers to Tangoio, the trends are less convincing if one looks individually at the two littoral cells separated by Bluff Hill. This is more apparent in Figure 5-10, which presents only Smith's (1968) results from his multiple sampling at the 19 profile sites, with the bars representing the ranges in the mean grain sizes of the samples collected at each site, and the circles being the average values of the means in the multiple sampling. The results illustrate the major problem of collecting representative samples from mixed sand-and-gravel beaches due to their extreme variations in sorting patterns and rapid changes with time. With Smith (1968) having depended mainly on single samples from approximately the mid-beach position, this variability is accentuated; the collection of multiple samples to derive a composite mean usually reduces this variability by averaging out the cross-shore sorting by grain size. When one includes this variability as seen in Figure 5-10, conclusions regarding the existence of a progressive longshore trend in the mean grain sizes is certainly less apparent than suggested by Figure 5-9. In the Haumoana Littoral Cell to the south of Bluff Hill, some trend in the averages of the means is again suggested by the data in Figure 5-10, with a progressive decrease in grain sizes to the north; this trend is probably real, even though it may not be statistically significant in view of the large ranges in mean sizes found by Smith at all sites. Within the Bay View Littoral Cell north of Bluff Hill, ignoring the much finer sample in the sheltered region to the immediate north of Bluff Hill and the breakwater, there is not an overall south-to-north decrease in the sediment sizes, but instead the pattern is one where slightly finer sizes are found midway along the length of the cell. These results are affected by the quantities of sand in the samples, as well as the actual grain-size distributions of the gravel. Smith (1968) reported that along the Bay View Cell significant quantities of sand occurred at profile sites 8 and 9, that is, in the stretch of shore sheltered by Bluff Hill and the breakwater. In the Haumoana Cell a significant sand component appeared mainly at profile site 19 that is similarly sheltered by Cape Kidnappers, and in profiles 13, 14 and 15 where the sand is presumably supplied by the Ngaruroro and Tutaekuri Rivers.

The studies of Marshall (1929) and Smith (1968) both concluded that on average the gravel in the Haumoana Littoral Cell is coarser and has an overall greater range in sizes than found in the Bay View Littoral Cell. This is apparent in Figure 5-9 for both data sets, if one focuses individually on the two littoral cells and ignores the apparent longshore variations. The use of composite samples in deriving this graph emphasizes this difference between the two littoral cells as it includes material collected from the top of the beach where the gravel tends to be coarser. This difference is less apparent in Figure 5-10 from Smith (1968), where results from single samples collected at the mid-beach positions are included, unless one considers the most extreme coarse means found at the sites. The differences in gravel sizes between the two littoral cells are most apparent when Smith (1968, Figure 21) graphed the spatial distributions of the mean sizes of all samples in the two cells collected during the first survey when composite samples were obtained. In both cells there is a general (but irregular) decrease in mean grain sizes across the beach profiles from their landward to offshore ends, a common cross-shore grain sorting pattern found on mixed sand-and-gravel beaches. However, in the Haumoana Cell the average grain size of the landward-most samples is about 20 mm, whereas that in the Bay View Cell is only 5 mm, showing the distinct grain-size difference between the two littoral cells. If one compares the mid-beach samples the difference between the cells is much less apparent, as there is a great deal more variation due to the presence of patches of sand and small pebbles versus coarser pebbles, accounting for the large ranges in means graphed in Figure 5-10 where single samples were used from the mid-beach level.

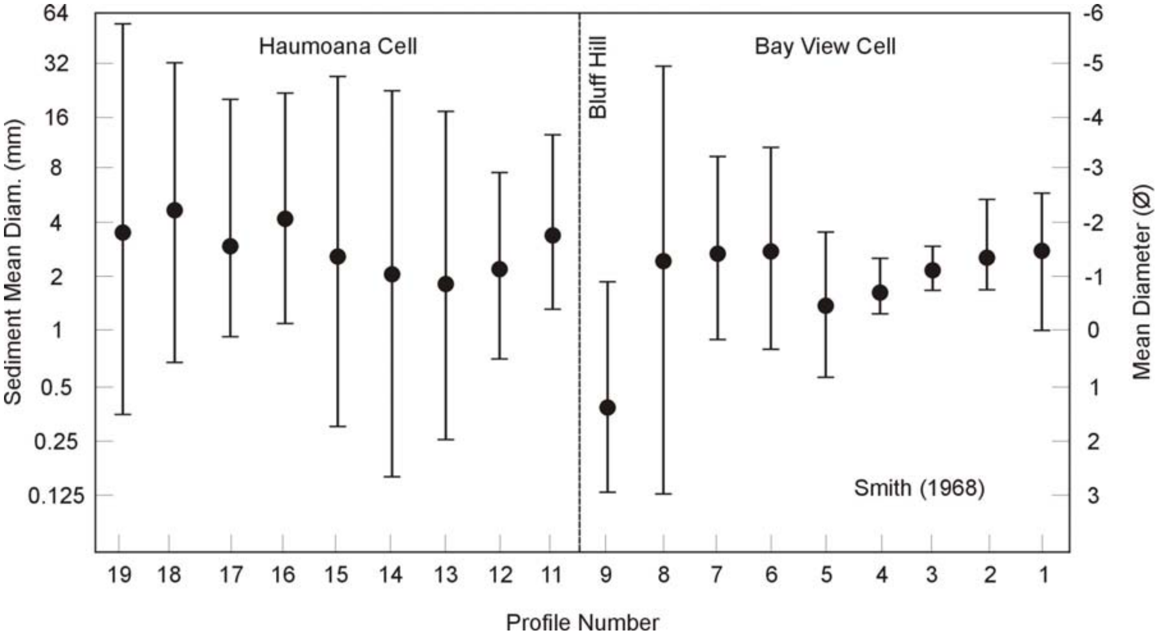


Figure 5-10 Analyses by Smith (1968) of mean sediment grain sizes at 19 sampling sites along the length of the Haumoana and Bay View Littoral Cells, numbered from north to south with Bluff Hill in Napier positioned between sites 9 and 11. The bars for each site span the range of mean diameters found in five sampling series, with the circle being the average of those means. [*after* Smith (1968)]

Smith (1968) surveyed beach profiles at each of his sediment sampling sites, during each of the five times of sampling. His objective was to relate the beach morphology derived from the surveyed profiles to the sediment grain sizes and visually measured wave parameters collected at each site. However, there was little change in the morphology of the beaches during the two-year time frame of his study. He did find a correlation between the mean grain size and beach slope (Smith, 1968, Fig. 30), but the data are very scattered with only a broad trend of increasing beach slopes with larger sediment sizes. This scatter was likely due in part to the inherent variability in the slopes of mixed sand-and-gravel beaches, seen in the review earlier, but it was also likely due to the problem of defining the mean grain size of the beach sediments. Many of the samples were likely bimodal, that is, they had two dominant sizes with lesser quantities of grains having intermediate sizes between the two modes. This is especially true for samples containing significant quantities of sand as well as pebbles, which is common for mixed sand-and-gravel beaches. The effects of having bimodal grain-size distributions was demonstrated by Smith (1968, Figure 23) in a graph of the sorting coefficients versus the mean grain sizes of the samples, showing that the poorest sorting occurs for the mid range of means, those generated by the mixing of the two modes in the bimodal distributions, commonly the mixing of the sand and gravel components. The result is that the means derived in the analyses very often did not correspond to the dominate sizes of grains in the beach sediment samples, but instead fell between the modes where there is actually a deficiency of sediment. As well as introducing scatter to Smith's graph of beach slopes versus mean grain sizes, this mixing of modes would also have been a contributing factor to the large ranges of means found at any individual profile site, seen in Figure 5-10, obscuring the existence of any longshore trends in grain sizes. In studying the Hawke's Bay beach sediments, Smith (1968) was following the then accepted grain-size analysis procedures used by geologists throughout the world. Those procedures have subsequently been replaced by modal analyses of the grain-size distributions, where one separates out the individual modes and determines their respective mean sizes and sorting coefficients. Such an approach could be expected to yield more understandable patterns of longshore variations in the gravel sizes considered as a separate mode; for example, we have used modal analyses of beach sediments on the Oregon coast that identified up to five size modes, which were shown to be transported at different rates along the coast (Shih and Komar (1994). Modal analyses would also likely provide a better understanding of the grain-size controls on the beach slopes, utilizing the recent research results on the porosity and permeability of mixed sand-and-gravel beaches and how that affects the beach slopes (Masseling and Ling Li, 2001).

As well as analyzing the beach sediment grain sizes, Smith (1968) undertook analyses of grain sphericity and roundness, centered on pebbles in the size fraction 1.5 to 3.0 cm. The "flatness ratio" is graphed in Figure 5-11, defined as the ratio of the particle's smallest and longest axial diameters. In both littoral cells the more spherical particles are found in the south, and as one moves northward the stones become flatter, having lower flatness ratios. The trends are seen in both littoral cells, but with 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 gravel around Bluff Hill and the Port's breakwater. Smith (1968, Figure 26) found the same general pattern for the "effective setting sphericity" calculated from all three axial diameters of the particles. He concluded that these alongshore variations in pebble shapes are the result of sorting by the waves, with the bladed or discoidal particles having larger surface areas in relation to their weights, and therefore are moved more easily by wave action. Alternatively, it could be the product of particle abrasion ("wearing") as indicated by the analyses of Marshall (1927, 1929) that included the full range of particle sizes found in the beach sediments. Most likely the observed variations in grain shapes are due both to selective hydraulic transport by the waves and particle abrasion, which also alters their shapes as they are transported along the shore.

Smith's (1968, Figure 27) measurements of the pebble roundness show a south-to-north increase in the roundness of the pebbles on the beach in the Haumoana Cell, while there is a near uniformity in the grain rounding in the Bay View Littoral Cell. Particles in the rivers and in the cliff of Cape Kidnappers showed greater angularity than those on the beaches. These results generally agree with those of Marshall (1929), who considered a broader range of grain sizes. The results again indicate that the two littoral cells are separate entities, with distinct differences in grain angularity as well as in their overall shapes.

Based on his analyses of sediment grain sizes and shapes, Smith (1968) concluded that the differences in those sediment properties between the Haumoana and Bay View Littoral Cells demonstrate that the cells are separate entities, further suggesting that this separation began with the construction of the Port's breakwater in 1887-1890. In addition, he suggested that since there is now no obvious source of gravel for the Bay View Cell, the pebbles there must have nearly reached their optimum degree of roundness, and noted that they are both more uniformly smaller and polished compared with the gravel of the Haumoana Cell. The conclusion followed that the Bay View gravel must represent an "old" deposit, in contrast with the Haumoana Cell where "new" gravel is being contributed by the sources, the Tukituki River and erosion of Cape Kidnappers. Since Smith assumed that gravel was able to bypass Bluff Hill and move from the Haumoana Cell into the Bay View Littoral Cell prior to the construction of the Port's breakwater, he presumably meant that "old" is represented by the time passed since the construction of the Port's breakwater and his gravel sampling in the 1960s, about 87 years. The question is whether the beach gravel in the two littoral cells could have evolved to the extent observed in their sizes, shapes and longshore sorting patterns in under a century, or whether Bluff Hill effectively separated the cells prior to the construction of the breakwater, providing a much longer period of time for the differences to have developed. This and other aspects of the breakwater construction will be considered at length in Section 6.

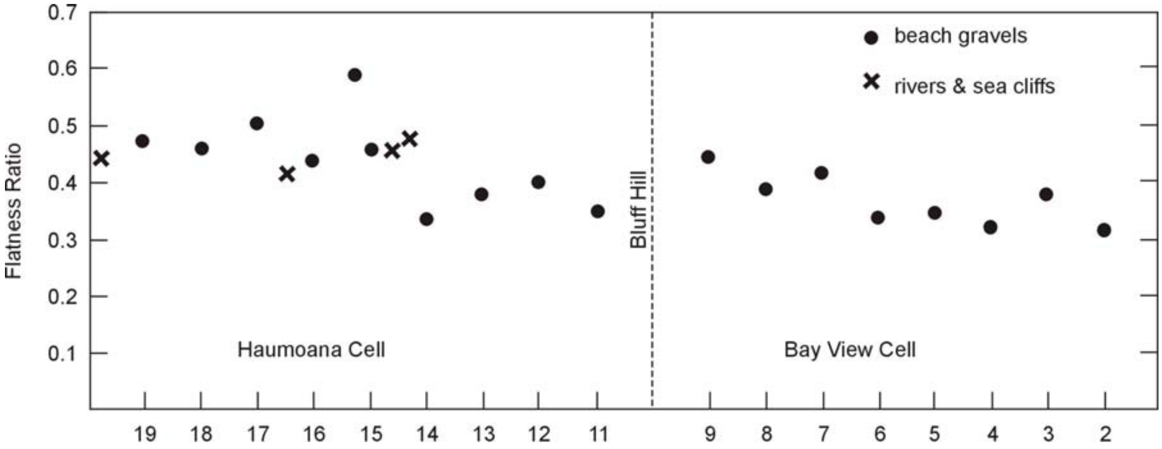


Figure 5-11 Longshore variations in the mean flatness ratios of pebbles in the size fraction 1.5 to 3.0 cm measured by Smith (1968) in samples from the Haumoana and Bay View Littoral Cells. [*after* Smith (1968)]

5.3.2 The Hawke's Bay Beach Monitoring Program

Somewhat offsetting the limited extent of scientific research that has been undertaken on the mixed sand-and-gravel beaches of Hawke's Bay has been the monitoring program in existence for on the order of 30 years. The principal emphasis of this program 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 the Haumoana and Bay View Littoral Cells. The history, procedures, and products of this monitoring program have been reviewed in detail by Gibb (1995a, 1995b), while studies such as Tonkin & Taylor (2003) that have relied on the survey data in applications provide updated reviews of the status of the accumulated profiles. The summary presented here is derived from those more comprehensive reviews.

The effort directed toward monitoring the beaches of Hawke's Bay with the collection of profiles was initiated as a reaction to the impacts of coastal erosion and flooding. According to Gibb (1975a), the earliest beach profiles date back to 1914 at East Clive, surveyed in response to the erosion that threatened the Hastings sewer outfall. Between 1936 and 1978 five additional surveys were made at that same site (Smith, 1984). 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. In 1984 Smith located and resurveyed 13 of those Westshore sites, and updated the shoreline changes (Smith, 1986). In response to a period of erosion and flooding, in 1939 the Public Works Department established 40 profile lines in the Awatoto area between Waitangi Bridge and Ellison Street, but only surveyed them sporadically until 1961. Smith also located and resurveyed those profile lines in 1984 (Smith, 1984). Five of these profile sites (the AWA Series) have been incorporated into the monitoring program of the Hawke's Bay Regional Council to evaluate the effects of gravel extraction from the beach at Awatoto. As reviewed above, as part of his thesis research Smith (1968) established 9 profile lines between Te Awanga and the Port of Napier, and surveyed them over the 2-year period of his research, 1967 and 1968, as well as analyzed beach sediment samples from those sites. He resurveyed them once again in 1984 to assess the subsequent shoreline changes (Smith, 1984). Gibb (1995a) found in his review of these early profile series that little of this survey data has been archived by the Hawke's Bay Regional Council, so generally these surveys have not been utilized in recent shoreline-change analyses. In 1972, again in response to an episode of severe coastal erosion and flooding, the Hawke's Bay Catchment Board established 12 profile sites (the CS Coastal Series) between Clifton and Awatoto. Although limited in the number of sites and dates when the surveys were repeated, this CS Series has been included in the Regional Council's archive of historic surveys to be used in analyses of shoreline changes.

The principal beach-profile monitoring program now underway was established by the Hawke's Bay Regional Council in 1974, following an episode of widespread coastal erosion. This initially consisted of the 9 profile locations of the Key sites (referred to as the K Series) between Clifton and Tangoio, and a number of Temporary sites (T Series). By 1981 three addition sites were added to the K Series at Westshore, for a total of 12 in that Series. The locations of the K and T Series of profile sites are shown in Figure 5-12; unfortunately, due to the later addition of profiles, while the K Series generally increases in numbers from south to north, the numbers are locally out of order in the Westshore area. The Temporary profile series (T Series), initially included to verify the trends recorded at the K Series of profiles, involved the collection of profiles beginning in 1984 along the stretch of shore from Awatoto to Napier, and since 1991 along the coast from Bay View to Tangoio (Gibb, 1995a, Table 1).

Soon after initiating the collection of profiles at the K Series sites in 1974, the monitoring program was greatly expanded in 1977 when the Regional Council established 22 profile sites along the Esplanade at Westshore (the E Series), complimenting the W and K Series profiles in that area. This high-density E Series has been used in particular to monitor the effects of the beach nourishment program that was begun at Westshore in 1985. The existing high-density coverage of profiles representing the monitoring program in the Westshore area is shown in Figure 5-13 from the review provided by Gibb (1995a). Similarly, in 1989 the Regional Council established 29 high-density profile sites at East Clive to monitor the erosion and effects of groyne construction.

Gibb (1995a, 1995b) also presents analysis procedures and products of the beach profiles derived from the Hawke's Bay monitoring program. The profile changes are presented both in terms of the variations between surveys in the sediment volumes (cubic metres) per metre of shoreline length, in effect representing the change in the cross-sectional area of the beach between surveys, and the horizontal displacement of a "reference shoreline". In analyses such as these previously undertaken by others, this "reference shoreline" has been taken to variously represent the toe of the foredunes backing the beach, or the contour at or above mean sea level (MSL). For the "reference shoreline" to be used in the Hawke's Bay monitoring profiles, Gibb (1995a, p. 19) selected the position of the 1.5-metre contour above the MSL Napier Datum as providing a good representation of the progressive advance or retreat of the Hawke's Bay beaches. Figure 5-14 shows an example of these analysis procedures, based on the profiles at the K-10 site in Westshore, just north of the Ahuriri moles (Figure 5-13). On each graph, an upward displacement of the data points from one year to the next represents net accretion during that year, while a downward displacement represents net erosion. Over the span of years the overall trends of the curves therefore depict whether there has been a prolonged period of accretion, of erosion, or perhaps the occurrence of significant reversals in the prevailing accretion versus erosion. This approach thereby provides a readily visual depiction of the changes that have been experienced at the profile sites in the monitoring program.

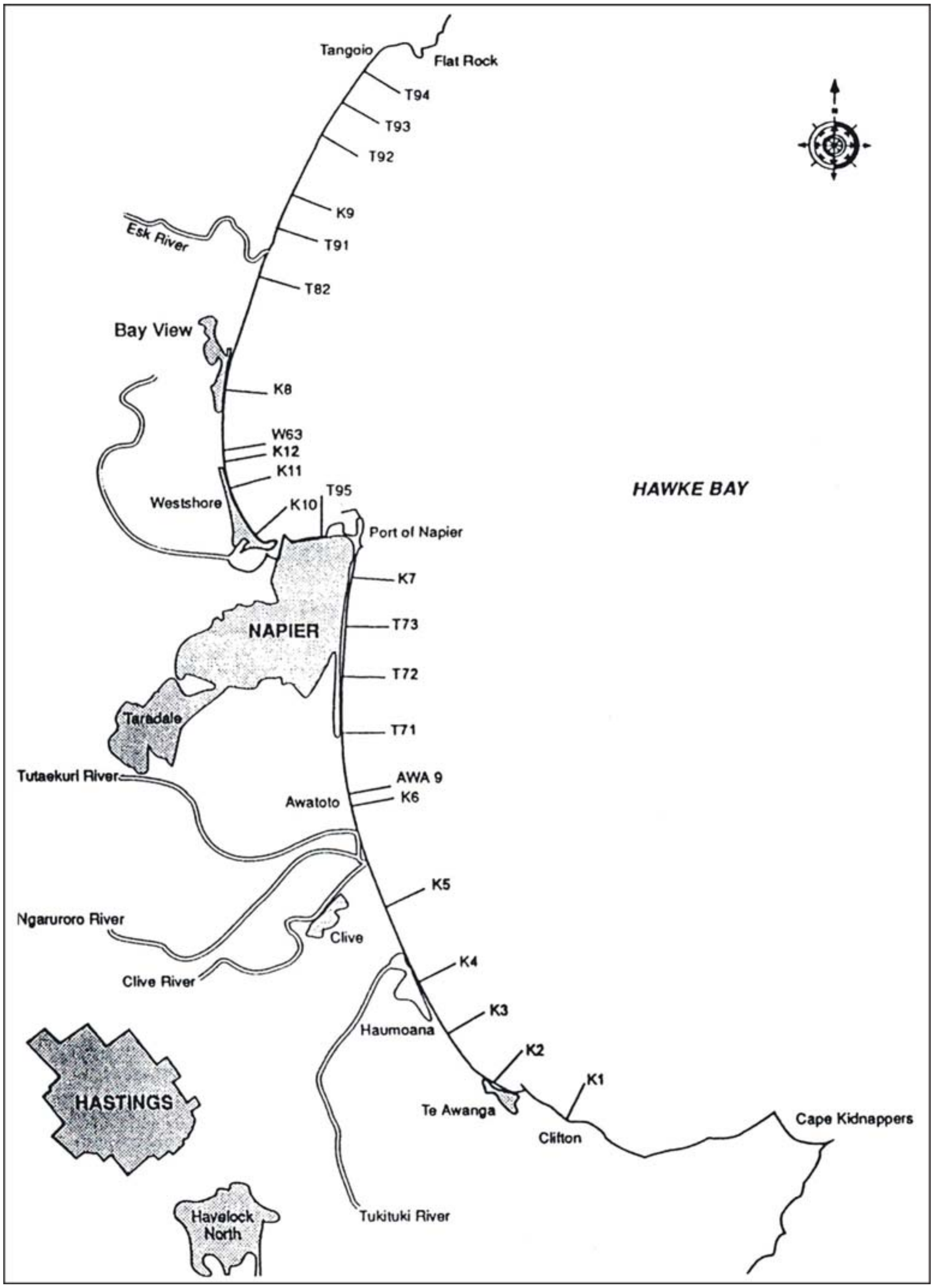


Figure 5-12 The locations of the K Series and T Series of beach profile sites that represent an important component of the Hawke's Bay Regional Council's monitoring program. [*from* Gibb (1995a)]

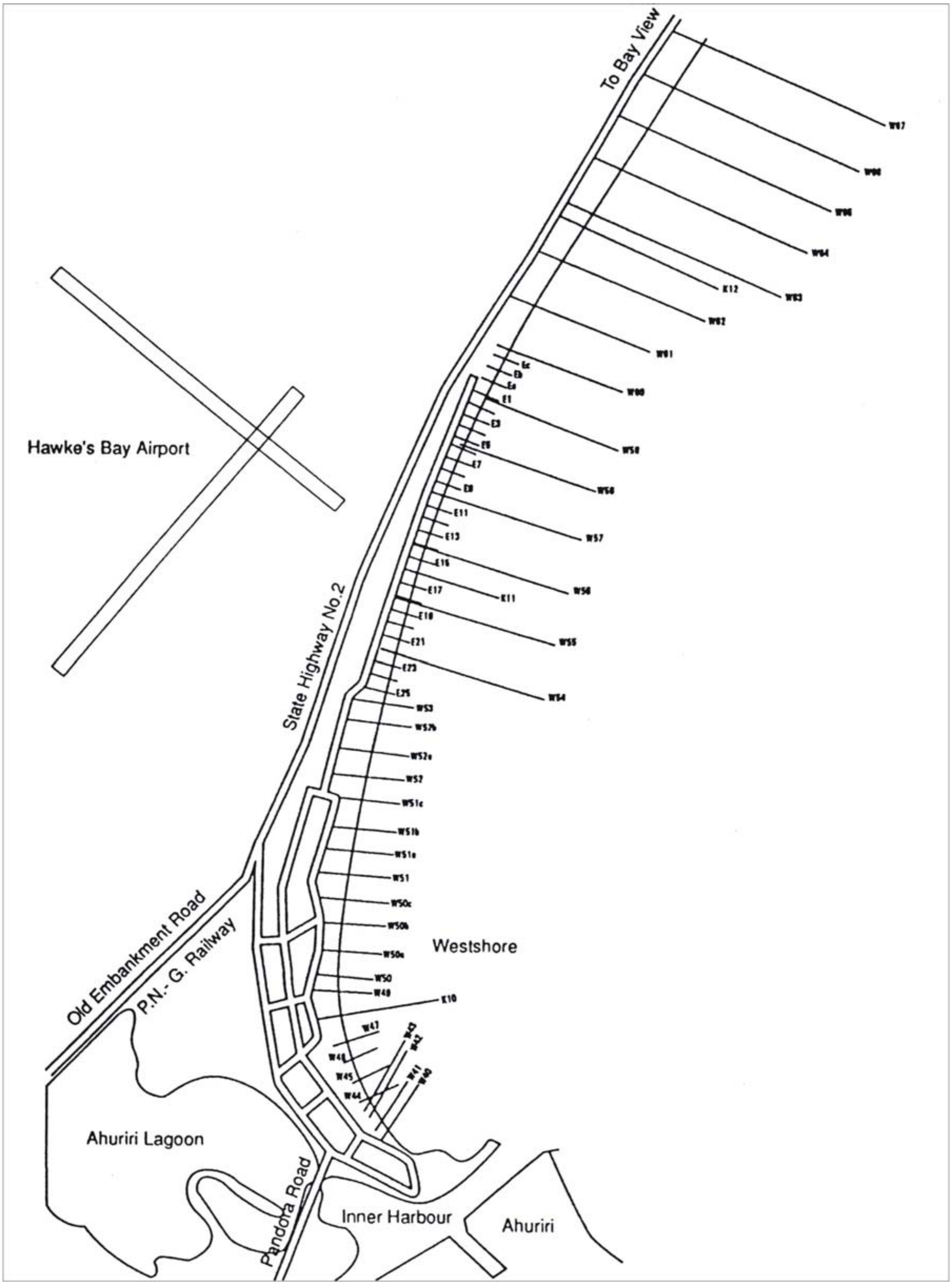


Figure 5-13 The concentration of beach-monitoring profile sites in the Westshore area of Napier. [*from* Gibb (1995a)]

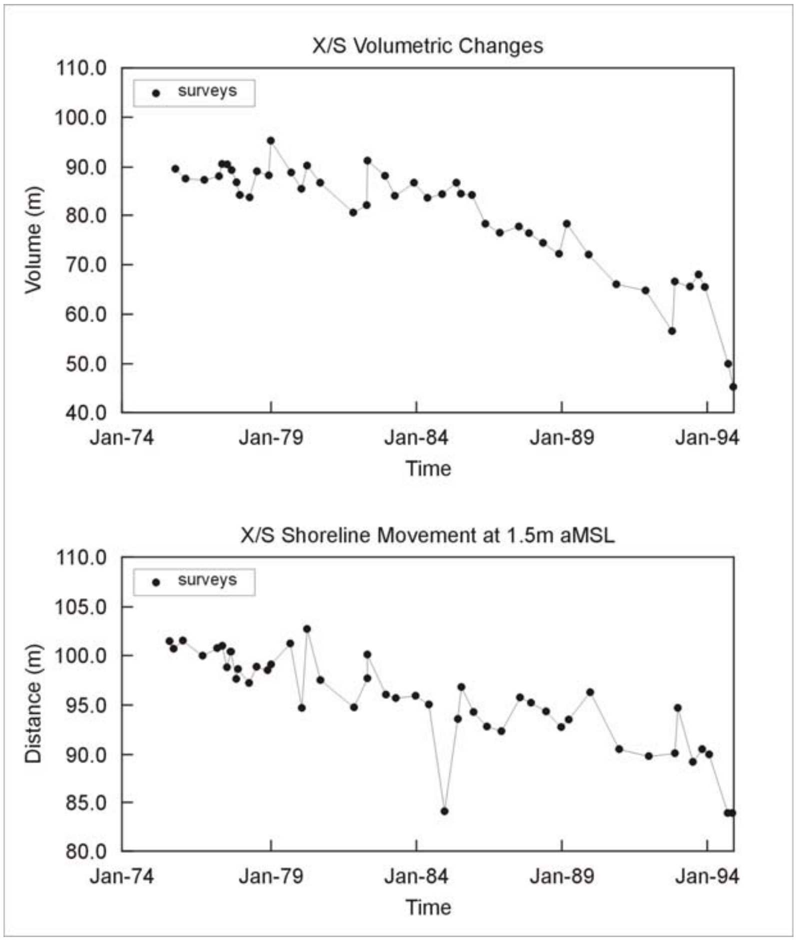
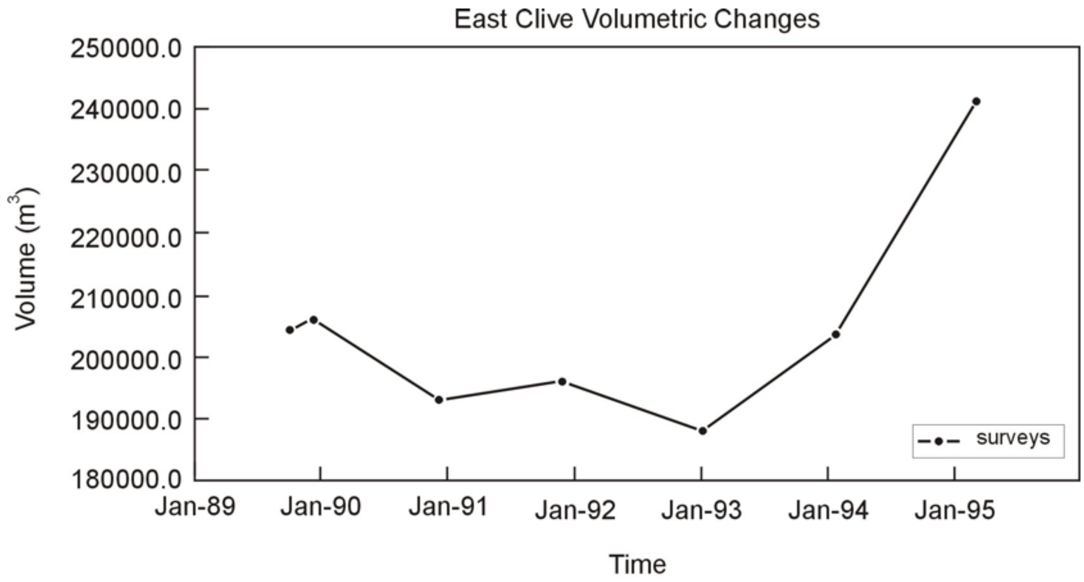


Figure 5-14 Analyses for the K-10 monitored profile site in Westshore in terms of annual variations in the beach sediment volumes and in the position of the "reference shoreline". [*from* Gibb (1995a)]

Gibb (1995a) also illustrated examples where the results from multiple profile lines are grouped together to evaluate the trends of accretion versus erosion experienced over a longer stretch of shoreline. The example below in Figure 5-15 from his report is for the East Clive shore. The upper graph is for the entire stretch of shore, and demonstrates the occurrence of net beach accretion from January 1993 through January 1995, while prior to January 1993 the total beach volume had been relatively stable. The lower graph contains three curves for separate, shorter segments of the East Clive shoreline, showing that the accretion mainly occurred in the southern-most stretch (profiles X/S 900S to X/S 100S), while the other two segments of shoreline experienced variations between periods of erosion and accretion.



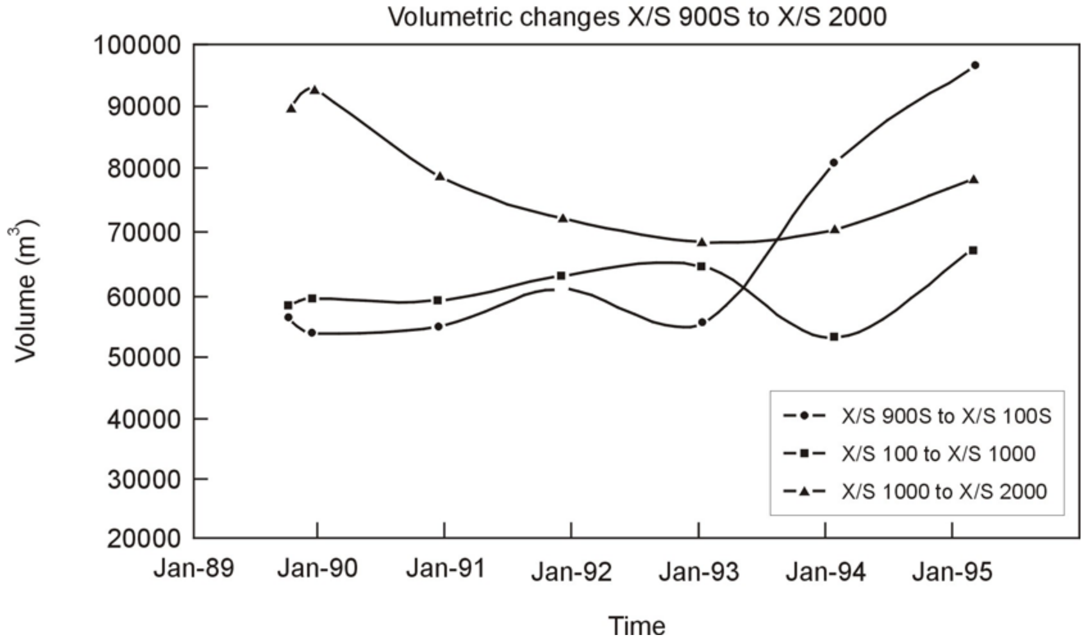


Figure 5-15 Trends of accretion and erosion along an extended length of the East Clive shore based on multiple survey sites in the monitoring program. (Upper) Results from the full length of shoreline; (Lower) Results from three shorter segments of the shoreline. [*from* Gibb (1995a)]

The primary objective in establishing the beach monitoring program for Hawke's Bay was the periodic collection of beach profiles along its entire length of shore in order to document the long-term trends of net erosion or accretion, and then to apply those results in the establishment of coastal hazard zones so that the construction of homes or other developments would be safe from the potential dangers inherent in living in close proximity to the ocean (Section 7). Another objective of monitoring the beaches has been more site specific, for example to assess the impacts of commercial beach sediment mining at Awatoto, and in another case to determine the effectiveness of the beach nourishment program at Westshore. By and large the data collected by these monitoring programs have served these objectives well. The three studies that have been responsible for the establishment of hazard zones are those by Gibb (1996, 2002), Oldman et al. (2003), and Tonkin & Taylor (2003); the Gibb and Smith analyses were limited to the shoreline of the City of Napier, whereas Tonkin & Taylor have developed hazard zones for the entire lengths of the Haumoana and Bay View Littoral Cells. In each study heavy reliance was placed on the long-term trends of shoreline erosion or accretion, trends that are then projected into the future to predict future hazards. Assessments of hazard zones also require evaluations of the dangers from erosion and inundation (flooding) that could result during extreme storms, the greatest impacts that might be expected during the next 50 to 100 years; this assessment also includes the potential sea-level rise during that time frame, and the probable responses of the beaches and shifts in the shoreline positions. In those analyses to establish hazard zones the assessments have been limited by our scientific and engineering capability to predict the responses of mixed sand-and-gravel beaches to the processes of extreme storms and a rise in sea level, and due to these limitations the studies have taken significantly different approaches that in some areas have yielded contrasting results in their final assessments. The studies should not be faulted for these differences, which point instead to the need for additional research beyond that included in the present monitoring program; these needs are discussed below.

5.4 SUMMARY AND DISCUSSION

The management of the Hawke's Bay coast is problematic in that its beaches are composed of variable mixtures of sand together with a coarse-grained component consisting of greywacke gravel and cobbles. This variability in sediment compositions exists at any given time along the lengths of shore in the Haumoana and Bay View Littoral Cells, and can change from day to day at any specific beach location due in particular to the high mobility of the sand component such that its distributions within the littoral cells respond quickly to the changing waves and currents. In the classification of beaches presented in Figure 5-1, the Hawke's Bay beaches can be either mixed sand-and-gravel or composite, but it should be recognized that these categories in the classification are artificially imposed on what in reality is a continuum of beach compositions and morphologic forms, so at times it may be difficult to categorize the beaches.

The significance of the Hawke's Beach beaches being mixed sand-and-gravel to composite is that relatively little scientific research has been undertaken on such beaches, at least in comparison to the considerable amount of research that has been completed on sand beaches, and even on “pure” gravel/shingle beaches. The best guide to understanding the processes and morphologies of the Hawke’s Bay beaches is derived from the research that has been undertaken on the similar mixed sand-and-gravel beaches of the Canterbury Bight of the South Island; that research has been reviewed by Kirk (1980). Even with that research there are missing components remaining in our understanding of the processes and dynamics of mixed sand-and-gravel beaches which are important to management applications; these include the predictions of swash runup elevations of the waves on the sloping beach, particularly during storms, the prediction of the morphologic responses of the beach profiles at times of storms, and more accurate assessments of the losses of the beach gravel particles to abrasion.

As reviewed in this Section, while the monitoring program underway for a number of years along the Hawke's Bay shore permits the projection of long-term trends of erosion or accretion, the problem remains in predicting what may happen to the beaches during a major storm, the 100-year event, that likely will produce significant erosion and flooding of the coast, impacting the developed properties. Although the studies that have developed hazard zones for the Hawke's Bay coast attempted to assess the potential impacts of extreme storms, they have been limited by their inability to make satisfactory process-based evaluations of the potential beach erosion and backshore flooding. The assessments of the erosion have instead been based on statistical analyses of the beach-profile fluctuations from year to year above the long-term trends, the assumption being that the fluctuations represent the responses to annual storms (Section 7).

This is not a safe assumption, and is questionable in that the monitoring profiles are generally collected only annually and therefore are not likely to fully represent the storm responses, and certainly have not captured the beach response of the 100-year storm. Assessments of the potential for inundation (flooding) are process based in the hazard assessments in that they generally involve the addition of the potential astronomical tide, the processes that can raise the measured tides above that predicted level (a storm surge being most important), and the swash runup of the storm waves on the sloping beaches. This in principle is the correct approach for making flooding assessments, but again due to the limited amount of research on these mixed grain-size beaches the evaluations of these processes remain uncertain.

As reviewed in this Section there has been only limited basic scientific research undertaken specifically on the Hawke's Bay beaches. This review examined the studies of Marshall (1927, 1929), Smith (1968) and Hemmingsen (2004) of the beach sediments, including the "wearing" or "reduction" (abrasion) of the greywacke gravel and ultimately its loss from the beach when it is reduced to fine sand and silt, and also the longshore variations in the gravel sizes and shapes due to the combined processes of grain abrasion and hydraulic sorting by the waves. While Smith (1968) included the surveying of beach profiles at his sediment-sampling sites, with the objective of determining how their morphologies respond to the longshore variations in grain sizes and changing wave conditions, the time frame of his study was too short to adequately document this, and some 40 years later this is still in need of research in order to better predict the dynamics of the Hawke's Bay beaches. The thesis research of Single (1985) on the shores of Hawke's Bay can also be viewed as a basic investigation into the effects of sea-level change on the shoreline; that study was summarized in Section 2 as part of the review of the effects of the 1931 earthquake on the coast, with the conclusion that although more than seventy years have transpired since that event, it is still a factor in the evolution of the shoreline and exerting a degree of control on the observed locations of erosion (e.g., Haumoana).

In the absence of a sufficient basic research undertaken on the Hawke's Bay beaches, it has been necessary to rely more on the investigations of mixed sand-and-gravel beaches that have been completed on other coasts. It was in light of this necessity that a modest review was provided in this Section of that research, at least of its aspects most relevant to the management of the Hawke's Bay coast. Fortunately, much of that research was undertaken in New Zealand, and although it was primarily on the mixed sand-and-gravel beaches of the South Island (Kirk, 1980), the results have direct relevance to Hawke's Bay where the beaches and processes are very similar. The recent review by Mason and Coates (2001) demonstrated the growing international interest in mixed sand-and-gravel beaches, and this interest is also indicated by the increasing number of journal publications in recent years. With time it can be expected that this expanding research into the processes and dynamics of mixed beaches will provide a firmer basis for the improved management of the Hawke's Bay coast. However, even with the expectation of additional research elsewhere, it remains necessary to undertake additional investigations of the Hawke's Bay beaches, either as specific research studies by coastal scientists and engineers, or as part of an expanded component of the monitoring program.

My recommendations with respect to this future research include:

- A select number of profiles in the monitoring program be systematically surveyed more frequently than the present annual basis, that is at least seasonally so as to better define their degrees of variability, with the results being analyzed with respect to the causative processes, the combinations of measured tides, wave heights, and swash runup elevations;

- Surveys be undertaken at all profile sites immediately after occurrences of major storms, with measurements also being made of the maximum levels reached by the swash runup, followed by analyses of the extent of the morphology changes at each site and the development of a hindcast analysis of the measured tides plus the calculated wave-swash runup, to be compared with the survey results;

- A network of volunteer coastal observers be established who can rapidly respond during storm events to provide visual estimates at selected survey sites of wave breaker heights, periods and angles, and observations of the runup elevations of the wave swash;

- Undertake periodic surveys of the shallow-water offshore to extend the beach surveys that are part of the present monitoring program, in order to provide the bathymetric data required in numerical models of wave shoaling and refraction, and to document any long-term variations in sediment storage directly offshore from the beaches.

Many of these recommendations are essentially the same as those made by Gibb (1995a) in his review of the Hawke's Bay monitoring program. The primary objective of these recommendations is to provide a better understanding of what happens to the beaches during extreme events, at the times of major storms that represent an erosion and flooding threat to the coastal properties. The results are needed to provide tests of the methodologies used to establish hazard zones for the Hawke's Bay coast, and to improve those methodologies.

While the fact that the Hawke's Bay beaches are mixed sand and gravel has made the management of this coast more problematic, at the same time it has rendered it more stable and less vulnerable to ocean hazards than is generally the case for coasts having sand beaches. By and large such coarse-grained beaches are more stable by virtue of their larger sediment sizes and because the steepness of their profile slopes cause them to be Reflective in the morphodynamics classification of Wright and Short (1983), Figure 5-2, a beach type that world-wide has been demonstrated to be more stable when impacted by severe storms. Another contributing factor to the stability of the Hawke's Bay beaches has been their general uplift at the time of the 1931 earthquake, which raised their elevations by up to 2 metres (Section 2). Prior to that earthquake the swash of extreme storms was able overtop the gravel and cobble ridges, with the waves carrying the beach sediment to the landward side of the ridge, producing its inland migration. The uplift by the earthquake now prevents wave overtopping during major storms, at least along the length of the Bay View Littoral Cell. In many respects, with their coarse-grained compositions and high elevations, these beaches along the Bay View Cell are akin to the "cobble berms" or "dynamic revetments" that have been constructed along coasts for shore protection (Ahrens, 1990; Allan and Komar, 2002, 2004). However, an important question is how long this fortuitous natural formation of what amounts to a dynamic revetment along the Hawke’s Bay shore will last, as erosion is slowly cutting away the beach ridge along some stretches of the shore, and with the expected rise in sea level in the future combining with storm events it might be expected to eventually fail, leading to the renewed erosion and flooding of backshore properties.

While the coarse-grained compositions of the beaches within the Haumoana Littoral Cell to a degree similarly enhance the stability of that shore, erosion problems are more prevalent than to the north, in large part due to its smaller degree of uplift from Napier south to Awatoto at the time of the 1931 earthquake, and especially to the south of Awatoto where the coast subsided. Another significant factor contributing to the hazards in this littoral cell are the variable quantities of beach gravel, which locally are insufficient to form a beach that is both wide and reaches sufficient elevations that it is able to buffer the backshore properties from the surge and waves generated by storms, resulting in the erosion and flooding of those properties. These important roles of the land-elevation changes and quantities of beach sediments as factors in the local erosion problems will be reviewed in greater detail in Section 7.

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6 The Coastal Response to the Construction of Moles (Jetties) and Breakwaters: The Hawke's Bay Experience

6.1 INTRODUCTION

There are many examples from the world's coastlines where the construction of moles (jetties) to stabilize and deepen an inlet for safer navigation, or the development of a breakwater on the open coast to serve as a harbour, have resulted in significant erosion of nearby beaches and the loss of shore-front properties. These impacts are mainly the result of the structures having blocked the natural longshore movement of beach sediment along the coast, their construction having prevented the former passage of the sediment to downdrift beaches so there is a prolonged period of nearly-continuous erosion. Such occurrences of coastal erosion associated with the construction of moles and breakwaters are so common that there is the tendency to attribute any occurrence of beach erosion to a nearby structure. In a few cases this initial claim has been refuted or moderated by further investigation.

The objective of this Section is to review the possible environmental consequences of construction related to the development of the Port of Napier. This includes the construction of the moles at the entrance to the Ahuriri Lagoon in 1876-1879, followed soon thereafter by the development of the Port's breakwater in 1887-1890. With this construction having been completed more than a century in the past, any analysis of its effects on the environment depends in large part on a historic reconstruction of the beach responses, but viewed with the present-day knowledge of what can happen when moles or breakwaters are constructed, this knowledge having been acquired through detailed studies of the effects such structures have had throughout the world.

This Section begins with a general review of the shoreline changes and associated erosion problems that have occurred on other coasts when moles (jetties) or breakwaters blocked the longshore movement of beach sediment. Also examined are cases where there was not a net longshore movement of beach sediment to be blocked, the question then being whether moles and breakwaters can still have significant environmental consequences. This Section then turns to an examination specifically of the Port of Napier, with separate considerations of the possible effects of having constructed the moles and then those induced by the later development of the Port's breakwater. This Section ends with a summary and discussion based on these analyses, including an attempt to put into perspective the possible negative consequences of having constructed the moles and breakwater at Napier versus their positive contributions to the development and economy of the Hawke's Bay region.

6.2 THE CONSTRUCTION OF JETTIES AND BREAKWATERS: A REVIEW OF THE COASTAL RESPONSES

As noted above, there are many examples throughout the world of the destructive beach and property erosion that has resulted from the construction of jetties (moles) and breakwaters that blocked the natural movement of sediment along the coast. I have written detailed reviews of those impacts elsewhere (Komar, 1983; Komar, 1998, p. 377-383), so only a brief summary is presented here.

On coasts where there are river estuaries, bays or lagoons, these bodies of water have been developed to serve as recreational harbours and commercial ports. In almost all cases this development has included the construction of jetties on the inlet to provide a greater control on water depths for safer navigation. In their natural condition inlets generally contain shoals and an offshore bar, with the deep-water channel through the inlet continuously changing position in response to the varying conditions of the ocean waves and tidal currents. At times the inlet may dramatically alter its position, with storm waves cutting a new inlet elsewhere on the shore, while the former opening to the estuary or bay is closed by the accumulation of beach sediment. These natural aspects of coastal inlets represent a hazard to recreational boats and commercial ships using the harbour, so the objective of constructing jetties is to both fix the position of the inlet and to deepen the water by constricting the flow, decreasing its width and thereby increasing the current velocities so they are able to scour a deeper channel.

Unfortunately, while the construction of jetties at harbour inlets does provide safer navigation, it can have negative consequences to the environment, including the erosion of nearby beaches. This primarily occurs when the jetties block the net longshore movement of sediment along the beach, the jetties in effect acting as a dam to that natural movement. This is illustrated schematically in Figure 6-1 (upper) where a net longshore transport by the dominant wave approach to the coast has been blocked by the jetties, with accretion occurring on the updrift beach and initially an equal volume of sand being lost from the downdrift beach, resulting in shoreline retreat there. The highest rate of erosion occurs adjacent to the downdrift jetty, with a progressively slower rate of shoreline retreat with distance from the jetties as the erosion offers some sand replacement to the beaches more distant from the jetties in the downdrift direction. With time the erosion progressively expands downcoast from the jetties, impacting an increasing length of shore, that is, until the sediment accumulation on the updrift side reaches the end of the jetties and begins to bypass them, and once again reaches the downdrift beach. However, this bypassing will not generally be complete as much of the beach sediment may be carried landward up the channel between the jetties, where it produces unwanted shoaling. Generally this shoaling is prevented by dredging the sediment entering the inlet, and disposing of it offshore; unfortunately, the common practice, at least in the United States, is to dispose of the dredged sand offshore in deep water, rather than to follow the more rational course of placing it on the downdrift beach that is eroding. In a few cases bypassing systems have been developed to pump the accumulating sediment from the updrift side of the jetties to the downdrift eroding side, but such systems are still comparatively rare.

There is a number of examples on the world's coasts where jetty construction has blocked the natural longshore transport of beach sediment, resulting in the advance of the beach on the updrift side of the jetties while the downdrift beach has suffered significant erosion. An example is shown in Figure 6-2 from Ocean City, Maryland, where the shoreline of the downdrift beach retreated by 450 metres during the first 20 years following jetty construction, requiring a lengthening of the jetty at its landward end to prevent its detachment from the shore (Komar, 1998). Fortunately, in this case the developed community of Ocean City extended along the accreting stretch of updrift shore produced by the jetty construction. A similar example, but where homes and other infrastructure were in the path of the erosion, is provided by the jetties leading to Charleston Harbor, South Carolina, constructed in 1896. These jetties block a net north-to-south beach sand movement, resulting in long-term erosion on the barrier islands to their south, along Morris and Folly Islands where in recent years the shoreline recession rates have respectively averaged 6.1 and 1.3 metres per year (Hansen and Harris, 1989). These rates of barrier island erosion are much greater than can be accounted for by a global rise in sea level and the subsidence of the islands, so clearly have been a response to the blockage of the southward longshore sand transport by the Charleston jetties. Evidence for the significance of the erosion is that the Moris Island lighthouse, constructed on the Island in 1876, is now found on a protective rock mound far offshore in the deep water of the Atlantic Ocean (Leatherman and Møller, 1991).

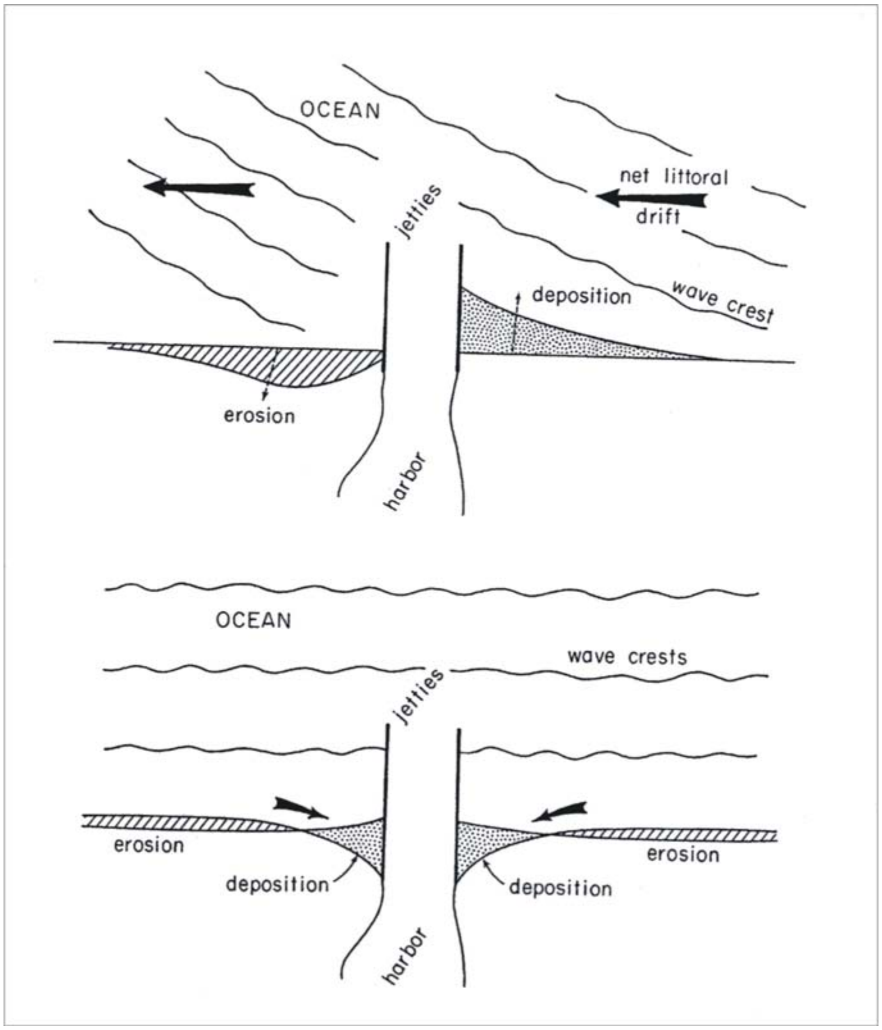

Figure 6-1 The patterns of shoreline change associated with jetty construction on an inlet: (Upper) Where the jetties block a net littoral drift of sediment along the beach; (Lower) The symmetrical pattern of shoreline change where there is not a net littoral drift of beach sediment for the jetties to block. [*from* Komar (1997)]

Not surprising, the general observation is that the greater the quantity of longshore sediment transport along a coast (the littoral drift), the greater the rate of beach erosion in the downdrift direction when jetties or a breakwater are constructed, and ultimately the greater the cumulative negative impacts to properties along an extended length of coast. Does it therefore follow that if there is not a net littoral drift to be blocked, there will be no negative consequences to constructing the jetties or a breakwater? While there have been only a few studies of this condition, the indication is that there could still be some shoreline erosion, but limited in its extent and persisting for only a few years as the shoreline approaches a new equilibrium condition in response to the presence of the structures. This has been found in particular in my research on the Oregon coast (Komar et al., 1976; Komar, 1997). The waves on that coast tend to arrive from the southwest during the winter and from the northwest during the summer. As a result there is a seasonal reversal in the directions of the beach sand transport; north in the winter, south in the summer. The net sand transport or net littoral drift, the difference between these north and south sand movements, is essentially zero, at least if averaged over a number of years. This zero net transport of sand along Oregon's beaches results from their being contained within littoral cells between rocky headlands, in effect being large pocket beaches. The bounding headlands extend into sufficiently deep water that they prevent beach sand from passing around them. Furthermore, there are no significant sources of new sand to the beaches, nor significant losses, so even over the relatively long term there are nearly fixed quantities of sand in each of the isolated pocket-beach littoral cells. Sand may move north and south within a littoral cell due to the seasonality of the wind and wave directions, but the long-term net movement must be zero. This makes the Oregon coast ideal for the study of shoreline changes induced by jetty construction on a coast having a net-zero longshore movement of beach sediment.

Figure 6-2 Shoreline changes resulting from the construction of jetties at Ocean City, Maryland. [*from* Komar (1998)]

Jetties were constructed on most of Oregon's tidal inlets early in the century to control them so the bays and estuaries could serve as harbours. In each case the U.S. Army Corps of Engineers, who undertook the construction, fully documented the shoreline responses by at least annual surveys, which we were able to use to analyze the effects of the jetties (Komar et al., 1976). A schematic version of the general shoreline changes due to jetty construction found for this condition with a net-zero transport is shown in Figure 6-1 (lower), where it can be contrasted with those resulting from jetty construction on a coast that experiences a net littoral drift. With a zero-net longshore transport the pattern is seen to be more symmetrical, with sand deposition and shoreline advances occurring in immediate proximity to the jetties, on both sides of the inlet where the pre-jetty shoreline had curved inward into the natural inlet. Further distant from the jetties there is some beach erosion and shoreline retreat, this erosion having in part supplied the sand for the beach accretion adjacent to the jetties. Figure 6-3 provides an example from the jetty construction on the inlet to Yaquina Bay, located on the mid-Oregon coast, a somewhat unusual case in that the jetties were constructed at an oblique angle to the north-south trend of the coast. The result of this jetty orientation was that more sheltering of the waves occurred to the south of the jetties, so a significantly greater volume of beach sand accumulated there compared with the beach to the north of the jetties, resulting in a greater advance of the shoreline to the south than to the north. The 1830 shoreline included in Figure 6-3 represents the condition prior to the construction of the jetties, while the subsequent surveyed shorelines document the infilling of the embayment created between the jetty and the pre-jetty shoreline. In this case the surveyed shorelines do not extend sufficiently far from the jetties to document any erosion that may have occurred. At the time of our study we concluded that the sand for the shoreline advance adjacent to the jetties was derived primarily from beach erosion more distant from the jetties, transported by the seasonally reversing littoral drift into the sheltered zones created by the jetties (Komar et al., 1976). However, subsequent studies to the north on the Washington coast have shown that jetty construction there resulted in the onshore migration of what had been the natural ebb-tide shoals or bay-mouth bar, that sand having been added to the beach, contributing to the shoreline advance adjacent to the jetties. With that source of sand to fill the embayments between the constructed jetties and the pre-jetty shoreline, there would be a smaller degree of beach erosion and shoreline retreat in response to the jetty construction.

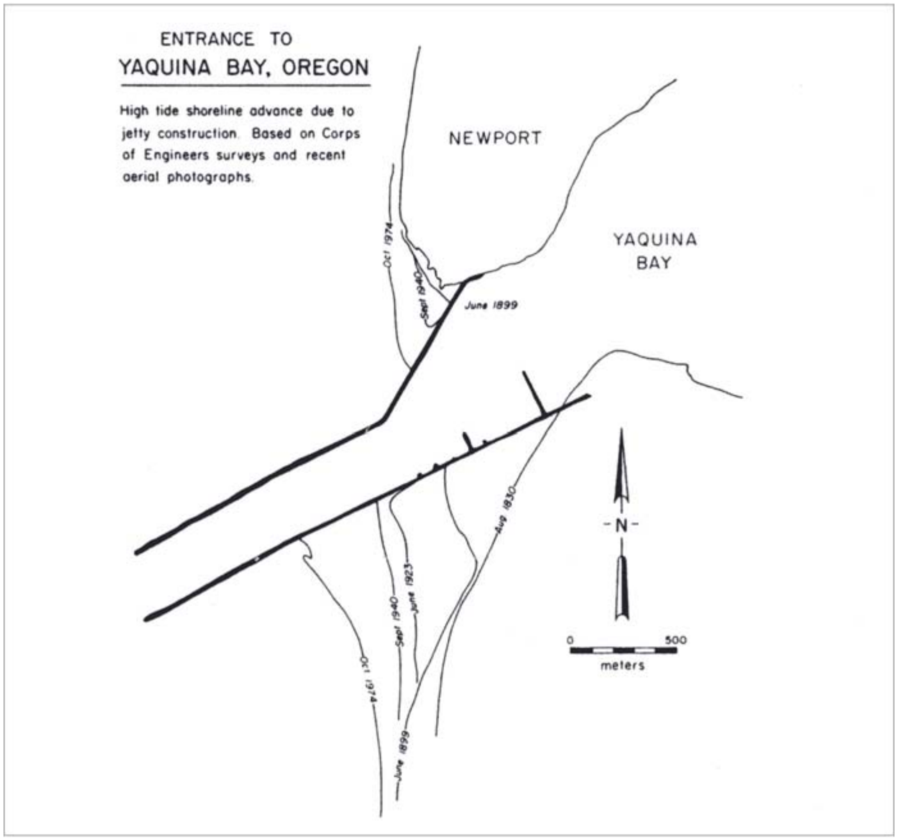

Figure 6-3 Shoreline changes resulting from the construction of jetties on the entrance to Yaquina Bay on the Oregon coast. [*from* Komar et al. (1976)]

It is seen in the Yaquina Bay example, Figure 6-3, that the shoreline advance can continue for decades, although most of it takes place in the first few years following construction, and it was even the experience at the time of the construction that initially the shorelines built out as fast as the jetties were extended. However, eventually the shorelines adjacent to the jetties built out to the extent that they achieved a new equilibrium, and are now relatively stable. As a result, the shoreline erosion induced by constructing jetties on the Oregon coast was limited to the early decades of the 20th century immediately following their construction, and has not been a continuous problem as experienced on coasts where the jetties or a breakwater block a net longshore drift of beach sediments as depicted in Figure 6-1 (upper).

It can be difficult at specific sites to distinguish between the two cases illustrated in Figure 6-1, to establish whether or not the observed shoreline changes are due to jetties blocking a net longshore transport of beach sediment. This is illustrated by jetty construction on the inlet to Tillamook Bay, Oregon, further complicated by the fact that initially, in 1917, due to a lack of funds only a north jetty was installed (Komar et al., 1976; Komar, 1997). As illustrated in Figure 6-4, the resulting general pattern of shoreline change was much like that in Figure 6-1 (lower) for the case of constructing a pair of jetties, with significant sand accumulation to the north of the Tillamook jetty, but with an extensive shoal forming to the south within the inlet rather than the sand having been trapped adjacent to a south jetty. This resulted in more extensive erosion of Bayocean Spit than would have occurred had a south jetty been constructed, resulting in the complete loss of the resort community of Bayocean Park that had been developed on the spit. In studying this erosion problem, the U.S. Army Corps of Engineers misinterpreted the pattern of shoreline changes as having been comparable to that in Figure 6-1 (upper), concluding that the jetty had blocked a net longshore sand transport of 600,000 cubic metres per year toward the south. In our later reanalysis, by recognizing the existence of the expanded shoal to the south of the Tillamook jetty (Figure 6-4) and the similarity to the shoreline changes on other Oregon inlets which conformed to the pattern of Figure 6-1 (lower), we concluded that there must be a net zero longshore transport of beach sand in this littoral cell (Komar et al., 1976).

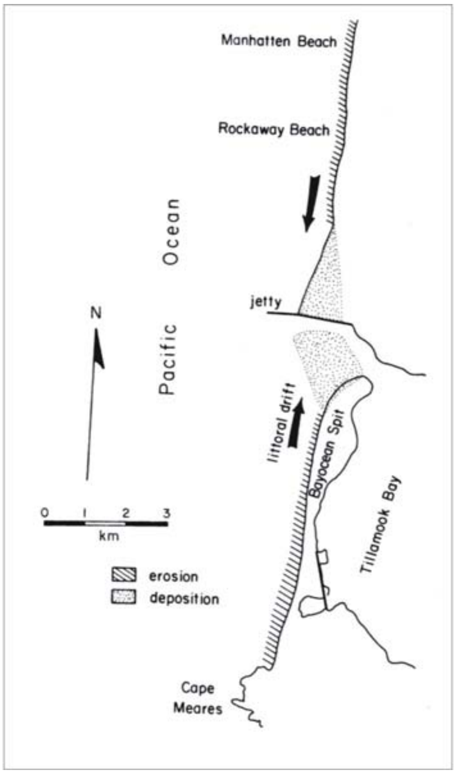

Figure 6-4 The pattern of erosion and sand deposition in response to the construction in 1917 of the north jetty on the inlet to Tillamook Bay, Oregon. [*from* Komar (1997)]

As will be reviewed below, these contrasting patterns of shoreline change where jetties do or do not block a net longshore transport of beach sediment have relevance to the interpretation of the coastal responses to the construction of the moles on the inlet to the Ahuriri Lagoon in 1876-1879. The challenge to the interpretation there is compounded by the lack of detailed surveys of the shoreline responses, which had been available in our study of the Oregon jetties.

Where natural estuaries or bays are unavailable or of inadequate size for the development of a harbour, the focus instead has commonly become the construction of a breakwater on the open coast. This generally took the form of an arched structure consisting of large rocks or artificial units such as massive concrete dolos, attached to the shoreline at one end and curving outward and then more nearly parallel to the shore towards its end to provide inshore sheltering from the waves. Ships could enter the harbour through a gap on the far side of the breakwater. This configuration is illustrated by the breakwater constructed in 1927-28 on the shore of Santa Barbara, California , Figures 6-5 and 6-6. This breakwater also provides an excellent example to consider with respect to the potentially negative impacts to the adjacent shorelines, both because they were well documented (Johnson, 1957) and because the structure has the same general form as the Port of Napier's breakwater, although their settings are very different.

Figure 6-5 The Santa Barbara breakwater, California, with sand accretion on its updrift side and within the harbour entrance as a spit of sand. [Photo courtesy of Prof. Robert Wiegel]

Figure 6-5 is an early photograph of the breakwater, while Figure 6-6 documents the rapid shoreline changes that were experienced during the decade immediately following its completion. The waves arrive predominantly from the west, producing a longshore sand transport to the east, estimated to average about 215,000 cubic metres per year. The breakwater interrupted that longshore transport, and resulted in rapid accretion along its updrift side, visible in the photograph of Figure 6-5 and documented by the series of shoreline surveys in Figure 6-6 that show a rapid seaward shift of the shoreline from 1930 to 1937. Sand accumulated to the west of the breakwater until the updrift area was entirely filled, after which the sand moved along the arm of the breakwater and deposited as a tongue or spit into the quiet water of the harbour opening. Without dredging the spit would eventually have grown across the harbour mouth, attaching to the opposite shore and closing off the entrance. Had this been allowed to occur the entire littoral transport of sand would then have passed around the breakwater, and a new equilibrium shoreline would have been achieved. However, to prevent closure of the harbour, dredging of the spit was initiated in the 1940s and has been in continuous operation since that time. The dredge has become a permanent resident of the harbour, removing sand accumulating on the spit that extends beyond the tip of the breakwater, with the dredged sand then pumped onto the beach to the immediate east of the breakwater, placed there to replenish the sand on the downdrift beach that had been lost by the blockage of the longshore transport. This continuous bypassing of the sand around the harbour is important in that its blockage had resulted in significant erosion for many kilometres in the downdrift direction, first through the loss of the beach itself and then the extreme impacts to shore-front properties.

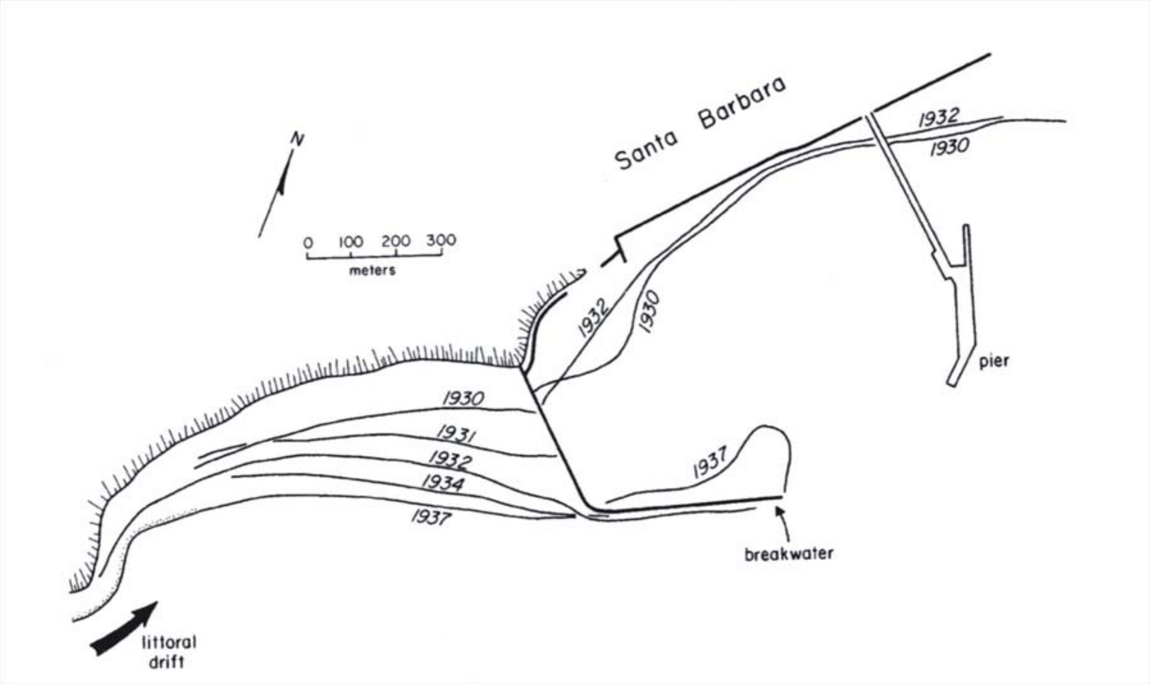

Figure 6-6 Shoreline changes from 1930 to 1937 following the completion of the Santa Barbara breakwater in 1927, documenting the rapid accumulation of sand to its west, the updrift side of the breakwater. [*after* Johnson (1957)]

A prime example of the shoreline changes and erosion problems that can result from breakwater construction having blocked a net longshore sediment transport are those that occurred at the Port of Timaru on the South Island. The changes there have been documented by the study of Tierney (1977), with Kirk (1992a, 1992b) having expanded the analyses and reported on the subsequent changes resulting from a later alteration in the breakwater. When originally settled in the mid-19th century, Timaru lacked an estuary or bay to serve as a harbour, so initially boat landings were made directly on a shingle beach that lined the shore of this otherwise resistant basalt-rock stretch of coast. The beach landings were limited to the north side of the headland, which offered some shelter from the highest waves that arrive from the southeast, where the city's Visitors Center is now housed in the original port warehouse, and with the former beach now being well inland beneath the adjacent parking lot. In 1878 construction began of a concrete-block breakwater on a line northeastward from this shore, and by 1887 the structure extended for a total length of 700 metres, with the last 215 metres shifting to a northerly direction to provide greater protection from the waves. Throughout this construction phase gravel built up rapidly on the south side of the breakwater, clear evidence for a significant northward transport of sediment along the Timaru beach. At the same time fine sand accumulated in Caroline Bay to the north of the breakwater, due to the protection offered by the structure such that the Bay has only a narrow window to small waves arriving from the northeast. In response to these shoreline changes, with the accumulating gravel and sand threatening to close the harbour's entrance in spite of annual dredging, the breakwater was extended in 1915 by another 915 metres, and a lee mole was constructed from the shoreline to prevent the entry of sand from Caroline Bay into the harbour. This progressive expansion of the Timaru breakwater is documented in Figure 6-7(a) from the study of Tierney (1977) and Kirk (1992b), with Figure 6-7(b) showing the major areas of sediment accumulation versus erosion, with the dashed shoreline being that prior to the breakwater construction. The most significant sediment accumulation occurred south of the breakwater, forming what is now South Beach, and also the area of the fine sand beach that formed in Caroline Bay. Between 1878 and the study of Tierney (1977) based on a 1967 survey, about 80 hectares of new land had formed in response to the construction of the Timaru breakwater, the darkened area identified in Figure 6-7(b). The shoreline shifted seaward along section B-B on South Beach by 500 metres between 1878 and 1967, while the sandy beach in Caroline Bay (A-A) advanced by 300 metres.

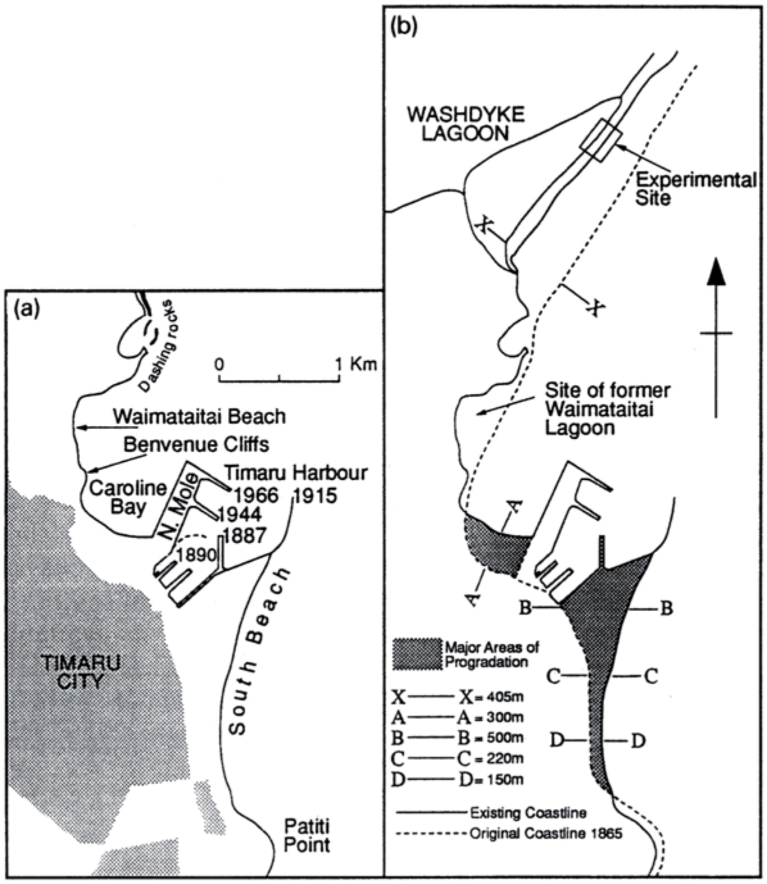

Figure 6-7 (a) The phases of construction of the Timaru Harbour breakwater, and (b) the areas of sediment accumulation and shoreline changes that occurred between 1879 and 1967. [*from* Tierney (1977) and Kirk (1992b)]

It is apparent that these shoreline changes were a response to the breakwater having blocked a net south-to-north transport of sediment on the Timaru beach, with the gravel at least initially having been completely blocked by the breakwater so it accumulated in South Beach. Tierney (1977) found that 5,310,000 cubic metres of gravel had been deposited at South Beach, representing an average annual northward net transport rate of 60,000 m^3/year. Some 2,745,000 cubic metres of sand had accumulated in Caroline Bay between 1878 and 1967, representing an average rate of 31,000 cubic metres per year. However, it is the very fine sand found offshore from the Canterbury beaches that accumulated in this Bay, not the coarser sand that is present in the beaches, so the formation of the Caroline Bay beach represents that fine sand having drifted into the area sheltered by the breakwater, not the bypassing of the coarse sand found on the beach to the south of the breakwater.

Kirk (1992a) reported on the construction of a spur groyne at the end the breakwater, placed transverse to the gravel that was being transported along the length of the breakwater, to prevent its being deposited in the harbour entrance where it had to be dredged. This groyne successfully blocked the transport and built out a beach along the entire length of the breakwater, protecting it from the damaging forces of the waves, and also reorienting the shoreline so the longshore transport of gravel was reduced from 60,000 cubic metres per year prior to the construction of the spur groyne to about 40,000 cubic metres per year.

Kirk (1992b) documented the downdrift erosion experienced to the north of the Timaru breakwater, and the development of an experimental beach nourishment program at Washdyke Beach where the erosional retreat of the shoreline has been greatest and threatens the loss of wetlands and commercial developments. This stretch of coast had experienced some erosion prior to the construction of the Timaru breakwater in 1879-1915, but it greatly accelerated following the construction. This is evident in Figure 6-7(b) where the pre-construction 1865 shoreline is compared with what is essentially the present-day shore. Just north of Caroline Bay a gravel beach ridge had stretched toward the northeast, but with the construction of the breakwater this downdrift beach lost its source of gravel arriving from the south and began to erode at a rapid rate due to the continued transport of its gravel to the north, with some loss also due to abrasion of the greywacke gravel. The loss of this sediment lowered the height of the beach ridge, increasing washover events to the backshore and the rate of the "rolling over" landward migration of the beach ridge. The Waimataitai Lagoon just north of Caroline Bay was lost during the 1930s, and this stretch of shore up to and along Dashing Rocks is now exposed to the direct forces of the waves, and has had to be protected by massive rock revetments. The most extensive erosion has occurred at Washdyke Beach, the most severe in New Zealand both in terms of the physical losses caused by the rapid retreat of the barrier beach and of the assets being threatened, a lagoon, the City's sewer outfall, and commercial developments. The progressive retreat in the shoreline is shown in Figure 6-8 from Kirk (1992b), the erosion from 1865 which pre-dated the construction of the breakwater to a surveyed shoreline 1934, and then as photographed in 1985. The roll-over landward migration of the beach ridge has progressively reduced the size of the Washdyke Lagoon; in 1881 the Lagoon had an area of 253 ha, but by 1955 its area had been reduced to 79 ha, and in 1984 the area was only 48 ha, an 88% reduction (Kirk, 1992b).

There has been a marked variation in the rates of erosion along the Washdyke Beach over time, from less than 2 m/year late in the 19th century, up to 9 m/year during the latter part of the 20th century (Kirk, 1992b). North of the Washdyke Lagoon the average shoreline retreat rates are 2.5 m/year, and are reduced still further to the north, down to an average of about 1.5 m/year, which is essentially the regional average for the erosion along the Canterbury coast. This is the typical pattern of beach erosion downdrift from jetties and breakwaters, initially occurring most rapidly in close proximity to the structure, but with delayed responses further from the structure due to the sediment being supplied from the area of maximum shoreline retreat. The cumulative sediment losses downdrift from the Timaru breakwater have therefore been considerable. According to Kirk (1992b), beach-profile surveys carried out since 1977 indicate an average net loss of 228 cubic metres per year of beach sediment from each metre or shoreline length; along the full stretch of coast from Washdyke to the Opihi River, this represents a total loss of 2.62 million cubic metres per year.

A primary objective of the Kirk (1992b) study was the development of an experimental project to undertake beach reconstruction and sediment renourishment along a 300-metre stretch of the Washdyke Beach. The purpose of this local project was to provide temporary protection for the city's sewage outfall until it could be relocated, and to evaluate this approach for shore protection to be applied to the full 3-kilometre length of the Washdyke barrier. The project involved elevating the beach ridge heights by 2.0 to 2.5 metres to reduce occurrences of wave overtopping and the washover of the beach sediment. The beach reconstruction was monitored for five years, and it was found that erosion rates were reduced by about 55% with no retreat of the reconstructed beach crest, and there were no overtopping events. In contrast, the neighboring untreated beach ridge retreated between 11.5 and 22.5 metres during the experiment. The results of this test therefore illustrated the success of shore protection by beach reconstruction and nourishment on coasts composed of mixed sand-and-gravel beaches.

Figure 6-8 A 1985 oblique aerial photograph of the eroding Washdyke Beach, with the positions of the pre-breakwater 1865 shoreline and that in 1934 surveyed about 40 years following the breakwater construction. [*from* Kirk (1992b)]

6.3 HARBOUR DEVELOPMENT AT HAWKE'S BAY AND ITS ENVIRONMENTAL CONSEQUENCES: A RE-EXAMINATION

The construction of the Ahuriri moles (jetties) in 1876-1879 and the Port of Napier's breakwater in 1887-1890 was reviewed in Section 3 as part of the early development of the Hawke's Bay region. It was extremely important to have a commercial harbour, initially for the export of wool and later for agricultural commodities, and for the import of the many items needed by the expanding population. Section 3 examined the environmental impacts that resulted from this early settlement and population growth, including the progressive deforestation of the river watersheds caused by both the Maori and Europeans, and the extensive extraction of sand and gravel from the river channels and from the beaches along the Hawke's Bay shore. It was concluded that these human-induced impacts were extensive during the early period of settlement, and continue today. While it was noted in Section 3 that the construction of the Ahuriri moles and then the Port's breakwater may also have had adverse consequences for the coast, possibly having caused shoreline erosion in the Bay View Littoral Cell, an assessment of that possibility was deferred until after we could first review (Section 4) the ocean processes of waves, tides and sediment transport that may have been altered by the harbour development, and the responses of the mixed sand-and-gravel beaches to those processes (Section 5). Such an assessment of the potential harbour impacts on the coast of Hawke's Bay can now be undertaken.

Diverse opinions have been expressed with respect to the degrees of environmental change resulting from the construction of the Ahuriri moles and then the breakwater, opinions offered by scientists and engineers who have been involved in studies of the Hawke's Bay coast. At the same time, individuals within the general public have forcefully maintained that the Port has been responsible for their beach erosion problems, specifically at Westshore. However, in some cases these opinions held by scientists and the general public appear to have been arrived at with little or no actual investigations of the causative processes and history of shoreline responses. Often it has been simply assumed that like so many other examples throughout the world of downdrift erosion caused by the construction of jetties or a breakwater, the harbour development at Napier had the same consequences. But as reviewed above, such a simple interpretation may in some cases be erroneous.

The range of interpretations by coastal scientists and engineers is illustrated in the reports written by Smith (1968, 1993), O'Callaghan (1986), Gibb (1996), and Kirk and Single (1999), wiith the majority of those studies having focused on the causes of the beach erosion experienced at Westshore. In his university thesis research investigating the gravel in the Hawke's Bay beaches, Smith (1968) maintained that the construction of the Port's breakwater at Bluff Hill had cut off the supply of gravel to the Bay View Littoral Cell (which he termed North Beach). This opinion is repeated several times in his thesis that otherwise dealt with the abrasion and sorting of the gravel on the beaches (Section 5), but Smith presents this opinion as an *a priori* assumption rather than offering any analyses or providing a discussion to justify this belief. With respect to his study of the beach sediments, having found differences between the gravels in the two littoral cells north and south of Bluff Hill, Smith (1968) concluded that the two cells are now separate entities, but he further associated this separation with the construction of the breakwater in the late 19th century; as will be discussed below, this is a doubtful assumption. Nearly twenty years later, in a study of the causes of erosion at Westshore, Smith (1986) undertook a more detailed analysis that included the history of the erosion problems at Westshore. In that study he was less emphatic concerning the causes, concluding that it was a mix of human-induced factors, including the fact that local construction around Napier had extracted large volumes of gravel from the beach, which locally resulted in its degradation. With respect to the impacts of the breakwater, Smith (1986) emphasized that these beaches were "nearly stripped of material used in constructing the breakwater", rather than placing the blame directly on the breakwater having blocked a northward movement of the beach sediment that presumably had bypassed Bluff Hill. In a still later study of the erosion at Westshore, Smith (1993) returned to his unqualified view that the "erosion of Westshore commenced with the construction of the Breakwater Harbour" due to its having "prevented the supply of new material to Westshore Beach". As will be reviewed below, in this study Smith did provide an analysis of the shoreline changes and erosion from 1889 to 1925 immediately west of the Ahuriri moles, inferred to reflect the downdrift erosion, but his analysis of the average annual changes in profiles in the Westshore area from 1916 to 1984 demonstrated the occurrence of reversing directions in the gravel transport along that shore, presumably due to changing wave directions, with perhaps at most only a very small net longshore sediment transport toward the west and then to the north.

O'Callaghan (1986), a European coastal engineer, also analyzed the erosion that had occurred at Westshore and similarly attributed it entirely to the breakwater: "The erosion in this area was almost certainly due to the effects of the new breakwater construction for the harbour in 1887." He noted the accumulation of sediment to the south of the breakwater and suggested: "The accretion process at the breakwater is nearly completed and so the quantity of material passing the breakwater and the grain size of that material can be expected to increase in the future." However, as will be reviewed below, even though a century has passed since the construction of the breakwater and twenty years since this prediction by O'Callaghan, there is still no sign of the beach gravel having bypassed the breakwater and entered the Bay View Littoral Cell. With respect to placing the Westshore erosion into perspective, it is of interest that O'Callaghan (1986, p. 7) concluded that the erosion at Westshore: "has not been severe in coastal engineering terms" and is "relatively minor".

Gibb (1996) presents the most detailed review of the historic documents and surveyed shoreline changes in support of his conclusion that the construction of the Ahuriri moles and then the Port's breakwater blocked a net northward transport of beach gravel that had bypassed Bluff Hill, and that the erosion at Westshore can largely be attributed to this cause. He forcefully stated this conclusion (Gibb, 1996, page 11):

> The greatest impact of both Maori and European occupation on the 10 km long study barrier coastline has been to significantly reduce the net northerly longshore drift of sand and gravel into and along the barrier system and caused a realignment of the foreshore at Westshore.

On the other hand, Gibb (1996, p. 11) readily acknowledged the uncertainty in his interpretation: "No evidence exists to either confirm or deny this opinion." Gibb's specific analyses related to the environmental impacts of the Ahuriri moles and the Port's breakwater will be reviewed below.

Kirk and Single (1999) provided the most forceful arguments against the construction of the Port's breakwater having been responsible for the erosion at Ahuriri and Westshore:

> The fact is that erosion of what is now Westshore is known to have been occurring long before Port Napier was built. Indeed, it was occurring before the Ahuriri Entrance was constricted by Moles and shoreline change was greatly accentuated once they and associated dredging activities occurred. This fact is significant because recent opinion, forcefully advanced, has favoured the over-simple notion that erosion at Westshore is the outcome wholly or mostly of harbour construction at Port Napier. In the view of the present authors this "causative connection" is NOT "scientifically established". Indeed, the preponderance of evidence presented above is already and quite clearly contrary to such a simplistic view.

The evidence presented by Kirk and Single (1999) included the historic accounts of Saunders (1882) and Carr (1893) as to the early erosion at Westshore, prior to and immediately following the harbour construction. They also reviewed a list of thirteen other factors, natural and human induced, that likely had been involved in causing the erosion, including such things as the human impacts in the watersheds on the sediment supplies and the effects of the 1931 earthquake, pointing to our still inadequate understanding of their roles and relative significance in bringing about changes in the Hawke's Bay coast.

The objective here is to revisit these issues. Like those previous studies the reliance again will have to be mainly on the historic documents, but with the interpretation guided in the light of the impacts experienced by the construction of jetties and breakwaters on other coasts, those reviewed above. This task is not simple since adequate information is not available concerning the details of shoreline responses based on frequent surveys undertaken at the time of the harbour construction, and there is only anecdotal information regarding dredging activities that would also have been important to the environmental changes. There is even relatively little firm documentation of the erosion that was experienced during those early years of harbour development. The review undertaken here follows in chronological order the environmental conditions prior to any harbour development, followed by the effects of constructing the Ahuriri moles, and finally an examination of the possible impacts of the Port's breakwater.

6.3.1 *The Pre-Construction Environmental Conditions*

In 1882 F. Saunders, the Chief Engineer of the Napier Harbour Board, wrote the earliest technical report concerned with the possible impacts of the harbour development. This report was timely as it was completed three years after the construction of the Ahuriri moles, and five years prior to beginning work on the breakwater. The focus of his analyses and report were therefore on the pre-construction "natural" conditions and the observed changes immediately following the construction of the moles.

In connection with his analysis of the shoreline changes prior to the construction of the moles, Saunders (1882) commented:

> . . . from 1855 until the training groins [the Ahuriri moles] were erected at the entrance, the distance between the Eastern and Western Spits gradually increased from 380 to 960 feet at low water. The widening of the channel was principally caused by the limestone boulders being taken from the Western Spit as ballast for vessels, which practice was allowed until 1860. The shingle thus left unprotected was gradually worn away by the action of the tides.

Saunders also concluded from his shoreline analysis that the sea cliff along the Lighthouse Reserve on Bluff Hill had experienced considerable erosion, thereby exposing the Western Spit more to the action of storm waves arriving from the south and southeast. If true, this would have had an erosional impact on the Hardinge Road shoreline to what is now Westshore. Saunders also noted that there had been considerable changes in the beach between the Bluff and the Ahuriri entrance, with cycles of erosion and accretion. He described the composition of that stretch of shore: "This beach is composed of shingle with limestone boulders scattered through it, and a base of boulders below low water." Saunders' (1882) observations of the shoreline changes at the time of the construction of the Ahuriri moles will be considered in the following section.

Also important are the early observations of Carr (1893), the Harbour Board Engineer. His report came three years after the completion of the Port's breakwater, and as indicated by the title of his Memorandum, it was prepared in response to a petition from the residents and property owners living on the Western Spit due to the "denundation" of the beach, which they presumably blamed on the breakwater's construction. Like Saunders, Carr examined the shoreline changes that had occurred there, and found that the records showed that the Western Spit had gradually eroded from 1854 to 1876, that is prior to even the construction of the moles, but that following their construction in 1876-1879 accretion and shoreline progradation had occurred. As will be reviewed below, Carr recognized that the post-construction changes were at least in part due to harbour dredging and the placement of those sediments on the Western Spit beach. He commented: "A reference to the records in this office shows that prior to 1882 there was no outer beach at the Western Spit and that where the Freezing Works now stand was water." Carr further concluded that: "The records show that prior to the construction of the Moles at the Spit, that portion of the Western Beach now under consideration was gradually being encroached upon, from 1854 to 1876. . ." According to Campbell's (1975) history of Napier, the North British and Hawke's Bay Freezing Works had been constructed in 1886, seven years after the construction of the Ahuriri moles and one year prior to initiating construction of the breakwater, and from Carr's analysis it appears that the Freezing Works were unfortunately located along a shoreline that four years earlier had been under water.

As discussed earlier in Section 4.7 where the directions and magnitudes of the net longshore sediment transport under the action of the waves were reviewed, it was found that one can expect significant variations in the volumes of beach gravel along the ocean shore of Ahuriri and at Westshore, due to its location at the south end of the Bay View Littoral Cell. With subtle changes in wave directions and intensities of storms from year to year, and from decade to decade perhaps associated with climate changes such as El Niños versus La Niñas, there could be accompanying reversals in the directions of the net longshore sediment transport, with periods during which the net transport was to the south and resulted in beach sediment accumulation at Westshore, reverting to periods with a net northward transport of beach sediments and extensive erosion. Such reversals have in fact been demonstrated by Smith (1993) in his analyses of beach-volume changes documented by profile surveys collected along Westshore from 1916 to 1984; these have been reviewed in Section 4, with his analysis results presented in Table 4-9. Although the beach profiles he relied on in his analyses were surveyed well after the construction of the moles and breakwater, we can be certain that the yearly to decadal cycles of erosion versus accretion he found are indicative of those experienced along Westshore prior to and immediately following the harbour development. Of particularly interest in the results from Smith's (1993) analyses is the demonstration of major shifts experienced between net beach erosion versus net accretion along Westshore; for example, between 1955 and 1956 there was 40,000 m^3/year accretion, but the following year this was reversed by 40,100 m^3/year of erosion. Those total volumes of sediment erosion and then accretion equated to about 10 cubic metres of sediment per metre of shoreline length, which would represent significant shifts in the shoreline positions, with it having moved seaward between 1955 and 1956, and then retreated between 1956 and 1957. Although this is an extreme example in the results found by Smith (1993), with the cycles between erosion and accretion more typically involving rates of 4 to 8 m^3/year per metre of shoreline length, of interest is that the cycles between predominant erosion versus accretion generally involved longer periods of time, with a decade dominated by accretion followed by a decade of net erosion. With such strong cycles between periods of net accretion at Westshore followed by erosion, one can perhaps understand how the Hawke's Bay Freezing Works could have been constructed in 1886 on "land", but in an area that had been under water prior to 1882, and soon after its construction the Freezing Works was threatened by a return of beach erosion when the cycle reversed. According to Campbell (1975), the Freezing Works was torn down in 1930.

Particularly relevant to the degree of beach erosion versus accretion at the south end of the Bay View Littoral Cell, including Westshore, is the question of whether or not beach gravel was able to bypass Bluff Hill prior to the construction of the breakwater, carried by the waves from the Haumoana Cell into the Bay View Cell. This is the critical question with respect to interpretations of the causes of beach erosion at Westshore, with the diverse opinions amongst coastal scientists and engineers noted above. There is not a simple and direct answer to this question, as it involves the sources of the sediments on the beaches of these littoral cells, the basic differences in their grain sizes, shapes and degrees of rounding by abrasion, and ultimately an interpretation of the shoreline changes when the Ahuriri moles were constructed.

The question regarding the sediment sources was considered by Saunders (1882) in his report completed three years after the construction of the Ahuriri moles but prior to the breakwater. Of particular interest to him was the origin of the gravel on the beach of the Bay View Littoral Cell. He noted that while the Esk River flowed into the Ahuriri Lagoon at that time and therefore was not contributing gravel to the ocean beach, during major floods it was able to break out of the Lagoon and flow directly into Hawke Bay. However, as will be reviewed in Section 7, the general assessment is that the Esk River is not a major source of beach gravel. Saunders also considered the Tutaekuri River as a source of gravel to the Bay View Cell, since at that time it entered the Ahuriri Lagoon near the inlet and was known to experience periodic flooding. However, Saunders observed that: "The Tutaekuri is shingle bearing as far as the south side of Meeanee, but at present no shingle is carried below that point." It was known that under natural conditions the Tutaekuri River periodically switched courses, at times entering the Lagoon and at other times flowing into Hawke Bay to the south, sometimes first joining the Ngaruroro River as it does at present. However, it is possible that in the past, prior to European settlement, the Tutaekuri flowed into the Lagoon for sufficiently long periods of time that it was able to transport some gravel into the Lagoon, where it could then be carried by the tidal currents out onto the nearby ocean beach.

Of the rivers reaching Hawke Bay, Saunders (1882) recognized that the Tukituki River was potentially the primary source of beach gravel, at least for the Haumoana Littoral Cell: "The Tuki Tuki carries large masses of shingle into the Bay, which are afterwards thrown upon the beach and carried northward by the sea." The question is whether any of that gravel, plus gravel supplied by sea cliff erosion at Cape Kidnappers, was transported to the north and eventually able to bypass Bluff Hill to reach the Bay View Cell, perhaps even having been its primary source of gravel. Answering that question is difficult as it involves knowing the actual quantities of gravel contributed by the Tukituki River and from sea cliff erosion, centuries in the past prior to the impacts of humans in the river watershed (Section 3), at the time of harbour construction a century ago, and also at present. It also requires assessments of the losses of the beach gravel by abrasion while it was being transported to the north, and the quantities required to build up the elevation of the beach along the length of the Haumoana Cell to offset the general subsidence of that shore that would produce a rise in the relative sea level. A consideration of these multiple factors requires the development of a sediment budget, as will be reviewed in Section 7, a difficult task such that we are not even positive concerning the present-day sediment contributions and losses on the beaches, much less being able to evaluate what they were more than a century ago prior to the construction of the Ahuriri moles and Port's breakwater.

Also relevant to answering these questions are the observed differences in the grain sizes, shapes and degrees of roundness of the gravels on the beaches of the Haumoana and Bay View Littoral Cells. Analyzing these differences and alongshore sorting patterns were the objectives of the research investigations by Marshall (1929) and Smith (1968), reviewed at length in Section 5. Smith (1968) in particular concluded that the differences in those sediment properties demonstrates that the these two littoral cells are now separate entities; specifically, he found that the gravel particles in the Bay View Cell are both more uniformly smaller and more highly polished compared with the gravel on the beach of the Haumoana Cell. From those differences Smith concluded that the Bay View gravel must represent an "old" deposit where the particles have been affected by the abrasive action of the waves for a long period of time, in contrast with the Haumoana Cell where "new" gravel is being contributed by the sources and so has not achieved the same degree of uniformly small sizes and surface polish by abrasion. As pointed out above, Smith (1968) had made the *a priori* assumption that gravel had been able to bypass Bluff Hill prior to the construction of the Port's breakwater in 1887-1890, so it necessarily followed that he would conclude that the isolation between the beaches of the two littoral cells had not occurred until the time of breakwater construction, and that by "old" with reference to the Bay View gravel he meant something on the order of 75 years, the period of time between the construction of the breakwater and his study of the beach gravels. As discussed in Section 5, it is questionable whether the beach gravels in the two littoral cells could have evolved to the extent observed in such a short period of time, producing the observed differences in their grain sizes, shapes, degrees of surface polish, and in their well developed longshore sorting patterns. An alternative interpretation is that Bluff Hill did represent a reasonably effective barrier between the Haumoana and Bay View Littoral Cells prior to the construction of the breakwater, providing a longer period of time for the development of the observed differences in gravel properties.

Based on such circumstantial evidence, it is not possible to establish with a high degree of certainty whether or not beach gravel was able to bypass Bluff Hill prior to the construction of the Port's breakwater in 1887-1890, that bypassing had been a significant source of gravel to the Bay View Littoral Cell. The situation may have been comparable to that presently found in the Canterbury Bight, where in spite of significant contributions of gravel by the large rivers and from extensive sea-cliff erosion, supporting an appreciable net northward transport of gravel along the beaches, none of that gravel bypasses the Banks Peninsula at the north end of that littoral cell; the interpretation is that the northward transport of that greywacke gravel is instead consumed by is abrasion, converted it into fine sand and silt that is lost into the offshore. The possibility of having had such an equilibrium balance in the Haumoana Littoral Cell between the gravel sources and abrasion losses, affected also by other components in the sediment budget (Section 7), is supported by the fact that at present with the breakwater acting as an extended headland, an equilibrium has been maintained with no evidence for gravel having bypassed the breakwater during the century since its construction.

As reviewed in Sections 3 and 7, there is clear evidence for long-term variations in gravel contributions from the rivers, specifically from the Tukituki River. There would also have been annual to decadal variations in the net northward gravel transport along the beach of the Haumoana Littoral Cell, due in particular to the sizes of the storm waves that dominantly arrive from the south to southeast. Thus, any balance within the sediment budget would have represented a quasi-equilibrium condition, and there would have been years during which the rivers supplied larger than average quantities of beach gravel or there could have been occasions of unusually extreme storms from the southeast resulting in a "slug" of sediment movement to the north. With this likely scenario, it is possible that occasionally gravel could have accumulated at the north end of the Haumoana Cell, along the present-day Marine Parade beach, with some gravel carried around Bluff Hill to reach the Bay View Littoral Cell. There is circumstantial evidence for such episodic bypassing of the gravel, which I have reviewed in Section 3 based on the 1873 chart (Figure 3-3) that shows the East Spit (Hardinge Road shore) and its relationship to the rocky shore of Bluff Hill. The Spit itself is identified as being a "Shingle Bank", which could be accounted for by shingle having arrived from the northwest under the reversing directions of transport and cycles between erosion and accretion described above. More suggestive, while the shore of the Bluff Hill headland is shown as consisting of scattered rocks with sand in the offshore, at two localized sites on the shore the chart records the presence of shingle, probably confined to pockets between the rocks. Although there may be other explanations for the presence of shingle having been found locally along the shore of Bluff Hill as recorded on that 1873 chart, it does suggest that at least episodically beach gravel was able to bypass this headland from the Haumoana Cell to the Bay View Cell. The quantities involved were not likely to have been large, and the bypassing of "slugs" of gravel may also have been limited to only one or two years, with many years between when there was no bypassing. It is also likely that the gravel carried around Bluff Hill to reach the Ahuriri beach would have been dominated by the smaller grain sizes, since the larger gravel particles would preferentially have been located at the top of the beach profiles along the Haumoana shore, therefore tending to remain behind while the finer gravel sizes moved around the headland; this could account in part for the contrasting gravel sizes in the two cells as found by Smith (1968). The fact that the Bay View beach gravel is also "old" as characterized by Smith due to its uniform grain sizes, shapes and degrees of surface polish, indicates that there could not have been large quantities of gravel bypassing Bluff Hill, but instead it must have involved only relatively small volumes supporting at most a small net longshore transport to the north along the shore of the Bay View Littoral Cell, a transport that would also have varied from year to year, and in many years not have occurred at all.

This interpretation, suggesting a small degree of gravel having periodically bypassed Bluff Hill prior to the construction of the Port's breakwater, is different from the opinions offered by Smith, O'Callaghan and Gibb; they apparently envisioned significantly greater volumes of gravel having bypassed Bluff Hill, sufficient to have supported a substantial northward transport of gravel along the Hardinge Road shore and Westshore, such that its blockage by the construction of the Ahuriri moles and then later by the Port's breakwater had been the primary, according their interpretation, almost the sole cause of the erosion experienced at Westshore. My interpretation instead is that the evidence argues for there having been only modest inputs of gravel to the beach within the Bay View Cell, possibly derived in part from the episodic bypassing of gravel around Bluff Hill. With bypassing having been episodic, it raises the question as to whether gravel bypassing was actually taking place when the Ahuriri moles were constructed, whether at that time there was a longshore sediment transport to be blocked. These contrasting interpretations can potentially be tested through analyses of the shoreline responses to the construction of the Ahuriri moles and Port of Napier's breakwater, according to the differing shoreline changes illustrated in Figure 6-1 and discussed earlier.

6.3.2 *The Ahuriri Moles*

Moles (jetties) of rock were constructed on the inlet to the Ahuriri Lagoon in 1876-1879. It will be recalled that according to Saunders (1882), the removal of limestone boulders for use as ship ballast had resulted in the rapid widening of the entrance from 115 metres in 1855 to 293 metres in 1860; this likely also led to shoaling within the harbour entrance, making it more dangerous for navigation. The objective of constructing the moles would have been to again narrow the channel, with a mole spacing of 122 metres having been decided upon. That spacing would have strengthened the tidal currents flowing into and out of the lagoon's entrance, leading to its self scouring and a deepened inlet that would provide safer navigation.

In his report completed three years after the construction of the moles, Saunders (1882) provides the best first-hand observations of the initial changes in the shoreline positions in response to the movement of the beach gravel. From his account it is apparent that the response to the construction was very rapid: "The shingle gathered behind the work as fast as the piling was carried out, and large masses were also deposited in the channel." By September 1877 the rate of accumulation had slowed:

> . . . the work got ahead of the shingle which gathered at a much slower rate; but although the high-water line did not advance, the shingle at low-water line was spreading further out and by March 1879, the shingle was carried round the extremity of the mole. The shingle did not rest in the channel, but was carried by the currents clear of the Western Mole, and thence gradually worked on to the Western Spit.

If one were to interpret these observations as evidence that the gravel, which accumulated to the east of the moles, had resulted from the blockage of a longshore transport supported via bypassing of the gravel around Bluff Hill, then according to the analysis of Saunders (1882) the rate of longshore transport would have had to been as much as 65,000 yd^3/year (50,000 m^3/year) to account for the rapid accumulation. Such an immense volume for a longshore transport is not supported by analyses of the potential sources of gravel in the Haumoana Littoral Cell and estimates of the net northward transport along its shore (Sections 4 and 7). Furthermore, as reviewed earlier, this volume of bypassed gravel is comparable to that blocked by the Timaru breakwater where major shoreline changes have been the result; nowhere near the same responses occurred at Napier during either the construction of the Ahuriri moles or the breakwater. Furthermore, the improbability of a large volume of gravel having bypassed Bluff Hill at the time of construction of the Ahuriri moles is also indicated by Saunders' (1882) observation: "At present the beach near the Bluff and opposite the town of Napier is greatly reduced . . ." — that is, there was not a substantial accumulation of gravel on the beach south of Bluff Hill, along the Marine Parade, available to be bypassed around that headland to become a source of gravel for the transport along the Ahuriri shore and its accumulation east of the constructed moles.

More indicative of what actually happened in response to the construction of the Ahuriri moles is the observation by Saunders (1882) that beach accretion actually took place on both sides of the moles: "Since the erection of the present works [i.e., the Ahuriri moles] the shingle has accumulated behind the Eastern Mole right out to its extremity. The Western Spit has also considerably increased in width." This suggests that the shoreline changes were more like those in Figure 6-1 (Lower) depicting the effects of jetty construction on a coast where there is not a net longshore transport of beach sediment.

The report by Saunders (1882) also indicates that significant storms occurred soon after the completion of the moles, providing a test of their effectiveness in protecting the harbour from wave attack:

> Two or three times a year a "black north-easter" occurs, bringing heavy seas into the Bay that break clean over the eastern mole, although it is 7 feet above the high-tide level. It is the only conditions that represents danger to vessels in the Ahuriri port.

As expected, these storm waves resulted in the additional movement and redistribution of the previously accumulated beach gravel adjacent to the moles: "When the works were completed part of the Bar outside of the pier heads was swept away, but the part inside the pier was only reduced in level, the shingle being scoured away, but the boulders remained and form a scour-proof coating."

A continuation of an account of the beach changes adjacent to the constructed Ahuriri moles is contained in the report by Carr (1893). He reiterated that the records showed that the Western Spit had gradually eroded from 1854 to 1876 prior to construction of the moles, but that following their completion in 1879 the beach had accreted and shoreline progradation had occurred. Three years after their completion, beginning in 1882, there was additional accretion to the west of the moles with the formation of an outer sand beach due to the placement of dredge spoils derived from deepening the Ahuriri harbour. However, six years later in 1888 the placement of the dredge spoils discontinued, and the outer sand beach began to diminish. Carr noted that in the next five years the beach retreated by some 200 to 240 metres in the area of Westshore, but there had been little change evident further to the north. From this Carr (1893) concluded that:

> During those years the material dredged from the Inner Harbour was deposited behind the Western Mole and therefore no doubt largely assisted to form the outer spit or beach. In 1888 the depositing of the dredgings behind the Western Mole was discontinued and the outer beach rapidly began to diminish, so much so that the Freezing Co. had very soon to take steps to protect their works by running out groynes.

It will be recalled from the above review that Carr (1893) had noted: ". . . prior to 1882 there was no outer beach at the Western Spit and that where the Freezing Works now stand was water", and that the Freezing Works had been constructed in 1886. With the cessation in 1888 of placing the dredged sand to form a fronting beach and the accompanying erosion of the gravel beach as part of the cycle between accretion versus erosion discussed above, the occurrence of erosion along Westshore and the necessity of protecting the Freezing Works by the placement of shore protection structures should not have come as a surprise, and cannot be interpreted as having resulted from whole-scale beach erosion caused by the construction of the moles. As further confirmation, Carr also reported that the groynes built at Westshore to halt the erosion by trapping the longshore drift of beach sediment were unsuccessful since there apparently was little drift to be trapped.

From this history of shoreline changes and the inferred movements of beach sediments in response to the construction of the Ahuriri moles, my conclusion is that it was very similar to the changes produced by jetty construction on the Oregon coast reviewed above. From the descriptions by Saunders (1882) and Carr (1893), it appears that the shoreline changes in response to the construction of the Ahuriri moles were more akin to those diagrammed in Figure 6-1 (Lower) depicting the shoreline responses to jetty construction on a coast having a net zero littoral drift of beach sediment, not like those depicted in Figure 6-1 (Upper) where the jetties block a net longshore transport of sediment. It follows that the gravel, which had rapidly accreted on the beaches immediately east and west of the Ahuriri moles, was derived from the onshore movement of the bay-mouth bar, as has been found during jetty construction on the Washington coast and was likely also significant for the Oregon jetties. This would account for the very rapid rates of gravel accretion adjacent to the Ahuriri moles, with the beach building out as rapidly as the moles were extended; comparable rapid rates of beach sand accumulated during the construction of the Oregon and Washington jetties. In conclusion, there is no firm evidence that the construction of the Ahuriri moles in 1876-1879 blocked a longshore transport of beach gravel derived from sediment that was bypassing Bluff Hill; indeed, there is significant evidence to the contrary.

6.3.3 *The Port of Napier's Breakwater*

The Port's breakwater was constructed in 1887-1890, a decade after the completion of the Ahuriri moles. It has a design typical of breakwaters, with an arcuate shape that provides a large area of water sheltered from the high ocean waves. Construction began as a groyne-like projection extending eastward out from the Bluff Hill shore, but then bent toward the north to follow a trend that is essentially parallel to the orientation of the coast to its south; the length of this segment has progressively increased over the years, extended to increase the Port's facilities (Stevenson, 1977). Having this form, the constructed breakwater in effect extends the area sheltered from the waves that predominantly arrive from the south to southeast, beyond that naturally offered by Bluff Hill to the shore along Hardinge Road and for much of the length of Westshore. This pattern of sheltered shore was examined in Section 4 as the product of wave refraction and diffraction to the north of Bluff Hill and the breakwater. Of significance, analyses of those processes demonstrated that the construction of the breakwater resulted in the heights of the waves reaching Westshore being on the order of half their heights prior to the breakwater construction; this factor alone is evidence for the breakwater having protected Westshore from the erosive forces of the storm waves.

Alterations in the coastal environment produced by the construction of breakwaters are more complex than those caused by jetty construction. This was already apparent in the review offered in the first half of this Section, where we examined the shoreline changes produced by breakwaters constructed in Santa Barbara, California, and at Timaru on the South Island. In terms of the ocean processes, this complexity results in large part from the altered patterns of wave refraction and diffraction in the lee of the breakwater, accounting for the reduced wave heights that are desired to provide shelter to ships using the harbour, but also change the wave directions and breaker angles along the shore. These modifications of the wave heights and directions affect the resulting movement of the beach sediment, accounting for the patterns of observed shoreline changes. The sheltering of the shore by the breakwater produces a longshore gradient in the wave heights and energies, from the unsheltered region where the wave heights are greatest to the innermost sheltered area where the wave heights are lowest. It has been shown both theoretically and in physical laboratory models that this longshore gradient in wave heights can generate a longshore current that flows in the direction of decreasing wave heights, that is, inward toward the breakwater, resulting in the tendency for sediment to be carried into the sheltered region and deposited there (Gourley, 1974). In the case of the breakwater in Napier, the gradient in wave heights would tend to generate southward-flowing currents along the shore from Westshore toward Hardinge Road. However, either supporting that process or opposing it would be the pattern of the waves breaking at angles to the shore, which can also generate a longshore current. At shoreline sites where the breaking wave angles open in the direction of decreasing wave heights the two processes support one another, generating stronger currents that flow into the sheltered region of the breakwater; where they oppose, the current strength is weakened and the resulting direction is determined by which of these two processes dominates. From this it is apparent that the patterns of wave-induced currents can be complex, with their directions and magnitudes varying under the hourly to daily changes in wave conditions. In general, however, the creation of a wave-sheltered region by the construction of a breakwater usually results in the accumulation of sediment within the sheltered region, a shoaling of the harbour that requires periodic dredging.

In the case of the Port of Napier's breakwater, the results of these processes are complicated further by the fact that the beaches are mixed sand and gravel, with an offshore deposit of fine sand immediately seaward from the gravel beaches. It is likely that the greatest effect of these wave-induced longshore currents in the sheltered region of the breakwater would be on the sand component, the sand in the beach and in the immediate offshore, such that there is a tendency for the sand to be carried into the zone of maximum sheltering, that is, into the lee of the breakwater. To further establish this, detailed analyses would have to be undertaken of the patterns of wave refraction and diffraction produced by the Port's breakwater, to quantitatively determine the alongshore variations in wave heights and breaker angles, to assess the changing directions and magnitudes of the longshore currents, and finally to determine the resulting movements of the sand and gravel along the shore.

Any changes in the beach deposits and offshore sediments induced by the construction of the Port's breakwater in 1887-1890 need to be considered in view of these altered processes, and also in light of the documented patterns of erosion versus accretion seen in the earlier reviews of the Santa Barbara and Timaru breakwaters. The problem is that there is far less documentation of the changes that occurred during and after the construction of the Napier breakwater. Furthermore, as discussed above, following the completion of the Ahuriri moles in 1879 there was a period during which the practice was to dispose of the sand dredged from that harbour onto the beach to the northwest of the western mole, a practice that would have acted to form a sand beach in front of the gravel ridge, extending the shoreline seaward. This practice was halted in 1888 (Carr, 1893), corresponding in time with the early phase of constructing the breakwater, making it difficult to establish whether it was the breakwater or the cessation of sediment disposal that was most important to the erosion experienced at Westshore. To complicate the interpretation still further, the decade during which the breakwater was constructed was characterized by unusually severe storms, with the waves at times overtopping the completed sections of the breakwater (Stevenson, 1977). Those storms resulted in the extensive erosion of the Marine Parade beach and flooding of downtown Napier (Cambell, 1975); we can be certain that these extreme storms also played an important role in the simultaneous erosion at Westshore.

With the construction of the breakwater having begun in 1887 as a groyne-like projection extending eastward out from the Bluff Hill shore, as expected the first observed shoreline responses were to its south, with beach accretion extending from the breakwater southward along the Marine Parade. The sediment accumulation there has been interpreted as a result of the breakwater blocking a northward transport that previously had bypassed Bluff Hill. Analyses by Finch (1919), and repeated later by Fisher (1976), of the volumes of sediment that had accumulated to the south of the breakwater, led them both to an estimated longshore sediment transport rate of 6,000 m^3/year. It is seen that there is an order-of-magnitude disparity between this estimate and the 50,000 m^3/year estimate of Saunders (1882) based on the volume of gravel that had accumulated to the east of the Ahuriri moles when they were constructed. Recall also that having assumed that the constructed breakwater had blocked the gravel from bypassing Bluff Hill, O'Callaghan (1986) predicted that the gravel still arriving to its south would soon be able to bypass that obstacle and once again reach Westshore. This has not occurred, it instead being well established that more than a century after its construction the gravel still has not bypassed the breakwater, nor apparently has the coarse sand that is found in the beach (Section 7). Such evidence indicates that rather than the breakwater having blocked a northward transport of the beach sand and gravel, having prevented it from bypassing Bluff Hill, the breakwater in effect behaves as a headland, an extension of Bluff Hill. Acting as an extended headland, the newly constructed breakwater would have altered the balance of waves reaching the beach to its immediate south, locally reducing the waves from the northeast. In response to this altered balance in the waves, the beach sediments would have accumulated to the south of the breakwater as observed, but this accumulation would not have been due to the breakwater having blocked a net northward longshore transport that had existed prior to its construction.

The appearance of beach erosion at Westshore did correspond approximately in time with the construction of the breakwater, but also with the cessation of the disposal of the dredged sand and with the period of unusually severe. A compilation of the mean high-water shorelines for that period is shown in Figure 6-9 from the study of Smith (1993), which documents the Westshore erosion from 1888-1889 until the mid-1920s.

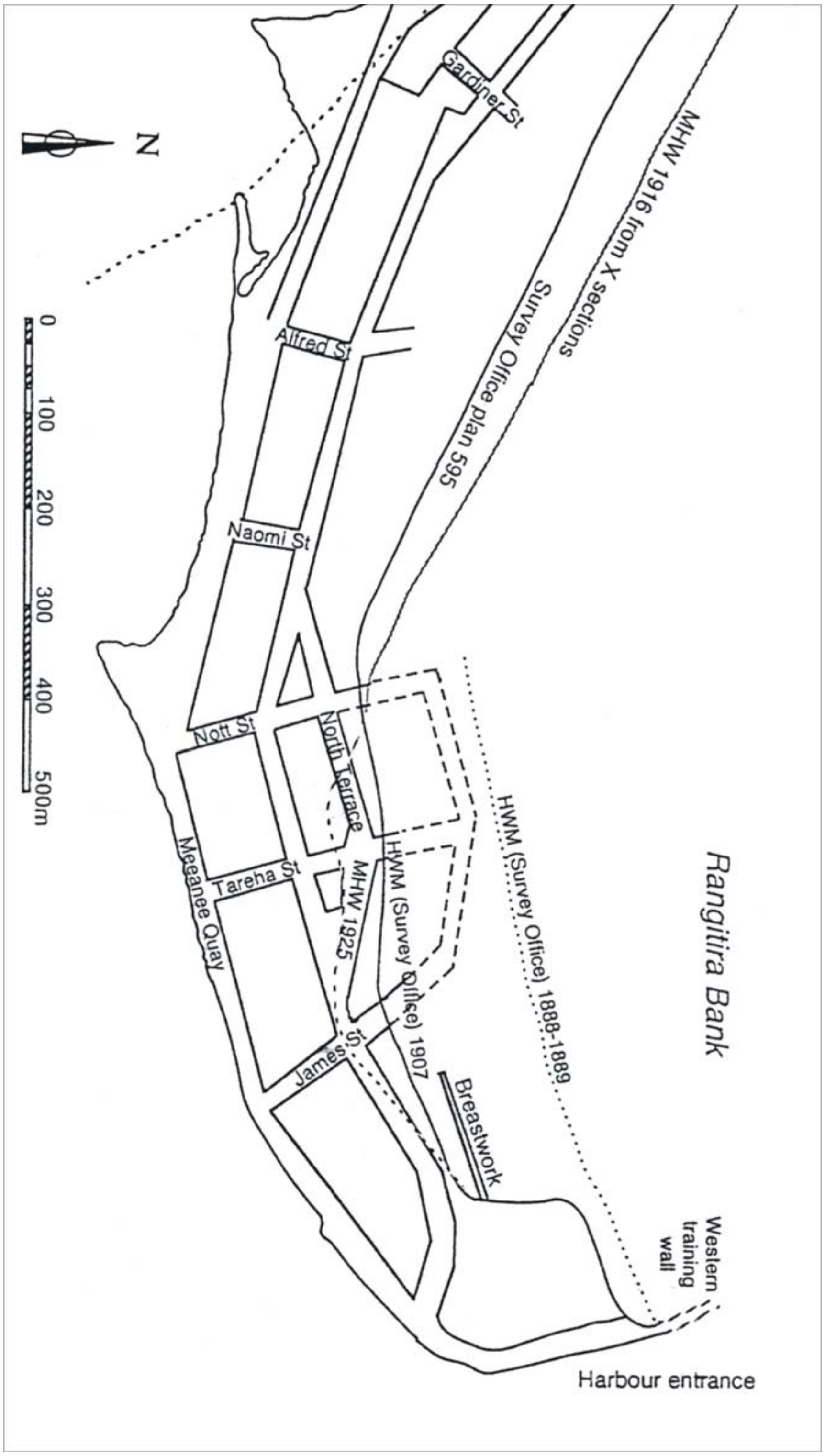

Figure 6-9 A compilation of surveyed shorelines for the years 1888-1889, 1907 and 1916. [*from* Smith (1993)]

The earliest shoreline given in Figure 6-9 is that in 1888-1889, at the time the breakwater was being constructed but also when the sand disposal was halted and the storms were occurring. The next survey is from 1907, by which time the shore had retreated by nearly 200 metres. According to the observations of Carr (1893), reviewed above, this 200-metre retreat of the beach occurred during the five years immediately after the disposal of the dredged sand on this beach had been halted; it is therefore reasonable to conclude that this erosion represented a loss of the sand beach that had formed along South Westshore from the previously dredged sand. The subsequent retreat of the gravel ridge backing that fronting sand beach could also have been relatively rapid under the forces of the major storms which occurred at that time. Smith (1993, page 4) describes the gravel ridge at Westshore as having been a low-lying deposit that was frequently overtopped by the waves, resulting in its landward migration by "rolling over". In 1909 beach protection works were installed along Westshore to reduce the losses to erosion, which included the placement of more than 5,300 cubic metres of stone between 1911 and 1923, the use of concrete blocks, and the placement of sheet piles and timber structures (Single, 1985, p. 39). While many of these structures ultimately failed, and their remnants can still be viewed to the west of the moles, as seen in Figure 6-9 the amount of shoreline retreat after 1907 was greatly reduced, having involved some erosion in close proximity to the western mole (the "Western training wall" as labeled in the diagram), but with beach accretion having occurred between 1907 and 1916 further to the west.

There is little evidence for the occurrence of significant erosion along Westshore subsequent to that documented in Figure 6-9, that is after the 1920s. The major change instead occurred in response to the 1931 Hawke's Bay earthquake, which resulted in the tectonic uplift of this shore by about 2 metres (Section 2). With the beach ridge having been raised by that amount, it was no longer prone to overtopping by storm waves, and the ocean shore had immediately shifted seaward by at least 20 metres; taken together, these changes resulted in Westshore being much more stable since that time (Section 7).

Of particular interest was the appearance of a sand beach along Westshore at the time of the earthquake, apparently exposing a deposit of sand that formerly had been subtidal. According to Campbell's (1975, p. 161) history of Napier, the earthquake: ". . . changed its beach [Westshore] from a dangerous shingle bank to a placid sandy expanse, [that] became an increasingly popular seaside residential area." By most accounts this sand beach slowly disappeared over the years, having remained until the late 1950s (e.g., Smith, 1986). The report by Mead et al. (2001) contains photographs taken between 1978 and 1981 at Westshore, showing the presence of a sandy beach, but any sand beach present at that late date was more likely a temporary development, occurring as part of the periodic reversals in the directions of sediment transport resulting in the cycles of beach accretion and erosion, not representing the last vestige of the beach that had formed in 1931.

The study by Mead et al. (2001) focused in particular on the transport of sand along the Ahuriri shore and how it may have been altered by the construction of the breakwater, this possibly having been a factor in the loss of this sand beach at Westshore formed in 1931. Their analyses involved the development of a series of numerical models of the offshore currents, the water currents of the ocean circulation and tides, and how they were affected by the breakwater. Their initial model runs were without the breakwater and with water depths based on an 1855 nautical chart; the results showed that a current was able to pass around the headland from the south into the Bay, presumably carrying sand to Ahuriri. The subsequent model runs included the presence of the breakwater and the shallower water depths after the coastal uplift by the 1931 earthquake; those models demonstrated that the breakwater acts to deflect the former sand movement to the north, where it now passes around the breakwater's arm and enters the dredged channel leading into the Outer Harbour. From this Mead et al. (2001) concluded that the construction of the breakwater in the late 19th century had been important to the loss of the sand beach formed at Westshore. While it is clear that the breakwater has acted to divert the movement of sand further to the north, away from Westshore, as reviewed in Section 5 this diverted sand is very fine grained, too fine to generally be stable on the beach such that it is quickly transported by the waves into the offshore. It instead can be argued that the sand beach formed at Westshore at the time of the earthquake would inherently have been unstable, and would have washed away more rapidly under the onslaught of storm waves had the breakwater not been present to shelter this stretch of shore. Furthermore, it is likely that the diversion of the Tutaekuri River in 1934 had greater consequences to the permanence of the Westshore sand beach. Prior to its diversion, the Tutaekuri appears to have transported large quantities of sand into the Ahuriri Lagoon, with the dredging there primarily having been conducted to remove that sand from the Inner Harbour. With the diversion of the course of the Tutaekuri River to the south of Napier in 1934, the consequence would have been the significant loss of this as a source of sand that reached Westshore, sand that would have been coarser and more stable on that beach than the very fine sand that bypasses the breakwater.

The fate of the sand at Westshore is primarily relevant to the desire to once again have a stable sand beach for recreation at Westshore. This will be examined in Section 7, in the context of proposals that have been proposed for the construction of groynes, designed to maintain a recreational sand beach while at the same time offering enhanced protection to Westshore from erosion and flooding.

The question considered here has been whether the erosion at Westshore was due primarily to the Port’s breakwater having blocked a northward transport of beach sediment that previously had bypassed Bluff Hill, assumed by some but doubted by Kirk and Single (1999). This review reached the conclusion that while some gravel had bypassed Bluff Hill prior to the breakwater’s construction, the quantities were small and the occurrences episodic. Thus, the potential for downdrift erosion when the breakwater was constructed was small; this is apparent when one compares the respective degrees of erosion experienced at Westshore compared with that in response to the breakwater construction at Timaru, which a century after its construction is still causing extensive downdrift erosion at Washdyke. Furthermore, the erosion at Westshore mainly occurred during the few years following the halting of the disposal of sand along its shore that had been dredged from the Inner Harbour, and also took place concurrent with the extreme storms that also produced erosion and flooding along the Marine Parade. I believe that it is safe to conclude, as Kirk and Single (1999) had suggested, that this early period of erosion at Westshore was due to these factors, not to the breakwater having prevented the bypassing of beach gravel around Bluff Hill. We can in fact be certain that the presence of the breakwater has actually served to protect Westshore from the forces of the storm waves during the century since its construction, thanks to its sheltering that on average has reduced the heights of the waves along Westshore by half, compared with those that had eroded this coast prior to its construction.

6.4 SUMMARY AND DISCUSSION

The objective of this Section has been to consider the possible consequences of the construction of the Ahuriri moles (jetties) in 1876-1879, and then the Port's breakwater in 1887-1890. This has been a contentious issue amongst the coastal scientists and engineers who have held divergent opinions as to the roles of this construction in the erosion at Westshore, and with the local residents also having strong opinions concerning this issue.

Part of the problem in resolving this issue has been the relatively poor documentation of the changes that occurred along the Hawke's Bay shore at the end of the 19th century when the moles and breakwater were constructed. In particular, it would have been helpful to have had a documentation through the collection of beach profile surveys, photographs of occurrences of beach and property erosion that occurred at that time, and additional written historic accounts. With this construction having taken place more than a century ago, any analysis today of its environmental consequences depends on an historic reconstruction of the beach responses, viewed with the present-day knowledge of what can happen when jetties or breakwaters are constructed. This was the reason for having reviewed in the first half of this Section examples of shoreline changes that transpired when jetties or breakwaters were constructed elsewhere on the world’s coasts, cases that have been better documented and included research investigations by coastal scientists and engineers into the effects of the structures on the waves and currents.

Most important in this Section has been the attempt to assess the coastal conditions and ocean processes prior to the construction of the Ahuriri moles and the Port’s breakwater, and then to examine how those conditions might have been changed by their construction. A definitive interpretation has been hampered somewhat by other environmental changes having taken place concurrent with the Port's construction. One complicating factor was the dredging activities in the Inner Harbour, the dredging of sand and its disposal to the west of the newly-constructed moles, but with this practice having been halted in 1888 during the initial stage of breakwater construction; the question is whether the erosion at Westshore was caused by first having initiated that sand disposal, which would have built out the beach to the west of the moles, but then halting the disposal such that the beach quickly eroded away, or whether the changes were in part caused by the construction of the moles and breakwater. Furthermore, the period during the construction of the breakwater was characterized by extraordinarily strong storms, with high waves and storm surges that eroded the beach along the Marine Parade and flooded downtown Napier; we can be certain that those storms would also have produced beach erosion at Westshore, irrespective of the construction of the breakwater, and indeed would have been greater without the sheltering of that shore provided by the breakwater.

My assessments of the possible effects of the construction of the Ahuriri moles and Port's breakwater have been based in part on the historic accounts, those in the general histories of Hawke's Bay written by Reed (1958) and Campbell (1975), but primarily on the memoranda of Saunders and Carr written respectively in 1882 and 1893. Having been first-hand accounts by the successive Chief Engineers of the Napier Harbour Board, their descriptions of the coastal processes prior to the harbour construction and the subsequent changes in the environment were particularly valuable. My assessments have also been influenced by the more recent reports by J. G. Gibb, R. M. Kirk, S. Mead and colleagues, R. B. O'Callaghan, M. Single and R. K. Smith, the coastal scientists and engineers who were primarily investigating the causes of the beach erosion experienced at Westshore. Even though these investigators maintained different views regarding the degrees to which the construction of the moles and breakwater were responsible for the erosion, I found each to have made significant contributions regarding the ocean processes and beach responses that I could draw upon in reaching my conclusions.

In summary, my principal assessments include the following:

- Prior to harbour development, it is likely that beach gravel was able to bypass Bluff Hill, carried from the Marine Parade beach in the Haumoana Littoral Cell to Ahuriri and Westshore in the Bay View Littoral Cell, but this involved only in relatively small volumes of gravel and with the occurrences of bypassing having been episodic; the differences in grain sizes, shapes and surface polish between the gravels of those two cells suggest that the volumes bypassed were small, and only occurred when larger than usual quantities had been supplied by the Tukituki River and from sea cliff erosion at Cape Kidnappers, building out the beach south of Bluff Hill;

- At the time the Ahuriri moles were being constructed (1876-1879) there was little or no active bypassing of gravel around Bluff Hill to support a longshore gravel transport at Ahuriri to be blocked by the construction; this conclusion is supported by Saunders' (1882) observation that the Marine Parade beach was "much reduced" in its width and sediment volume at that time, inadequate to support bypassing, and is also supported by the observed shoreline responses adjacent to the moles as they were being constructed, with gravel accumulation to both the east and west sides of the moles;

- According to Saunders (1882), the rate of gravel accumulation to the east of the moles as they were being constructed was so rapid it kept pace with their extension, with the rate of accumulation having been on the order of 50,000 m^3/year; such a large rate of gravel accumulation is unrealistic for the sediment volumes that could have bypassed Bluff Hill, in view of the estimated transport rates along the Marine Parade beach being on the order of 6,000 m^3/year;

- The rapid rate of gravel accumulation to the east of the constructed moles, and also to their west, is better interpreted as having been the response to jetty construction on a shoreline that has a zero-net littoral drift of sediment as depicted in Figure 6-1 (Lower), with the beach and shoreline accretion supported by the rapid onshore movement of gravel from the bay-mouth bar; this interpretation is made complex by the simultaneous practice of having disposed of sediments dredged from the Inner Harbour to the west of the moles, but that disposal would mainly have involved sand whereas it appears that most of the accretion involved the arrival of gravel;

- The construction of the breakwater (1887-1890) has had the effect of enhancing the natural headland of Bluff Hill, producing a localized seaward progradation of the shoreline to its south and a greater degree of wave sheltering along the Ahuriri shore and at Westshore; as an enhanced headland, the breakwater has prevented the northward transport of the beach gravel, with there being no evidence for it having bypassed the breakwater during the century since its construction;

- The orientation and shape of the shoreline along the Bay View Littoral Cell in effect represents a quasi-equilibrium net-zero transport of beach sediments, that is, there can be periodic reversals from year to year and decade to decade in the directions of the transport, but in the long term the net is effectively zero; as discussed in Sections 4 and 7, this is the expected equilibrium condition for a shoreline such as that found in the Bay View Cell where there are minimal sources of new sediment to the beach; it follows that any change in the shoreline positions within this cell needs to be interpreted primarily in terms of redistributions of a nearly-fixed total volume of gravel contained within its beach, its redistribution being caused by the changing waves and currents;

- The periodic erosion at Westshore has most likely been caused primarily by cycles between accretion and erosion of sediments on its beach, the accretion having occurred whenever there is a subtle shift in the waves and currents that produce a southward transport of beach sediment for a year or for a few years, while the episodes of beach erosion at Westshore have occurred when those processes produce a temporary northward transport of the beach sediments.

The bottom line is there is no firm evidence that the construction of the Ahuriri moles and the Port's breakwater blocked large quantities of a longshore transport of beach gravel that had bypassed Bluff Hill; instead, there is significant evidence to the contrary. The construction of the breakwater has redirected the path of the alongcoast movement of the sand, such that it is now transported to the north where much of it is trapped in the Fairway leading into the Outer Harbour and has to be dredged; however, this is very fine sand that is not stable on the Hawke's Bay beaches, so its loss from Westshore has not been a significant factor in whether or not beach erosion occurs there. The loss of the sand beach that had formed at the time of the 1931 Hawke's Bay earthquake is more likely to have resulted from the diversion of the Tutaekuri River in 1934, which previously had transported large quantities of coarser-grained sand into the Ahuriri Inner Harbour, which did have the potential for making a contribution to the Westshore beach. The presence of the Port's breakwater would have had the positive effect of sheltering that sand beach formed at the time of the earthquake; without that shelter from the storm waves, the sand would have dispersed very rapidly. The presence of the breakwater continues to offer protection to Westshore, decreasing by about half the heights of the waves that reach its shore. Thanks to this protection and the 2-metre uplift of Westshore by the earthquake in 1931, it has not experienced significant erosion in many decades; accordingly, O'Callaghan (1986), a European coastal engineer, concluded that the erosion of Westshore "has not been severe in coastal engineering terms" and has been "relatively minor". As will be discussed in Section 7 where we consider the management of the Hawke's Bay coast, it is time to turn away from the past obsession with the perceived erosion problems at Westshore, and instead focus on its development as a recreational asset for the community.

6.5 REFERENCES

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