Geomorphological assessment including historical (long-term) shoreline analysis: Central-Northern Poverty Bay

A report prepared for the Gisborne City Council's Erosion Hazard Assessment programme

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TABLE OF CONTENTS

1 Present geomorphology

1.1 Overview

Poverty Bay is a semi-circular embayment located on the northeastern coast of the New Zealand North Island (Figure 1). The Bay is bounded by headlands some 10 km apart; Young Nicks Head to the south and Turanganui Point to the north. Two main inlets enter the Bay, the Waipaoa and the Turanganui. Because of the prevalence of relatively soft, fine grained rocks in the river catchments around East Cape, ~97% of the fluvial sediment load is suspended (Foster and Carter (1997).

The Waipaoa Rivermouth is located about 8.5 km south of Gisborne's Port and 5 km north of the Young Nick's headland/beach intersect. The catchment area is ~2200 km^2 which drains highly erodible uplifted, jointed and otherwise deformed clay-rich marine sedimentary rocks of the Cretaceous and Pliocene Age. Such materials are predisposed to mass movement, gullying and mechanical disintegration which is enhanced by episodically intense precipitation, seismic activity and human activities removing vegetation (Marden, 2011). The annual sediment load is estimated at 12.9 Mt/yr (Foster and Carter, 1997) and results in one of the highest specific sediment yield in the world estimated at 7216 tonnes/ km^2/yr (Hicks, 2011)

By comparison, the Turanganui River system has a catchment area of only 300 km^2 and an annual sediment yield of 0.7 Mt/yr (Foster and Carter, 1997). While still susceptable to shallow earth slides, its catchment geology excludes the older Cretaceous lithology of the upper Waipaoa which is so prone to mass movement (earthflow and slumping) and gullying, these being the major producers of sediment.

The 10 km wide entrance to Poverty Bay is about 25 m deep with arcuate contours to landward. The bathymetric contours and shoreline show little presence of deltaic development - indicating wave power dominates tidal and fluvial processes.

Both rivermouths are controlled: the Waipaoa by stopbanks, training wall and a realignment mouth cutting regime, and the Turanganui by diversion and training walls which extend - these structures are located on Figures 2A and 2B.

The Kuri Bank extends into the Bay to the northeast of Young Nicks Head (Figure 1) and effects (refracts) waves approaching between south and east. Local wave statistics based on wave buoy data collected by between December 1978 to July 1980 (Miller, 1981) found a mean significant wave height (Hs) of 1 m (0.2 to 3.2 m) and mean period of 8.7 seconds (3 to 14). The lack of directional wave data prevented computation of longshore currents and sediment transport.

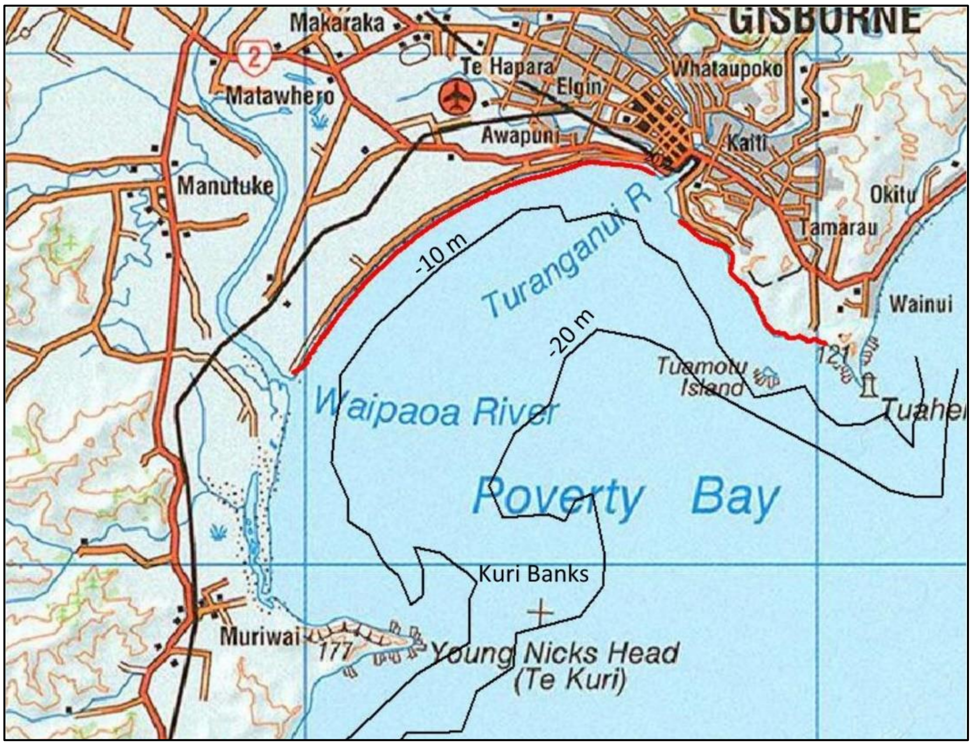


Figure 1 Location map of Poverty Bay with the Erosion Hazard Assessment coast marked by the red shoreline.

The present Erosion Hazard Assessment study area lies between the Waipaoa Rivermouth and Sponge Bay as depicted in Figure 1. For reference purposes we have assigned chainage (alongshore distances) using the Port's eastern breakwater as datum for distances running to Sponge Bay (0 to +4.7 km): this reach being termed the *eastern study area* or *eastern coast*, and the western wall of the Tauranganui Rivermouth as datum for distances running to the Waipaoa Rivermouth (0 to -8.6 km): this reach being termed *the western study area* or *western coast.*

Radio carbon dating (Brown, 1995) of Holocene materials show the western study area has three tectonic sub-regions as marked in Figure 2B. The area eastward of chainage -2.2 km has undergone uplift averaging 1 to 4 mm/y, while the area west of chainage -5.7 km has undergone down-drop averaging -1 to -7 mm/y (Gibb, 1995). Between these areas of contrasting tectonic response lies a static/pivotal area.

1.2 Eastern study area geomorphology

Much of the coast east of the port if fronted by an intertidal wave-cut platform and backed by active cliffs. The exception being the sandy Kaiti Beach reach which mantles the platform between 0.6 km (edge of port reclamation area) and 1.9 km (cliffs begin intersecting the high tide shoreline) As indicated by the contours shown in Figure 2A, the highest hills (140 m) back Kaitai Beach which is also fronted by the most extensive/coherent area of intertidal platform – indicating more resistant lithology

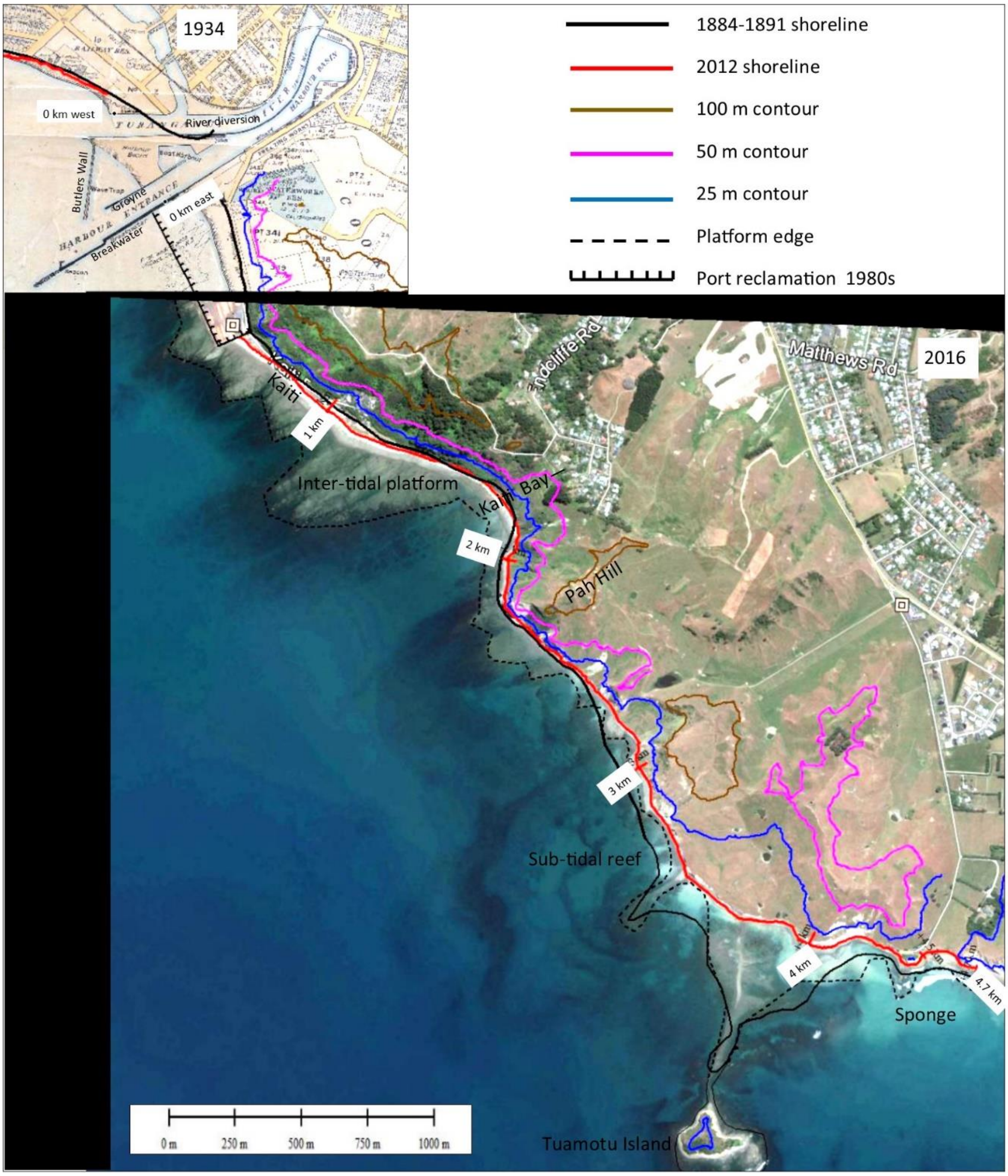


Figure 2A Geomorphological features and places of the eastern study area referred to in the text, including chainage and port structures established shortly after the still-water harbor was created in the 1920s.

At the eastern end of Kaiti Beach the platform extent reduces and the shoreline is backed by a large valley. The terrestrial height vs inter-tidal platform width relationship can be seen in Figure 2A to occur throughout the eastern sector and is explained by valley incision during glacial periods when sea-level can be over 100 m lower than at present.

Beyond the Kaiti valley, the shoreline beach changes to gravels and boulders fronting cliffs which begin at Pah Hill (~2 to 2.5 km), a bluff-like structure some 125 m high and so

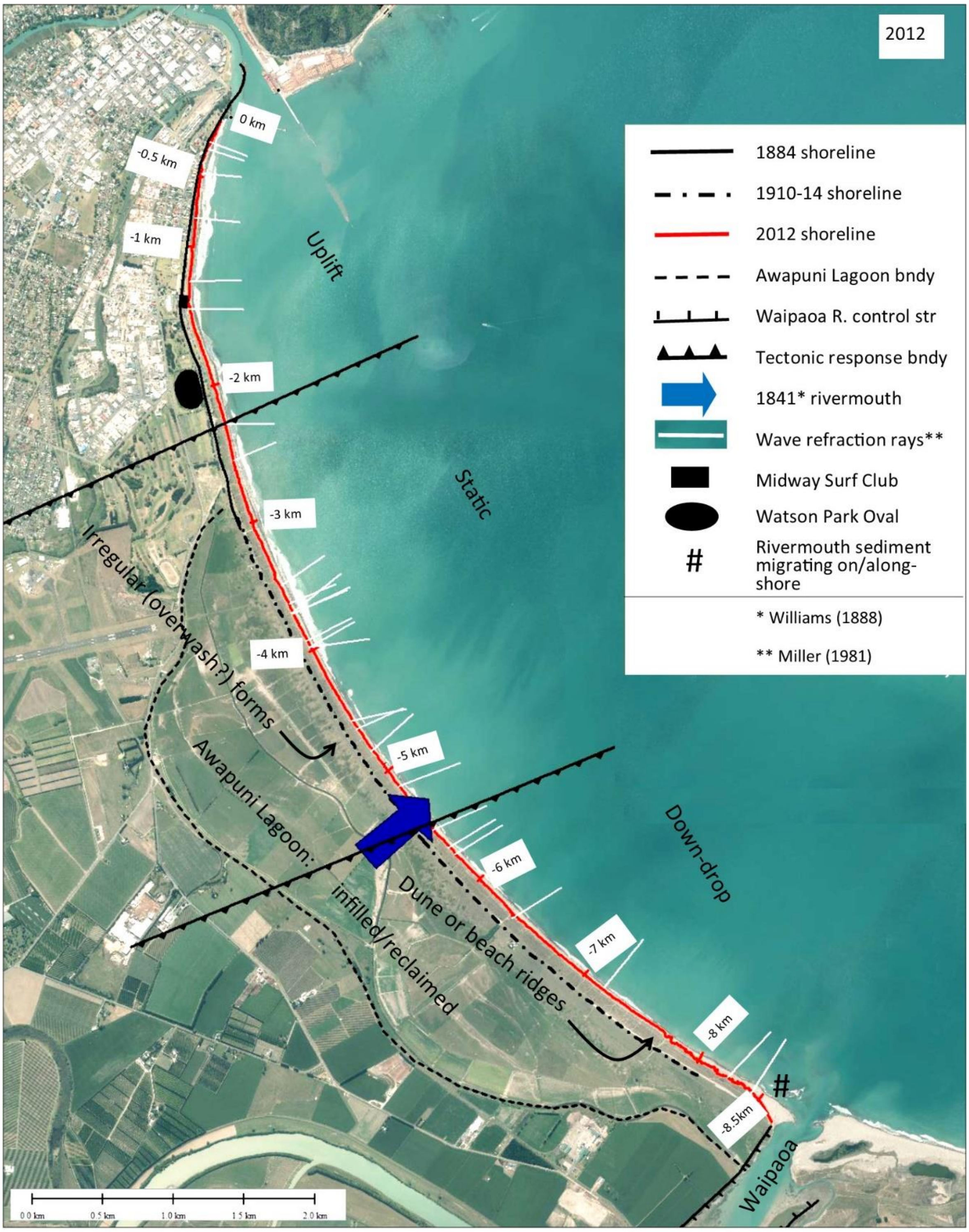


Figure 2B Geomorphological features, places and chainage of the western study area referred to in the text.

named in Whyte's (1984) account of the Port's history. The associated relatively resistant exposed strata (see Figure 3D) shows a *Miocene flysch sequence* that was formed in a deep marine environment and subsequently subjected to significant uplifted and tilt.

Beyond Pah Hill the relief reduces – typically to between 50 and 70 m, and is punctuated by valleys fronted by a narrower intertidal platform. These hills also contain shallow landslip and earthflows indicative of localized higher clay content and weaker lithification. These features are illustrated in Figure 3A and 3C. Further evidence of the increased erosive-prone nature of the coast eastward of Pah Hill is suspended sediment discolouring the seawater in the embayment between 4 and 4.5 km in the 2016 satellite image underlying Figure 2A. This image also shows the much wider sub-tidal reefs and rock formation in this area indicating greater erosive susceptibility marine processes (waves and currents). However, at the Sponge Bay end of the study area the relief increases somewhat and earthflows are lacking indicating more resistant lithology.

Several valleys are truncated at the shoreline (e.g. see Figure 3A); these are filled with colluvium, estuarine sediments, soil and other unconsolidated materials that often reach the narrow, clastic beach, as do rockfalls and slips from the cliff face itself. However, current beach processes appear able to disburse such episodic input. Miller’s (1981) heavy mineral analysis (Augite and Hypersthene) showed sediment along the eastern coast are sourced from the adjacent hillsides, with sediment from the western beach system apparently unable to cross the Turanganui Rivermouth. Sediment accumulation against the Kaiti side of Port structures indicate longshore transport from east to west - at least along the Kaiti coast.

Finally it is noted that at the time of our site inspection, the Kaiti Beach morphology indicated a stable shoreline at the western end, an accretionary section in the centre and a 400 m long erosional section leading around into the embayment before Pah Hill.

The geomorphological characteristics described above indicate eastern sectors will include the Kaiti coast, Pah Hill, and the remainder of the cliffed coast around to Sponge Bay. A separate erosional-based reach may also be appropriate between Kaiti and Pah Hill and at the Sponge Bay end of the study area.

1.3 Western study area geomorphology

The coast west of the Turanganui Rivermouth consists of a relatively uniform sandy beach and one or two submarine sandbars with the inner bar often displaying three-dimensionality, i.e. contains seaward directed rip morphologies. The shoreline has a broad arcuate planform with less uniformity closer to the Turanganui Rivermouth; in particular between -0.4 and -1.4 km and -1.4 to -2.8 km (see Figure 2B). Driftwood mantles the backshore and consented sand mining was observed during out site inspection at approximately -3 km. The operator informed us that he had been taking sand from the lower beach at this location since the 1970s with about 5,000 m^3 being removed annually. Another consented site at approximately -6.5 km was rarely used due to the transportation distance.

Sediment texture and heavy mineral analysis by Miller (1981) suggests that while both rivers supply beach sand, the Waipaoa is the primary source with the longshore transport volume only dropping off some 2 to 3 km from the Turanganui Rivermouth.

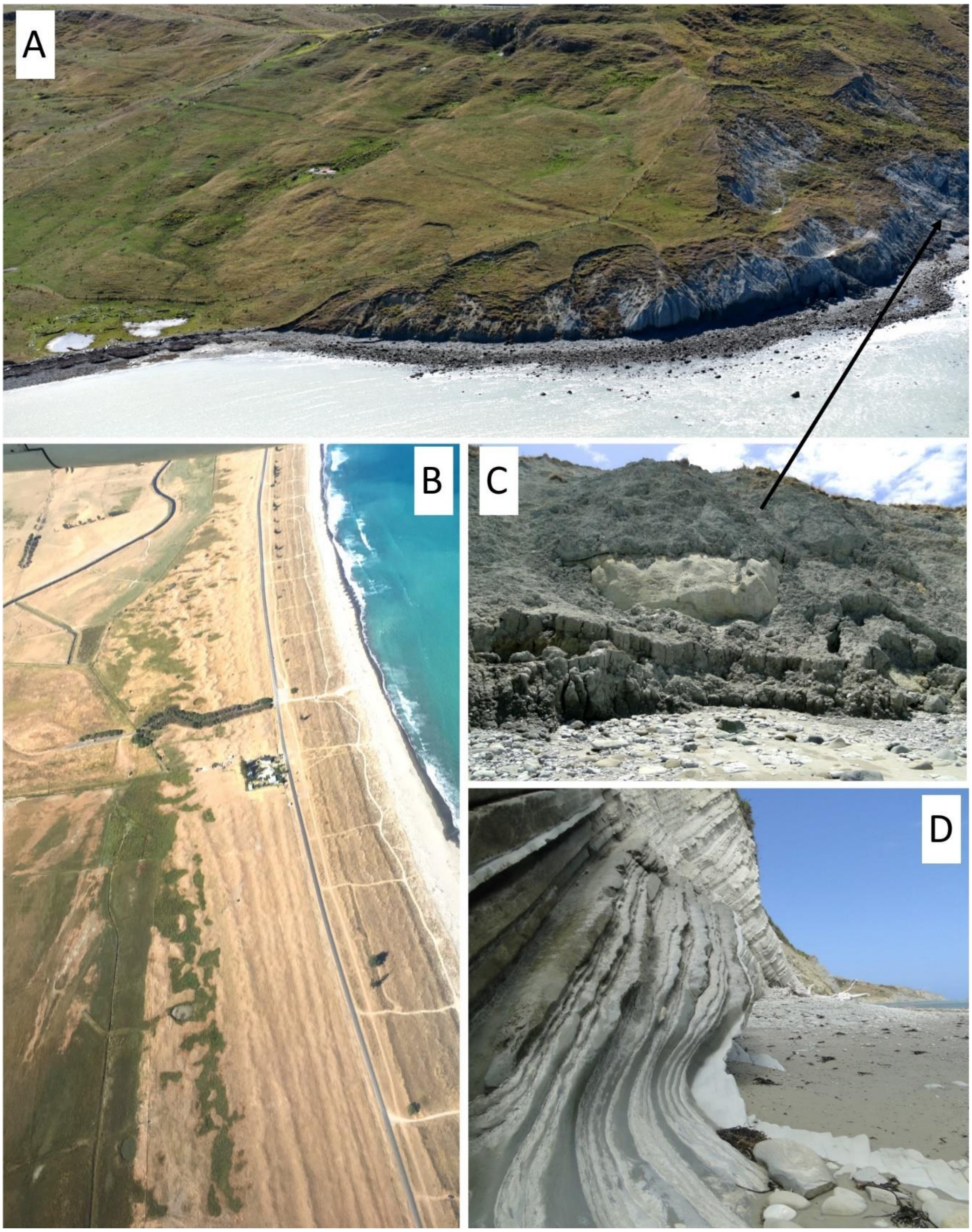


Figure 3 Photographic illustration of several geomorphological features described in the text. Photo A (23-3-2015) spans 3.8 to 4.2 km chainage (see Figure 2A) and depicts a truncated valley and adjacent hillside with active earthflows. Photo C (28-1-2017) further illustrates the instability of the same earthflow area. Photo B (27-1-2017) spans –5 to –7 km chainage (see Figure 2B) and illustrates the dune ridge system backed by undulatory (overwash?) forms, and further landward is the infilled/reclaimed Awapuni Lagoon. Photo D (28-1-2017) depicts the relatively resistant steeply dipping Miocene flysch sequence underlying Pah Hill. Taken at chainage 2.2 km with 3.5 km in the far distance. Note how this formation forms the wave cut platform (lower right of photo) with boulder lag and patches of sand also present on the beach.

Using directional wave data from Hawke Bay and Hicks Bay, Miller (1981) constructed a basic/approximate wave refraction diagram which indicated energy concentration at the shoreline in the centre of the western study area and a secondary peak some 300 m south of the Turanganui Rivermouth. There was also a lack of rays at 2 to 3 km from the rivermouth. The wave refraction ray landfalls are marked in Figure 2B. Miller speculated that the irregularities in the shoreline plan resulted from the associated longshore variation in wave energy.

The present shoreline (dune toe/vegetation edge) is backed by a foredune some 4 to 5 m high reducing to 3 m closer to the Waipaoa Inlet. Landward of the foredune are a series of dune ridges (also referred to as beach ridges); these increase in landward extent (and number) in a southward direction (50 to 70 m wide at -1 km; 130 m at -2 km; 150 m at -4.5 km and 250 m at -7.5 km). This dune configuration is indicative of faster shoreline progradation toward the south.

The infilled/reclaimed Awapuni Lagoon is some 6 km in length (extending from chainage distance -2.8 km to the Waipaoa Rivermouth), and extends up to 1 km inland. The lagoon surface is < 1 m above MSL.

Between the infilled/reclaimed Awapuni Lagoon and the dune ridges are irregular undulatory features somewhat lower than the ridges but higher than the lagoon surface. These features have a broad shore-normal orientation indicating marine influences.

Landward of the ridges to the north of the lagoon, is a low lying relatively uniform area up to 200 m wide (Watson Park Oval-Salisbury Road area) with yet older dunes further landward.

The various morphological units landward of the present beach are marked in Figure 2B and illustrated in Figure 3B. Their origin is interpreted as coming from a barrier beach that formed between the rivermouths with the intervening lowland infilling over time as the barrier increased in size and the shoreline prograded enabling the dune system to develop. The undulatory features between the dune ridges and the lagoon may have resulted from storm wave or tsunami overwash earlier during the formation sequence of the dune system.

The geomorphological characteristics described above indicate representative sectors for the western coast could include areas adjacent to the two inlets, and the intervening sandy coast being partitioned between chainage 2 to 3 km.

2 Geomorphological behavior (change)

2.1 Shoreline change drivers

Coastal change in Poverty Bay is primarily the product of geology, Holocene geomorphological evolution and anthropogenic influences. The basic geology has been described in the preceding section. During the present sea-level highstand (the Holocene), the shoreline has advanced seaward up to 12 km and at a decreasing rate: up to 5 m/yr to 5000; up to 1.5 m/yr to 3000, and 0.4 m/yr over the past 2000 yrs. (Brown, 1995). Prior to the Holocene was the Pleistocene – a period characterized by dramatic sea-level change with the most recent minimum being some 20,000 yrs ago when the level was about 120 m lower than at present and valleys existed where flood plains now occur.

While annual averages of shoreline change provide an appreciation of relative change, long-term accretion along the western coast has been episodic with Pullar and Penhale (1970), and Grant (1985) showing that periods of major hill country erosion/flood plain infill during the past 1000 yrs (so far identified) have occurred between 1270 to 1370; 1530 to 1620; 1780 to 1800; 1870 to 1900, and 1950 to the time of Grant's 1985 publication. These authors consider the primary cause of such very low frequency (VLF) episodes of erosion to be long-term climatic fluctuations characterized by a sustained increase in the frequency of major rainstorms. While they considered earthquakes and deforestation (burning) to be compounding factors, more recently McFadgen (2007) has provided evidence that earthquakes played a major role in slope destabilization.

Between these periods of severe erosion, relatively "tranquil" conditions occur enabling vegetation to re-establish and slopes and flood plains to stabilize. Reduced sediment supply to the coast would have lead to more stable or eroding shorelines. However, the linking mechanism between river sediment discharge and shoreline change is not well enough understood to define the inevitable lag between catchment change and coastal response.

Deforestation since European settlement in particular, has had a dramatic effect on hillcountry erosion. Much of the lowland deforestation (cut and burn) had occurred by 1875 and by the 1920s 97% of the hill country's indigenous forest had been destroyed and converted to pasture. Marden (2011) notes that the onset of hillside erosion likely occurred within a decade or two of deforestation as root strength declined, soil moisture reduced and runoff increased. Such Land-Use Change (LUC) activity led to a 6.5 to 10-fold increase in suspended sediment discharge in the Waipaoa River and this would have significantly increased the sediment supply to the adjacent coast.

Between 1958 and 1998 central government agencies planned and planted 1350 km^2 of exotic forest and within about 20 to 40 years of planting canopy closure and root growth drastically reduced erosion (Bergen et al., 1995, and Marden 2011). However, during the 20 yrs since that project finished, new and untreated gullying is occurring once again (Marden et al., 2012).

The current very low frequency (VLF) extreme weather effects coupled with anthropogenic land use change (LUC) effects have likely led to the present accretional phase apparent along the central and southern western coast and this is described in the following section

2.2 Historical (long-term) shoreline change

Historical shoreline behavior was determined using regression analysis of shoreline data abstracted and digitized from the following aerial photographs: 1942 (SN 225); 1957 (SN 1044); 1958 (SN1206); 1979 (SN 5373); 1993 (SN 12040A) and 2012 (LINZ). The vegetation front was used to define the shoreline – this being best practice in New Zealand erosion hazard assessments. In addition, shorelines were abstracted and digitized from the following cadastral (survey) plans: 1884 (SO 422); 1886 (ML 803); 1886 (SO 310); 1887 (SO 305); 1888 (DP 587); 1891 (ML 950); 1899 (DP 1149); 1900 (ML 1333); 1910 (ML 1683); 1914 (ML 1939); 1914 (ML 1946) and 1925 (DP 2956) – with each plan only covering parts of the study area. The shoreline indicator on survey plans is typically the high-water mark (HWM) at the time of survey and this can result in significant non-resolvable differences when comparing with aerial photo-based data. The plans may also contain substantial plotting, scanning and digitizing errors. For these reasons the cadastral data were not merged with the aerial-based data for the regression analysis, but were used help interpret geomorphological change and identify non-linear historical shoreline change and inlet behavior.

Combined errors associated with the abstracted/digitized shorelines were estimated as follows: 1884 to 1925 survey plans = +/-20 m; 1942 to 1979 aerials = +/-5m; 1993 aerial = +/-3m, and 2012 aerial = +/-1m. These errors were incorporated into the hazard assessment modelling.

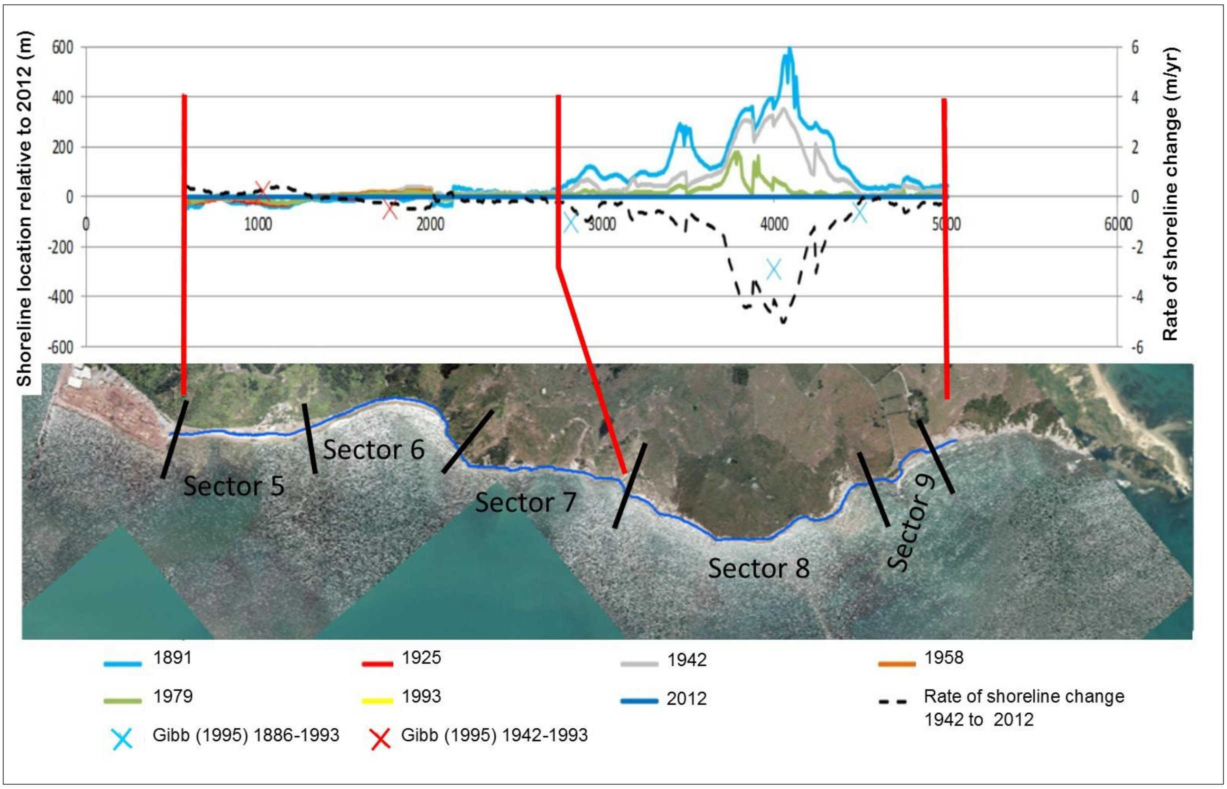
The aerial shoreline data were subject to linear regression analysis with the slope coefficients used to define rates of shoreline change in m/yr in accordance with practitioner best practice (NIWA, 2012). The resulting coefficients are plotted in Figure 4. As the analysis was carried out at 10 m intervals in the alongshore direction it also enables more precise determination of sector boundaries and the resulting reaches are also marked in Figure 4.

2.3 Sector analysis

The historical shoreline behaviour and regression analysis are now described for each sector beginning at the Waipaoa end of the study area. The minimum, mean and maximum co-efficient plus standard deviation for each sector are listed in Table 1. All samples had symmetric distributions (indicative of normality) according to the following test:

$$|Skewness/(6n)^{0.5}| > 2$$

A. Eastern coast



B. Western coast

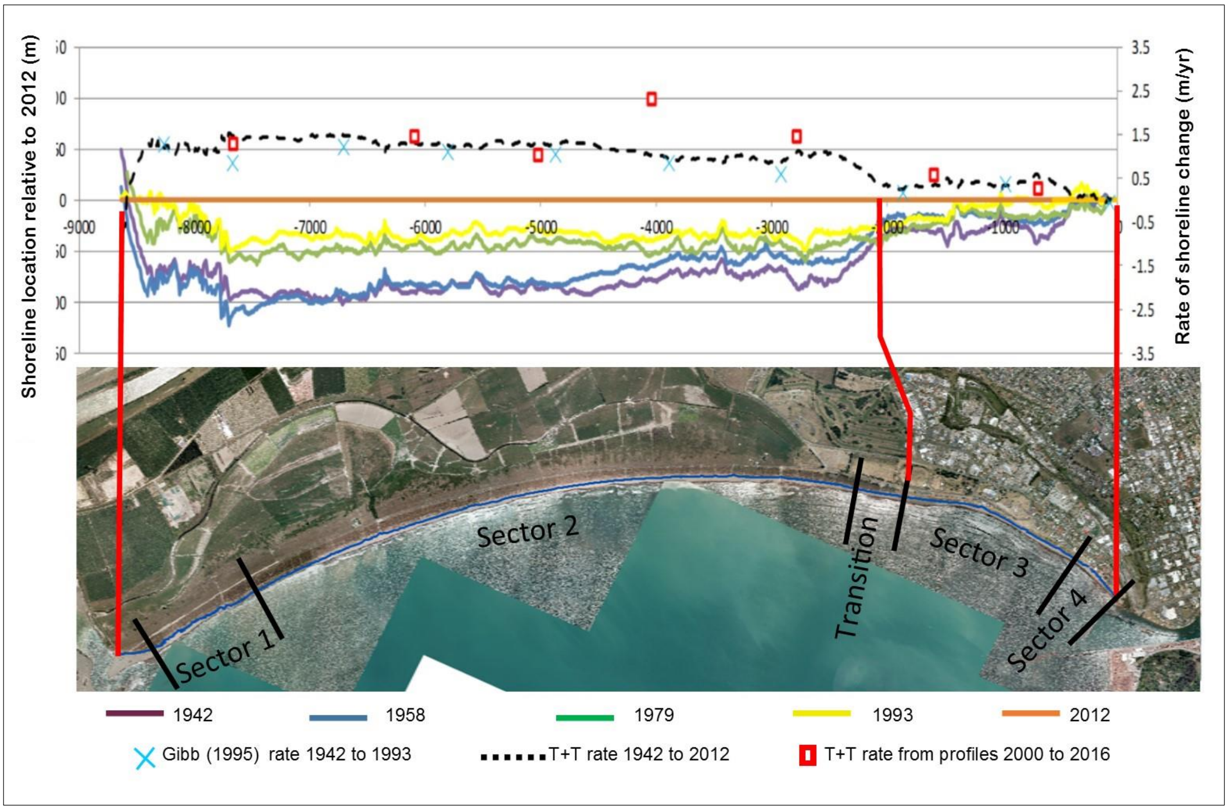


Figure 4 Spatial depiction of relative shoreline locations, linear regression-based rates of change and representative section boundaries for eastern coast (A) and western coast (B). Rates based on Gibb's (1995) end point analysis, and linear regression analysis of 2000 to 2016 profile data are also shown.

Table 1 Summary of longshore sector partitions and Long-Term (LT) parameter values based on regression analysis of historical shorelines and adjustment of most conservative (minimum) values for additional/alternate driver influence in the future. Terms explained further in text.

Sector	Name	Chainage[1] (km)	Regression rates (m/yr)			Standard deviation (m/yr)	100 yr extreme prediction influences3			Extreme adjustment (%) to minimum rate
			Min	Mean	Max					
1	Waipaoa Inlet	-8.40 to -7.40	+1.01	+1.28	+1.54	0.13	VLF	LUC	CCGW	50
2	South coast	-7.40 to -2.46	+0.81	+1.19	+1.50	0.18	VLF	LUC	CCGW	50
	Transition	-2.46 to -2.06	+0.41	+0.76	+1.07	0.21	VLF	LUC	CCGW	50
3	Midway	-2.06 to -0.55	+0.20	+0.37	+0.60	0.08	VLF	LUC	CCGW	15
4	Turaganui Inlet	-0.55 to 0	+0.06	+0.12	+0.36	0.12	-	-	-	0
5	Kaiti Beach	+0.58 to +1.21	+0.04	+0.20	+0.38	0.10	-	-	CCGW	10
6	Kaiti Bay	+1.21 to +2.08	-0.52	-0.24	0	0.16	VLF	-	CCGW	15
7	Pah Hill	+2.08 to +2.89	-0.26	-0.15	-0.05	0.09	-	-	CCGW	10
8	Tuamotu Is. Reach	+2.89 to +4.22	-1.01	-0.56	0.23	0.25	VLF	-	CCGW	30
9	Sponge Bay	+4.22 to +4.70	-0.65	-0.29	-0.04	0.16	VLF	-	CCGW	20

Where:

1. Measured along 2012 shoreline. Positive: east from northern breakwater. Negative: west from Turanganui mouth training wall/seawall.

2. Erosion inducing influences

3. VLF = Very Low Frequency (century scale) climatic fluctuations; LUC = Land Use Change in terms of deforestation to afforestation; CCGW = Climate change induced by global Warming, i.e. wind, wave, rainfall effects. Note that sea-level rise is a separate, and essentially independent, parameter in the hazard analysis.

Sector 1: Waipaoa Inlet open coast shoreline (-8.6 to -7.4 km)

The Waipaoa mouth has migrated between Young Nicks Head and up to 3 km north (of its present location) into the Awapuni Lagoon during historical time (Figure 2B). Indeed, the shape of the lagoon's landward boundary indicates the Waipaoa River has flowed throughout the lagoon in pre-historical time. Following an extreme southerly orientation in the 1940s, the entrance was aligned seaward by Waipoao River Flood Control Scheme's stopbanks in the 1950 and 1960s. After Cyclone Bolla (1988), the mouth migrated northward and a 400 m training wall was constructed seaward from the existing stopbank terminus to prevent such a reoccurrence. More recently the tendency has been for the mouth to migrate southward and a mouth-cutting regime is used to limit this remaining excursion (pers. comm. Mr Paul Murphy, GDC, 2017).

Although the rivermouth's lateral migration is artificially constrained, rivermouth dynamics (release of slugs of bar sediment that migrate onshore and alongshore) still effect the shoreline for several hundred metres. Our analysis of available profiles and aerial shoreline data indicate this influence extends 1 to 1.5 km northward of the mouth. Because of the extent of rivermouth dynamics coupled with the small number of temporal samples, results showed an unrealistic bias so the first 300 m were discounted. The resulting mean shoreline accretional rate = 1.28 m/yr, minimum = 1.01, maximum = 1.54 m/yr and standard deviation = 0.13 m/yr.

Sector 2: Waipaoa-affected southern shoreline (-7.4 km to -2.5 km)

The Waipaoa River effects several kilometres of the northern shoreline by varying the available sediment supply. As noted earlier, Millar's (1981) sedimentation analysis indicates the Waipaoa's influence extends some 6.5 km with the accretional rate reducing significantly thereafter. The Sector 2 rate of change statistics are: mean = 1.19 m/yr (0.81 to 1.50 m/yr), and standard deviation = 0.18 m/yr.

Transition between Sectors 2 and 3 (-2.5 to -2.1 km)

Between this Waipaoa-effected section (2) and Section 3, there is a broad transition zone between -2.5 to -2.1 km with a mean regression value of 0.76 m/yr (0.41 to 1.07 m/yr) and an increase in standard deviation to 0.21 m/yr which indicates more changeable shoreline behavior.

Sector 3: Midway (-0.6 to -2.1 km)

The shoreline is prograding along this stretch at a reduced average rate of 0.37 m/yr (0.2 to 0.6 m/yr) and a much reduced standard deviation of 0.08 m/yr.

The effect of the Waipaoa on sediment supply greatly reduces in this sector and the Miller (1981) sediment analysis indicates the Turanganui River system is the dominant source. The indentations in the 2012 shoreline plan along this sector (Figure 2B) are also evident in all historical shoreline shapes as far back as the 1884 (also shown in Figure 2B) indicating consistent forcing such as by deformed waves as suggested by Miller's refraction analysis.

Sector 4: Turanganui Inlet (0 to -0.6 km)

The shoreline along this Sector is very slowly prograding at an average rate of 0.12 m/yr (-0.06 to +0.36 m/yr) and standard deviation = 0.12 m/yr.

Erosion along Waikanae Beach was noted by Miller (1981) as having occurred in 1935, 1957 and 1958 and resulted in a "concrete and boulder seawall being constructed in 1959". We have not been able to determine the location of such erosion nor the existence/location of such a wall other than the wall fronting the bathing complex which was marked on survey plans as far back as 1925. The inference in Millar's thesis is that this erosion was related to port development and this will now be described based on Whyte (1984) and key features illustrated/marked on the 1934 plan which is inset within Figure 2A.

To control depths and sedimentation, port structures were established incrementally between 1886 and 1931. Between 1886 and 1890 the concrete breakwater was constructed seaward from the eastern (Kaiti) side of the rivermouth and this was followed in 1900 by a parallel training wall (referred to as the groyne) built out from the western (Waikanae) side of the mouth. The original eastern breakwater was extended between 1910 and 1914. Despite extensive dredging, high sedimentation in the rivermouth port resulted in an entirely different rivermouth/port configuration being constructed in the 1920s.

In particular, the rivermouth was diverted through the adjacent Waikanae Beach and the river separated from the port by a concrete wall extending back to the town bridge and to seaward some 300 m beyond the original Waikanae Beach shoreline. Finally, a 300 m breakwater (Butlers Wall) was constructed from this training wall across toward the eastern breakwater. Over subsequent decades the original western (groyne) training wall was removed and the contained area dredged to create the present Turning or Swing Basin. A still water port had been achieved, although a continuous dredging programme has been required to maintain depths in the entrance and approach channel. In the 1970s and early 1980s a 10 ha reclamation was carried out adjacent to the eastern breakwater and extended some 600 m eastward along Kaiti Beach.

While Miller's refraction analysis indicated a slight concentration of wave refraction rays at -0.5 m chainage which may have contributed to the observed shoreline erosion, it seems likely that the realignment and maintenance dredging programme also played an erosive role for the following reasons. Typically, a rivermouth with shore-normal alignment has a bar seaward of the mouth, adjacent (lateral) bar or platform to landward on each side of the rivermouth bar, and shoreline erosion typically occurs further alongshore (termed rip-embayment erosion). When the rivermouth orientation changes to a more oblique alignment, as occurred in the Turanganui case, the lateral bar typically merges with the shoreline thereby reducing wave energy and causing the shoreline to prograde. However, the opposite appears to have happened at Waikanae and this may have resulted from dredging removing the seaward bars/sediment accumulations.

Sector 5: Kaitai Beach shoreline (0.6 to 1.2 km)

This sandy beach begins some 600 m from the Port's eastern breakwater (the eastern chainage datum) following reclamation in the 1970s-80s, and extends to about the 2 km chainage where the cliff-base the becomes the shoreline. Based on our regression analysis we further divide this reach into two sectors (5 and 6) characterized by long-term accretion and long-term erosion respectively, with the partition occurring at 1.21 km. Sector 5, referred to hereafter as Kaiti Beach, is charaterised by an average long-term accretion rate of 0.20 m/yr (0.04 to 0.38 m/yr) and standard deviation of 0.10 m/yr.

The earliest cadastral plan shoreline (1886, SO 310) has been marked in Figure 2A and shows the then shoreline approximating the base of the hill (landward of the present road), and as evidence described earlier (in Section 1.2) indicates, east to west net longshore transport occurs, so it seems likely that Kaiti's sandy beach may only exists because of the port breakwater acting as a littoral barrier.

Sector 6: Kaiti Embayment (1.2 to 2.1 km)

Sector 6 is the eastern section of the sandy shoreline that is characterized by long-term erosion; this section is referred hereafter as the Kaiti Bay or Embayment. The mean long-term erosion rate is -0.24 m/yr (-0.52 to 0 m/yr) which systematically increases from west to east. The standard deviation is 0.16 m/yr.

These shoreline data indicate the embayment has not been effected by the port structure-inducing accretion, at least in the more recent past. The cause of the systematic onset of erosion is unclear, but it may be related to reduced sediment availability from the adjacent hillsides and valley.

Sector 7: Pah Hill (2.1 to 2.9 km)

The Pah Hill sector mean value is -0.15 m/yr (-0.26 to -0.05 m/yr) and standard deviation is 0.09 m/yr. This sector has a lower erosion rate and standard deviation than the adjacent sectors (6 and 8) and this relates to the more resistant material of which the bluff is composed. Of note is a 50 m reach of positive shoreline rates of change (just evident in Figure 4A). However, these were not included in Table 1 as they were outliers resulting from recent erosion debris extending the 2012 shoreline seaward; debris that would subsequently be removed by wave action. Beyond (eastward of) the 2.9 km sector boundary, erosion rates increase markedly.

Sector 8: Tuamotu Island reach (2.9 to 4.2 km)

This sector is fronted by Tuamotu Island lying some 800 m seaward of the present shoreline and has undergone dramatic morphological change over the past 130 years (since the 1887 survey, SO 305). At that time a gravel-boulder spit extended from the mainland toward the island which was separated by only 125 m at high tide. Another gravel spit also existed at that time, this being located 500 m to the west of the island spit and protruding some 200 m seaward (see Figure 2A). This area of particularly dramatic instability occurred over the eastern portion of Sector 8, i.e. from 3.4 to 4.2 km and is characterized by a mean rate of change of -2.2 m/yr (-5.05 to -0.53 m/yr) and standard deviation = 1.49 m/yr. However, such dramatic change resulted from erosion of projecting landforms by coastal processes during the interim. We consider future behavior will more closely resemble that of the western portion of this sector, i.e. between 2.9 to 3.4 km, so the associated statistics will be applied to the full sector (2.9 to 4.2 km). The representative statistics for Sector 8 are thus, mean rate = -0.56 m/yr (-1.01 to -0.23 m/yr) and standard deviation = 0.25 m/yr.

Sector 9: Sponge Bay (4.2 to 4.7 km)

This sector lies within the embayment between Turanganui Point and Tuamotu Island and has lower erosion rates (mean = -0.29 m/yr [-0.65 to -0.04 m/yr] and standard deviation = 0.16 m/yr) which implies a relative increase in material strength.

Other long-term rate analyses

Finally it is noted that the discrete end-point analysis of Gibb (1995), and also the discrete regression-based profile analysis (2000 to 2016) are broadly consistent with the present spatially continuous linear regression analysis from the present historical study - compare the three types of result in Figure 4. This similarity indicates relatively uniform temporal change occurs with any significant differences being a product of the reduced temporal coverage associated with the discrete analyses. The continuous approach also allows sector boundaries to be more precisely defined.

3 Predicted shoreline behavior

3.1 Future influences

When predicting how the shoreline will behave over the next 100 years, factors influencing the historical record may change and/or new influences apply, so prediction based solely on extrapolation of historical behavior may result in under or over estimation. Of particular relevance to the present hazard assessment are effects of very low frequency (VLF) climatic reversals, land-use change (LUC) and climate change associated with global warming (CCGW). It is noted that there will be some inter-dependence between these factors.

Grant (1986) claimed that a very low frequency climatic-induced hillcountry erosion fluctuation was currently active. A reversal could then be expected during the next 100 yrs and this result in reducing the rate of accretion along the western coast.

The effects of colonial land clearance and subsequent afforestation have likely been affecting historical shoreline data, i.e. enhancing progradation. While the government's 1958 to 1998 afforestation programme may have had some recent influence in constraining shoreline progradation, its effectiveness during the prediction period will also depend upon the level of future (re)afforestation. Modelling under optimal conditions (plant all remaining gullies and also all new gullies) shows that the annual sediment yield in the Waipaoa catchment would be <u>halved</u> by 2050 (Herzig et al., 2011). Conversely, if no treatment occurs then the sediment yield will <u>double</u> by 2050. There is thus considerable uncertainty as to if and how landuse practice will influence future shoreline behavior.

Climate change effects driven by global warming (excluding shoreline adjustment induced by sea-level rise which is considered separately in the Hazard Assessment model) is fraught with uncertainty. Present predictions are for an increase in mean, extreme and seasonal temperatures (greater in the east of New Zealand), mean rainfall decreasing in the north and east, a general increase in westerly wind flow, and a 4-fold reduction in storm return periods by the 2080s (MfE, 2008, and Marden, 2011). These factors may act to reduce catchment erosion and hence lead to an eventual increase in erosion along the Waipaoa-effected western shoreline.

By contrast, the intensity of tropical cyclones is also predicted to increase and this in turn can increase hillcountry instability as illustrated by Cyclone Bola. Cyclone Bola impacted the east coast between the 5th and 10th March 1988 following several lesser storm events during the 1980s. The Waipaoa recorded its highest flow on record, 10 to 20% of East Coast hill county underwent severe landsliding, the Waipaoa's suspended sediment load was more than 5 x the mean annual value, and reef communities on the inner shelf were inundated (Foster and Carter, 1997). However, an analysis of how the newly afforested areas responded by Philips et al., (1990) found where plantations were older than 8 years, they provided 10x the protection against earthflow and 20x the protection against landslides than areas under grass. So if the backcountry is afforested in the future, the effect of more intense cyclones may be minimal compared with a scenario where future afforestation is lacking (leading to enhanced shoreline accretion).

However, the predicted increase in the intensity of extra tropical cyclones poses an increased risk of cliff erosion along the eastern coast via wave impact regardless of the status of backcountry vegetation.

3.2 Sector predictions (extreme)

How the three future behavioural modifiers may impact on each sector is now addressed. Of particular interest in a hazard assessment is how the lowest (minimum) historical-based regression co-efficient may be further reduced. These adjustments are presented as a % in Table 1, and together with the historical shoreline behaviour parameter values (minimum, mean and maximum), are used to define LT for various scenarios in the erosion hazard assessment model.

Sectors 1, 2 and the Transition zone (-8.6 to -2.1 km) are all effected by the Waipaoa catchment response so have been assigned a 50% reduction, comprising VLF = 10%, LUC = 20% and CCGW = 20%.

Sector 3 (Midway) has a much reduced influence by the Waipaoa and minimal Turanganui influence given its less erosion-prone geology. This sector was assigned a total reduction of 15% (VLF = LUC = CCGW = 5%).

Sector 4 (Turanganui Inlet) response is constrained by the port and coastal structures so the minimum regression rate was not altered, i.e. reduction = 0.

Sector 5 (Kaiti Beach) response is also constrained by port structures, but some increase in cyclonic-driven wave processes may be influential so a 10% reduction was assigned. It is assumed present land cover will prevail along the eastern study area, so the total reduction = 10%.

Sector 6 (Kaiti Bay) is more erosive-sensitive so 5% (VLF) reduction was assigned in addition to the 10% increased cyclonic-wave effect giving a total reduction of 15%).

Sector 7 (Pah Hill) is more resistant than the adjacent Kaiti valley (Sector 6) so only the 10% cyclonic wave effect was applied (total reduction = 10%).

Sector 8 (Tuamotu Island reach) is particularly erosion-prone so a 10% VLF was applied coupled with 20% cyclonic-wave effect, giving a total reduction of 30%.

Sector 9 (Sponge Bay) resistance is similar to Kaita Bay (5% VLF), but somewhat more exposed/responsive to cyclonic wave effects so a 15% CCGW reduction was applied giving a total reduction of 20%).

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