Coastal Erosion Hazard Assessment for the Kāpiti Coast: Review of the Science and Assessments Undertaken for the Proposed Kāpiti Coast District Plan 2012

June 2014

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Details

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Executive Summary

ES.1 Overview

The Kāpiti Coast District Council (KCDC) appointed a Panel of Experts to assist them in resolving issues raised concerning methodologies and the resulting coastal hazard zones developed in the reports by Coastal Systems Ltd (CSL, 2008a, 2008b, 2008c, 2012). This Panel consisted of the following individuals who have experience in undertaking investigations of coastal hazards, and a statistician:

- James Carley, Principal Coastal Engineer, Water Research Laboratory, UNSW, Australia
- Dr Paul Komar, Emeritus Professor of Oceanography, Oregon State University, USA
- Dr Paul Kench: Professor and Head of Department, School of Environment, University of Auckland, NZ
- Dr Robert Davies, Statistician, Statistics Research Associates Limited, Wellington NZ.

The Panel attended a Workshop on the Kāpiti Coast from 2 to 6 December 2013, with the first day spent on a field excursion along the coast, to acquire a first-hand familiarity with its environments, property development, and potential erosion problems. The following two days were dedicated to attending meetings with residents, other stakeholders, and with technical experts and Council staff. Subsequent to that meeting, the Panel concentrated on reviewing the CSL reports, and others related to the Kāpiti Coast hazards to determine the availability of data sets that document this coast's waves, tides, storm-induced surges, and evaluations of the rate of rising sea levels, processes that are important to sound, scientifically-based assessments of coastal erosion and flooding hazards. Also important to the Panel's review were the written comments by stakeholders and technical experts, provided to the Panel at the time of the Workshop, and their comments offered later in review of the first draft of this report. All of these materials were read by each of the Panel members, and received careful consideration in forming our opinions.

While each Panel member was responsible for writing separate sections of this report, this final draft sets out our collective opinion, all members being in agreement with the findings and recommendations.

It was during this review of the materials that the Panel decided to also consider the report by Lumsden (2003), who had earlier undertaken hazard assessments for KCDC. The significance of its inclusion is that John Lumsden is a coastal engineer and provided process-based analyses and hazard assessments, in contrast to those by CSL competed by Dr Roger Shand, a coastal geologist/geographer who had followed different methodologies, having focused on documentations of the changing positions of the Kāpiti shorelines, the long-term trends of erosion or accretion.

Based on its review, it is the opinion of this Panel that the hazard lines recommended by CSL are not sufficiently robust to be incorporated into the Proposed District Plan, and those completed by Lumsden in 2003 need to be updated to account for more recent analyses of the ocean processes, in particular the higher rates of rising sea levels that are now projected by climatologists. With the results of their analyses having complimented one another, respectively having focused on the long-term trends of rising sea levels and the progressive erosion of the Kāpiti shores, and the short-term destructive impacts of extreme-storm events, it is this Panel's recommendation that these contributions by both should be considered by KCDC in the development of more robust hazard lines to be included in their District Plan.

ES.2 Coastal Hazard Zones

Important to the development of hazard zones on the coasts of New Zealand are the guidelines contained within the New Zealand Coastal Policy Statement 2010 (NZCPS, 2010). In particular, Policy 24 provides a list of the risks that should be assessed "…over at least 100 years", including:

- the physical drivers and processes that result in coastal change, including sea-level rise;
- short-term and long-term natural dynamic fluctuations of erosion and accretion;
- the cumulative effects of sea level rise, and the wave heights and surge levels under episodic storm conditions; and
- the effects of climate change on the above, taking into account the best available information on the likely effects of climate change on the region or district.

Evident in this list is the recognition of the importance of short-term hazards produced by extreme storms that could happen this year or at any time in the future, and also the long-term progressively enhanced hazards due to rising sea levels, both having climate controls. These individual hazards are components in the standardised methodology developed by Dr Jeremy Gibb, which has seen widespread applications including in the CSL and Lumsden reports for the Kāpiti Coast. As formulated by Gibb, the resulting hazard zone distance is the summation of the following components, each contributing a distance to the dune and property erosion/recession:

- Short term storm erosion produced by extremes in wave heights and tides elevated by a storm surge;
- Dune stability, the additional retreat of the dune's scarp following the episode of storm erosion;
- Long term trends of coastal change (due to the sediment budget, the sand sources and losses);
- Recession due to sea level rise, based on projected future levels; and
- A factor of safety to account for the uncertainties in the analyses.

These factors were included by CSL (2008a, 2012c, 2012) in their analyses of the Open Coast hazards, with the addition of other factors when analysing the environmental hazards within river inlets (CSL, 2008b, 2012). Although the report by Lumsden (2003) included assessments of the impacts by the long-term rise in sea levels, of particular interest is his analyses of the short term, storm-induced impacts, in which he followed a process-based methodology, accounting for the combined effects of extremes in the storms wave heights and elevated tides due to its generated surge. Due to the importance of these factors, each has been reviewed in detail in this report, with summaries provided here for the long-term and short-term processes, and the methodologies applied in the CSL and Lumsden reports.

ES.3 Sea-Level Rise, Sediment Budgets, and Long-Term Changes in Kāpiti Shorelines

The Panel concluded in its review that the primary contribution in the CSL (2008a, 2012) open coast hazard assessments was their analysis of the long-term changes in locations of the shoreline positions, based on series of aerial photographs available since the 1940s, and old maps dating back some 135 years. Their analyses involved a detailed programme to cover the extent of this coast's 38-kilometre length of shore, the coverage including 68 analysis sites, 12 representing environmental-specific analyses for river inlets.

These analyses by CSL provide a valuable data set to be utilised in hazard zone assessments for the Kāpiti Coast. Examples of the time series of shoreline positions are included here in Figure ES1, respectively from the northern shore (C25-70) dominated by long-term accretion, a site on the apex of the cuspate foreland (C13-24) that has a more complex history with accretion since about 1960, and Queen Elizabeth Regional Park (C4-18) on the southern shore that has experienced shoreline recession and the most severe property erosion. Evident in these examples is the occurrence of non-linearity in their trends of shoreline locations over the decades, this being a problem in that linear (straight line) statistical regression analyses are applied to determine a trend, representing the rate of change in shoreline position (metres per year), either erosion/recession or accretion. In response to this problem, CSL (2008a) used only the more recent measurements at these sites showing a lot of non-linearity, starting where the data appeared more linear.

The change in measured positions of the shoreline over the decades, seen in these time-series, can result from a combination of the rise in sea level experienced during the 20th century, and the balance between the beach sand volumes supplied by its sources, versus its losses (the so-called "budget of beach sediments"). It is evident from these representative examples that the sediment budgets must have been the primary cause of their contrasting patterns of change, since the rise in sea level acting alone would have resulted in all three time series showing a progressive shoreline recession, each having essentially the same rate. The positive trend in the time series for C25-70, a persistent net accretion, demonstrates that it has acquired significant volumes of sand from the rivers to the north, sufficient that its net gain reflected in its accretion exceeds the potential recession from the rising sea levels. It is clear from these examples that analyses are required to separate the effects of sea-level rise from the site's sediment budget, in order to account for the net shoreline changes found in the site's time series, analysed by CSL.

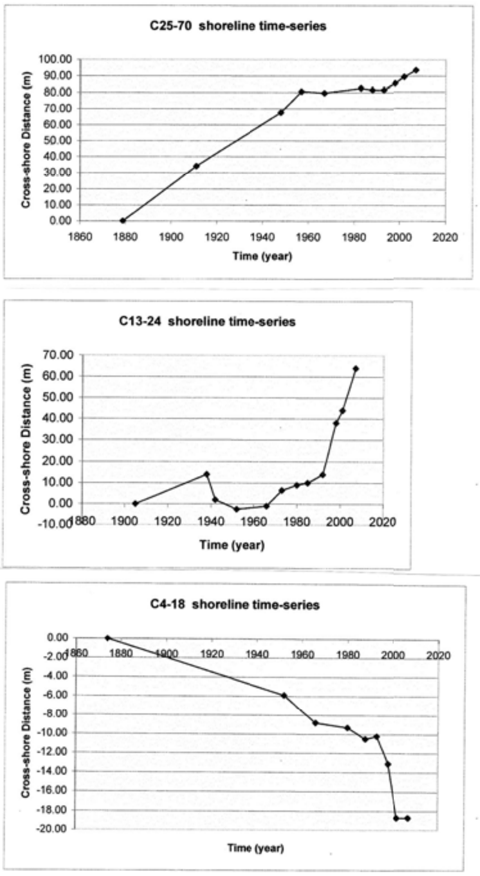

Figure ES1: Time series of shoreline positions based on aerial photographs and old maps. [Source: CSL (2008c)]

Unfortunately, CSL did not undertake analyses to isolate the causes, to remove the portion of the change due to the rise in sea levels, which would identify the portion due to the balance in the sediment budget that is primarily responsible for the site's accretion or recession. An important consequence of not having removed the contribution by the 20th century rise in sea level is that ultimately in calculating the future hazard lines they "double counted" the effects of the rise in the relative sea level, in that separate analyses were also undertaken on the changes in sea levels projected for time frames of 50- and 100-years, entered as a separate factor in Gibb's equation. To avoid this duplication, the preferred approach would have been to remove the contribution of the 20th century rise in sea level from the analysed trend of shoreline change, leaving only the portion that resulted from the gain of beach sand acquired from it sources, or its losses, the balance in that site's sediment budget, available for additional analyses.

In view of its importance, the Panel recommends that KCDC undertake analyses of beach-sediment budgets, in order to determine the gains and losses of the beach sand that account for the shoreline changes found in the CSL time series, and in the programme of beach-profile surveys (Lumsden, 2013). The quantification of the sediment budget should permit an assessment of whether the accretion of Kāpiti's central cuspate shore will revert to erosion in the near future, the positive balance in the budget being exceeded by future accelerated rates of rising sea levels. It is also important that investigations be undertaken of the rivers, the dominant sources of the beach sand, including considerations to determine how climate change or human impacts (e.g. sediment mining) could alter them, resulting in reduced volumes of sand being contributed to the Kāpiti beaches.

ES.4 Extreme Storm Events and Short-Term Erosion Hazards

By "short-term", the inference is that the hazard being considered could represent an immediate threat to the erosion of ocean-front properties, most clearly represented by the episodic occurrence of an extreme-storm event that might last for only a few hours or days. Of importance, however, it also denotes a hazard that could happen this year, or at any time in the next 100 years. In that respect, occurrences of extreme storms represent the most significant component in hazard assessments. While the rise in sea level is important, if it were to act alone, during the span of this century it would slowly flood over the inland properties, while their actual destruction would be produced by future storms, the zone of impacts by storm waves and tides being elevated by the rising water levels, and moving inland over additional properties.

It is in the analyses of such short-term hazards that the methodologies of CSL (2008a, 2008b 2012) and Lumsden (2003) differ the most. CSL follows an approach that expands their analyses of the historic trends of change in shoreline positions over the decades to include a focus on the variations in shoreline positions above and below the regression line that determined the long-term hazards. In contrast, the Lumsden (2003) analysis is based on the ocean processes, the waves and tides, their extreme combinations when exceptionally high tides combined with the occurrence of a storm and its extreme waves.

While the "residuals" and the resulting "fluctuations" determined by CSL in the time series of shoreline distances are of interest and worthy of analysis, it is necessary to understand the ocean processes and beach responses that are responsible for their occurrences. However, this was not attempted in the CSL analyses of the short-term hazards for the Kāpiti Coast, not having included any analyses of the available data sets for the waves and tides that actually represent the short-term hazards. Furthermore, it is clear that the recorded residuals and fluctuations are not responses to extreme, rare storm events that pose the greatest hazards. Accordingly, the conclusion of this Panel is that the CSL assessments of the short-term hazards cannot be viewed as being robust, that it does not sufficiently represent the extreme conditions necessary to account for present-day and future erosion and flooding hazards.

When an examination of past erosion events and their processes is undertaken, it becomes evident that an important consideration is the simultaneous occurrence of high storm-generated waves, together with elevated measured tides, or more specifically the increased swash run-up levels produced by the storm waves when they reach the beaches, occurring atop the elevation of a high predicted astronomical high tide that has been elevated still further by a surge also produced by the storm. Other contributing factors to the elevated measured tides might be the normal seasonal cycle of monthly-mean water levels, being highest when the water is warm (thermal expansion), and changes in water levels associated with the El Niño/La Niña range of climate events. The Kāpiti Coast hazard analyses completed by Lumsden (2003) focused on such combinations of the processes, to determine the total water levels (TWLs) at the shore produced by episodic storm events, following the methodology of Ruggiero et al. (2001) as illustrated in Figure ES.2. Having calculated the TWLs based on the combined processes, particularly their extremes during major storms, the water levels are then compared with elevation of the toe of the dunes, the beach/dune junction elevation, this determining whether or not the waves can reach and erode the dunes. The second diagram in Figure ES.2 is a schematic depiction of a dune-erosion model that is applied to estimate the potential erosion of the dunes for those TWLs, the model being based a projection of the water level to where it meets an extension of the sloping beach face. Application of this model provides an estimate for the potential maximum extent of the dune recession in response to the storm's waves and generated surge, with there also being the possibility of the fronting beach being lowered, for example by the presence of a rip current and its eroded embayment. As such, application of this model is conservative in providing a precautionary approach required in hazard assessments (NZCPS 2010). However, having evaluated this potential maximum, lesser degrees of potential hazards could be based on field evidence from the site being investigated, commonly in the form of the dune morphology such as remnants of past erosion scarps, or flotsam such as drift logs carried inland and found within or beyond the dunes.

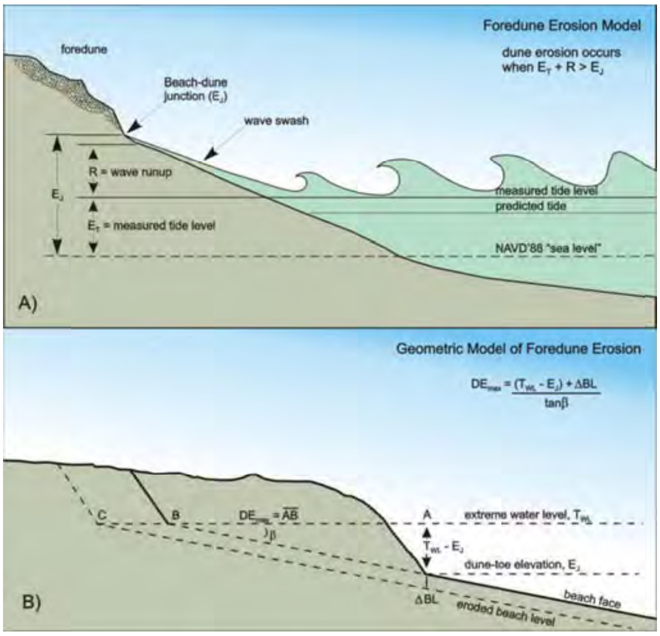

Figure ES2: The models to respectively calculate the total water levels, the measured tides plus the wave swash runup, and the maximum dune erosion produced by that water level compared with the dune-toe elevation.

It is the recommendation of this Panel that the analysis methodologies applied by Lumsden (2003) be adopted for evaluations of the short-term hazards on the Kāpiti Coast, updated in light of additional process data on waves, tides and sea levels having been made available.

ES.5 Inlets

Complex and less well understood processes occur around coastal inlets. The Panel supports the separate consideration of inlets in the hazard assessment.

The Panel endorsed the use of the CSL inlet approach, though refinements in application would be useful in future iterations to:

- Allow probabilistic analysis of shoreline positions within the envelope of change; and
- Evaluate alongshore variations in inlet location.

Along with revised open coast assessments, scenarios of change under accretionary coast conditions should be considered. Both managed and unmanaged inlet scenarios should be evaluated – the purpose of this evaluation would be to inform stakeholders of the consequences of an unmanaged scenario.

How the inlet and open coast hazard zones are merged should be reconsidered and a transparent procedure invoked.

Given the long history of hard and soft inlet management, the unmanaged scenario should not become the default without further stakeholder consultation, as well as social, environmental and economic assessment.

ES.6 The Kāpiti Coast Hazard Lines — Recommendations

While it has been the conclusion of this Panel that the hazard lines proposed by CSL in 2008 and updated in 2012 are not sufficiently robust for incorporation into the Proposed District Plan, and those completed earlier in 2003 by Lumsden need to be updated, it is recognized that both investigations completed quality analyses that are important components of the Kāpiti Coast's erosion hazards, that when revised could yield best practice hazard lines for its coast. In summary, included in our recommended revisions and additional investigations are the following:

- That the time series of shoreline changes derived by CSL for the 68 sites along the Kapiti Coast be analysed to separate the respective contributions produced by sea-level rise during the 20th century, and that produced by gains and losses of beach sand at that site, its sediment budget, eliminating the "double counting" of the rise in sea level from the projected 50- and 100-year hazard zones.
- Undertake analyses of beach-sediment budgets to determine the gains and losses of the beach sand that should account for the shoreline changes found in the CSL determinations, including particular attention given to the rivers, the principal source of the beach sand, and how global warming or human environmental impacts could change the volumes of sand being contributed to the Kāpiti beaches.
- Compare the sediment budget analyses with the projected rates of rising sea levels to assess if and when the accretion of its central cuspate shore might revert to erosion and eventually disappear, exposing the properties along that shore to storm impacts.
- The analyses by Lumsden (2003) be updated to include the additional wave hindcast data available from the MetOcean reports, and the increased sea levels that are now projected by climatologists, with the revised results used for the short-term factor in the Kapiti Coast's hazard lines, replacing CSL's "fluctuation" values.

With the combined contribution from the Lumsden processes-based analyses of short-term hazards resulting from extreme storm events, with those from CSL that documented the long-term trends of changing shoreline positions, the Kāpiti Coast District Council would obtain the desired robust erosion hazard zones, in which both the engineering and geologic aspects have been accounted for, in effect "the best of both worlds".

ES.7 Need for Coastal Management

The study of coastal processes and the determination of coastal hazards is of fundamental academic interest, however, it is generally only of concern to local government and communities when present or future coastal hazards potentially impact the built environment.

Although coastal management was not explicitly part of the Panel's Terms of Reference, a substantial number of submissions related to risk assessment and coastal management.

The assessment of coastal hazard zones should consider a range of plausible scenarios (e.g. low, mid, high, or best estimate and extremes). The range of scenarios (particularly for 100 years' time) should be considered in future planning, but automatic retreat of development behind the projections for the most extreme scenario should not be a default management plan.

In the formulation of planning policies for coastal hazard management, a full range of management options needs to be considered in conjunction with stakeholders, and include policy, economic, environmental, cultural and social factors. Noting that the definition of *risk* is likelihood times consequence, risk may therefore be managed by changing either the likelihood or the consequence.

In short, this management may consider combinations of the following options in increasing order of strength (of intervention):

- No action;
- Retreat and relocation;
- Accommodation (optimising the coexistence of the built environment and natural processes); and
- Protection through:
    - Soft engineering (such as beach nourishment);
    - Hard engineering (such as seawalls).

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1. Introduction

Author: P D Komar and J T Carley

An important aspect of most coastal management programmes is an assessment of erosion and inundation hazard zones, to identify homes and infrastructure that may be vulnerable to impacts from present-day extreme storm events, and future elevated sea levels. This practice has gained significance in recognition of Earth's changing climate, which is expected to produce an intensification of the ocean's processes, including accelerated rates of rising sea levels, and changes in the intensities of storms that generate more extreme wave heights and surge levels.

In 2013 we were appointed by the Kāpiti Coast District Council (KCDC) to serve as a Panel of Experts[1], to assist them in resolving issues raised in regard to the science and methodologies applied in hazard assessments undertaken by Coastal Systems Ltd (CSL), detailed in their reports to the Council completed in 2008 and 2012. In our review it was necessary to examine other relevant reports, including those important to having documented the ocean processes that determine the present day and future hazards experienced on the Kāpiti Coast. This led to a decision to also consider the hazards report prepared by Mr John Lumsden, who earlier in 2003 had undertaken hazard assessments for the KCDC; of significance, with Lumsden being a coastal engineer, he applied different methodologies than those followed by CSL, those undertaken by Dr Roger Shand, a coastal geologist/geographer. The reports that pertain directly to the proposed hazard zones for the Kāpiti Coast, those we have reviewed, include the following:

- Lumsden, J. (2003) *Strategies for Managing Coastal Erosion on the Kāpiti Coast*: Draft report prepared for the Kāpiti Coast District Council, 2 volumes, 362 pp.
- Coastal Systems Ltd. (2008a) *Kāpiti Coast Erosion Hazard Assessment — Part 1: Open Coast:* A report prepared for the Kāpiti Coast District Council, 80 pp.
- Coastal Systems Ltd. (2008b) *Kāpiti Coast Erosion Hazard Assessment — Part 2: Inlets:* A report prepared for the Kāpiti Coast District Council, 68 pp.
- Coastal Systems Ltd. (2008c) *Kāpiti Coast Erosion Hazard Assessment — Part 3: Data-Base:* A report prepared for the Kāpiti Coast District Council.
- Coastal Systems Ltd. (2012) *Kāpiti Coast Erosion Hazard Assessment 2012 Update:* A report prepared for the Kāpiti Coast District Council, 105 pp.

These reports were based on a spectrum of methodologies used to guide coastal hazard assessments, with the earliest by Lumsden having been based on analyses of the causative ocean processes and their extremes, the ocean waves, the measured tides that have been enhanced by storm surges, and rising sea levels, the processes that potentially combine to produce serious erosion and inundation impacts along the Kāpiti Coast. KCDC later engaged Coastal Systems Ltd. (CSL) to undertake assessments of the hazards, yielding the four CSL reports listed above. CSL's approach followed what can be characterised as a geographic or geologic-based methodology, foremost being analyses of trends in shoreline erosion (landward recession) or accretion (the shoreline advancing seaward), with the rate of progress of the erosion being projected through this century. Having applied different methodologies, the investigations by CSL and Lumsden complement one another in their contributions.

The members of this Panel attended a workshop held on the Kāpiti Coast from 2 to 6 December 2013 (Appendix B), the first day having been guided on a tour that covered nearly the entire length of the Kāpiti shore, providing us with the opportunity to inspect its beaches and dunes,

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[1] A list of the Panel members is given in Appendix A, including affiliations and brief descriptions of their technical expertise and professional experience.

inlets, its ocean-front properties, and to become familiar with the range of shore-protection structures constructed to defend those properties. The following two days of the Workshop were devoted to first meeting with residents and stakeholders of the Kāpiti Coast, listening to their presentations and with their having provided us with written statements[2]. The following day we met with technical experts (listed in Appendix C), including the primary author of the CSL reports (Dr Shand), time well spent in providing useful exchanges of opinions and suggestions for improving the hazard-zone assessments. A number of technical reports from a variety of sources were also provided to the Panel and made available to all participants in the December meetings via the Council website. These contained important background information concerning the processes that are responsible for the hazards (waves, tides, etc.). The final day of this Workshop was devoted to internal discussions by the Panel members, covering the information that had been presented to us, and concerning organisational matters to be followed in preparing our review report for the KCDC.

The task faced by the Panel proved to be daunting, with the CSL and Lumsden reports being both voluminous and detailed in their contents. To this was added the materials provided by Workshop participants, and we also found it necessary to read and absorb as much as possible from past reports concerned with the Kāpiti Coast's erosion processes and hazards. The first draft of this report was completed in March 2014, having been prepared in haste. That draft was submitted to KCDC by the Panel Chair, James Carley, who made oral presentations to KCDC and at two public forums[3], summarising our findings and responding to questions. The next day he similarly met with homeowners, at which time they were provided with copies of the report. This was followed by a period of time during which the stakeholders and technical experts could submit written comments about our March draft, with the Panel considering these submissions in finalising their report.

In the interim, while waiting for those comments we had additional time to go through the reports and materials that had been provided to us earlier at the Workshop, and then to review the wide-ranging comments, suggestions and criticisms offered by the 21 reviewers of the March draft. The present report is the product of the Panel's deliberations, having considered the results of the coastal hazard investigations undertaken thus far by CSL and Lumsden, and the input provided by stakeholders and technical experts. As directed by KCDC, this report focuses on the scientific validity of the methodologies and resulting hazard-zone assessments followed in those reports, confined to the erosion and recession hazards. The inundation and tsunami hazards are being assessed in separate studies, and therefore are beyond the scope of this Panel.

It is the opinion of this Panel that the respective investigations by Lumsden and CSL complement one another in having followed different methodologies, the Lumsden study having included analyses of the ocean processes important to hazards from extreme storm events, while those by CSL include analyses that document the long-term trends of shoreline change and their projected future hazards. It is important to consider the results of both studies, supporting decisions by KCDC directed toward the establishment of sound, scientifically-based coastal erosion hazard zones.

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[2] Copies of written statements and other materials submitted by the homeowners and technical experts were provided to and read by each of the Panel members.

[3] At which time the draft report was publicly released.

2. Climate Change and Enhanced Erosion Hazards

Author: P D Komar, Editor: J T Carley

Important to considerations of the Kāpiti Coast hazards is to first acquire a perspective of global climate change and the resulting hazards faced world-wide by coastal developments. Our main focus will be on projections by climatologists of accelerating rates of rising sea levels, and evidence for the increased intensities of storms that generate more extreme waves. Coastal management programs need to be aware of the research undertaken on those important issues, recognising that to varying degrees debates still exist among the communities of climatologists and marine scientists, including conflicts in research results and divergent opinions that have been summarised in the presentations by Dr Willem de Lange, orally at the December Kāpiti Workshop and in his written comments provided to the Panel (de Lange, December 2013, April 2014)[4]. Some of these issues, although important, are beyond the scope assigned to this Panel by the KCDC, so might only be mentioned in passing in this report, or not at all. It also needs to be recognised that climate change represents an extremely active area of research, with large numbers of publications appearing each year, making it difficult to extract the results needed in assessments of coastal hazard zones, the primary example being projections of future sea levels. A major impetus for coastal management programs focusing on the development of hazard zones is the documentation of Earth's changing climate and the prospects for enhanced coastal hazards through the 21st century. According to the definition by the Intergovernmental Panel on Climate Change (IPCC, 2013):

> Climate change refers to a change in the state of the climate that can be identified (e.g., by using statistical tests) by changes in the mean and/or the variability of its properties, and that persists for an extended period, typically decades or longer.

Included in its causes are: "modulations of the solar cycles, volcanic eruptions, and persistent anthropogenic changes in the composition of the atmosphere or in land use." IPCC goes on to define Hazards as:

> The potential occurrence of a natural or human-induced physical event or trend or physical impact that may cause loss of life, injury, or other health impacts, as well as damage and loss of property, infrastructure, livelihoods, service provision, ecosystems, and environmental resources.

It is evident that the term "climate change" is very broad and can include a considerable number of causes (natural and human), and also suffers from multiple definitions other than that by IPCC given above. With our interest being directed towards coastal hazards produced by the global rise in sea levels and extreme storm events, our focus will be almost entirely on the consequences of "global warming" as the major cause, preference therefore being given to that term throughout this report, rather than the broad concept of "climate change". With respect to the coastal impacts, also important is the significance of the El Niño/La Niña range of climate events, and the Interdecadal Pacific Oscillation (IPO), the alternating dominance of those respective climate conditions on time scales of 20 to 25 years. The changes in Earth's climate of interest to hazard assessments, therefore, consist of a progressive trend (global warming), with superimposed individual extremes represented by El Niños and La Niñas, and their multi-decadal cycles (the IPO). These climate variations have been found to affect both sea levels and storm

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[4] Written materials provided to the Panel by homeowners and technical experts are cited in this form, giving the source and date, rather than being listed in the references at the end of this report.

intensities, being important respectively in long-term enhanced hazards and episodic extremes of erosion and inundation events.

2.1 Rising Sea Levels: Rates and Future Projections

The inception of significant degrees of global warming and its effects on the environment can be traced back to the late 19th century, the period of rapid industrialisation, with the most obvious environmental consequence being the global rise in sea levels measured by tide gauges throughout the world. This history of changing globally-averaged sea levels from 1800 to 2010 is shown by the graph in Figure 1. The thick black line represents the approximate average rise during the early 19th century, based on a variety of environmental evidence such as tree rings and coral reef growth (termed “proxy sea levels”), transitioning to the red line that is based on world-wide measurements by tide gauges, with the average rate of rise spanning the 20th century having been about 1.7 mm/year, but more meaningful to coastal hazards the average rate has been about 2.0 mm/year since 1930. The short green line is derived from satellite altimetry sea-level measurements that began in 1993, which covers the entire extent of the ocean but can be integrated to yield the global averages graphed in Figure 1. There is good agreement between the tide-gauge and satellite measurements from 1993 to 2010, indicating that the rate of rise has been of the order of 3.3 ± 0.4 mm/year, suggestive of there being an acceleration in the rate of rising sea levels, that rate being greater than 2.0 mm/year experienced during the 20th century. While the concave-up curvature of the 19th century proxy data plus the tide-gauge and satellite measurements indicates that there has been an overall acceleration in the rate of sea-level rise spanning those 200 years, debate exists as to the occurrence of an acceleration when considering the tide-gauge data alone for the 20th century. This uncertainty mainly results from the variations in the annual-average sea levels produced by multiple natural and human-induced environmental effects, for example major volcanic eruptions that temporarily produce global cooling due to their emissions of aerosols, the similar effects of air pollution caused by humans, and variations associated with the annual to decadal climate changes that include El Niños and La Niñas.

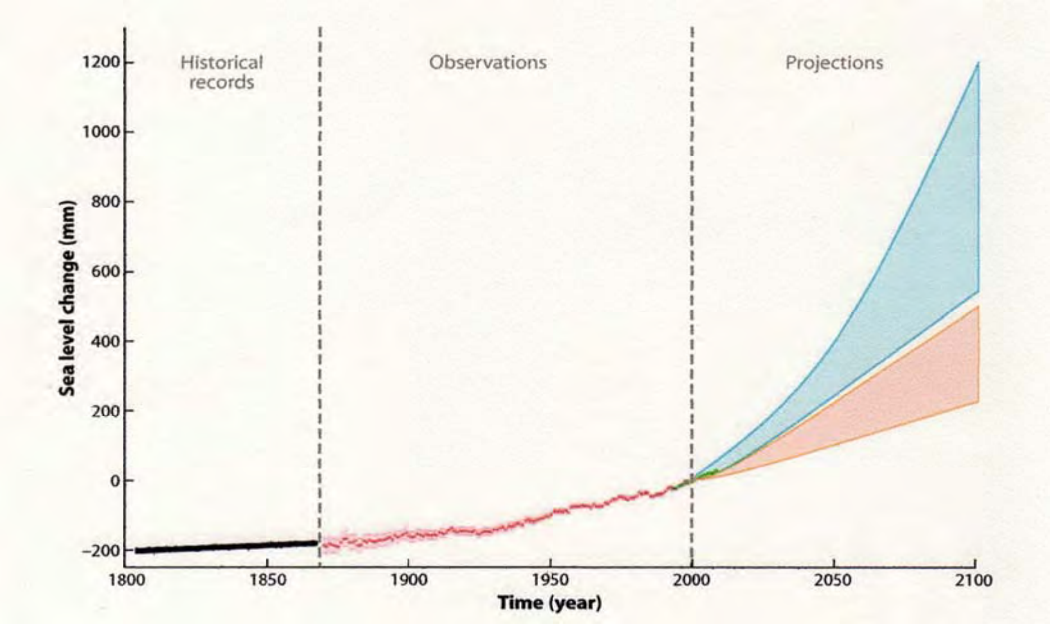

Figure 1: Global mean sea levels from 1800 to the present, and projected to 2100 [*Source:* Cazenave and Llovell (2010)]

Projections of future sea levels through the 21st century are included in Figure 1, being critical to assessments of potential future hazards along the ocean's shores. Deriving such projections has been a primary goal of the Intergovernmental Panel on Climate Change (IPCC), with their most recent detailed report having appeared in 2007, and a revised *Summary for Policy Makers* released in late 2013. The IPCC-2007 projections to the year 2100 are included in Figure 1, the pink-shaded region, having been based on global climate models and a series of scenarios that represent potential degrees of future greenhouse gas emissions by humans, the driving force responsible for global warming; the curves in Figure 1 encompassing the pink-shaded region range from representing high to low modelled emissions. More extreme projections have been derived in analyses by Rahmstorf (2007), and by other recent investigations, based on correlations between the global sea-level rise and Earth's past changes in mean atmospheric temperatures, yielding the blue-shaded region in Figure 1, projecting sea-level increases of 50 to 120 cm by the year 2100. In his review of the March draft of this report, Willem de Lange (comments, April 2014) cited studies by other climatologists who have argued against the analysis approach taken by Rahmstorf, and against their projected higher rates of future sea levels, illustrating the debate among climatologists and coastal scientists regarding projections of future environmental conditions (global temperatures, rainfall and floods, sea levels, storm intensities, etc.). There may be some encouragement in the recent projections by IPCC (2013), which somewhat close the gap between the ranges of projections offered by climatologists; the IPCC (2013) projections for 2100 now range from a low of 0.3 metre (300 mm as graphed in Figure 1) to a high of 0.98 metre (980 mm), with their middle scenario projecting a rise of 0.475 metre (475 mm), which, however, still remains lower than the mid-range value of Rahmstorf (2007) that is at about 800 mm as graphed in Figure 1.

These remaining uncertainties in the projections of future globally-averaged sea levels have obvious ramifications to the development of coastal hazard zones, with any uncertainties in the ocean processes being carried into assessments of future hazards. It is hoped that continued research by climatologists will resolve these differences, and provide more confident assessment of future sea levels required in coastal hazard assessments.

While the trends of globally-averaged measured sea levels and their future projections are of immense interest, as are their climate controls, of more immediate significance to the hazards faced by specific coasts is their local trend in the “relative sea level”, which includes the direction and rate of change in its land elevations, combining with the increase in the global ocean-water levels. It is this trend in the relative sea level that can be derived directly from tide-gauge records, by computing the annual averages of the gauge’s hourly measurements through the year, and tracking its changes over the years to derive a trend, a rate of change that could either be greater or less than found for the global average, depending on the subsidence or uplift of the coast. This difference can be significant in tectonically active regions such as New Zealand, due to the collision and subduction of Earth’s tectonic plates. For the North Island and the Kāpiti Coast this collision is between the Pacific plate to the east and the Australian plate to the west, with subduction of the Pacific plate occurring along the Hikurangi Margin that extends the length of the east coast (Wallace, et al., 2009).

Important to hazard assessments for the Kāpiti Coast is the close proximity of the tide gauge in Wellington Harbour, its record having received detailed analyses by Bell and Hannah (2012). Its measurements of the tides extend back to the late 1800s, initially recorded in the form of annual mean sea levels up to the 1940s, with monthly-mean sea levels available from 1944 to the present, yielding the analysis in Figure 2 from their study, the linear regression spanning the century up to 2010 showing a trend of 2.30 ± 0.15 mm/year. With this long-term rate of rise in the relative mean sea level being greater than the global average rate (Figure 1), the indication is that this coast has experienced subsidence, of the order of 0.3 mm/year. Subsidence along this coast is expected from the Pacific and Australian plates being “locked” on their subduction interface, storing tectonic energy, not having been released by occurrences of major subduction earthquakes during historic times. Subsidence of this shore and all along the east coast of the North Island is also demonstrated by GPS units that have measured land-elevation changes for about a decade (Beavan and Litchfield, 2009). As analysed by Bell and Hannah (2012), a GPS unit located near the Wellington tide gauge shows a subsidence rate of about 1.7 mm/year since 2000, a localised higher rate of subsidence of the land that is attributed to “slow-slip” tectonic movements on the subduction interface, a gradual slip that does not generate a strong earthquake, having been identified by seismologists (Wallace and Beavan, 2010). Similar GPS measurements on the Kāpiti Coast show a smaller subsidence rate of 1 mm/year.

The annual-average sea levels graphed in Figure 2 demonstrate a degree of variation that is fairly typical of such analyses, the origin of which for the Wellington record has been investigated by Bell and Hannah (2012). These anomalies above and below the linear regression line were found to vary between -0.16 and +0.17 metre, a range of 0.33 metre. The lowest level occurred during August 1977, coinciding with a strong El Niño; the highest in October 1989 occurred during the strong 1988-89 La Niña. Correlations were found with the Southern Oscillation Index (SOI), which provides a measure of the range of intensities between those climate events. The higher than normal mean sea levels at Wellington during La Niñas are attributed to warmer coastal and ocean water temperatures, resulting in its thermal expansion, plus a general set-up of the water levels in the western Pacific produced by a strengthening of the easterly Trade Winds. The opposite occurs during El Niños, with the colder water temperatures and increased densities lowering the Wellington water levels.

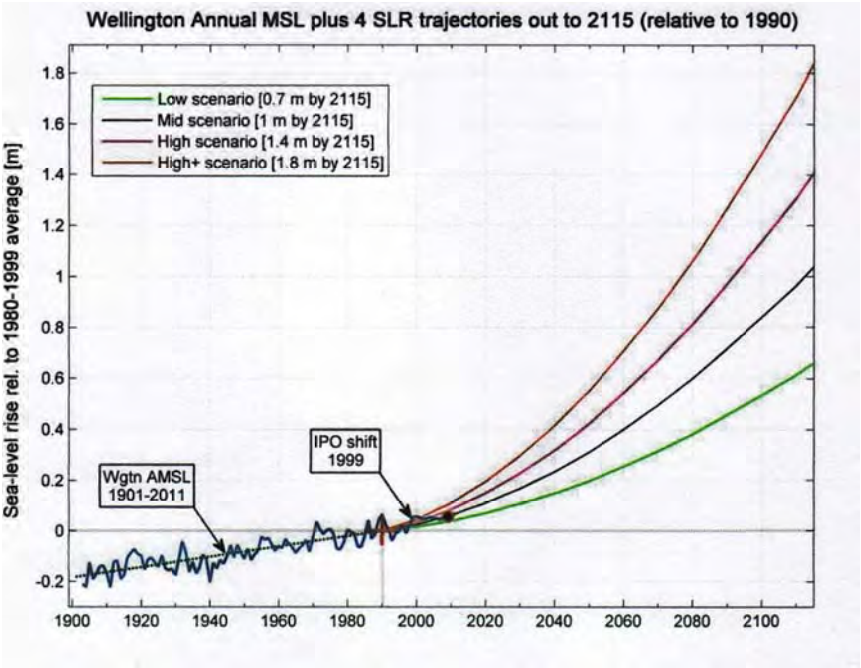

Figure 2: Analysis of the Wellington tide-gauge measurements from 1900 to 2010, the linear regression yielding a 2.30 ± 0.15 mm/year rate of rise in the relative sea level, and including a range of projections for future sea levels to 2115. [*Source:* Bell and Hannah (2012)]

Included in Figure 2 are projections by Bell and Hannah (2012) of future sea levels, extending beyond the regression trend for the 20th century based on the gauge's measurements, such that the projections account for the long-term rate of subsidence for this coastal site. The series of curves represent scenarios reflecting different degrees of global warming, much as undertaken in the IPCC (2007, 2013) projections, but here having been adopted from those used for planning purposes in Australia, the UK, and The Netherlands. In the case of Australia, three scenarios have been considered by CSIRO:

- *low scenario*, considered to be unavoidable;
- *medium scenario*, the upper end of the IPCC (2007) assessments;
- *high-end scenarios*, that considers ice-sheet dynamics and the post-IPCC (2007) more extreme projections.

In their review of the IPCC (2007) projections and those offered by subsequent investigations, Bell and Hannah (2012) concluded: "Credible estimates of sea-level rise by 2100 are more likely to be in the range 0.5 to 1.0 m, but rises above 1 m cannot be ruled out." The mid-point in the four projection curves in Figure 2 for the year 2100 falls at about 0.9 to 1.0 metre, corresponding to that conclusion, but Bell and Hannah (2012) provide projections to 2115, with the mean sea levels being listed in the diagram, having on average reached a rise of about 1.2 metres, higher than the IPCC-2007 projections in that the consequences of ice dynamics have been included, but lower than the projections by Rahmstorf (2007).

It is the recommendation of this Panel that analyses of projected increasing sea levels be based on the analysis results of Bell and Hannah (2012) for the Wellington tide gauge, Figure 2, including model results for all scenarios in order to demonstrate the uncertainties inherent in those projection, giving most credence to a mid-level projection. Differences in rates of subsidence between Kāpiti and Wellington should be accounted for, and if available, include later modifications by climatologists of projections for the future global sea levels.

2.2 Increasing Storm Intensities and Wave Heights

In addition to rising sea levels due to global warming, in recent decades Earth's changing climate appears to have also produced an intensification of storms in some regions, which have generated more extreme waves contributing to enhanced coastal impacts. However, just as in the case of future sea levels, debate exists amongst climatologists and coastal scientists regarding future increases in storm intensities and trends of increasing storm wave heights, projected through the 21st century. However, sufficient documentation exists for there having been an increase in both storm intensities and wave heights over significant areas of the world's oceans, based on measurements from wave buoys and satellites, that potentially should be considered in assessments of future coastal hazards, even though projected magnitudes are uncertain.

Global climate models applied to investigate environmental changes in response to global warming indicate that the intensities of storms may be expected to regionally increase, with the model projections to a degree having been confirmed by measured wind speeds and atmospheric pressures within both tropical storms (cyclones, typhoons and hurricanes) and extra-tropical storms at higher latitudes. The expectation, therefore, is that the heights and periods of the waves generated by those storms would also have increased during the 20th century, and potentially could continue to increase in the future, leading to greater coastal impacts.

An increase in wave heights has been documented by long-term measurements in the North Atlantic, collected since the 1960s using a recorder mounted on the Seven Stones Lightship located off the southwest coast of England, yielding the earliest and longest record of wave climates; its record was the first to demonstrate a statistically significant trend in the annually-averaged significant wave heights, defined as the average of the highest one-third of the hourly measured wave heights (Carter and Draper, 1988; Bacon and Carter, 1991). Wave-height increases have similarly been found in the Northeast Pacific, in measurements from several buoys along the US west coast (Allan and Komar, 2000, 2006), showing that the rate of increase has been greatest at the higher latitudes of the Pacific Northwest, the coasts of Washington and Oregon, whereas on the shores of southern California the waves have been most extreme during major El Niños due to the southward shift of storm tracks during that climate event. The increase in the wave heights measured by a buoy off the Pacific Northwest is shown in Figure 3, representing a series of graphs for the annual averages of the hourly-measured significant wave heights. The top-most graph is a plot of the annual averages for the entire year, with the regression yielding a rate of increase of 0.018 m/year, while the remaining series of graphs represent progressively more extreme storms and assessments of the wave heights. The second plot is for the averages of the measured significant wave heights during the "winter" (October through March), being most relevant to coastal impacts since erosion events are largely confined to that season; the rate of increase has been 0.032 m/year (an increase of 0.8 metres in 25 years), substantially greater than for the annual averages. The third and fourth graphs are respectively the annual averages of the 5 highest recorded wave events experienced each winter, the rate of increase having jumped to 0.095 m/year, while the highest measured significant wave height each winter yielded a rate of increase of 0.108 m/year (2.7 metres in 25 years). Therefore, in analyses of waves generated by extratropical storms in the North Pacific, it has been possible to demonstrate that the highest generated waves have substantially increased with time, a high rate of increase that is also displayed by the statistically projected 25- through

100-year extreme significant wave heights, occurrences that could be generated by the most severe future storms (Ruggiero et al., 2010).

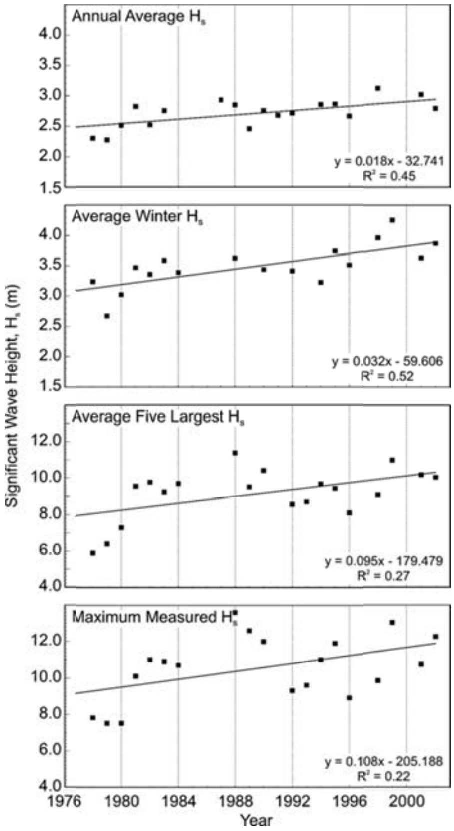

Figure 3: Increasing significant wave heights off the coast of the U.S. Pacific Northwest, the series of graphs representing progressively more extreme assessments. [*Source:* Allan and Komar (2006)]

The analysis in Figure 3 of buoy-measured significant wave heights serves as an example of an important factor that needs to be recognised in environmental parameters and their responses to the changing climate — the more extreme the focus taken in the analysis, the greater the rate of increase. This has been demonstrated, for example, in analyses of the trends of global-averaged atmosphere temperatures, rainfall and flood discharges in rivers, as well as seen here for ocean wave heights. The cause of this pattern is that the distributions in the magnitudes of these environmental processes are not symmetrical as represented by a Gaussian distribution, instead being skewed (asymmetric) toward their higher magnitudes, evident in the distributions of the waves measured off the coast of the Pacific Northwest (Komar and Allan, 2007; Ruggiero et al., 2010). It is also important to recognise that in analyses of extreme values, projecting the 50- to 100-year ARI potential extremes, where there is an increase in magnitudes with time as evident in Figure 3, standard statistical methodologies developed for “static” populations are not valid; it is instead necessary to apply advanced statistical techniques that account for time-dependent trends, this being illustrated by Ruggiero et al. (2010) in application of those techniques to analyses of the Pacific Northwest wave climate.

Unfortunately, long-term records of buoy-measured waves are rare, so it is not possible to derive a global perspective of trends that might be a response to Earth's changing climate, to both global warming and El Niño/La Niña variations. Important for a global view are the satellite-borne instruments that in recent years have acquired measurements of wave heights and periods, and of surface-level winds that generated the waves. Almost continuous measurements on a global scale exist since 1985, data that have been analysed by Young et al. (2011) for 2° by 2° regions covering the globe. For each of those small areas, multi-decadal trends in both the wind speeds and wave heights have been found, including the annual means and 90th-percential, with the 99th-percentile extremes shown in Figure 4. It is evident from this satellite data that there have been increases in winds and the most extreme wave heights generated by storms, those important to coastal impacts, with the red dots signifying the areas where the results are statistically significant.

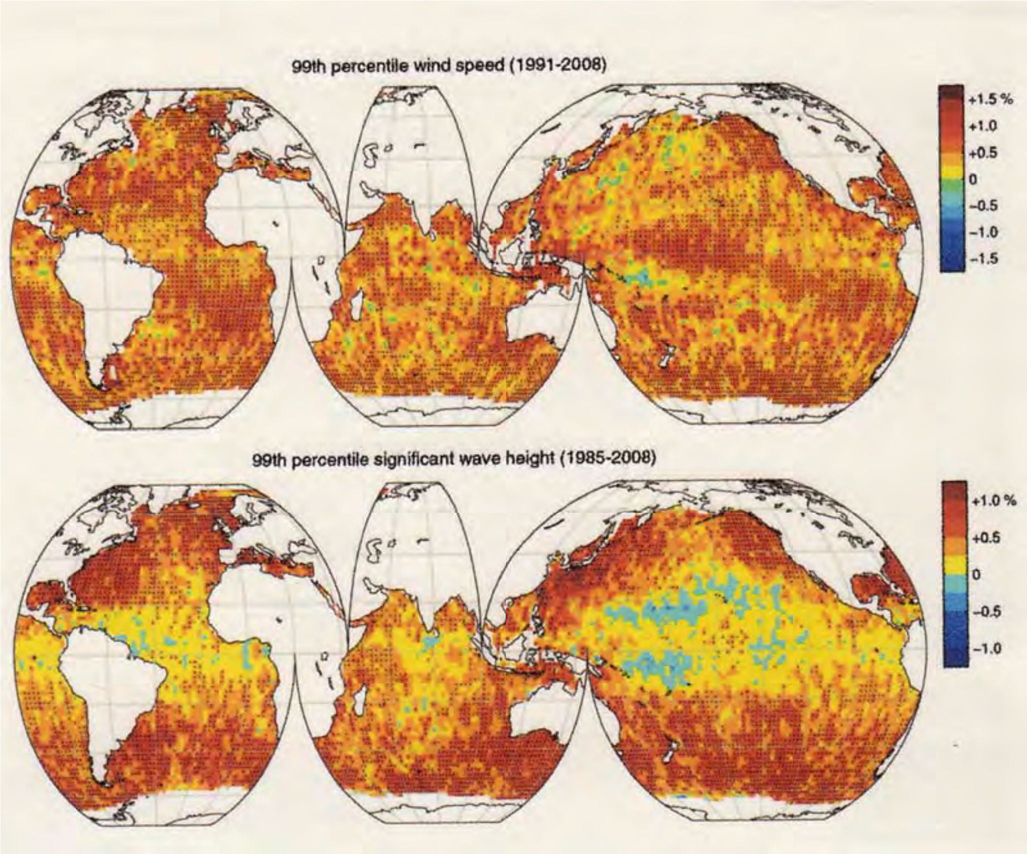

Figure 4: Trends of increasing wind speeds and significant wave heights measured by satellites, their 99th-percentile trends (percent per year). [*Source:* Young et al. (2011)]

It is seen in Figure 4 that the highest rates of increase have prevailed in the high latitudes of both the Northern and Southern Hemispheres, including around the shores of New Zealand. The trends graphed by Young et al. (2011) around the coasts of New Zealand for this 99th percentile amount to about a 1% increase in height per year, of the order of a 5 cm increase per year. This rate might seem to be modest, but is significant when compared with the heights of waves along this coast, with the cumulative increase over the span of a decade to 25 years potentially constituting an enhanced hazard to the ocean shores of New Zealand.

One submitter (Simon Arnold, April 2014) commenting on the March draft of our report noted that while Young et al. (2011) had documented an increase in the extreme 99th percentile significant wave heights, Figure 4, the trends in the mean significant wave heights remained close to zero, suggesting that there has not been a climate-induced increase. The data itself, however, show that the annual means in the Northeast Pacific off the west coast of the United State and at high latitudes in the Southern Hemisphere showed rates of increase predominantly being about 0.25%, increasing to on the range 0.25 to 0.50% for the 90th percentile, and then as seen in Figure 4 achieving an increase of about 1% per year for the 99th percentile. Important, the satellite measurements of the wind speeds follow this same trend of increase for their rates, the percentage rates being greater than those for the wave heights, and with most being statistically significant. These patterns of change in the satellite measurements of the winds and waves correspond to and agree with those seen in Figure 4 for the buoy wave data measured off the coast of the US Pacific Northwest — the rates of increase of both the winds and generated wave heights increase as progressively higher extremes are analysed, this being expected for their skewed distributions of magnitudes, and of obvious importance to coastal hazard assessments since it is these extremes in storm winds, storm surges and generated wave heights that are important to the episodic erosion and flooding of coasts.

There is reasonably compelling evidence for potential increases in both storm intensities and their generated wave heights, with the rates of increase in their magnitudes posing enhanced hazards to the ocean's shores. It is recognised that there have been few analyses of long-term buoy records to document this increase, and that satellite measurements of storm winds and wave heights are limited to only two decades, with the magnitudes of their rates of increase therefore being uncertain. The global satellite data show regional differences, with the higher rates of increasing storm intensities and extremes in the wave heights occurring at high latitudes, encompassing the ocean shores of New Zealand. Uncertainties remain as to the climate controls on extratropical storms that dominate those higher latitudes, with research by climatologists predominantly attributing the increases to global warming. Furthermore, it has been suggested that the increased storm intensities in the North Pacific have been produced by "black carbon" aerosols emitted by power plants and factories in China and India. Therefore, the connection of storminess with global warming is less certain than rising sea levels being caused by global warming; specifically, the melting of glaciers and return of the water to the oceans, and the thermal expansion of the ocean's waters representing the most important processes.
While there have been analyses of wave climates for Cook Strait and the shores of the Kāpiti Coast based on hindcast analyses (Laing et al., 2000; MetOceans, 2007, 2010), those investigations did not include examinations of a possible increase over the decades, and likely would have been unsuccessful given the limited accuracies of hindcasts. The isolation of the Kāpiti Coast within the confines of the Strait likely decreases the probability of their being increasing locally-generated wave heights, but there is the possibility for storm waves arriving from the Tasman Sea to produce an increase along the Kāpiti Coast, the satellite data having shown a significant rate of increase in the Tasman Sea (Figure 4).

It is plausible that there will be an increase in wave heights along the Kāpiti shores in the future, enhancing the impacts of storm events, but there are uncertainties in the research completed thus far by climatologists and marine scientists, and there is not at present a clear direction to be followed in providing an analysis of the potential hazards faced on the Kāpiti Coast. It is clear that the global measurements being obtained from satellites will be important to this assessment, but with there being only two decades of measurements thus far, it becomes a case of "wait and see" until a longer data set becomes available, but that would likely require multiple decades of additional measurements.

Until longer term data sets become available to assess whether storm-generated wave heights are increasing, globally and within the Cook Strait, it would be informative to expand the already completed wave climate analyses of Laing et al. (2000) and MetOceans (2007, 2008) to include more detailed analyses of the heights of waves that reach the Kāpiti shores from the Tasman Sea. Of interest would be to derive at least an order-of-magnitude estimate of increase over the next 25 to 50 years, permitting a comparison with the expected impacts from projected rising sea levels. Such model-generated estimates of the wave-height increases should not, however, be included at this stage in the hazard-zone assessments, but potentially could be in the future after there is greater certainty in the documented trends of storm intensities and of their generated waves, and a better understanding of the climate controls.

3. Kāpiti Coast Ocean Processes and Hazard Assessment Methodologies

Author: P D Komar, Editor: J T Carley

3.1 Introduction

A major effort in most coastal management programmes is directed toward the acquisition of data that documents the magnitudes of the coastal processes that represent hazards to ocean-front homes and infrastructure, required to support the development of hazard zones. The objective of this Section is to provide a review of the availability of data collected and analysed for the Kāpiti Coast, the processes that are the foundation in evaluations of its erosion and inundation hazards. That review is followed by a summary of the methodologies that can be applied in scientifically-based assessments of coastal hazard zones. The reviews here are intended to serve as background for the examinations in Section 4 of the techniques that have been employed by Lumsden (2003) and CSL (2008a, 2008b, 2012), in their analysis of the Kāpiti Coast hazard zones.

A number of oral presentations at the December Workshop, and written comments by homeowners and stakeholders (e.g., Joan Allin, April 2014 Statement), brought to our attention the significance of the New Zealand Coastal Policy Statement 2010 (NZCPS 2010), prepared by the Department of Conservation (DOC NZ), its purpose being to present a summary of policies that "….guides local authorities in their day to day management of the coastal environment." It contains 29 policies covering a wide range of issues that need to be considered in the management of the New Zealand coast. Of primary significance to scientifically based hazard assessments, Policy 24 focuses on the identification of the ocean processes and other factors that cause the hazards:

Policy 24: Identification of coastal hazards

1. Identify areas in the coastal environment that are potentially affected by coastal hazards (including tsunami), giving priority to the identification of areas at high risk of being affected. Hazard risks, over at least 100 years, are to be assessed having regard to:
    a. physical drivers and processes that cause coastal change including sea level rise;
    b. short-term and long-term natural dynamic fluctuations of erosion and accretion;
    c. geomorphological character;
    d. the potential for inundation of the coastal environment, taking into account potential sources, inundation pathways and overland extent;
    e. cumulative effects of sea level rise, storm surge and wave height under storm conditions;
    f. influences that humans have had or are having on the coast;
    g. the extent and permanence of built development; and
    h. the effects of climate change on:
        i. matters (a) to (g) above;
        ii. storm frequency, intensity and surges; and
        iii. coastal sediment dynamics;

    taking into account national guidance and the best available information on the likely effects of climate change on the region or district.

In addition, Policy 22: *Sedimentation* includes "Assess and monitor sedimentation levels and impacts on the coastal environment", and Policy 27(2) states that in evaluating options under (1):

a. focus on approaches to risk management that reduce the need for hard protection structures and similar engineering interventions;
b. take into account the nature of the coastal hazard risk and how it might change over at least a 100-year timeframe, including the expected effects of climate change; and
c. evaluate the likely costs and benefits of any proposed coastal hazard risk reduction options.

The recommendations made in NZCPS 2010 are what one should expect in analyses of coastal hazards (excluding tsunami) on any coast, not just New Zealand. However, as will become evident in the reviews in Sections 4 and 5 of the Lumsden (2003) and CSL (2008a, 2008b, 2008c, 2012) reports, individually they did not include considerations of all of these processes and factors that govern the hazards, but when considered together with their respective contributions they come close to meeting these recommended goals, with a couple of omissions (e.g., analyses of the beach sediment budget). In terms of our review, it should be noted that while the NZCPS 2010 identifies the important hazards, it does not specify the methodologies that could or should be applied in undertaking their analysis, this wisely having been left to the coastal scientist or engineer who is undertaking the investigation. While having kept in mind the recommendations offered by NZCPS 2010, the main focus in our review of the Lumsden and CSL reports has been directed toward the technical methodologies they applied, their scientific validity and the resulting hazard zones they proposed.

3.2 Processes and Factors Important to Coastal Hazards

The NZCPS 2010 guidelines include mention of multiple processes and factors that need to be accounted for in coastal-hazard assessments — the waves and surge levels of elevated tides during major storm events, the effects of rising sea levels, the sediment "levels" on the beaches and in the dunes, and the natural "dynamic fluctuations" of the beaches over the short and long term. The analyses of coastal hazard zones, their quantification, therefore require long-term data sets for the waves and tides, and surveys of the beach morphology over a sufficiently long period of time that both its dynamic responses to individual storms and the net long-term rate of shoreline recession or accretion can be determined. Furthermore, efforts need to be directed toward evaluations of what is termed the "budget of beach sediments", which includes assessments of the volumes of beach sediments acquired annually from their sources (e.g., rivers), and their possible losses (e.g., the transport of the sand offshore or alongshore). All of these processes and factors need to be considered in terms of their variations and possible trends produced by Earth's changing climate.

The determination of a hazard zone for a particular stretch of coast represents a challenge to the coastal scientist or engineer, in that it requires data sets (measured, modelled, or estimated) for the waves and tides, with it being necessary to account for the extremes in those processes that are responsible for occurrences of erosion or flooding. It also requires a documentation of the long-term net trend of changing shoreline positions, and its causes in terms of the sources and losses of beach sediments, yielding a balance in the beach-sand budget that accounts for the net surveyed trend of shoreline recession or accretion.

The availability and analysis of tide data applicable to assessments of the Kāpiti Coast hazards were reviewed in Section 2, there being more than 100 years of measurements derived from the Wellington tide gauge, which have been analysed in detail by Bell and Hannah (2012). The results of their analyses yielded a rate for the long-term trend of sea-level rise along this coast, locally affected by tectonic-induced subsidence of the land. They also undertook analyses of the variations in the annual average sea levels above and below that net trend, concluding that they are produced in part by climate variations, the Interdecadal Pacific Oscillation (IPO) cycle that represents alternating 20- to 25-year periods dominated by La Niñas that elevate the measured tides, versus El Niños that lower water levels. Both the trend and variations in the sea levels measured by the Wellington tide gauge are directly applicable to the Kāpiti Coast, with a minor adjustment apparently needed to account for its lower rate of subsidence of the land compared with Wellington.

An earlier study by NIWA (Laing et al., 2000), commissioned by Lumsden (2003) to provide assessments of waves and tides required in his hazard assessments, included analyses of the predicted astronomical tides for the Kāpiti Coast, and also the potential magnitudes of storm surges that could elevate water levels above those predicted tides. The predicted astronomical tides were analysed using standard models, the results showing that there are significant along-coast variations in the elevations and ranges of the tides, an important variation that needs to be taken into account in the hazard-zone assessments. Storm surge elevations during past major storms were evaluated from barometric pressure measurements at the Paraparaumu Airport, the highest 0.7-metre surge having been found for the September 1976 storm, when the hindcast deep-water significant wave height had reached 3.6 metres, and the accompanying calculated wave run-up was 2.6 metres above the tide levels. The most severe storm impacts in recent history occurred during that storm, having produced extensive dune erosion and property losses along the Kāpiti Coast, particularly at Raumati and Paekākāriki (Gibb, 1978). Based on the analyses by Laing et al. (2003), it was recommended that surge levels of 0.75 and 0.85 metre be adopted respectively for the 50- and 100-year projected extremes, with wave run-up levels contributing another 3.0 and 3.5 metres increase above the tides, to yield the total wave levels.

The existing assessments of the “wave climate” for the Kāpiti Coast, including the ranges and extremes in the magnitudes of its wave heights, is based on the wave hindcast analyses undertaken by Laing et al. (2000), supplemented by those completed for KCDC by MetOceans (2007, 2010). For hindcasts of the deep-water wave climate (the significant wave heights, periods and directions), a 20-year record was developed by NIWA for representative winds across the expanse of Cook Strait. It was found in their analyses that the deep-water significant wave heights rarely exceeded 3 metres, the highest having been 4.5 metres generated by a storm in November 1995. Corresponding time-series for ten shallow water sites along the Kāpiti Coast (at the offshore 10-metre depth contour) were derived based on wave refraction analyses, the results showing the expected sheltering effects of Kāpiti Island. MetOceans (2007, 2010) similarly undertook wave hindcast analyses, for the 10-year period July 1997 through July 2006. Their hindcasts yielded hourly directional wave spectra for 16 locations along the Kāpiti Coast, demonstrating the significance of the wave-energy shadow zone directly behind Kāpiti Island, there being of the order of a 0.7-factor reduction in the mean wave heights; the maximum hindcast significant wave heights accordingly ranged from 3.13 to 4.83 metres along this coast. Extreme-value projection analyses were undertaken for the 1, 10, 50 and 100-year return periods, the 100-year extremes away from the shadow zone being 5.50 to 5.95 metres, while those in the direct lee of the Island are reduced to 3.16 metres.

While no tests were undertaken by either of these studies of the wave climate to determine whether there has been a multidecadal trend of change in the significant wave heights, the histogram of the deep water wave-height magnitudes determined in the hindcast by Laing et al. (2000) showed a pronounced skewness toward the highest waves; as discussed in

Section 2, this signifies that if there is a trend of increasing heights the extreme magnitudes generated by the strongest storms would increase at the greatest rates, potentially enhancing the Kāpiti erosion and inundation hazards.

An investigation of the ocean processes within the Cook Strait is apparently underway by Dr Iain Dawes, our awareness of his analyses having been derived from a printed copy of an undated (but apparently recent) power-point presentation, *Wellington Region Storm Surge Modelling*. According to his graphics, while his model analyses include the entire area of the Cook Strait, the focus of his presentation was on the southern Kāpiti Coast, illustrated by photos of the high water levels and impacts resulting from storms on 17 October 2007, and at Raumati on 23 July 2008. Of particular interest to the Kāpiti hazards are his analysis results graphing the hindcast significant wave heights versus storm tide water levels, showing a positive trend in their respective increases depending on the storm's magnitude, with the maximum significant wave heights reaching about 5 metres, accompanied by storm tides in the range 1 to 1.2 metres above mean sea level (excluding wave setup and runup). Another graphic shows analyses of the alongcoast variations in the storm tide plus the wave setup, undertaken for 8 major storm events dating from the 1960s to the present, the highest levels on the Kāpiti Coast having been achieved by a storm on 6 September 1994, when water levels reached 2.0 to 2.5 metres above mean sea level. As will be reviewed later in this Section, such analyses by Iain Dawes come close to the total water elevations reached during storms, only the wave swash runup on the beach not having been included to yield the total water levels from the combined processes, which are used in models that have been developed to evaluate property erosion impacts during major storms, and in projections of the most extreme potential future hazards (Ruggiero et al., 2001).

The investigations of the ocean processes by Laing et al. (2000), MetOceans (2007, 2010), those recently completed by Bell and Hannah (2012), and underway by Iain Dawes, are extremely important in providing assessments of the waves, predicted tides, raised water levels by storm surges, the IPO climate control with La Niñas raising water levels, and rates of rising sea levels locally affected by subsidence of this coast. It is the conclusion of this Panel that these investigations have yielding data sets for the ocean processes that can support scientifically-based evaluations of the Kāpiti Coast's hazard zones, as recommended by NZCPS 2010.

While investigations have supplied documentations of the ocean processes along the Kāpiti Coast, there have been only limited studies of its beaches — the sources of its sediments, its morphologies, and documentations of the processes and resulting impacts to the beaches and shore-front properties during major storm events. Its beaches are composed of fine to medium-grained sand, with their profiles having low slopes, of the order of 0.010 to 0.015 (1V:100H or 0.6° to 1V:67H or 0.9°) according to the surveys contained in the recent report by Lumsden (2013). Kāpiti Island provides significant protection from high storm waves to the stretch of shore centred on Paraparaumu and Raumati, the result being that wave heights are moderated within that sheltered shore, while retaining their long periods so they become regular low steepness swell waves. With this combination of low-sloping beaches and reduced energy swell, the beaches within this south-central part of the Kāpiti Coast are "dissipative" in the morphodynamics classification of beaches by Wright and Short (1983), representing a relatively stable beach in that the arriving waves break well offshore, beginning to break where the wave height is approximately equal to the water depth, continuing to lose their energy while they cross the wide surf zone as turbulent bores. When a storm occurs, the increased wave heights break further offshore, creating a wider surf zone so that much of their energy is dissipated, significantly reducing the wave heights prior to reaching the shore. During at least the winter months, dominated by seasonally higher waves compared with the summer, it is likely that beaches along the entire length of the Kāpiti Coast are dissipative, although during the summer they appear to be “intermediate” in the Wright and Short (1983) classification (based on our observations during the December 2013 field trip), this morphology being more dynamic, three dimensional, and more susceptible to property erosion. However, with this representing the summer morphology, it’s not likely to result in significantly increased hazards to the Kāpiti properties.

Locally, mainly in proximity to inlets, the fine sand beaches are backed by accumulations of gravel and cobbles, this combination being termed a “composite beach”, in which the gravel acts to further dissipate the wave energy, providing additional protection to the foredunes and properties. The central portion of the coastline sheltered by Kāpiti Island has also historically been accreting, gaining sand so that the shoreline has built out to form a cuspate foreland (a local widening), the sand having been supplied by rivers to the north. The present-day hazards from foredune erosion and recession therefore exist primarily along the shores beyond this stretch of sheltered accreting shore, mainly to its south, although in the future with rising sea levels the cuspate foreland could revert to being dominated by erosion with a retreating shore, increasing the hazards to properties.

From the standpoint of the morphologies of the beaches, with their being predominantly “dissipative” due to having low slopes, they provide a natural buffer protection to the ocean-front properties, dissipating the energies of the waves and also their swash runup levels at the shore. On the other hand, the impacts from a rise in the mean water levels, however temporary when it occurs as a storm surge, or during La Niñas produced by warmer ocean-water temperatures, the low beach slopes magnify the horizontal shift in the shoreline, moving it landward, with major storms completely flooding over the beach, allowing the waves to directly attack the dunes and properties, even potentially overtopping substantial seawalls (Gibb, 1978). For example, the analyses by Iain Dawes determined during the severe storm on 6 September 1994 the storm tide plus the wave setup (but not the swash runup) raised water levels by 2.0 to 2.5 metres above mean sea level — the water’s edge could therefore have shifted landward by some 200 to 250 metres, with water levels reaching the elevations of the dunes and seawalls according to the surveyed beach profiles graphed in the report by Lumsden (2013).

Important to hazard assessments for the Kāpiti Coast is the availability of beach profiles surveyed at intervals along its shores, permitting comparisons between dune elevations and the combined ocean processes — the predicted tides, the actual tides elevated by a storm surge, the swash runup of storm waves, and in the longer term with the water levels raised relative to the land by rising sea levels. The history of beach and offshore profile surveys along the Kāpiti Coast has been reviewed by Lumsden (2013), the earliest dating back to the 1970s, undertaken in response to the storm damage experienced in 1976 and again in 1979. There was increased surveying during the 1990s, and especially in 2000 as part of a coastal hazard management study, the surveys since then including 27 sites along the length of the Kāpiti Coast. The report by Lumsden (2013) of the survey results included graphs of profiles at each of the sites, with comparisons between those in June 2000, December 2007, and June 2011. The report contains tabulations of the changes in sand volumes between 2000 and 2011, horizontal beach displacements at the mean high water spring (MHWS), mean seal level (MSL), mean low water spring (MLWS), and Dune Toe, and the width of the dry beach. A commentary describes each of the profile sites, and the report discusses those areas that have the greatest risk of future impacts from erosion and inundation.

The accumulation of surveyed beach profiles is particularly important to two components of the Kāpiti hazard-zone assessments. Surveys over a number of years have yielded records of changing shoreline positions in response to the net erosion or accretion of the beach (the trend depending on the site), and at some sites the extent of erosion of the sand dunes and ocean-front properties. As will be reviewed in Section 4, these surveyed profiles are supplemented in the analyses of CSL (2008a, 2012) by records from old maps and aerial photographs, which document the longer-term evolution of the shoreline spanning the 20th century. The other potential application for the surveyed profiles is in an analysis of the Kāpiti Coast's "budget of sediments", involving assessments of the contributions of sand to the beach derived from its sources, evaluations of its potential losses, with there being either a net gain or loss (Komar, 1998). Being conceptually analogous to a monetary budget, the sources in the sediment budget are termed "credits", the losses are "debits", while the net "balance" in the sediment budget determines whether in the long term that beach experiences net erosion (recession) or is accreting (the budget is respectively either in the "red" or "black"). In applications on coasts such as Kāpiti where there has been a programme of annual beach surveys, the status of the balance in the budget is better established and has less uncertainty than the volumes of the individual credits and debits, this balance having been determined from the surveys over the years, providing a direct documentation of whether it has experienced net erosion or accretion. Efforts to assess the credits and debits are then directed toward understanding the factors that are responsible for that balance; for example, whether commercial sediment extraction in a river, the construction of a dam, or changes in rainfall and river runoff has reduced the supply of sand and gravel to the coast, being responsible for erosion its beaches and potential property losses.

The survey monitoring programme for the Kāpiti Coast provides tabulated values of the volumes of sand per year gained or lost from each of the 27 survey sites, which could be combined to yield the balance in the sediment budget for this entire stretch of shore. Or more informative would be obtained if three separate budgets are developed, respectively for the growing cuspate foreland sheltered by Kāpiti Island (where the budget is in the "black"), and separate budgets for the shores to its north and south, the latter apparently being in the "red". This would complicate the analysis somewhat by also requiring evaluations of the directions and rates of the longshore transport of the sand on the beaches, representing exchanges between these separate sections, the loss of sand from one section (a debit) becoming a gain (credit) for the other. A much higher level of sophistication in the analysis is provided by applications of numerical shoreline models that divide the shore into a large number of sections ("cells"), the model calculating the net longshore transport of sand between the cells based on the wave climate, followed by calculations of the gains and losses of sand in each cell to determine its change in shoreline position, this in effect constituting a localized sediment budget for each cell. An excellent example of such a model application is that by Tonkin & Taylor (2005) for the shores of Hawke's Bay, undertaken to evaluate the impacts of commercial mining of sand and gravel from its beach, determining the increased risks to coastal properties. In the case of the Kāpiti Coast, the model's "cells" could correspond to the 27 survey sites, and could analyse the future evolution of this shore in response to the projected rise in sea levels, determining the fate of the cuspate foreland that has accumulated along the shore sheltered by Kāpiti Island.

While the programme of periodic surveys of beach profiles along the Kāpiti Coast supports a determination of the balance in its sediment budget, the objective then becomes to evaluate the budget's "credits" and "debits", the sources of sand being the rivers and streams along its shores, including those north to Wanganui and beyond, their supplies of sand to the beaches then being transported southward by the waves, eventually reaching the Kāpiti shores, accounting for the history of accretion along most of its coast. The potential debits could include sand blown inland to accumulate in dunes, or carried offshore into deep water or alongshore by the waves; however, the erosion of the dunes or the onshore transport of sand could equally represent credits to the beach-sand volumes. As a Panel we have not reviewed past reports that considered these factors expected to affect the sediment budget, assuming such studies exist. Important to the balance in the Kāpiti beach sediment budget are human-induced environmental impacts in the river watersheds, in the past or are planned for the future, that would alter the volumes of sand delivered to the coastal beaches — commercial sediment extraction and dams reducing the volumes, while deforestation and the resulting increased land erosion could have increased the quantities of sand carried by the rivers. Future changes in the climate also need to be anticipated, with the potentially altered rainfall, river discharges and flood extremes affecting the contributions of sediments by the rivers, in turn affecting the balance in the Kāpiti sediment budget and trends in its rates of shoreline accretion or recession.

Past investigations and those underway have yielded data sets on the waves, tides and beach profiles, with their analyses leading to assessments of storm-surge levels, trends in sea levels, and extremes in the processes. These are the processes that are required in hazard assessments, and it is the opinion of this Panel that they serve as an important foundation in analyses of the Kāpiti Coast's hazard-zone analyses, and additional research is to be encouraged by KCDC. Missing and recommended as being an important additional investigation are analyses of this coast's beach-sediment budget, with the balance in its budget determined from the beach profile surveys, accompanied by examinations of the effects of human impacts and climate change on the sand volumes contributed to this shore by rivers.

3.3 Coastal Hazards as a Concept, and Analysis Methodologies

Based on the reviews above of the ocean processes, it is apparent that some are episodic, associated with major storm events, while others are long term and progressive, most important being the rise in sea level. Both have climate controls, including global warming, and short-term climate events such as the occurrence of a La Niña known to elevate the measured tides by 10s of centimetres above their predicted levels, and the IPO cycles spanning decades, the alternating dominance between La Niñas and El Niños. The evaluation of hazard zones requires an integration of their combined effects, the goal being to evaluate their present-day potential extremes, and to project the enhanced hazards through the next 50 to 100 years. This goal is illustrated schematically in Figure 5, with the seaward-most portion labelled "Storm Bite", representing the extent of properties already under the threat of impacts from severe storms, the combination of the tides raised by its surge, and the wave setup and swash runup produced by extremes in wave heights and periods. Beyond this immediate potential danger from major storms are the future hazards due primarily to rising sea levels, their accelerated rates projected by climatologists, and possibly also by an increase in storm intensities that generate greater wave heights and surge elevations.

It should be noted that in hazard-zone assessments based on the causative processes, the focus of coastal scientists and engineers is primarily on the zones, colour coded in the cross-section diagram of Figure 5, with the lines between those being requested by management concerns (the 50- and 100-year projections), imposed on what in reality is a continuum in the processes responsible for the hazards, their enhanced trends produced by Earth's changing climate. Furthermore, we generally make a distinction between "hazard zones" based the evaluated causative ocean processes and sediment budgets, and "set-back lines" established in management programmes, recognising that the latter take into consideration many other factors, such as those recommended in the New Zealand Coastal Policy Statement 2010 (NZCPS 2010).

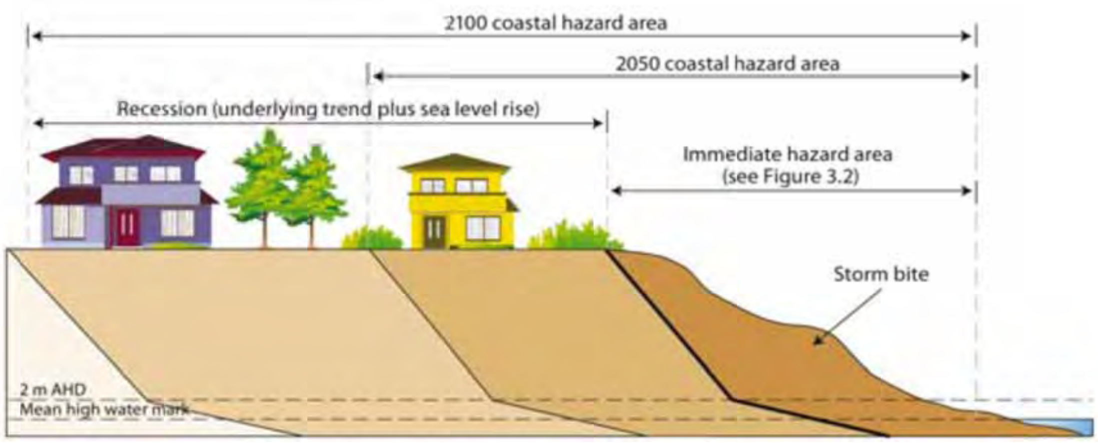

Figure 5: Schematic illustration of Coastal Hazard Zones, including that presently threatened by impacts from extreme storms, those projected for the future due to rising sea levels and the long-term trend of shoreline recession.[Source: NSW DECCW (2010)]

A degree of standardisation in the strategy for calculating hazard zones, based on the causative processes, has been established and is especially adhered to in New Zealand where it originated. This includes the formula introduced more than 35 years ago by Dr Jeremy Gibb (1976, 1978, 1983), which is applied to the calculation of erosion hazard zones along shores that consist of a beach backed by foredunes, an equation that includes factors that account for both the episodic erosion during major storms, and the longer-term progressive recession of the shore due to rising sea levels. The formula for a calculation of the Coastal Erosion Hazard Zone ($CEHZ$), the distance inland from the existing dune edge or other reference position, as applied by Gibb (CMCL, 2005) in recent analyses undertaken for the Hastings District, is expressed as:

$$CEHZ = (S + D)F_1 + [(R + X)F_2]T \qquad (1)$$

where:

S is the horizontal distance subject to maximum short-term dune erosion, primarily during a major storm;

D represents the subsequent retreat of the top of the eroded dune, when its nearly-vertical face following cut back by the waves slumps to the angle of repose (approximately 32° for dry sand);

F_1 and F_2 are “safety factors”, included to account for the uncertainty in the assessment, although not necessarily having the same values, generally with the range being from about 1.15 to 1.30 according to Gibb (CMCL, 2005, 2007).

Taken together, $S + D$ accounts for the episodic recession of the dunes that represents a potential hazard to shore-front properties, generally representing a 100-year extreme occurrence, one having an average recurrence interval (ARI) of 1% annual exceedance probability (AEP).

The second bracketed term in Equation (1) provides an evaluation for the long-term changes in the position of the shoreline or seaward edge of the foredunes, where:

R is the average rate of long-term recession;

X is the calculated rate of recession produced by the local relative rate of sea-level rise, affected by both the global rise in sea level and any local change in land elevations.

Both of these parameters represent long-term average rates of recession (metres per year), so that in order to assess the resulting horizontal retreat of the shore and dunes they must be multiplied by the hazard assessment period in years, denoted by T in Equation (1), generally 50 and 100 years, at present providing projections through this century to 2065 and 2115, representing something of a "moving target" that depends on when the assessment is calculated.

There is the possibility of including other factors in Equation (1), for example if an increase in the storm intensities and their enhanced wave heights and surge levels in the future need to be accounted for. As included in Equation (1), S is evaluated on the basis of the present-day wave climate, without a time dependence, so any progressive increase in the future needs to be treated as a rate, much like the rise in sea level, the resulting recession of the foredunes again depending on the assessment period, T. An interpretation of the factor R is complicated in that having been based on the rate of recession of the shoreline or dune edge over time, yielding an average rate, it is the result of both the sediment budget, the net gains and losses of beach sand at that profile site, and the local rise in the relative sea level. But according to Equation (1), the rise in sea level at present and projected into the future is directly accounted for by X, raising the possibility that it has been "double counted". In recognition of this, the present-day rate of sea-level rise could be subtracted from the measured shoreline recession, leaving a value of R that represents only the balance in the sediment budget, or an alternative approach is that X accounts only for the increase in the rate of rise of the sea level due to its future acceleration.

The details involved in the methodology applied to evaluate S, the extent of the potential dune erosion caused by an extreme storm, is particularly important in that it is the primary agent of dune erosion and property losses, the causative processes being storm surge that elevates the tides, atop which the increased levels of the swash of the storm-wave runup on the sloping beach impact the toe of the dunes. Without the impacts of storms, the slow rise in the level of the ocean would simply flood over the land, slowly covering the properties. This significance of storm occurrences is illustrated, for example, in studies undertaken in the Great Lakes of North America, where there are cycles in the levels of the lakes spanning decades. During periods of rising lake levels, beach surveys and measurements of the erosion of the dunes have shown that the erosion lags well behind the increased lake levels, the recession instead depending on episodic occurrences of storm-generated waves. Therefore, in a view of the coastal hazards that depend on the climate controlled ocean processes, it is preferable to focus on occurrences of storms and their extremes, at present and possibly enhanced in the future, while the rise in sea levels with time simply raises the elevations of wave attack, moving their zone of impacts upward and inland across the coastal properties.

The evaluation of S in Equation (1) can be viewed as being the "short-term" or "immediate" hazard, the inference being that it constitutes a relatively immanent threat of erosion or inundation of ocean-front properties, that "long-term" trends such as rising sea levels and increasing wave-heights are not included. This immediacy is most clearly represented by the occurrence of a major storm, or perhaps the cumulative erosion of a sequence of storms during the winter, which could happen this year or at any time in the future. However, when an examination of past erosion events is undertaken, it becomes evident that an important consideration is the simultaneous occurrence of high storm-generated waves together with an elevated measured tide. Examining this combination in still greater detail, it is generally found that the erosion occurs in response to the increased swash run-up levels produced by the storm waves when they reach the sloping beaches, occurring atop the elevation of a high predicted astronomical tide, with the measured tide elevated still further by the surge produced by the storm. Other contributing factors to the elevated tide might be the normal seasonal cycle of monthly-mean water levels, being greatest when the water is warm (thermal expansion), and changes in water levels associated with the El Niño/La Niña range of climate events.

The summation of these processes and the potential erosion of ocean-front properties within foredunes is illustrated in Figure 6, with Figure 6.A being the model developed by Ruggiero et al. (2001) that was first applied to assessments of erosion hazards along shores of the US Pacific Northwest (Oregon and Washington). This diagram shows the processes combining to yield the total water level (TWL), illustrating that whether or not foredune erosion occurs depends on its elevation compared with that of the toe of the foredune, denoted by E_J, the beach/dune junction elevation. It is also possible to include considerations of the elevations of the top of the foredunes, to model their potential overtopping during storms, inundating the properties.

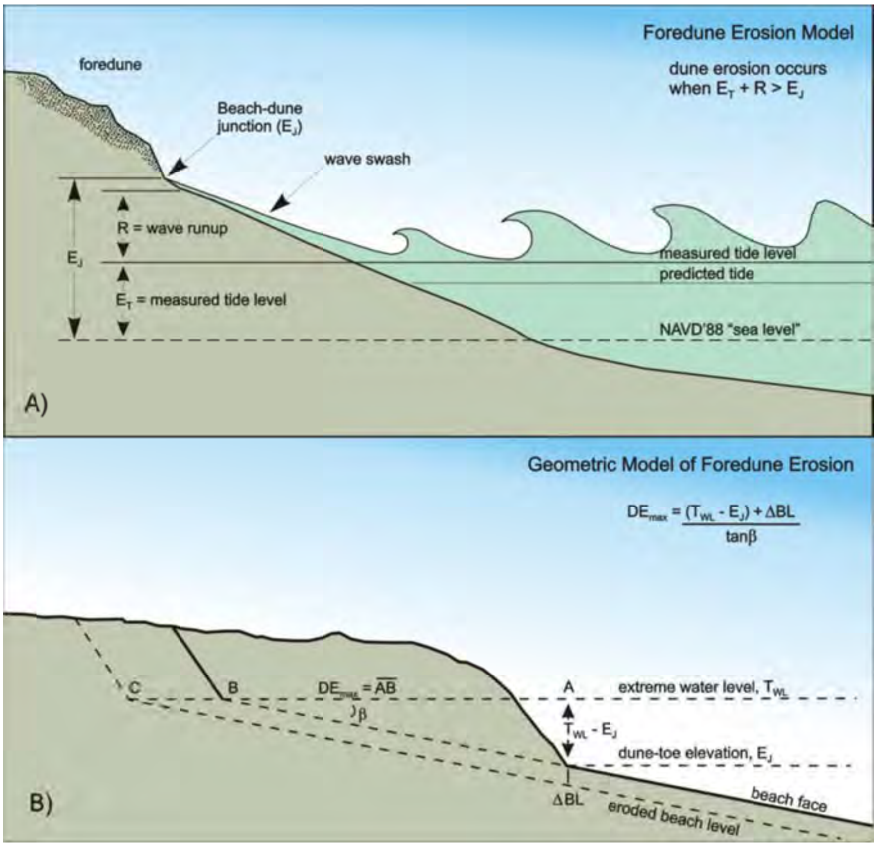

Figure 6: The models of (A) Ruggiero et al. (2001) and (B) Komar et al. (2002) to respectively calculate the total water levels, the measured tides plus the wave swash runup, and the maximum dune erosion produced by that total water level compared with the dune-toe elevation.

Conceptually this model is simple, but applications generally require detailed data analyses, with various approaches being possible. In applications to the coast of the US Pacific Northwest, Ruggiero et al. (2001) utilised the available long-term tide gauge records to document the hour-to-hour variations in measured tides, the records having been sufficiently long that a large number of extra-tropical storms were represented by their range of surge levels, with the record also having included the 1982-83 major El Niño when throughout the winter measured tides were raised by about 0.5 metre above predicted levels. Hourly buoy measurements of the waves were also available, corresponding in time with the tide measurements and spanning the decades back to the 1970s, permitting hourly calculations of the swash run-up levels on the beaches. Determinations of the hourly TWLs from the model (i.e., the measured tides plus the vertical component of the wave run-up) yielded a multi-decadal documentation of the numbers of hours during which those combined processes and their TWLs could impact the toe of a foredune or sea cliff, depending on its elevation. Such analyses also permitted assessments of the extreme events that had occurred over the decades, the extremes in the TWLs being most important in assessments of property erosion and flooding hazards. Beyond that, the time series of evaluated TWLs was applied to project the 50- and 100-year TWL extremes that represent the potential future hazards to properties, extremes that would be more important than the deep-water significant wave heights that comprise the wave climate, the TWLs reflecting the joint occurrences of the causative processes.

Having determined the TWLs and their extremes during major storms, the next step in the hazard assessment involves an analysis of the resulting potential extent of erosional retreat of the backshore properties. In the case of foredunes, this involves the model shown in Figure 6.B (Komar et al., 1999, 2002), a geometric analysis that is conceptually similar to Bruun's (1962) beach recession model that is directed toward impacts from rising sea levels. The difference from the Bruun model is that in the present application it is the measured tides plus the wave swash run-up that drive the erosion process, although changes in sea levels could also be included to project future hazards. As illustrated in Figure 6.B, the erosion of the dune is modelled by projecting the beach slope up to the elevation reached by the TWLs during a major storm, the resulting extent of dune erosion being given by the equation:

$$\mathrm{DE}_{\mathrm{max}} = \frac{(\mathrm{TWL}-\mathrm{E_J})+\Delta\mathrm{BE}}{\tan\beta} \tag{2}$$

where

$\tan\beta$ is the beach slope; and

ΔBE is the potential reduction in the level of the beach face at the time of the storm, produced either by the storm waves or possibly by the local presence of a rip-current embayment.

The calculated result from this model is expected to be the potential maximum dune retreat during the storm, in that the model does not account for there being a significant delay in the erosion relative to the water levels. This assumption has been acceptable in management applications in that it provides a conservative assessment of the hazard zone, in effect a worst-case margin of safety for homes constructed in vulnerable foredunes. With that extreme having been evaluated, lesser degrees of hazard elevations could be based on field evidence from the site being investigated, commonly in the form of evidence from the dune morphologies (e.g., remnants of past erosion scarps), or flotsam (e.g., drift logs) carried inland and found within or beyond the dunes.

With these models having been developed to be used in calculations of erosion hazards along the coast of the US Pacific Northwest, their initial testing included both the storm induced erosion of sandstone sea cliffs, dependent on the TWLs and resistance of the rocks composing the cliff, and of properties within foredunes where the tests involved the predicted dune retreat based on the geometric model and TWLs during specific storm events, compared with the actual measured dune retreat distances (Ruggiero et al., 2001; Komar et al., 2013). In the most extreme comparison, the erosional retreat of the dunes was the cumulative impact of three severe storms during the winter, with the last having been the most extreme in terms of both its wave heights and TWLs, one of the most extreme events in decades. Recently the models have also been applied in analyses of the erosion and flooding hazards along the shores of Hawke's Bay, first examining the present-day hazards associated with major storms and their TWLs based on hourly measurements of waves and tides, followed by projections to 2100 that included rates of rising sea levels and increasing wave heights, both having been based on tide-gauge and wave-buoy records (Komar and Harris, 2014).

Rationally-based methodologies have been developed to be applied in quantitative assessments of hazard zones, including Equation (1) formulated by Gibb (2005) that includes the multiple factors that need to be evaluated, clearly differentiating between the "short-term" episodic impacts of storms, versus "long-term" progressive trends of change, foremost being a projected accelerated rate of rising sea levels, and shoreline recession or accretion depending on the sediment budget, the gains and losses of sand from the beach. Models have also been developed to evaluate the extent of dune recession during major storms, produced by the ocean processes of high predicted astronomical tides, further elevated by the storm surge, plus the swash runup levels of the waves on the sloping beaches, combined to yield extreme total water levels that reach and erode the dunes and properties backing the beaches. It is the recommendation of this Panel that with the necessary data being available for the Kāpiti Coast, these models be employed in calculating its hazard zones.

4. Hazard Analyses for the Kāpiti Coast (Reviews of the Reports by CSL and John Lumsden)

Author: P D Komar, Editor: J T Carley

The Kāpiti Coast District Council (KCDC) requested that this Panel assist them in resolving issues raised in regard to the science and methodologies applied in hazard assessments for the Kāpiti Coast, those undertaken by Coastal Systems Ltd (CSL). Initially CSL prepared three reports that were completed in 2008, but the results were not adopted at that time for inclusion in the KCDC District Plan, the expectation being that there would soon be a revised New Zealand Coastal Policy Statement, that being the NZCPS 2010 recommendations reviewed in Section 3, that called for the inclusion of 100-year hazard projections. This resulted in a fourth report by CSL in 2012, to update their analyses.

The four CSL reports reviewed by the Panel are:

- Part 1 (CSL, 2008a) dealing with the open coast hazards, providing discussions of the methodologies applied, and the analysed recommended hazard zones for a 50-year time frame;
- Part 2 (CSL, 2008b) focused on the special conditions and hazards in the inlets to rivers, requiring modified methodologies;
- Part 3 (CSL, 2008c) presented the data-base, the collection of graphs and analysis results for each of the open coast hazard assessment sites;
- CSL (2012) provided an update in the analyses required by changes arising from the NZCPS (2010) management goals, for the open coast but with most of this report's attention given to the inlets.

These four reports by CSL have been the primary focus of this Panel's reviews, with the results for the open coast presented in this Section, those for the Inlets appearing in Section 5.

In order to understand the hazards occurring on the Kāpiti Coast, at present and projected into the future, it was also necessary for this Panel to examine other relevant reports. This included a review that considered the availability of data sets for the tides, waves, etc., required to support scientifically-based quantitative assessments of the hazard zones, the result of our review having been discussed in Section 3. This expanded consideration also led to a decision by the Panel that we needed to consider the hazards report prepared by Mr John Lumsden, who prior to the CSL assessments had undertaken hazard evaluations for the KCDC (Lumsden, 2003). Of significance, with Lumsden professionally being a coastal engineer, he applied different methodologies than those followed by CSL, authored mainly by Dr Roger Shand, a coastal geologist/geographer. Specifically, the methods used by Lumsden were based mainly on analyses of the ocean processes and beach erosion responses, whereas the emphasis by CSL had been directed toward measurements of trends and variations in the shoreline change over the decades, the rates of its landward recession or seaward accretion. As will become evident in the review presented here, our conclusion is that both studies make contributions to understanding the Kāpiti Coast hazards, their respective results complementing one another so that both should be considered by KCDC in defining erosion hazard zones for their District Plan.
The analysis approaches applied to the Kāpiti Coast assessments by both Lumsden (2003) and CSL (2008a, 2012) for the open coast basically followed the methodology developed by Dr Jeremy Gibb, with his Equation (1) presented and discussed in Section 3.

As applied by CSL, the calculated Coastal Erosion Predicted Distance ($CEPD$) has been written as:

$$CEPD = LT + ST + SLR + DS + CU \qquad (3)$$

where

LT is the long-term historic shoreline change;
ST represents the short term processes that produce more immediate impacts;
SLR is the long-term shoreline recession due to the rise in the relative sea-level;
DS is a dune stability facto; and
CU is the combined uncertainty in the assessment.

The main difference from the original Equation (1) formulated by Gibb is that each factor in this CSL version is a horizontal distance of foredune retreat, these several distances being cumulative to yield the total estimated recession distance projected into the future, the recommended erosion hazard zone. Equation (3) has absorbed the time frame being considered, T in Gibb's original Equation (1), so that LT and SLR in Equation (3) need to be evaluated twice, separately for the 50- and 100-year required projections.

The reviews presented here consider each of these components in Equations (1) and (3), important to the present-day and future erosion hazards. It will be seen that the main differences between the Lumsden and CSL reports are in the methodologies they have applied in assessments of these individual contributing factors, differences that reflect their engineering versus geologic/geographic backgrounds. This review begins with the long-term projection LT of the shoreline and dune recession, it representing the focus of the CSL (2008a, 2012) analyses, also serving as the basis for their short-term ST analyses, that will be reviewed later and compared with the process-based analysis methodology of Lumsden (2003).

4.1 Long-Term Projections of Shoreline and Dune Recession (Factors *R and LT*)

Author: P D Komar, Editor: J T Carley

Projections of long-term rates and the resulting potential extent of erosion and inundation (generally 50 and 100 years into the future) are the primary goals of most coastal hazard assessments, with the results directed toward the establishment of hazard zones (set-back lines or hazard management zones). Such projections, however, represent the most uncertain components in defining hazard zones, and this is also true for the Kāpiti Coast. This uncertainty was already evident in Section 2, there being a large range of projected future sea levels based on research undertaken by climatologists, and also concerning the possibility of there being increased storm intensities and the heights of the waves they generate. This problem in making projections is also inherent in the analyses of long-term trends of changing shoreline positions, and of the corresponding dune recession. The difficulty in defining shoreline changes is reflected in the published literature by coastal scientists, debating how it should be accomplished, raising questions concerning:

- How to define the shoreline;
- How to account for the effects of seawalls and other structures on the shore's position;
- Whether or not those structures will be maintained and survive through the 21st century with rising sea levels; and
- How one approaches an analysis of the changing shoreline positions over the decades, to derive meaningful trends and statistically significant rates for the inland migration of the shore and erosion of coastal properties.

The investigations yielding the series of the CSL reports, dealt with such issues in analyses of the long-term shoreline changes along the Kāpiti Coast (CSL, 2008a, 2008b, 2008c, 2012). Their analyses involved a detailed programme to cover the extent of that 38-kilometre length of shore, the coverage including 68 analysis sites, 12 representing environmental-specific analyses for river inlets. However, even with this large number of sites subject to analyses, the results from CSL still represent sections of shoreline extending for a few hundred metres up to a kilometre, not having provided results at the level of individual properties.

The primary shoreline data included in the CSL analyses were derived from aerial photographs, the earliest dating from the 1940s, and available at approximately 5- to 10-year intervals. In the photographs the vegetation line was used as the shoreline indicator, a common practice that provides a relatively clear demarcation between the beach and foredunes. Problems occur, however, where the beach is backed by a seawall or other type of shore-protection structure, with CSL having completed analyses that compared the natural dune-edge shorelines with positions of adjacent structures, to determine their differences. Additionally, in making future projections along the southern Kāpiti coast where seawalls are common, the CSL erosion assessments considered three future scenarios:

- Seawalls hold, remaining fully functional;
- Seawalls will be repaired if they fail; and
- Seawalls fail but are not repaired.

According to the Updated report (CSL, 2012), for the 50-year projections both the managed and unmanaged scenarios needed to be analysed, whereas for the 100-year projection only the unmanaged scenario was to be considered. A series of hazard lines were accordingly created in the CSL reports, the choice being left to KCDC, depending on their management policies.

Prior to the availability of aerial photographs, the main source of shoreline data for the CSL analyses came from cadastral maps, extending back as much as 135 years. The limitations of using old cadastral boundaries dating from the 1800s were elucidated by CSL, as was their value as an indicator of long term coastal change. Old maps can depict a variety of shoreline indicators, most commonly being the high water mark at the time of the survey; as discussed by CSL (2008a), this high water indicator is affected by the ocean's waves and tides, resulting in its greater variability that introduces a random error in the shoreline data, with there also being a systematic displacement of the map shorelines from those based on the beach/dune demarcation line derived from aerial photographs. For each site, the data for the assessed shoreline positions included on average about nine aerial-photo based data points, and one or two older map-based data points, although at some sites the numbers were significantly less. The resulting graphs of the shoreline time-series analyses for all of the measurement sites are presented in CSL (2008c), their Data Base report.

The data acquired by CSL to determine the changes in shoreline positions for the Kāpiti Coast, spanning the past 135 years, appear to have been carefully collected and with their methodology being cognisant of the potential problems with defining shoreline positions and the effects of seawalls, a considerable effort having been required to complete this task. Although, as will be seen in our comments directed toward questions concerning the CSL methodologies applied in their analyses of the trends and variations in shoreline positions, it is our opinion that the shoreline change time-series histories documented by CSL represent a valuable source of data, to be used in assessments of the Kāpiti Coast's future hazards.

Examples of CSL time series of cross-shore distances of the shoreline are included in Figure 7, referenced to the earliest available determination from old maps. The three examples included are ordered from north to south: time series C25-70 is from the shore south of Te Horo, beyond the immediate sheltering of Kāpiti Island; C13-24 is near the apex of the accreted cuspate foreland, within the community of Paraparaumu; and C4-18 is from Queen Elizabeth Regional Park to the south of Raumati. Each site is distant from river inlets, and the shoreline is "natural", signifying that there not a seawall present at that site. (According to submitters, there was some sand extraction in the vicinity of C13-24 in the 1990s). It is seen in Figure 7 that there are marked differences in the patterns and directions of shoreline changes for these three shoreline locations, with consistent accretion having occurred in the north (C25-70), a more complex pattern on the foreland (C13-24) where accretion has mainly occurred since about 1960, and with shoreline recession dominating the south (C4-18), its erosion having increased since the 1990s. These three time series are representative of their respective areas, the other nearby time series showing much the same pattern, although there obviously have been marked differences between the three stretches of shore, with accretion to the north and on the cuspate foreland, recession (erosion) in the south.

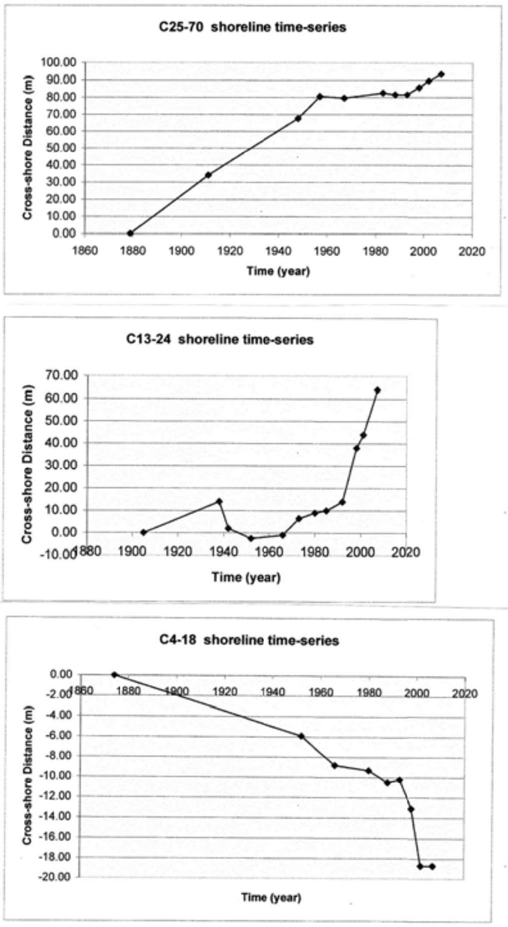

Figure 7: Time series of shoreline positions based on aerial photographs and old maps, for site C25-70 on the northern Kāpiti shore, site C13-24 located on the apex of the cuspate foreland, and C4-18 in the south on the shore of Queen Elizabeth Regional Park. [Source: CSL (2008c)]

Evident in these three time-series shoreline analyses included in Figure 7, and even more so in others (CSL, 2008c), is the frequent occurrence of non-linearity of their trends over the decades. This non-linearity is problematic as linear-regression analyses are often applied to determine a trend from the regression slope, representing the rate of change in shoreline position (metres per year), either erosion/recession (negative slope), accretion (positive slope), or a stable shoreline position (no slope). Decisions were made by CSL (2008a) as to altered methodologies to be applied to sites having nonlinear trends, generally such that the projected rates represent a more conservative/precautionary result, recognising that uncertainties in future projections based on these regressions will be greatest for those sites having nonlinear time series.

In their treatment of the time series, CSL (2008a) also undertook linear regression analyses for three separate time periods: the entire record (1870s to 2007); the earlier period (1870s to early 1950s); and the later period (1940s to 2007). The significance of the division at 1950 is that it represents a stage in the development of the Kāpiti Coast that was marked by the inception of the construction of seawalls and other shore-protection structures, and also the availability of more reliable aerial photos. Accordingly, by considering the different time periods, erosion-rate assessments were derived for the pre-development natural conditions of the coast, pre-dating the structures or other management practices. This transition in about 1950 is also evident in the three time series included in Figure 7, and although no seawalls are present at those sites they still could have been affected by structures in close proximity. It is also possible that for some sites, this change could reflect the difference in shoreline positions having been derived from aerial photographs versus older maps, or it might be the result of a change in the ocean processes.

As discussed in Section 3, a change in measured positions of the shoreline over the decades, seen in the time-series, can result from a number of factors including the balance between the beach sand supplies versus its losses (the “budget of beach sediments”), the global rise in mean sea level, and local changes in land elevations that can either be episodic or progressive, being of tectonic origin on the Kāpiti Coast. In that the projected future rise in the sea level is separately evaluated in the methodology, the X and SLR factors respectively in Gibb’s Equation (1) and in Equation (3) employed by CSL, there is the potential for “double counting” the effects of the rate of rise in the relative sea level. The preferred approach taken to avoid this is to remove the contribution of the 20th century rise in sea level from the analysed trend of shoreline change based on the time series, leaving only the portion that resulted from the gain of beach sand acquired from it sources, or its losses, the balance in that site’s sediment budget. This approach is preferred in view of the importance of evaluating the sediment budget for the Kāpiti Coast, the goals of which were reviewed in Section 3. It also corresponds to the actual environmental changes, whereas alternative approaches sometimes taken to avoid double counting apply an artificial “fix”, and as such are more confusing to the general public.

There is concern that there may also be a double counting when the “catch-up” term is applied in analysis of sites where a seawall has not been maintained and is lost due to wave impacts, or for some other reason has been removed, the shoreline then shifting to where it should have been under natural conditions.

It is evident from the three representative time series included in Figure 7 that the sediment budgets must have produced their contrasting patterns of change. If the rise in sea level spanning the past century was the only factor causing the changes in shoreline positions, all three would show a progressive recession, at essentially the same rate. The positive trend in the time series for C25-70, a persistent net accretion, demonstrates that the balance in its sediment budget must be well into the “black”, far exceeding the recession that would have been produced by the rising sea levels. The analysis of that site with its positive balance also demonstrates that it has acquired more sand reaching that shore, having been supplied by the rivers to its north, than is being transported by the waves alongshore further to the south, reaching the foreland sheltered by Kāpiti Island, which has also experienced accretion since about 1960, according to its time series (C13-24) in Figure 7. Of interest, its increased rate of accretion corresponds to the post-1960 reduction in the rate of shoreline accretion seen to the north at C25-70, evidence that the balance in the budget to the north is now closer to zero, suggesting that it is bypassing more of the longshore sand transport to the south, increasing the supply to the expanding cuspate foreland.

The increased rates of shoreline recession to the south, evident in time series for C4-18, has been interpreted as the result of the growth of the foreland having blocked its arrival from the rivers to the north, the foreland having captured more sand and bypassing less to this southern-most stretch of shore. However, surveys of the offshore bathymetry show the existence of a shoal seaward of this shoreline south of the cusp's apex, interpreted as being the pathway of the southward movement of sand that is bypassing the apex, with the wave-induced sand transport along the shore itself being directed toward the north, this pattern more probably accounting in part for the erosion problems at Paekakariki (Gibb, 1978; de Lange, December 2013). The CSL (2008a) report attributes part of the erosion experienced in the Queen Elizabeth Regional Park, an unprotected "natural" shore, to the end-effects of the seawalls to both its north and south, this being a possible factor but not likely the dominant cause of the Park's erosion.

One additional assumption included in the CSL methodology, which received considerable criticism by homeowners, is that of neglecting any benefits to properties based on their being located on an accreting shore, most obvious being those along the shores of the cuspate foreland sheltered by Kāpiti Island, but also those to its north that have also experienced beach accretion throughout the 20th century. As justification for this practice, CSL (2008a, page 24) offers the explanation:

> "Of particular note is that for all areas subject to a positive (seaward) shoreline trend, the rate was set to zero. This approach is common when assessing hazards for accreting coats as it removes the assumption of continued accretion, provides an increasing safety margin."

The Panel recognises that CSL is correct in this being a common practice in methodologies applied to erosion hazard projections, although in the case of the Kāpiti Coast it represents a rather extreme assumption that future rates of rising sea levels will overcome the positive balance provided by the sediment budget. The question of this being a valid assumption, that the cuspate foreland would soon disappear under rising sea levels, could be addressed by an evaluation of the sediment budget, thereby accounting for the dominant factor in past changes shown in the CSL (2008c) time series of shoreline evolution, projected into the future to assess changes with higher rates of rising sea levels. On a more sophisticated level, as described in Section 3, numerical computer models are available that could be applied to simulate the evolution of the entire cuspate foreland, an analysis that would account for this coast's wave climate and the variable rates of longshore sand transport that have an important role, it not simply being a case of the existing foreland being flooded by the waters of the rising sea.

Based on series of aerial photographs and old maps, Coastal Systems Ltd has carefully compiled measurements of the changes in the Kāpiti Coast's shoreline positions, this being a valuable source of data to be used in assessments of this coast's future hazards. However, it is important to separate the components responsible for those measured shoreline changes, in part caused by the rise in relative sea levels spanning the 20th century, but otherwise dominated by the sediment budget, with sand contributed to this beach by rivers, accounting for the accreting shores to the north and especially forming the cuspate foreland, reflecting the positive balances in their budgets. It is important to undertake this separation in order to remove the portion of measured trend of shoreline change that was caused by rising sea levels, leaving only the sediment budget component, in order to avoid “double counting” the effects of sea-level rise, with it having also been included in a direct analysis that projects the future effects of accelerating rates of rising sea levels (Section 4.2).

In view of its importance, the Panel recommends that within the next decade KCDC undertake analyses of beach-sediment budgets, in order to determine the gains and losses of the beach sand that account for the shoreline changes found in the CSL time series, and by Lumsden (2013) in recent programmes of beach-profile surveys (Section 3). Such budgets may provide an explanation for the nonlinear time-series variations found at some sites, and should also permit an assessment of whether the accretion of its central cuspate shore will revert to erosion in the near future. It is also important that investigations be undertaken of the rivers, the sources of the beach sand, particularly to determine how climate change could alter them, resulting in altered volumes of sand being contributed to the Kāpiti beaches.

The panel also recommends that over the next decade, probabilistic estimates of long term change be developed. The greatest present impediment to this is assigning probabilities to future emissions scenarios and the consequent sea level rise.

4.2 Projections of Shoreline Recession due to Rising Sea Levels (Factors *X* and *SLR*)

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Projections of the long-term rates and the potential resulting extent of property erosion, estimated for 50 and 100 years into the future, are the primary goals of most coastal hazard assessments, yet they are the most uncertain of the components in Equation (3) that contribute to the Coastal Erosion Predicted Distance ($CEPD$). This uncertainty was evident in Section 2 where projections of future accelerated rates of rising sea levels, and potential levels by the year 2100, were reviewed, the analyses by climatologists having yielded a large range of projections. As will be reviewed here, there are additional uncertainties in evaluating the extent of shoreline recession, or dune erosion, compounding the problem in evaluating the distance X in the Gibb’s Equation (1), and SLR in Equation (3) applied in the CSL methodology.

According to tide-gauge measurements the average rate of rise in sea level spanning the 20th century was about 1.7 mm/year, with a rate of 2.0 mm/year for the latter half of the century. Since 1993 the tide-gauge and satellite data agree that there has been an increased rate of about 3.3 mm/year, a possible indication for there being an acceleration produced by global warming. It was also seen in Section 2 that over the years there have been revisions in the magnitudes of future projections by climatologists, with the IPCC (2007) report having projected an increase of the order of 0.20 to 0.59 metre (excluding ice melt), with an upper value of 0.79 metre by the year 2100 if a contribution by ice melt is included. Applying different methodologies than IPCC, still higher projected sea levels have been derived by Rahmstorf (2007) and other researchers, supporting an increase of 0.50 to 1.20 metres in 100 years. It is noteworthy that the most recent IPCC (2013) projections are for sea levels to rise between 0.26 and 0.98 metre by 2100, the highest value being based on their model scenarios assuming the highest rates of greenhouse gas emissions. It is apparent in applying these projections offered by climatologists, including those by IPCC, that there is a range of possible future sea levels to be considered in management applications, directed toward evaluations of future coastal erosion and flooding hazards.

In analyses of the erosional recession of beaches and of backshore properties within dunes, produced by a long-term rise in sea levels, the traditional approach has been to apply the model developed by Bruun (1962, 1988), which represents an upward and landward shift of an equilibrium beach profile, with erosion of the upper portions of the beach profile and dunes, with the offshore transport and deposition of that eroded sand, which accumulates and raises the seafloor in the immediate offshore at the same rate as the rising sea level, there having been a conservation in the volumes of sand during this transfer. Being a two-dimensional geometric model, the resulting landward shift in the profile and shoreline depends on the change in the level of the sea, and on the beach slope over which this migration occurs.

In its simplest form, the resulting Bruun equation for the shoreline retreat distance can be expressed as:

$$Shoreline\ Recession\ (X\ or\ SLR) = \frac{SLC}{tan\beta} \tag{4}$$

where

SLC is the sea-level change; and

$tan\beta$ is the average profile slope, generally taken as that of the profile across the beach and into the offshore out to a “closure depth”, the seaward limit of profile changes that occur in response to seasonal cycles in surveyed profiles, and during major storms.

The ratio $1/tan\beta$ in Equation (4) is commonly referred to as the Bruun Factor (BF), representing an “application factor” in the distance of shoreline recession as a function of the rise in sea level. Over the “closure depth” length of profiles having decreasing bottom slopes in the offshore, it has been found in applications that generally $tan\beta \approx$ 0.02 to 0.01 (BF ≈ 50 to 100), with Equation (4) thereby indicating that the amount of erosional recession of the shoreline will be of the order of 50 to 100 times the rise in sea level.

A number of research investigations have provided tests of the Bruun model predictions, comparing the assessments derived from Equation (4) with measured rates or distances of shoreline and dune recession. While some tests found significant disagreement between the predicted and measured erosion, resulting in considerable criticism of the Bruun model and equation, it has been determined in more detailed studies that this disagreement can often be accounted for by the balance in the “budget of beach sediments”, evaluations of a beach’s gains in sand from its sources (e.g., rivers) versus losses, its effect on the changing shoreline positions far exceeding those due to the extent of the rising sea level during the few years of the research comparisons (see Komar (1998, p. 121-129) for a review of these tests).

An alternative approach to evaluate the shoreline recession in response to a rise in sea level is to apply the Ruggiero et al. (2001) model, reviewed in Section 3, based on evaluations of the TWLs (Figure 6A), here simply including the rise in future sea levels, it being added to the extremes in the measured tides plus the swash runup levels evaluated from the wave heights and periods during storms, thereby combining the short-term erosion processes with the long-term rise in sea levels (and also the trend of increasing swash runup levels due to a potential intensification of future storms, if included in the analyses). The assumption behind this approach is that the long-term progressive rise in the mean level of the sea will gradually result in the landward and upward migration of the beach and its short-term storm impacts, progressively cutting back the foredunes and then continuing inland. If one simply algebraically adds the Bruun Equation (4) to

Equation (3) for the geometric dune erosion model, one essentially obtains the same result as simply including the sea-level rise in the value for the TWL. However, in that model analysis the slope $tan\beta$ will be that of the swash zone in proximity to the shore, generally a higher slope than the 0.01 to 0.02 (1V:100H to 1V:50H) values commonly used in analyses applying Bruun's equation, there accordingly being less predicted recession, and smaller hazard distances, when applying the Ruggiero et al. (2001) model with an inclusion of the sea-level projection.

This model based on evaluations of TWLs, including the projected rise in sea levels, followed by application of the geometric dune erosion model, Equation (2), has been applied in hazard-zone assessments along the coast of the US Pacific Northwest, and in analyses of the future stabilities of the gravel barrier ridges on the shores of Hawke's Bay (Komar and Harris, 2014). This was the approach also followed by Lumsden (2003) in his analyses of the Kāpiti Coast hazard zones, although at the time of his study he used the mid-range projections of future sea levels provided by earlier IPCC publications and in the NIWA study (Laing et al., 2000), specifically an increase of 0.45 metres by 2100. Although his analysis methodology had been sound, it needs to be updated to account for more recent sea level rise projections, and also changes in management policies. The analyses by Lumsden (2003) will be examined at length in the following section, in considering the short-term erosion hazards produced by major storm events.

In the reports by CSL (2008a, 2012) for the Open Coast erosion hazards, the analysis of the SLR factor to account for the shoreline recession due to a rise in the relative sea-level was based on application of Equation (4), originally formulated by Bruun (1962, 1988). This initially raised confusion in our review in that CSL attributed this equation to Komar et al. (1999), the publication that instead had proposed the geometric dune erosion model, Equation (2), which depends on the TWLs of the tides plus the wave swash runup, although the sea-level rise could be included. However, in their application of Equation (4), CSL based the calculation on the average inter-tidal beach, which would be steeper than the slope based on the profiles closure depth, normally used in the Bruun equation, but less steep than the swash zone as applied by Ruggiero et al. (2001) in calculating the wave runup at the shore to determine the TWL, in turn used in the geometric dune erosion Equation (3). The $tan\beta$ slopes used by CSL (2008a, fig. 7A) ranged from a minimum of about 0.015 (1V:67H; the apex of the cuspate foreland) to a maximum of 0.09 (1V:50H; just south of the Otake River Inlet), with most being of the order of 0.02 (1V:50H); this corresponds to a Bruun Factor (BF) amplification range of 11 to 67, with the majority at 50, overlapping the 50 to 100 values commonly used as a "rule of thumb" in applications of the Bruun model. Although the methodology applied by CSL does not exactly conform with that generally employed in basing the shoreline and dune erosion on the Bruun model, with the slope depending on the "closure depth", nor on the methodology involving calculations of the total water levels (TWL) and the resulting dune recession, the results can be viewed as being reasonable, while at the same time illustrating the resulting large uncertainties in the calculated SLR recessions, being sensitive to the beach slopes chosen.

The 2008a report by CSL for the Open Coast was limited to a 50- to 60-year projection, based on the NIWA/MFE recommendation relating to the then most recent IPCC projections, with the most probable value being sea-level rise of 0.31 metre, and an extreme of 0.42 metre. The resulting values for the SLR dune recession, graphed in CSL (2008a, fig. 7B), ranged from 0 to 21.4 metres, with a mean of 11.6 metre, the 0 metre recession values being sites having shore-protection structures, the highest values being those with the lowest profile slopes. The updated CSL (2012) report retained those earlier estimates for the 50-year recession, adding calculations based on a 0.9 metre rise in the relative sea level for the 100-year projections, the SLR dune recession values having increased to range between 14.5 and 64.3 metres, with a mean recession of 44.3 metres. The CSL analyses therefore indicate that by the end of this century the extent of erosional retreat of the dunes and ocean-front properties could exceed 50 metres, extending inland from the present-day seaward edge of the foredunes, results that are consistent with those projected on other coasts by other investigators, where the analysis methodology had also been based on the Bruun model.

According to the shoreline time-series analysed in the CSL reports and presented as graphs in CSL (2008c) for the changing Cross-Shore Distance, net recession has dominated the shores south of Raumati throughout the 20th century, the rates having increased since about 1960. The example in Figure 7 for C4-18, within the Queen Elizabeth Regional Park, shows an overall shoreline retreat of about 18 metres since 1870, 12 metres of it having occurred since 1950 when the documentation was based on aerial photographs. The maximum retreat in the study was found for site C6-57, a “natural” location that appears to be just south of the Raumati sea wall, it having experienced 70 metres recession since about 1910, about 55 metres since 1955, this higher recession rates likely in part due to the end effects of the seawall (CSL, 2008a, 2008c), but with there being an order-of-magnitude agreement with the CSL future projections with higher rates of rising sea levels. In contrast, along the accreting shores to the north, seen in the examples of C13-24 and C25-70 included in Figure 7, the net shoreline accretion seaward has respectively amounted to 60 and 90 metres, again demonstrating the significant role in the site’s sediment budget being in the “black”.

As already discussed, the assessments by CSL (2008a, 2008b, 2012) of the trends in the cross-shore distances to yield the long-term trend, LT, and here to determine the recession SLR of the dunes produced by the relative rise in sea level, their summation in Equation (3) to yield the Coastal Erosion Predicted Distance ($CEPD$) represents a “double counting” of the recession caused by the rise in sea levels, that which occurred during the 20th century. This practice has been justified by Dr Shand (April 2014) in his comments on our March draft, followed in that it provided a more conservative result that could in part substitute for not having included analyses of potential future increases in storm-generated wave heights. Purposely double counting is a decidedly unconventional approach, and should not be followed, the question whether or not to account for a future increase in wave heights, and other decisions within the methodology of the analyses instead, should instead be accounted for in the uncertainty of factor of safety (Section 4.5).

The SLR projections calculated by CSL (2008a, 2012) for the shoreline recession due to a rise in sea levels on the open coast are reasonable, but have moderately significant uncertainties based on the selection of the beach-profile slope used in the calculations. Revisions of the results could be required, with updated projections of future sea levels 50- and 100-years in the future.

There are large uncertainties in the projected 50- and 100-year sea levels, compounded by those in the analysis methodology applied to calculate the resulting shoreline recession and property erosion. Within that range of projected sea levels, differences of opinion also exist as which should be used in management applications, there being arguments for the maximum projected levels in that they best represent a precautionary approach, while others have recommended that a mid-level “best estimate” as being the preferable choice (Willem de Lange, April 2014 comments), especially in the longer-term 100-year projections where the uncertainties are substantial. Whatever projections of rising sea levels are accepted now for application in the analyses, they should be reappraised frequently in the future, based on measured sea levels showing accelerated rates of rise, improvements in the science applied by climatologists to provide more confident projections, and the availability of documentation of whether storm intensities and the generated waves are increasing, and should be included in these projections.

4.3 Short-Term Dune Recession from Major Storms (Factors *S* and *ST*)

Author: P D Komar, Editor: J T Carley

By “short-term”, the inference is that the hazard being considered represents a relatively immediate threat to the erosion or inundation of ocean-front properties, that long-term trends such as rising sea levels are not included. This immediacy is most clearly represented by the episodic occurrence of a major storm, or perhaps during the span of a winter when a sequence of storms combine in their impacts. Of importance, “short-term” denotes a hazard that could happen this year, or at any time in the future.

It is in the analysis of such short-term hazards that the methodologies of CSL (2008a, 2008b 2012) and Lumsden (2003) differ the most. CSL follows a geologic/geographic approach that expands on their analyses of the historic trends of change in shoreline positions over the decades (Section 4.2), the focus now being on the variations in shoreline positions above and below the regression line that was important in determining the long-term hazards. In contrast, the Lumsden (2003) analysis is based on the ocean processes, the waves and tides, their extreme combinations when exceptionally high tides combined with the occurrence of a storm and its extreme waves.

The assumption in the CSL (2008a) approach is that the variations in the shoreline positions from year to year, above and below the trend of the linear regression, or deviating from the overall pattern of a non-linear trend, represents a major storm event or some other cause that has been important to the short-term hazards faced by shore-front properties. These variations are referred to as “fluctuations” by CSL, and are adopted in their analyses to define the magnitude of the *ST* factor in Equation (2). The analysis procedure is illustrated in Figure 8, based on site C18-85 north of the Waimeha River inlet, the upper diagram being its time series, the lower being the “residuals” that are used to statistically determine the short-term “fluctuations” taken to represent the *ST* component in Equation (3).

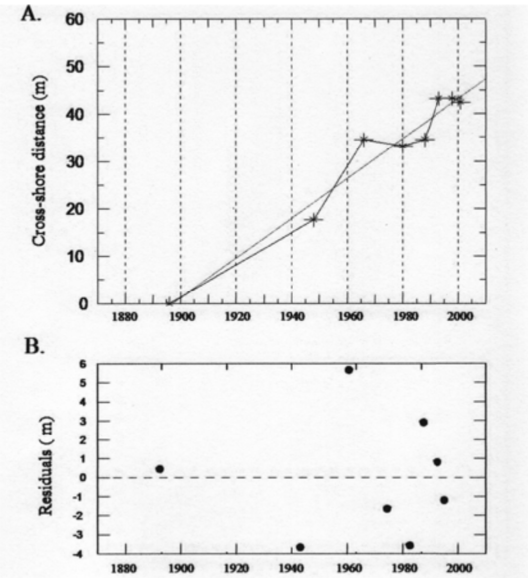


Figure 8: Analysis methodology of CSL (2008a), to determine the “residuals” of the individual shoreline distances above and below the trend of the linear regression line, in turn used to calculate the “fluctuations” and *ST* factor in Equation (3).

Although such fluctuations do represent short-term variations in shoreline positions and widths of the protective beach, and have been applied in other studies of New Zealand coastal hazards, it is unclear what processes have produced them. In the time series (C18-85) used in Figure 8 as an example of the CSL methodology, the magnitudes of the residuals are seen to be small, with the largest value having recorded a period of beach accretion, the maximum erosion having been less than 4 metres. Based on an examination of all of the time-series graphed in the CSL (2008c) Data Base report, and as seen here in Figure 7, the example presented in Figure 8 to demonstrate the methodology is from a site that has one of the most extreme variations, with the origin of its fluctuations possibly being due to its close proximity to the Waikanae River, which is known to experience significant variations in the morphology of its inlet.

The pattern of variations displayed in this time series (see Figure 8), also does not correspond to those expected from an extreme storm event, with the rapid recession of the dunes during the hours to days of the storm, followed by years to decades of dune accretion during its recovery phase. The best example of such a storm-induced cycle is seen in the time-series for site X0-48 in Figure 9, the stretch of shore south of Paekakariki to the Fisherman's Table Restaurant, the other sites from that area showing the same pattern. Evident in this time series is a recession event of about 12 metres in 1959, followed by an accretion period that lasted about 17 years, at which time there was a repeat occurrence of dune erosion in 1976, again amounting to about 12 metres, and once more followed by a period of recovery that has continued up to the present. This 1976 event is of course recognized due to its property impacts (Gibb, 1978), and analyses of its processes including both a 0.7 metre storm surge and high waves (Bell and Hannah, 2012). It is interesting that this distinct pattern seen in Figure 9 for site X0-48 is not evident in any of the time series to the north along the Kāpiti Coast, their graphs included in the CSL (2008c) Data Base report. The probable explanation for the locally extreme shoreline erosion and property impacts south of Paekakariki is the enhanced recession produced by rip currents and the embayments they eroded into the beach, permitting a more forceful assault by the storm surge and high waves. Lumsden (2003) was conscious of this shore being at greater risk of erosion due to the presence of rip embayments, and included it as a significant factor in his process-based hazard assessments for that shore.

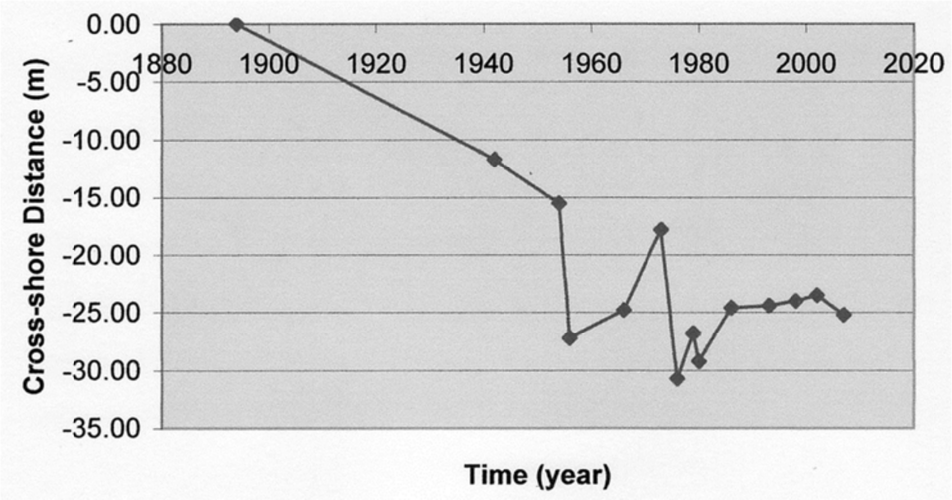


Figure 9: The variations in the X0-48 time series from CSL (2008c), south of Paekakariki, showing two episodes of rapid dune recession, in each case followed by long period of dune recovery, superimposed on an otherwise long-term recession of this shore.

While the "residuals" and the resulting "fluctuations" in the time series of shoreline distances are of interest and worthy of analysis, it is important to understand the ocean processes and beach responses that are responsible for their occurrences. The review comments by Richard Reinen-Hamill (Tonkin and Taylor, April 2014) spoke favourably of their use in hazard assessments, based on his application of this approach, presumably because he was able to account for their origins. However, this was not attempted in the CSL analyses of the short-term hazards for the Kāpiti Coast, not having included any analyses of the available data sets for the waves and tides that actually represent the short-term hazards.

It is clear that the recorded residuals and fluctuations in the CSL analyses are not responses to major storms, and certainly not to the extreme but rare storm events that have annual exceedance probabilities (AEPs) of only 2% (50 year ARI) to 1% (100 year ARI). Accordingly, their assessments of the SL component in Equation (3) cannot be considered to be robust, and does not sufficiently represent the "design" conditions needed to account for potential short-term erosion and flooding hazards.

When an examination of past erosion events and their processes is undertaken, it becomes evident that an important consideration is the simultaneous occurrence of high storm-generated waves, together with elevated measured tides. Examining this combination in greater detail, it generally is found that the erosion occurred in response to the increased swash run-up levels produced by the storm waves when they reached the sloping beaches, occurring atop the elevation of a high predicted astronomical high tide that has been elevated still further by the surge also produced by the storm. Other contributing factors to the elevated measured tides might be the normal seasonal cycle of monthly-mean water levels, being highest when the water is warm (thermal expansion), and changes in water levels associated with the El Niño/La Niña range of climate events.

The Kāpiti Coast hazard analyses completed by Lumsden (2003) focused on such combinations of the processes, to determine the total water levels (TWLs) at the shore produced by episodic storm events, following the methodology of Ruggiero et al. (1996, 2001) that has been summarised in Section 3 and graphed in Figure 6(A). Lumsden also included considerations of the El Niño/La Niña 20 to 30-year climate cycle, with elevated water levels occurring during La Niñas, and in the long term included 50- and 100-year projections of the rise in sea levels. Having derived process analyses of the resulting TWLs, for the present-day conditions and projected into the future, Lumsden (2003) applied the geometric dune-erosion model, also summarized in Section 3. It was recognized that while assessments of the TWLs resulting from the combined processes yield a reasonably accurate evaluation of the potential erosion and inundation of shore-front properties, the geometric dune-erosion model provides an estimate for the possible extent of the maximum dune recession and property loss. Although it exceeds the likely extent of the erosion, the model's assessment of a conservative maximum erosion is of interest in management application, serving as the basis for a precautionary approach as recommended in the NZCPS 2010. However, having calculated this potential maximum, it may be desirable to also determine "more likely" dune recession distances, by including analyses of storms of lesser magnitudes in terms of the generated wave heights and surge levels, events that would have a more frequent occurrence. It would also be beneficial to base the dune erosion assessments on geomorphic evidence from the site, it commonly being that following cut-back of the dune during an extreme storm, there is a prolonged period of dune regrowth, but with the preserved erosion scarp and the presence of drift logs providing direct evidence for past major storms.

It is significant that in his analyses of the Kāpiti Coast erosion hazards, Lumsden (2003) relied on the data sets for the waves and tides as recommended in the NZCPS 2010, recognising the significance of calculating the extreme TWLs that combine the processes, followed by providing an estimate (however approximate) of the potential dune recession. As reviewed in Section 3, direct measurements of these processes were not available for the Kāpiti Coast when Lumsden began his investigation. Instead, to support his evaluations of storm-induced erosion scenarios, Lumsden (2003) commissioned NIWA to undertake model analyses of the waves, tides, storm surges and sea levels, with the results reported by Laing et al. (2000). Hindcasts of the deep-water wave climate (the significant wave heights, periods and directions) were based on a 20-year record for the representative winds across the expanse of Cook Strait. The NIWA analyses yielded a deep-water climate, and a corresponding time-series for ten shallow water sites along the Kāpiti Coast. The predicted astronomical tides were analysed using standard models, the results showing that there are significant along-coast variations in the elevations and ranges of the tides, an important matter to take into account in the hazard-zone assessments (Laing et al., 2000). Storm surge elevations during past major events were evaluated from barometric pressure measurements at the Paraparaumu Airport. As reviewed in greater detail in Section 3, these analyses by Laing et al. (2000) of the ocean processes continue to be important in the development of scientifically based hazard zones for the Kāpiti Coast.

In addition to being based on the waves and water levels determined by NIWA, Lumsden (2003) also commissioned the collection of detailed surveys of beach profiles, and in the deeper water offshore. His analyses were completed for seven surveyed sites along the length of the Kāpiti Coast shore. The wave swash run-up levels on the beaches were calculated using the semi-empirical equation of Holman (1986), based on field data. The calculated swash run-up level on the beach is its vertical component, and includes both the wave set-up in the nearshore and the swash of individual waves, the calculation depending on the significant wave height, wave period and of the beach slope. An updated version of the Holman's (1986) equation, supported by additional field data, has been published by Stockton et al. (2006), and can be employed in future analyses.

As tabulated by Lumsden (2003, Tables 3.3 and 3.4), analyses are presented for both 50- and 100-year projected scenarios, and included 0.20 and 0.45 metre increased sea levels for those respective projections based on the IPCC (2007) report. Also included was a 0.10 metre increase in the measured tides to account for the potential occurrence of a La Niña climate event, known to elevate the tides throughout the winter. Excluding longer-term climate projections, the evaluated TWL for an exposed Kāpiti shore (Paekākāriki) was of the order of 4.0 metres elevation above mean sea level (MSL), reduced to 3.5 metres (MSL) on the shore sheltered by Kāpiti Island (Paraparaumu - Raumati South). As an example result, the beach profile at Paekākāriki had a slope of 0.057 (1V:17.5H, 3.2°) and dune-toe elevation of 2.5 metres (MSL), the geometric dune erosion model Equation (2) then yielding 26 metres for the predicted dune erosion setback during an extreme storm event.

The importance of episodic extreme storm events in hazard assessments is apparent from these results, involving TWL magnitudes of the order of 3.5 to 4.0 metres (MSL) for the Kāpiti Coast, greater than the projected rise in sea level spanning 100 years. However, with rising sea levels the impacts of episodic extreme-storm events will achieve corresponding higher elevations, and reach further inland to affect many more properties than at present.

In summary, the CSL (2008a, 2012) methodology directed toward assessments of the short-term hazards from dune erosion and potential property losses are based on evaluations of the "residuals" and the resulting "fluctuations" in the time series of shoreline distances. A major shortcoming of this approach is that no analyses were undertaken to account for the causative ocean processes and beach responses. It is the opinion of this Panel that the CSL assessment of the short-term ST component is not sufficiently robust to be used in Equation (3) to calculate the Coastal Erosion Predicted Distance ($CEPD$), as it does not adequately represent the extremes in the waves and tides needed to account for the Kāpiti Coast's potential erosion and inundation hazards.

In contrast to the CSL methodology, the methodology applied by Lumsden (2003) in his hazard analyses takes in account the wave conditions, the extremes in wave heights and swash runup levels on the Kāpiti beaches, and also on the measured tides that provide elevations of the predicted astronomical tides raised by the surge of major storms, and also climate controls such as the elevations of water levels elevated during La Niñas. His analyses are based on the summation of the processes to determine the extremes in total water levels, which can be compared with the surveyed elevations of the dunes to assess the potential erosion and flooding impacts. A dune-erosion model is applied to estimate the potential maximum erosion of the dunes for those total water levels, appropriate in providing a precautionary approach required in hazard assessments, as recommended in NZCPS 2010.

It is the recommendation of this Panel that the analysis methodologies applied by Lumsden (2003) be adopted for evaluations of the short-term hazards on the Kāpiti Coast, although they will need to be updated in light of additional process data having been made available from recent investigations, and in particular due to changes in the projected future sea levels that are now more extreme than used in his 2003 analyses.

Having completed revised evaluations of the 100-year extreme storm events, including the wave energies and total water levels (tides plus wave run-up) along the Kāpiti shore, it is recommended that engineering analyses be undertaken of the existing shore-protection structures, its variety of seawalls, to assess their capability of surviving the ocean forces and water levels expected to impact them. Such analyses should first consider the present-day conditions, in view of there already being the potential for experiencing such an extreme storm event, and then analyse the 50- and 100-year projections with elevated sea levels, increasing the probability of these structures being overtopped and failing.

4.4 Dune Stability Term Increase in the Dune Recession (Factor *D and DT*)

Authors: J T Carley and P D Komar, Editor: P S Kench

When storm waves and tides combine to yield total water levels (TWL) that achieve the elevations of the dunes backing the beach, their erosional retreat can be very rapid since the dune's loose sand provides minimal resistance. The process is one in which the reach of the wave swash cuts away at the toe of the dune, initiating the collapse of the upper portions of the dune face, the waves then carrying away the sand into the offshore. The result of an episode of dune recession is a nearly vertical scarp cut into the dune, devoid of vegetation cover. The resulting scarp is unstable, and slumping soon occurs, particularly as the sand dries, with the slumped sand forming a talus accumulation in front of the dune. The degree of slumping tends to slow with time as more talus accumulates, but the rate at which this occurs depends on the internal structure of the dunes (e.g., the presence of soil horizons) that locally provide some cohesion of the sand and resistance to slumping.

While the analyses in Section 4.3 of the S and ST components accounted for the rapid erosional retreat of dunes at the time of the storm, they do not include this slower post-storm phase in the retreat of the dunes caused by the instability of wave-cut scarp. The extent of the resulting horizontal retreat of the dunes depends on their height, the higher the dunes the greater the potential retreat, but the time required to accomplish that degree of loss also increases. The result can be a significant additional recession of the dunes, beyond that originally produced by the storm, the D and DT components included in Equations (1) and (3). The incorporation of this dune stability hazard component on sandy coasts is therefore supported by this Panel.

The methodology applied by CSL (2008a) to calculate the distance DT of the post-storm retreat of the dunes, due to its instability, is acceptable for the northern portion of the Kāpiti coast, north of about Raumati, where the dunes are generally sandy (with isolated areas of cobble) and have a crest elevation below approximately 5 metres MSL. This distance is relatively small for low dune crest heights, being approximately 74% of the dune crest elevation. That is, a 5 metre dune crest would have a dune stability component of about 3.7 metres. As a result, applying the CSL methodology is non-conservative relative to other accepted methods such as that of Nielsen et al. (1993), which assumes fully dry sand, and incorporates a factor of safety that reflects conventional geotechnical engineering practice.

More elevated portions of the coast (south of about Raumati) are subject to more complex slope stability processes than the simple dune stability model used in CSL (2008a). Issues include (but may not be limited to) the sand grain size adopted and the assumption of dry sand. It is recommended that specialist geotechnical engineering advice be sought regarding slope stability in these areas.

In areas where seawalls are present, consideration of a dune stability component is acceptable when investigating a scenario of seawall failure or removal.

However, the dune stability component should be omitted from hazard zone calculations for an engineered seawall maintenance/repair/rebuilding scenario, since an engineered seawall would be designed to ensure slope stability.

4.5 Uncertainty and the Factor of Safety (Factor *CU*)

Author: J T Carley, Editor: R B Davies

There are inherent uncertainties in defining coastal hazard zones. CSL (2008a, 2012) applies a combined uncertainty distance of 6 metres for the 50-year projections, 10 metres for the 100-year estimate. Note that CSL (2008a) did not include the statistical error in the linear regressions and one can question the calculation of the uncertainty distances.

The Gibb's equation includes a factor of safety (a multiplier on the coastal hazard zone distance) that can range from 1.0 (essentially representing no factor of safety) to 2.0, and is generally in the range 1.15 to 1.30.

Other jurisdictions specify a factor of safety on all, some, or none of the typical coastal hazard zone components. This is largely a product of policies or accepted practices that have evolved in the jurisdiction.

Where no factor of safety is adopted, conventional practice has been to adopt conservative/precautionary values. While it is appropriate to include a safety margin, this needs to be done in a transparent way and after taking account of the uncertainties involved in the estimates.

5. Hazard Zone Assessments for Kāpiti Coast Inlets

Author: P S Kench. Editors: J T Carley and P D Komar

5.1 Overview of CSL Inlet Methodology

The Panel acknowledges that tidal inlets/river mouths pose particular difficulties with respect to accounting for their behaviour under future scenarios of sea level change and capturing their dynamics in coastal hazard assessments. There are no standardised approaches for the assessment of inlets in coastal hazard assessments. However, a number of studies have examined the past geomorphic behaviour of inlets to inform potential future responses (Kench et al., 1999).

Tidal inlets (river mouths) are one of the more dynamic features of any coastal compartment as they can change in configuration and location along the coast in response to on-going changes in ocean (wave and tide) and river processes (e.g., floods). Over the short (seasonal) and medium (decades-century) timescales, an entrance may migrate alongshore by up to hundreds of metres under the influence of prevailing wave energy and littoral drift gradients. There is commonly a maximum extent of alongshore migration as river floods tend to breach the alongshore spit and reset the alignment of the inlet with the river channel. Examination of the natural dynamics of inlets over decadal to centennial timeframes provides an understanding of the envelope within which the inlet can migrate.

There are a number of specific considerations unique to assessing inlet hazards:

- The alongshore dynamics of inlets, and shifts in alongshore location, where they intersect the coast
- The shoreward translation of inlet entrances
- Shoreward translation of landward side lagoon shorelines, and
- How management practices should be included into assessment of inlet hazard zones.

In order to account for the differences between the open-coast shorelines and inlets, CSL applied a different methodology to assess the hazards in the immediate proximity to inlets. In particular, CSL modified the open coast method by replacing the “short-term” components of the open coast methodology with the inlet migration curve (IMC). The inlet erosion hazard distance (*IEHD*) was computed using the following equation:

$$IEHD = IMC - (LT + RSLR + DS + CU) \qquad (5)$$

The IMC captured the envelope of changes in shoreline position around the vicinity of each inlet based on aerial photograph analysis dating from approximately 1939. Calculation of the *IEHD* involved the following steps depicted in Figure 10.

- Identification of the landward limit of inlet shorelines from available historical records.
- Construction of the *IMC* as an interpolated curve connecting the landward limit of inlet positions. In places the interpolation process introduced additional conservative estimates on the landward position of the inlet.

- The inlet erosion hazard line was located landward of the IMC by a distance equal to the sum of the hazard component values for *LT, SLR* and *DS* from the adjacent open coast site, plus CU for inlets.
- Finally, the resulting erosion hazard line was merged with the open coast erosion hazard line.

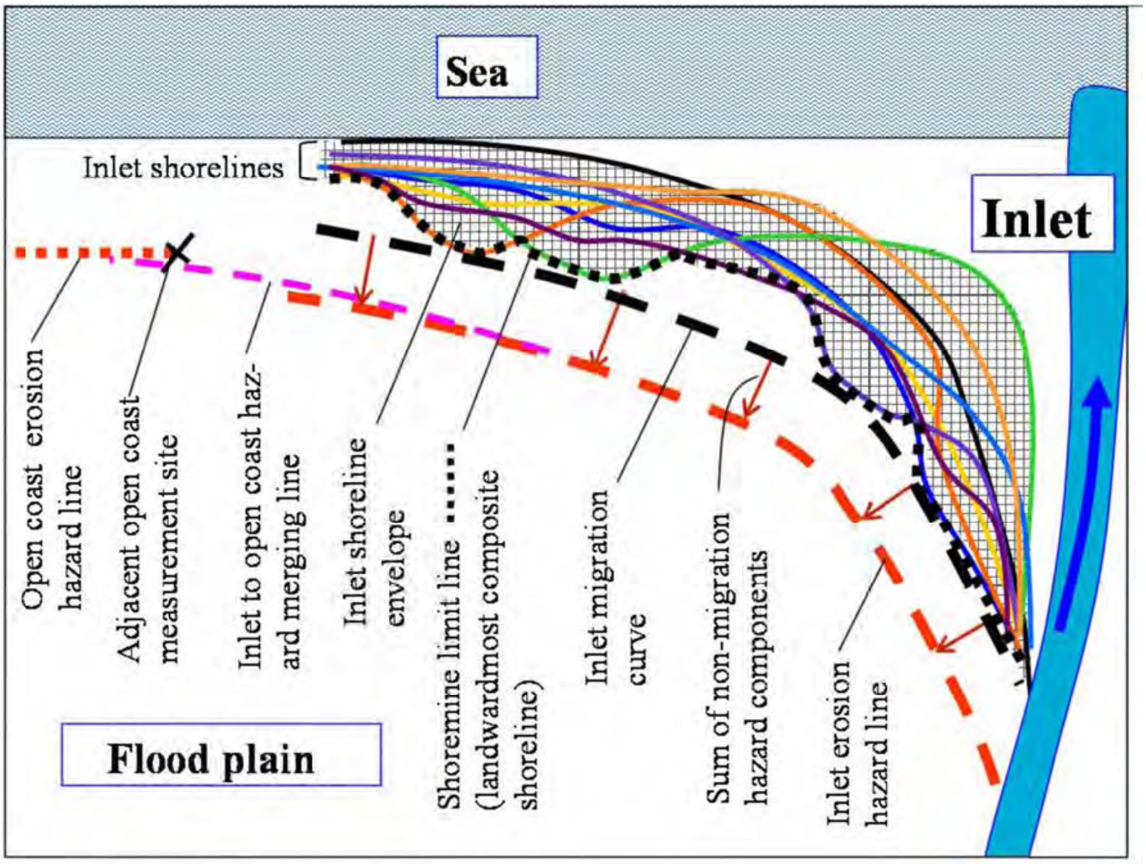


Figure 10: Illustrated derivation of the inlet erosion hazard line and its relationship with the open coast hazard line [Source: Figure 3 from CSL (2008b)]

There are several points to note on the development of the *IMC*s:

- They define the historical footprint at the coast which the inlet has occupied over the historical record assembled. For some inlets management actions in recent decades have constrained the inlet dynamics. Consequently, the *IMC*s are not necessarily determined by natural process, and therefore, have significant limitations if used to project future natural dynamics.
- The *IMC* is used by CSL as a reference to examine the landward translation of inlets rather than depict alongshore variations in inlet position.
- The composite of the most landward limit of inlet shorelines was used as the reference location to translate the inlet zone landward under future scenarios of sea level change. It should be acknowledged that for some inlets the *IMC*s are not defined by natural processes and, therefore, it is inappropriate to apply such *IMC*s for consideration of *IEHD*s under future natural process conditions, as they would not reflect the true variability of inlet dynamics.

Once the *IMC*s were defined, the IMC was translated landward by the values of the long-term historical shoreline behaviour, sea level rise and dune stability from a neighbouring open coast site to yield the inlet erosion hazard distance (*IEHD*). This will likely lead to conservative estimates, as the energetics on inlet/estuarine shorelines are typically lower than open coasts and are also heavily influenced by channel processes.

The modified methodology developed by CSL for application to inlets is simple and not unreasonable given the inherent complexities in evaluating alongshore and cross-shore dynamics of inlets, and given the stated intent of the CSL (2008b, 2012) inlet reports to develop a 'first approximation' of inlet erosion hazards. Defining the envelope of historic inlet change is an accepted first order approach to projecting likely future envelope within which the inlet may be located along the coast into the future. However, it should be noted that defining the envelope of inlet change is constrained by available historic evidence of inlet positions. There are several weaknesses in the approach, which include:

- Definition of the *IMC*s in some inlets has been constrained by management activity. In such instances the *IMC*s do not reflect the behaviour of inlets under natural processes making their application questionable to unmodified inlet scenarios.
- The approach masks variability in the alongshore dynamics of inlet entrances.
- The approach also assumes that the lagoon shorelines will migrate landward under the influence of coastal processes, which ignores the likely primary control on such shorelines, which are related to fluvial processes in the channel and the channel alignment before it breaches the sand/gravel spit.
- As currently applied, it is assumed the coast will be erosional/recessionary, despite evidence that some parts of the coast and inlets have been in net accretion in the past.

It is important to acknowledge that the CSL (2008b, 2012) inlet reports produced a first approximation of inlet erosion hazards. It is clear that the nature of the inlets along the Kāpiti Coast vary markedly in their physical and hydrodynamic characteristics and their history of modification. Consequently, better resolution of inlet hazards will require site-by-site analysis that allows the unique characteristics and historical behaviour of each inlet to be examined in isolation and incorporated into better contextualised analyses of inlet erosion hazards that account for the weakness outlined above.

5.2 Issues of Submissions

A significant number of submissions by coastal residents, presented at the December 2013 meeting, involved issues related to properties adjacent to inlets. These submissions should be carefully considered if analyses for individual properties are undertaken at a future date. Two specific areas of concern in the submissions are examined below.

First, a number of submissions raised the issue of incorporating on-going management of inlet entrances and rivers and whether these should be included in future projections of inlet zones. Many of the inlets have physical training works and/or bridge abutments in their lower reaches, stabilising channel alignment prior to the coast. In general, such practices constrain the dynamic behaviour of inlet entrances. Consequently, management practices have led to a smaller envelope of change than would normally exist under unmanaged scenarios. It was also noted that soft-engineering practices are used to reconfigure inlet entrances. Such practices involve manipulation of the sand volume at entrances to reorient inlet channels.

The Panel is of the view that the determination of whether or not management works are included in scenarios of future change is a planning policy decision, based on the medium to long-term intention to maintain river training works. However, the Panel would highlight the value of undertaking non-managed scenarios as they are instructive in highlighting what is potentially at risk and it informs the value of management interventions. However, the unmanaged scenario should not become the default management option without additional stakeholder consultation and studies which consider social, economic and environmental factors.

A second issue raised by submitters centred on the methodology of smoothing results of inlet analysis with adjacent open coast hazard zones. In particular, a number of submitters were concerned that they were affected by overly conservative hazard zones due to the spacing of open coast assessment sites. It was unclear precisely how this integration occurred as part of the CSL assessment; however, it is clearly an issue that requires consideration in refining the assessments.

5.3 Panel Summary and Recommendation Regarding Inlet Hazard Assessments

- The panel recognises that evaluating erosion hazards at inlets is complex and that the CSL methodology was developed to provide a first approximation only.
- The panel agree that definition of the spatial extent of inlet dynamics provides a useful analogue to assess future behaviour. However, the construction of the Inlet Management Curves in some instances is constrained by historical management practices. In such instances the application of the *IMC* to future prediction should be undertaken with full recognition of the limitations of such curves as they can yield errant results.
- It is recommended that site-specific assessments are undertaken at each inlet to better refine inlet erosion hazards. Such assessments should reflect the differing hydrodynamic and physical characteristics of inlets, differing morphological variability of inlets, estuarine shoreline dynamics of each system and the full history of management of each inlet to be captured.
- The panel recommends that future inlet assessment include an analysis of the alongshore variations in inlet position.
- Along with revised open coast assessments allow for scenarios of change under accretionary coast conditions.
- Both managed and unmanaged scenarios should be evaluated.

6. Statistical Techniques

Author: R B Davies and P D Komar, Editor: J T Carley

As stated previously, the Panel acknowledges that in developing the CSL reports, the authors have faced difficult problems. Any project involving forecasting with limited data requires substantial judgement and ad hoc decisions, which may then be scrutinised by parties affected by the outcome. It is, therefore important that all parties have ready access to the data and the line of reasoning.

It is recommended that studies such as these involve an experienced statistician, preferably one familiar with time-series analysis. There seems to have been only limited involvement of a statistician in the CSL analyses. In particular, the simple regression analysis, linear or not, used in the CSL analyses is likely to be inappropriate for the data sets considered here.

By and large, the linear regression analysis and associated calculations undertaken in the CSL reports were carried out as described. However, in several places there were additional "precautionary" adjustments. In addition, analysis of vegetation line measurements is most likely not adequately handled by the simple linear regression model used in the CSL analyses.

While calculating the short-term (*ST*) variation from the variability of the vegetation line measurements is elegant and approximately consistent with statistical principles, there is not enough data for this and there are assumptions that are probably not satisfied. Therefore, it would be preferable to estimate the short-term *(ST*) variation from physical processes using conventional coastal engineering/science methods. In any case, this term needs to allow for potentially increased wave heights due to climate change.

Submitters pointed out to us that there had been sand extraction on the North Paraparumu coast in the 1990s and this needs to be allowed for in the regression analyses.

From a statistical perspective, it is recommended that "best estimates" rather than precautionary values be adopted, with margins of error or factors of safety kept separate from the estimates and added at the end if appropriate. Alternatively, one could give several scenarios based on best, worst and mid-way cases.

An economic assessment of the consequences of planning restrictions needs to be undertaken before imposing them, since the restrictions may have been made on the basis of calculations which may be excessively precautionary. One needs to balance the cost to property owners of any restrictions with the actual risk (and its time scale) and one can't do this if there are hidden "precautionary" adjustments.

It appears that the sea level rise preceding 2008 has not been taken into account in the CSL calculations. One can adjust for this by subtracting the rate of sea level rise during the period the regressions were fitted from the rate of sea level rise during the forecast period.

In the modelling of the "remove sea-walls" scenario the "catch-up" term in the 100-year projection appears to be incorrectly handled. It is doubled along with the rest of the *LT* term when updating from the 50-year projection. It should be left as is. There is additional uncertainty regarding the current calculation of the *LT* term in the "remove sea-walls" scenario. The present calculation assumes that when the sea-wall is removed the coast reverts to what it would have been if there had been no sea-wall, which may be too precautionary.

It needs to be recognized that traditional extreme-value projections (such as 100 year ARI waves and water elevations) may no longer apply under a paradigm of changing climate, since the assumption of a “static” population no longer holds.

7. Coastal Management

Author: J T Carley, Editor: P D Komar

The study of coastal processes and the determination of coastal hazards is of fundamental academic interest, however, it is generally only of concern to local government and communities when present or future coastal hazards potentially impact the built environment.

The vulnerability of some parts of the Kāpiti coast to historic and existing coastal hazards, and previous management responses to these hazards are clearly evident from the substantial number of coastal protection structures (seawalls, revetments, managed dunes and previous no-build zones) that have been constructed/adopted on the coast.

Although coastal management was not explicitly part of the Panel's Terms of Reference, a substantial number of submissions related to risk assessment and coastal management. In response to these, and because the purpose of coastal hazard assessment is to inform coastal management, the Panel has provided a brief section on coastal management. Many of the issues relating to the CSL series of reports arose from their direct incorporation into the planning scheme without risk assessment and full consideration of management options.

The steps to coastal management are influenced by local policies, practices and legislation, however, the broad principles for best practice are universal. A graphic illustrating recommended steps in coastal management is shown in Figure 11. The CSL series of reports undertook work pertaining to step 1, part of step 2 and step 3 in Figure 11, with a further six steps suggested. The Panel recommends that the entire process (Steps 1 to 9) be revised approximately once per decade and/or if future climate change projections are substantially revised (e.g., new revisions of IPCC).

While probabilities can reasonably be attributed to present day future hazards, assessment of hazards for 50- and 100-year planning periods, particularly within an environment of changing climate, involves high uncertainty and can never be definitive. The principles of "*adaptive management*" as illustrated in Figure 12 (DEFRA UK, 2006) are a method of managing this uncertainty. Adaptive management provides a realistic alternative to excess speculation regarding definitive future coastal hazards.

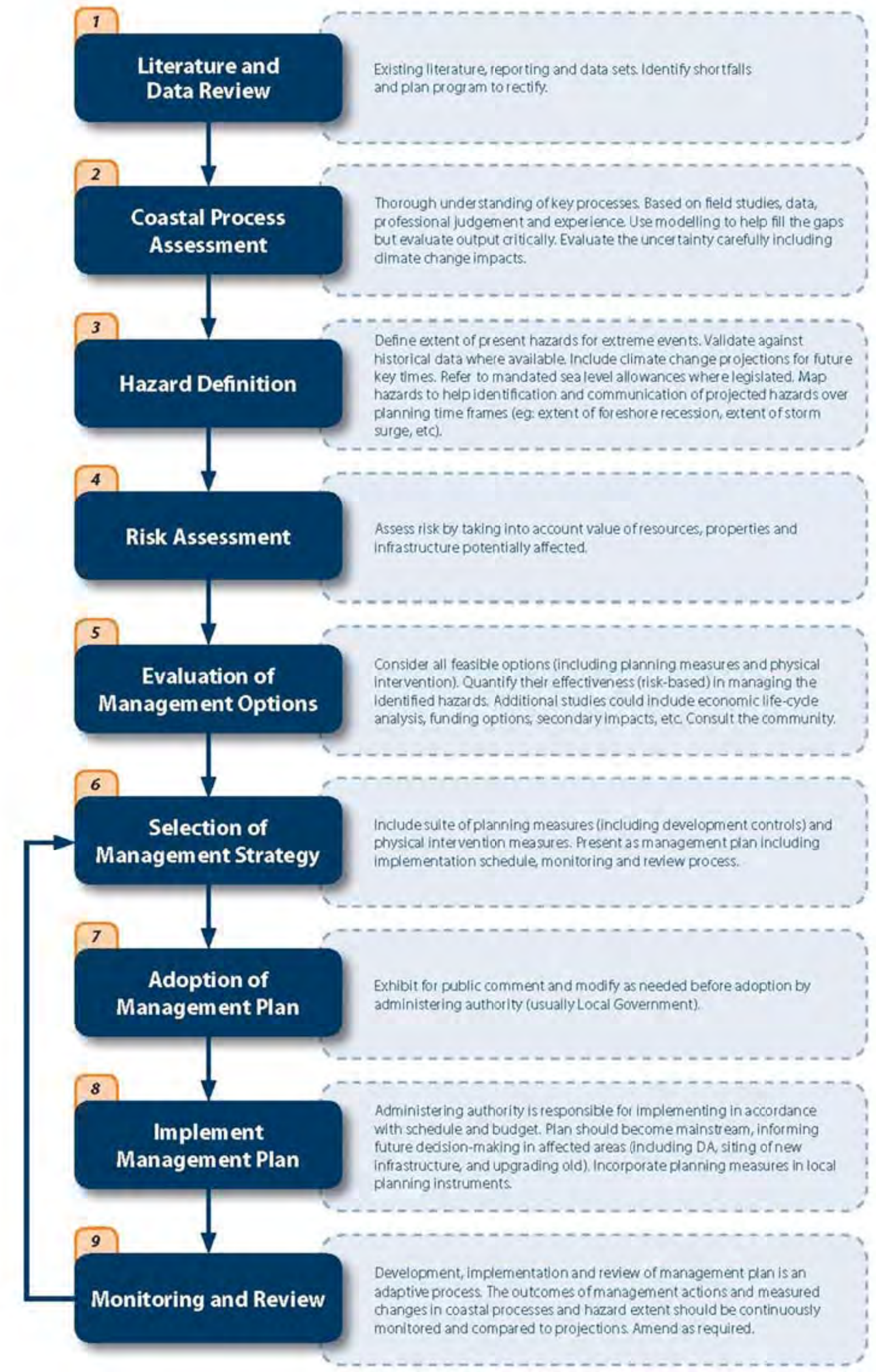
The assessment of coastal hazard zones should consider a range of plausible scenarios (e.g. low, mid, high, or best estimate and extremes). The range of scenarios (particularly for 100 years' time) should be considered in future planning, but automatic retreat of development behind the projections for the most extreme scenario should not be a default management plan.

In the formulation of planning policies for coastal hazard management, a full range of management options needs to be considered in conjunction with stakeholders, and include policy, economic, environmental, cultural and social factors. Noting that the definition of *risk* is likelihood times consequence, risk may therefore be managed by changing either the likelihood or the consequence.

In short, this management may consider combinations of the following options in increasing order of strength (of intervention) (Figure 13):

- No action;
- Retreat and relocation;

- Accommodation (optimising the coexistence of the built environment and natural processes); and
- Protection through:
    - Soft engineering (such as beach nourishment);
    - Hard engineering (such as seawalls).



1 Literature and Data Review

Existing literature, reporting and data sets. Identify shortfalls and plan program to rectify.

2 Coastal Process Assessment

Thorough understanding of key processes. Based on field studies, data, professional judgement and experience. Use modelling to help fill the gaps but evaluate output critically. Evaluate the uncertainty carefully including climate change impacts.

3 Hazard Definition

Define extent of present hazards for extreme events. Validate against historical data where available. Include climate change projections for future key times. Refer to mandated sea level allowances where legislated. Map hazards to help identification and communication of projected hazards over planning time frames (eg: extent of foreshore recession, extent of storm surge, etc).

4 Risk Assessment

Assess risk by taking into account value of resources, properties and infrastructure potentially affected.

5 Evaluation of Management Options

Consider all feasible options (including planning measures and physical intervention). Quantify their effectiveness (risk-based) in managing the identified hazards. Additional studies could include economic life-cycle analysis, funding options, secondary impacts, etc. Consult the community.

6 Selection of Management Strategy

Include suite of planning measures (including development controls) and physical intervention measures. Present as management plan including implementation schedule, monitoring and review process.

7 Adoption of Management Plan

Exhibit for public comment and modify as needed before adoption by administering authority (usually Local Government).

8 Implement Management Plan

Administering authority is responsible for implementing in accordance with schedule and budget. Plan should become mainstream, informing future decision-making in affected areas (including DA, siting of new infrastructure, and upgrading old). Incorporate planning measures in local planning instruments.

9 Monitoring and Review

Development, implementation and review of management plan is an adaptive process. The outcomes of management actions and measured changes in coastal processes and hazard extent should be continuously monitored and compared to projections. Amend as required.

Figure 11: Key Steps in the Coastal Management Process [Source: Engineers Australia (2012)]

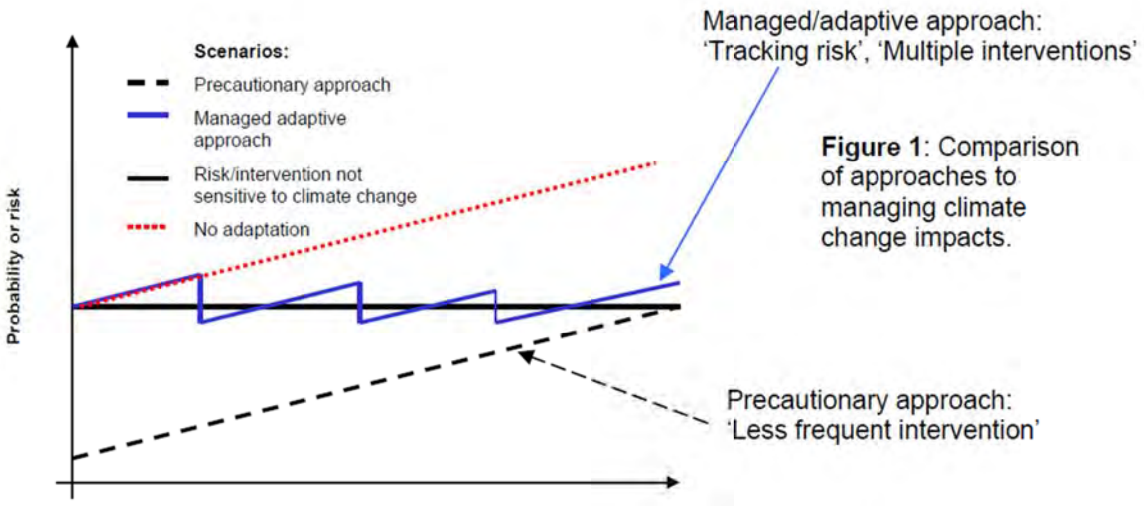


Figure 12: Managed Adaptive Approach [Source: DEFRA UK (2006)]

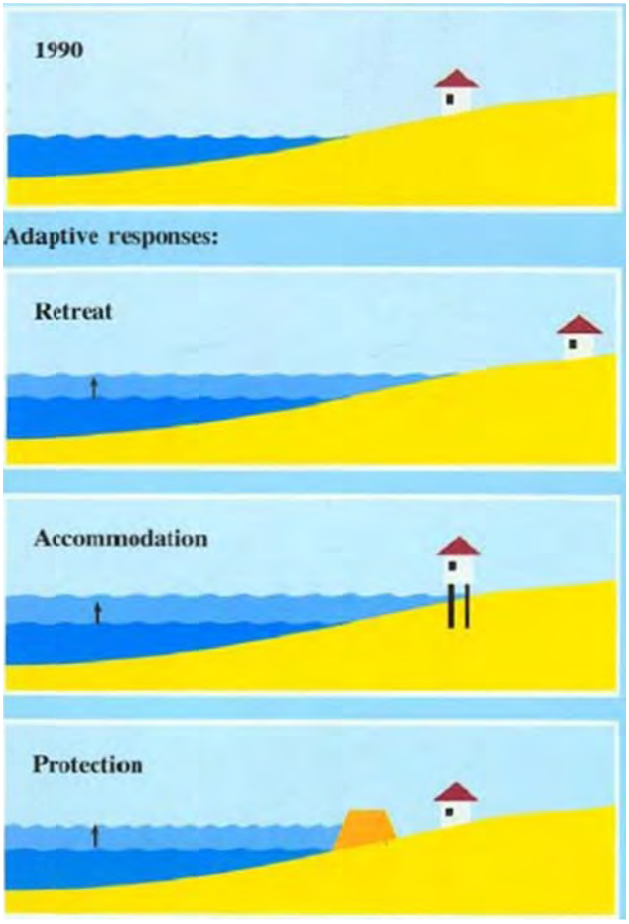


Figure 13: Broad Principles of Coastal Adaptation [Source: IPCC (2001)]

8. Summary and Recommendations

Authors: P D Komar, P S Kench, J T Carley and R Davies

8.1 Overview

The task set for this Panel by the Kāpiti Coast District Council (KCDC) was to provide a review of the methodologies and results derived from recent investigations of the Kāpiti Coast's potential hazards from future coastal erosion, taking into account Earth's changing climate (global warming). This review has considered the reports prepared by Lumsden (2003) and Coastal Systems Ltd (CSL, 2008a, 2008b, 2012), that respectively applied coastal engineering and geologic/geographic based methodologies for coastal hazard assessments, both studies having provided analyses that led to recommendations for hazard zones (set-back distances) for the years 2050 and 2100.

The opinion of the Panel based on its review is that the existing recommended hazard lines are not sufficiently robust for incorporation into the Proposed District Plan. However, there are components of the analyses undertaken by Lumsden and CSL, which if updated and combined could potentially yield scientifically-sound, best practice hazard lines for the Kāpiti Coast.

The 2003 investigation by John Lumsden, a coastal engineer, primarily focused on analyses of the ocean processes (waves, tides, storm surges, sea levels, etc.), including the extreme storm events that pose an existing threat to this coast, and during this century will migrate upward and inland with rising sea levels, continuing to represent the primary agent responsible for the erosion and flooding of shore-front properties. In contrast, the 2008-2012 reports by CSL, mainly followed a geologic/geographic methodology in analysing changes in shoreline positions, based on series of aerial photographs and old maps, yielding time series of data to which linear regressions provide an assessment of the site's rate of change, either accretion or recession (erosion). The resulting data sets of shoreline change can be separated into portions due to rising sea levels experienced during the 20th century, and the balance between the gains and losses of beach sand at that site, its sediment budget, with their past trends then being projected into the future to evaluate the 50- and 100-year hazard lines.

These respective investigations by Lumsden and CSL of the storm impacts and future projections are viewed by the Panel as complementing one another, and encourages KCDC to consider the results of both in the establishment of what could prove to be robust hazard zones for the Kāpiti Coast.

8.2 Summary of Coastal Hazards and Analysis Methodologies

During the past decade, research by climatologists and coastal scientists has led to conclusions that the processes affected by global warming and the resulting impacts along coasts will be significantly greater than previously estimated. While in 2007 the IPCC projected that the rise in the global-averaged sea level during the 21st century could amount to the order of 0.40 to 0.59 metre (excluding ice melt), more recent analyses by climatologists project the expected increase to be of the order of 1 metre, with the prospects for enhanced coastal impacts expected to be extreme. Furthermore, there is evidence globally that the intensities of storms have been increasing, also attributed to global warming, with measurements by buoys and acquired from satellites demonstrating that the extreme heights of waves generated by the storms have also increased. However, the existence of such an increase in the Cook Strait, enhancing the Kapiti Coast's hazards, has not yet been demonstrated, although it could be a factor in the heights of waves reaching this shore from the Tasman Sea. Therefore, this potential hazard cannot at present be accounted for in assessments for this coast, but may need to be added later following additional research.

Assessments of erosion hazard zones for the coasts of New Zealand follow the direction developed by Dr Jeremy Gibb, who formalised the approach in the relationship presented in Equation (1), that contains components that account for the short-term impacts (denoted by *S* in Equation (1)), the long-term trends that include the existing rate of change in the site's shoreline positions (*R*), plus the change produced by the expected accelerated rate of rise in sea levels (*X* or *SLR*). Our review of the Lumsden (2003) and CSL (2008a, 2008b, 2013) analyses have focused primarily on their respective methodologies directed toward assessments of these components.

The greatest difference between the Lumsden and CSL methodologies is in their short-term assessments, in relation to the present-day hazards from occurrences of major storm events, such as the 1976 storm and its impacts. The Panel's review of the different approaches in the analyses supports the need to base the short-term storm erosion assessment on evaluations of the total water levels (TWL) reached by the combined elevated measured tides plus the swash run-up levels of the storm waves on the beaches, the measured tides having included storm surges and other processes that elevate water levels above the predicted astronomical tides. This is the approach that was followed in the Lumsden (2003) report, which was based on model assessments of both the waves and tides, since direct measurements are not available for the Kāpiti Coast. His analyses need to be updated, however, in that additional assessments of the waves have subsequently become available (MetOcean, 2007, 2010). The analyses also need to be revised for the increased projection of the 2100 sea level, having previously used the mid-range IPCC level. With the methodology followed by Lumsden (2003) being directly related to the waves and tides, it most easily incorporates an analysis that accounts for the increasing wave heights and their swash run-up levels on the beaches, if they are later demonstrated to be important on this coast. With these updates, the results will be predictions of the present, 50 and 100-year hazard zones for the Kāpiti Coast, based on considerations of the extremes in the ocean processes.

A major contribution by the CSL reports is their analysis of the long-term trends of changing shoreline positions, based on data derived from aerial photographs and older maps, completed for 68 sites including 12 inlets that required applications of modified analysis methodologies that account for channel migrations of the shorelines. The analysis procedures are complicated, having accounted for the presence of shore-protection structures (e.g. seawalls) and whether they will be maintained in the future with rising sea levels. They are also complex in the applications of linear regression analyses, where for some shoreline sites the multi-decadal trends of shoreline positions are significantly nonlinear. Questions have been raised in our report concerning assumptions made in these analyses, that need to be considered with revisions possibly needed in the estimated hazard zones.

The procedure used by CSL to assess the short-term changes in the shoreline positions – i.e., their "fluctuations" – depends on their "random" variations over the years from the linear regression line. While an analysis of these variations is of interest, the processes that produced them remain uncertain, and it is likely that they do not represent the potential extreme impacts of a 100 year ARI (1% AEP) storm event, required in the development of a conservative recommended hazard zone.

Complex and less well understood processes also occur around the coastal inlets. The Panel supports the separate consideration of inlets in their hazard assessment. The Panel endorses the use of the CSL inlet approach, though refinements in application would be useful in future iterations to:

- Allow probabilistic analysis of shoreline positions within the envelop of change; and
- Evaluate alongshore variations in inlet location.

Along with revised open coast assessments, scenarios of change under accretionary coast conditions should be considered for inlets. Both managed and unmanaged inlet scenarios should be evaluated – the basis of this is to inform stakeholders of the consequences of an unmanaged scenario. How the inlet and open coast hazard zones are merged should be reconsidered and a transparent procedure invoked. Given the long history of hard and soft inlet management, the unmanaged scenario should not become the default without further stakeholder consultation, social, environmental and economic assessment.

8.3 Recommendations

While the hazard lines proposed by CSL are not sufficiently robust for incorporation into the Proposed District Plan, data sets and components of the analyses completed by Lumsden and CSL are of sufficient quality to be adopted in the development of revised hazard lines, but need to be modified somewhat in details of their methodologies, and updated to account for the most recent analyses of trends in rising sea levels, changes that are required to yield best practice hazard lines for the Kāpiti Coast.

There are a number of immediate actions recommended by the Panel that should be undertaken to improve the robustness of the hazard mapping before any consideration of the management of risk is undertaken as part of the formulation of planning policies. In the longer-term (i.e., over the ten year term of the next District Plan), the Panel recommends that a series of studies be undertaken to enhance the information base applied in the coastal hazards mapping.

8.3.1 Immediate Actions

The Panel's recommendations based on its review therefore include the following:

1. The analyses by Lumsden (2003) be updated to include the additional wave hindcast data available from the MetOcean reports, and the increased sea levels that are now projected by climatologists to be of the order of 1 metre by the end of this century. Expected to be particularly significant are improved assessments of the "short-term" factors that represent present-day hazards, as well as providing determinations of potential future hazard zones based on the causative processes affected by Earth's changing climate. The updated results from Lumsden should be used for the short-term factor, replacing CSL's "fluctuation" values in the recommended hazard-zone lines.

2. Having completed revised evaluations of the short-term, 100-year ARI extreme storm events, including the wave energies and total water levels (tides plus wave run-up) along the Kāpiti shore, it would be informative to undertake engineering analyses of the existing shore-protection structures, its variety of seawalls, to assess their capability of surviving the ocean forces expected to impact them.

3. The respective contributions produced by sea-level rise during the 20th century be separated from that produced by gains and losses of beach sand at that site, its

sediment budget, and eliminate the "double counting" of the rise in sea level from the projected 50- and 100-year hazard zones.

8.3.2 Future Studies

The Panel recommends that the following actions be undertaken as part of ongoing revisions to coastal hazard assessment and planning for Kāpiti over the next decade:

1. Analyses of beach-sediment budgets be undertaken to determine the gains and losses of the beach sand that should account for the shoreline changes found in the CSL determinations, possibly providing an explanation for the nonlinear trends found at some sites, and with the sediment budget also permitting an assessment of how far into the future the accretion of its central cuspate shore will revert to erosion and eventually disappear. It is also important to undertake investigations of the rivers, the sources of the beach sand, specifically how global warming or human environmental impacts could alter them, resulting in changes in volumes of sand being contributed to Kāpiti beaches.

2. Develop probabilistic methods for quantifying coastal hazards in future assessments, rather than just "extreme", "design", 100-year ARI or high-range projections.

3. Continue ongoing monitoring of the beaches, including periodic surveys with an extension of the bathymetric surveys.

4. If the long-term trends are used in setting the hazard zones, the regression analyses should be reworked in conjunction with a qualified statistician, preferably one with experience with time-series analysis.

8.4 Concluding Remarks

The Panel has concluded that the reports by John Lumsden and CSL represent contributions directed toward assessments of hazard zones for the Kāpiti Coast. However, the current hazard mapping is not sufficiently robust to be used for planning policies and regulation within the District Plan.

With the combined contribution of the Lumsden processes-based analyses of short-term hazards resulting from extreme storm events, with those from CSL that document the long-term trends of changing shoreline positions, the Kāpiti Coast District Council would derive erosion hazard zones in which both the engineering and geologic aspects are accounted for, in effect "the best of both worlds".

In terms of the implementation of these recommended zones, in many respects, the most important consideration should be the short-term hazards since they are immediately relevant in the form of the potential occurrence of a 100-year ARI storm during the coming winter. In comparison, the long-term progressive rise in sea levels and increasing wave heights begin slowly and only make significant contributions to the hazards decades in the future, their main effect being to shift the zone of short-term hazards landward, impacting additional homes and infrastructure. Such differences in the immediacy of the hazards could be reflected in the management approaches adopted to minimise human impacts; for example, in the degrees of restrictions placed on residents.

Finally, it is important to recognise that the coastal hazard zones are not a management plan as such, but simply inform management options, the Panel recommends that a range of management options be developed and considered with the community before hazard lines and their respective policies and regulations are introduced into the District Plan. Noting that the definition of *risk* is likelihood times consequence, risk may therefore be managed by changing either the likelihood or the consequence.

9. Cited References

Allan, J. C., and P.D. Komar (2000) Are ocean wave heights increasing in the eastern North Pacific? *EOS, Transactions American Geophysical Union*, v. 81, no. 47, pp. 561, 566-7.

Allan, J. C., and P.D. Komar (2006) *Climate Controls on US West Coast Erosion Processes*: Journal of Coastal Research, v. 22, no. 3, p. 511-529.

Bacon, S., and D.J.T. Carter (1991) *Wave Climate Changes in the North Atlantic and North Sea*: International Journal of Climatology, v. 11, p. 545-558.

Beavan, R.J., and N.J. Litchfield (2009) *Sea Level Rise Projections Adjusted for Vertical Tectonic Land Movement Along the Hawke's Bay Coastline*: GNS Science Consultancy Report 2009/128, 42 pp.

Bell, R.G., and J. Hannah (2012) *Sea-Level Variability and Trends: Wellington Region*: NIWA report prepared for the Greater Wellington Regional Council, 74pp.

Bruun, P. (1962) *Sea Level Rise as a Cause of Shore Erosion*: Journal of Waterways and Harbors Division, American Society of Engineers, v. 88, p. 117-130.

Bruun, P. (1988) *The Bruun Rule of Erosion by Sea-level Rise: A Discussion of Large-scale Two and Three-dimensional Useages*: Journal of Coastal Research, v. 4, p. 627-648.

Carter, D.J.T., and L. Draper (1988) *Has the Northeast Atlantic Become Rougher?*: Nature, v. 332, p. 494.

Cazenave, A., and W. Llovel (2010) *Contemporary Sea Level Rise*: Annual Reviews of Marine Sciences, v. 2, p. 145-173.

CMCL (2005) *Coastal Hazard Risk Zone Assessment for Ocean Beach*, Hastings District: report by Coastal Management Consultancy Limited.

CMCL (2007) *Revision of the 2005 Ocean Beach Coastal Hazard Zone*, Hastings District: report by Coastal Management Consultancy Limited.

CSL (2008a) *Kāpiti Coast Erosion Hazard Assessment — Part 1: Open Coast*: A report prepared for the Kāpiti Coast District Council, Coastal Systems Ltd., Wanganui, 80 pp.

CSL (2008b) *Kāpiti Coast Erosion Hazard Assessment — Part 2: Inlets*: A report prepared for the Kāpiti Coast District Council, Coastal Systems Ltd., Wanganui, 68 pp.

CSL (2008c) *Kāpiti Coast Erosion Hazard Assessment — Part 3: Data-Base*: A report prepared for the Kāpiti Coast District Council, Coastal Systems Ltd., Wanganui, 166 pp.

CSL (2012) *Kāpiti Coast Erosion Hazard Assessment 2012 Update*: A report prepared for the Kāpiti Coast District Council, Coastal Systems Ltd., Wanganui, 105 pp.

DECCW (2010), *Coastal Risk Management Guide: Incorporating sea level rise benchmarks in coastal risk assessments,* Department of Environment, Conservation and Water NSW Australia.

DOC NZ (2010), *New Zealand Coastal Policy Statement 2010 (NZCPS 2010)*,New Zealand Department of Conservation http://www.doc.govt.nz/publications/conservation/marine-and-coastal/new-zealand-coastal-policy-statement/new-zealand-coastal-policy-statement-2010/

DEFRA UK (2006), , *Flood and Coastal Defence Appraisal Guidance FCDPAG3 Economic Appraisal Supplementary Note to Operating Authorities – Climate Change Impacts October 2006,* UK Department for Environment, Food and Rural Affairs http://archive.defra.gov.uk/environment/flooding/documents/policy/guidance/fcdpag/fcd3climate.pdf

Engineers Australia National Committee on Coastal and Ocean Engineering (2012), *Climate Change adaptation guidelines in coastal management and planning*, Authors: P Cummings (KBR), A Gordon (Coastal Zone Management and Planning), D Lord (Coastal Environment), A Mariani (WRL, UNSW), L Nielsen (WorleyParsons), K Panayotou (GHD), M Rogers (MP Rogers & Assoc.), R Tomlinson (Griffith University); Editors: R Cox (UNSW), D Lord (Coastal Environment), B Miller (WRL, UNSW), P Nielsen (UQ), M Townsend (NCCOE, EA), T Webb (UNSW).

Gibb, J.G. (1976) *Coastal Erosion along Wellington's West Coast*, Soil and Water 13(3): pp6-7.

Gibb, J.G. (1978) *The Problem of Coastal Erosion Along the Golden Coast*, Western Wellington, New Zealand: Water and Soil Technological Publication 10, 20 pp.

Gibb, J.G. (1983) *Combating Coastal Erosion by the Technique of Coastal Hazard Mapping*: New Zealand Engineering, v. 38, n. 1, p. 15-19.

Holman, R.A. (1986) *Extreme Value Statistics for Wave Run-up on a Natural Beach*: Coastal Engineering, v. 9, p. 527-544,

IPCC (2001) *Technical Summary of the Working Group I Report and Summary for Policymakers,* The United Nations Intergovernmental Panel on Climate Change, Cambridge University Press, UK.

IPCC (2007) *Climate Change 2007: The Physical Science Basis; Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, IPCC, Paris, France, 18 pp.

IPCC (2013) *Summary for Policymakers*. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA

Kench, P.S., R.M. Kirk, and M. Single (1999) Assessing and Managing Coastal Hazards: An Integrated Approach. Coastal Consultants NZ Ltd., unpublished report for the Auckland Regional Council, 69 pp.

Komar, P.D. (1998) *Beach Processes and Sedimentation*: Prentice Hall, 544 pp.

Komar, P.D., W.G. McDougal, J.J. Marra and P. Ruggiero (1999) *The Rational Analysis of Setback Distances: Applications to the Oregon Coast*: Shore & Beach, v. 67, n. 1, p. 41-49.

Komar, P.D., J.J. Marra, and J.C. Allan (2002) *Coastal erosion processes and assessments of setback distances: Proceedings, Solutions to Coastal Disasters Conference*, American Society of Civil Engineers., p. 808-822.

Komar, P.D., and J.C. Allan (2007) *A Note on the Depiction and Analysis of Wave-Height Histograms*: Shore & Beach, v. 75, n. 3, p. 1-5.

Komar, P.D., J.C. Allan and P. Ruggiero (2013) *US Pacific Northwest Coastal Hazards: Tectonic and Climate Controls*: Coastal Hazards, edited by C.W. Finkl, Springer, p. 587-674.

Komar, P.D., and E. Harris (2014) *Hawke's Bay, New Zealand: Global Climate Change and Barrier-Beach Responses*: Report to the Hawke's Bay Regional Council.

Laing, A.K., et al. (2000) *Kāpiti Coast Erosion Hazard Investigations: Waves, Tides, Storm Surge and Sea-Level Rise*: NIWA report prepared for J. Lumsden and the Kāpiti Coast District Council, 57 pp.

Lumsden, J.L. (2003) *Strategies for Managing Coastal Erosion on the Kāpiti Coast*: Draft report prepared for the Kāpiti Coast District Council, 2 volumes, 362 pp.

Lumsden, J.L. (2013) *Kāpiti Coast Beach Profiles Monitoring Report*: Report to the Kāpiti Coast District Council, 73 pp.

MetOcean Solutions Ltd. (2007) *Design Wave and Water Levels for the Kāpiti Coast*: Report prepared for Kāpiti District Council, 30 pp.

MetOcean Solutions Ltd. (2010) *Paekākāriki Beach: Summary of Waves, Currents and Water Levels*: Report prepared for the Kāpiti District Council, 23 pp.

Nielsen A.F., Lord D.B. and Poulos H.G. (1992) *Dune stability considerations for building foundations*, Civil Engineering Transactions of the Institution of Engineers Australia, CE34(2) June, 167–74.

Rahmstorf, S. (2007) *A Semi-empirical Approach to Projecting Future Sea Level Rise*: Science, v. 315, p. 368.

Ruggiero, P., P.D. Komar, W.G. McDougal and R.A. Beach (1996) *Extreme water levels, wave runup and coastal erosion*: Proceedings 25th International Coastal Engineering Conference, American Society of Civil Engineers, p. 2793-2805.

Ruggiero, P., P.D. Komar, W.G. McDougal, J.J. Marra, and R.A. Beach (2001) *Wave runup, extreme water levels and the erosion of properties backing beaches*: Journal of Coastal Research, v. 17, no. 2, p. 407-419.

Ruggiero, P., P.D. Komar and J.C. Allan (2010) *Increasing Wave Heights and Extreme-value Projections: the Wave Climate of the US Pacific Northwest*: Coastal Engineering, v. 57, p.539-552.

Shand, R.D. (2005) *Peer Review: Strategies for Managing Coastal Erosion on the Kāpiti Coast*: A report prepared for the Kāpiti Coast District Council, 17 pp.

Stockdon, H.F., R.A. Holman, P.A. Howd, and A.H. Sallenger (2006) *Empirical Parameterization of Setup, Swash, and Run-up*: Coastal Engineering, v. 53, p. 573-588.

Tonkin and Taylor (2005) *Shoreline Modelling Report*: Unpublished report to the Hawke's Bay Regional Council.

Wallace, L. M., and others (2009) *Characterizing the Seismogenic Zone of a Major Plate Boundary Subduction Thrust: Hikurangi Margin, New Zealand*: Geochemistry, Geophysics, Geosystems, v. 10, n. 10, 32pp.

Wallace, L. M., and J. Beavan (2010) *Diverse Slow Slip Behavior at the Hikurangi Subduction Margin, New Zealand*: Journal of Geophysical Research, v. 115, B124012, 20pp.

Wright, L.D., and A.D. Short (1983) *Morphodynamics of Beaches and Surf Zones in Australia*: In Handbook of Coastal Processes and Erosion, P.D. Komar (editor), pp. 35-64, CRC Press, Boca Raton, Florida.

Young, I. R., S. Zieger and A.V. Babanin (2011) *Global Trends in Wind Speed and Wave Height*: Science, v. 332, p. 451- 455.

10. Appendix A: Members of the Panel of Experts

James T. Carley

Principal Coastal Engineer, Water Research Laboratory, UNSW Australia

James Carley has a master of engineering science degree in coastal engineering, and over 22 years' experience, specialised in consultancy and research regarding coastal processes, coastal hazard assessment, sea level rise impacts and coastal structures. He has undertaken coastal projects in all states of Australia, the south Pacific, the middle-east and south-east Asia. He has designed and/or tested coastal structures ranging from single boatsheds to billion dollar infrastructure ports. These projects have included seawalls, breakwaters, boat ramps and surfing reefs, and have included designs from rock, concrete, geotextiles, car tyres and vegetation. His work has been published in technical reports, conference proceedings and journals. James has served on the Institution of Engineers Australia's Maritime/Coastal Panel for over 15 years, including two years as Chair. He has also been a surfer, surf-life saver, and an ocean swimmer for over 30 years.

Robert B. Davies

Director and Associate, Statistics Research Associates Limited, Wellington, NZ.

Dr Davies received an MSc in Mathematics (1964) from the University of Auckland and a PhD in Statistics (1969) from the University of California at Berkeley. He was director of the Applied Mathematics Division of the NZ Department of Scientific and Industrial Research from 1982 to 1990. He has been a director, consultant and researcher with Statistics Research Associates since 1999. His interests are time-series analysis, practical analysis of non-standard situations in statistics, and computing methods for statistics. Recent work has been relating road crash data to road geometry and road surface data.

Paul S. Kench

Professor and Head of School, School of Environment, University of Auckland, NZ.

Dr Kench received his Master degree from the University of Auckland (1990) and PhD in Coastal Processes from the University of New South Wales (1994). He undertakes research and teaching in coastal processes and coastal management. His specialist research interests are on understanding the processes that control the development and change of coasts. He has also investigated the hazards impacting coastal systems including modelling of the effects of sea level change on shoreline stability. He has successfully undertaken projects throughout New Zealand and a number of mid-ocean atoll countries including Kiribati, Tuvalu and the Maldives. He has authored more than 80 scientific publications in his field of expertise. Over the past 18 years Dr Kench has also undertaken a variety of investigations on coastal processes and coastal management issues, and has been contracted to undertake numerous coastal hazard assessments in New Zealand, including the review and redefinition of coastal hazards in Eastern Bay of Plenty. He has also been engaged by a number of international organisations and countries to undertake specific investigations into coastal hazards and coastal management practices including: the World Bank in 1999/2000 to assess the physical impacts of sea-level rise on reef islands as part of the 2000 Cities and Seas project; The UNDP to assess coastal erosion and coastal management frameworks in the Maldives; and, by the World Bank as the Coastal Expert in design of the Kiribati Adaptation Project.

Paul D. Komar

Emeritus Professor of Oceanography, Oregon State University, Corvallis, Oregon, USA.

Dr Komar received Masters Degrees in Mathematics and Geology (1965) from the University of Michigan, and a PhD in Oceanography (1969) from the Scripps Institution of Oceanography, having undertaken thesis research on the processes of sand transport by waves and currents on beaches. He then spent 1970 on a NATO post-doctoral fellowship in the UK, six months at St. Andrews University in Scotland, and six months at the Wallingford Hydraulic Research Station in England where he worked with coastal engineers. The balance of his career has been in Oceanography at Oregon State University, with the focus of his research having been on the processes of erosion along the coast of the U.S. Pacific Northwest, including the impacts of climate change (global warming and the El Niño/La Niña cycles) on sea levels and storm-generated wave heights. In recent years he has been involved in studies of the Hawke's Bay coastal hazards, undertaken for the Regional Council. He is author of the textbook *Beach Processes and Sedimentation* (1976 and 1998 editions, Prentice-Hall).

11. Appendix B: Programme of Expert Panel Review

Monday 2 December 2013: Site visits and inspections by Panel
Tuesday 3 December 2013: Submissions by stakeholders to Panel
Wednesday 4 December 2013: Submissions by experts to Panel
Thursday 5 December 2013: Round table discussion between experts and Panel
Friday 6 December 2013: Internal discussions by Panel

12. Appendix C: Experts who Presented to the Panel

Mr John Harding
Mr Angus Gordon
Mr Simon Arnold
Mr Bryce Wilkinson
Dr Jeff Ashby
Dr Willem de Lange
Mr Warren Dickson
Dr Peter King
Dr Philip Tortell
Mr Jim Dahm
Dr Roger Shand
Mr Mike Jacobson

13. Appendix D: Individuals and Organisations that Provided Written Comments on the Panel's Draft Report

Joan Allin
Simon Arnold
Jeff Ashby
Rob Buckett
Coastal Ratepayers United
Willem de Lange on behalf of Coastal Ratepayers United
Don Frampton
Angus Gordon on behalf of Kotuku Park Ltd
Dick Jessup
Ian Kennedy
John Maassen on behalf of North Otaki Beach Residents Group (NOBRG)
Bryce Moller
Larry Paul
Quentin Poole
Richard Reinen-Hamill (Tonkin and Taylor) on behalf of Department of Conservation
Christopher Ruthe
Roger Shand - Coastal Systems Ltd
Jonathan Streat on behalf of Greater Wellington Regional Council
Philip Tortell
Mike Weir
Bryce Wilkinson