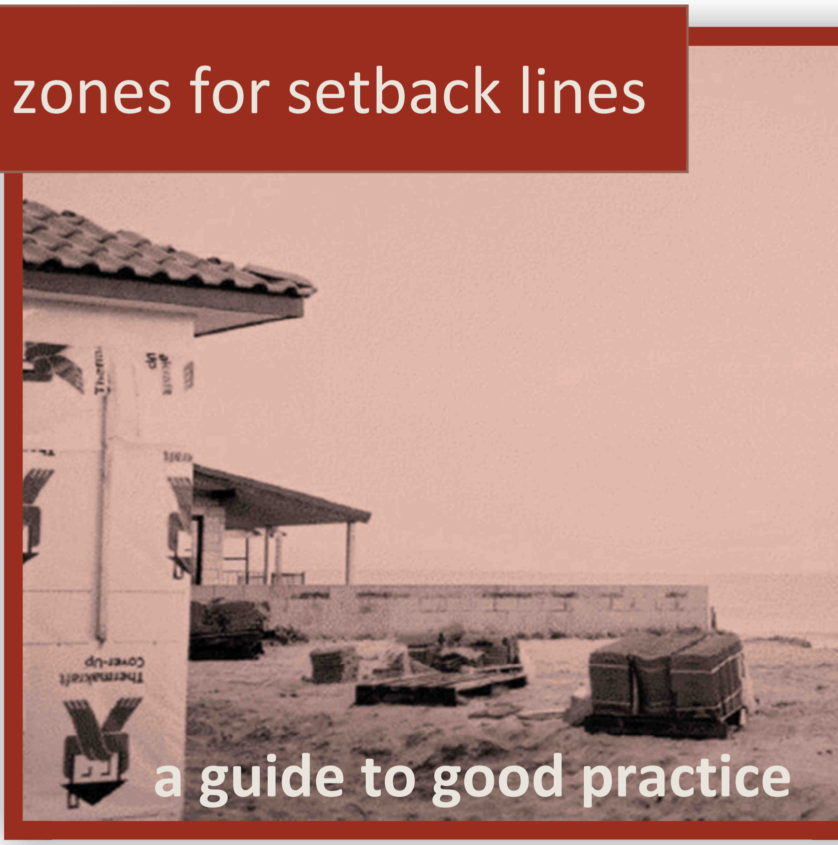
Defining coastal hazard zones for setback lines



envirolink

Defining coastal hazard zones for setback lines

A guide to good practice

Doug Ramsay, NIWA

Bronwen Gibberd, 4D Environmental Ltd

Jin Dahm, Eco Nomos Ltd

Rob Bell, NIWA

About this guide

The guide was funded by the Envirolink Tools programme through the Ministry of Science and Innovation (now part of the Ministry of Business Innovation and Employment).

Acknowledgements

Advice and assistance with the preparation of this guide was provided by wide range of individuals including from Regional Councils (Northland, Auckland, Waikato, Bay of Plenty, Hawkes Bay, Wellington, Canterbury, Otago, West Coast and Southland), District Councils and Unitary Authorities (Gisborne, Tasman, Whakatane, Western Bay of Plenty, Tauranga City, Thames Coromandel, Kapiti Coast and Dunedin City), academics (Universities of Auckland, Waikato and Canterbury), and practitioners (Coastal Management Consultancy Ltd, Tonkin and Taylor, Coastal Systems Ltd and DTEC). The advice and assistance provided is gratefully acknowledged.

The resulting text does not necessarily represent the views of any of the organisations or the individuals consulted.

Copyright

Citation

Ramsay, D.L., Gibberd, B., Dahm, J., Bell, R.G. (2012) Defining coastal hazard zones and setback lines. A guide to good practice. National Institute of Water & Atmospheric Research Ltd, Hamilton, New Zealand.

Cover photograph: R Bell, NIWA

Contents

Executive Summary

This best-practice guide has been developed to assist Local Authorities make sustainably-based decisions for the avoidance or mitigation of coastal hazard risks within their coastal land-use planning and development decision-making.

The guide focusses on approaches to defining present and future coastal hazard exposure as an input to development setbacks to manage risk from coastal-related hazards and the effects of climate change.

The guide has been written to aid technical staff from Regional or Unitary Councils, coastal Territorial Authorities, and coastal hazard practitioners. It is designed to complement the Ministry for the Environment guidance manual *Coastal hazards and climate change: A guidance manual for local government* (Ministry for the Environment, 2008) in encouraging a risk management approach by Local Authorities in ensuring that coastal hazards, and the impacts of climate change on these coastal hazards, are appropriately taken in to account in policy, planning and resource consent decision-making.

The basic rationale applied within this guide is that **Coastal hazard zones** should more effectively encapsulate and present the inherent uncertainties to better inform **development setback lines** based on acceptable and appropriate levels of **risk**.

The guide promotes a framework to enable increased robustness and accounting of uncertainties within coastal hazard assessments and associated development setbacks. Whilst the guide is not designed to be prescriptive on the methods used to define areas of coastal margins at risk from coastal hazards, it aims to build on the current deterministic approaches commonly used in New Zealand and the expertise and experience held by practitioners, to determine future coastal change, but to better characterise uncertainty by applying it within a pragmatic probabilistic way. This would improve the baseline information for incorporation of risk-based considerations within coastal land-use planning and development decision-making.

1 Introduction

"Coastal processes are a critical part of the natural character of the dynamic coastal environment. As with any system, the coastal environment oscillates through a range of conditions, and occasionally experiences extremes. These fluctuations and extremes help develop the characteristics of the system, and are a natural part of them.

Natural hazards arise from the interaction of such processes with human use, property, or infrastructure. Left to its own devices, there is nothing inherently 'hazardous' about the coast. The risk imposed by hazards is the result of this nature/human interaction, and the effect of these dynamic and variable processes on the rather less dynamic and more static human resources of the coast."

Auckland Regional Council (2000)

1.1 Purpose of this guide

This best-practice guide has been developed to assist Local Authorities make sustainably-based decisions for the avoidance or mitigation of coastal hazard risks within their coastal land-use planning and development decision-making. It has been developed to help achieve the purposes of the RMA (1991) and Objective 5 and Policies 24-27 of the New Zealand Coastal Policy Statement 2010. The guide has been written to sit alongside and support the Ministry for the Environment guidance manual *Coastal hazards and climate change: A guidance manual for local government* (Ministry for the Environment, 2008). It also dovetails with the *Pathways to Change* guidance (Britton et al., 2012) in relation to developing and implementing strategic plans for coastal adaptation to climate change.

It aims to provide concise guidance to enable:

- A consistent and transparent framework for defining present and future coastal hazard exposure as an input to development setbacks to manage risk from coastal-related hazards and the effects of climate change.
- Increased robustness and accounting of uncertainties within coastal hazard assessments.
- Improved baseline information for incorporation of risk-based considerations within coastal land-use planning and development decision-making.
- Achievement of the purposes of the RMA (1991) and Objective 5 and Policies 24-27 of the New Zealand Coastal Policy Statement 2010.
- Appropriately defined requirements for consultants or resource-consent applicants conducting coastal hazard and risk analysis associated with coastal development.

1.2 Who this guide is for

This guide has been written for:

- Technical staff from Regional or Unitary Councils and coastal Territorial Authorities who are involved in:
    - Defining and quantifying coastal erosion and inundation hazards within their regions.
    - Specifying term of references for external consultants assisting Local Authorities to define and quantify such coastal hazards.
    - Reviewing resource consent applications for development within coastal margins.
    - Advising their planning and policy colleagues on incorporating coastal hazards to achieve more effective land-use planning and policy and inform civil defence emergency management group plans.
- Consultants who provide coastal hazard-related services for Local Authorities and for resource consent applicants.

1.3 Need for this guide

Existing methodologies to define coastal hazards typically used within New Zealand are relatively simplistic, somewhat subjective and are often re-litigated in the Environment Court – often with several experts using similar approaches and reaching quite different conclusions. There is also a lack of transparency and consistency in the application of some methodologies, how uncertainties are dealt with, and, on occasions, an over-reliance on the use of un-calibrated empirical or numerical approaches.

In some coastal environments, such as harbour and estuary margins where a significant amount of development has occurred, or is likely to occur, suitable methodologies for predicting coastal change are limited, or other approaches developed for specific conditions have been applied out of context.

Whilst hazard identification is often required to be expressed in probabilistic terms (e.g. 1% Annual Exceedence Probability) application of probabilistic methods to derive such results from available data is often not appropriate or robust. This can result in actual hazard levels being poorly or inaccurately specified which can in turn severely complicate effective and appropriate management of the risk. Furthermore the treatment of uncertainty, which is inherent when the future is being considered in coastal hazard analysis, is typically simplistic, not robust, and seldom encapsulates or communicates the characteristics of such uncertainty satisfactorily.

During consultations associated with the revision of the Ministry for the Environment guidance manual *Coastal hazards and climate change: A guidance manual for local government* (Ministry for the Environment, 2008), the need for improved technical guidance on defining coastal hazard zones was highlighted. The need was further refined during the consultations with Local Authority staff, a number of practitioners and academics involved with coastal hazard-related assessments for regional and district planning purposes. This included the need to:

- Reduce the potential for major litigation over the use of coastal hazard exposure information in defining development setbacks which often results in a lengthy and expensive process and does not necessarily result in good land-planning or sustainable outcomes.
- Improve collaboration and communication between technical experts and planners to enable:

- Development of appropriate development setbacks that are increasingly based on the need to avoid or reduce risk, and acceptance of the uncertainties.
- Development setbacks that can be translated in to planning rules and management actions in a pragmatic and effective way.

- Guide the use of appropriate methodologies in different contexts and coastal/estuarine environments.
- Incorporate increased robustness in probabilistic assessments and in the treatment and communication of uncertainty.
- Provide consistency and transparency in the application of methodology. Whilst consistency of methods would be ideal, the level of information available and the physical environment does not always make this practical or possible.

1.4 Guide structure

The guide is designed to support the Ministry for the Environment guidance manual *Coastal hazards and climate change: A guidance manual for local government* (Ministry for the Environment, 2008) in encouraging a risk management approach by Local Authorities in ensuring that coastal hazards, and the impacts of climate change on these coastal hazards, are appropriately taken in to account in policy, planning and resource consent decision-making. It also aims to compliment the *Pathways to Change* guidance (Britton et al., 2012) in relation to developing and implementing strategic plans for coastal adaptation to climate change.

This guide is not designed to be prescriptive on the methods used to define areas of coastal margins at risk from coastal hazards. It is appreciated that there are a wide range of techniques and methods available for use by practitioners. Rather it aims to build on current approaches and provide a generic framework of good practice within which a variety of approaches can be applied or appraised to address some of the issues identified above.

Following this introductory section, the guide is structured as follows:

- **Section 2** provides an overview of coastal hazard and setback zones in the New Zealand context, along with a summary of the framework for carrying out coastal hazard assessments and a checklist of good practice.
- **Section 3** provides guidance around approaches used in identifying and defining coastal erosion hazard zones.
- **Section 4** provides guidance around approaches used in identifying and defining coastal inundation hazard zones. This focuses primarily on storm-related inundation. For approaches to define tsunami hazard areas and integration into land use planning, see (Saunders et al., 2011).
- **Section 5:** provides links to various technical resources and supporting information.

Appendix 1 summarises the relevant provisions in the New Zealand Coastal Policy Statement, with Appendix 2 containing background information on Average Recurrence Intervals and Annual Exceedence Probabilities.

2 A basic framework

2.1 Coastal hazards and coastal hazard risk

2.1.1 Introduction

Coastal hazards, such as erosion and storm-related inundation of low-lying coastal margins are natural processes. They become a risk or a problem when they pose, or are perceived to pose, a threat to things that humans value. Around the New Zealand coast, as in many other coastal margins around the world, there has been rapid growth over the last five or six decades in coastal-related development, particularly in areas backing sandy beaches.

Within New Zealand much of the increase in coastal hazard risk particularly that associated with coastal erosion and inundation is due to:

- Subdivision, development and infrastructure located too close to the shoreline to accommodate the full range of natural changes that occur over the lifetime of the development.
- Human alteration of, or interference, in natural coastal dynamics and function of beach systems.
- Past development of low-lying coastal swamps and coastal-wet plains, that are naturally prone to inundation.

This level of risk is being exacerbated over time as coastal development intensifies (Blackett and Hume, 2006).

Taking a precautionary approach to planning new development, infrastructure and services to avoid coastal hazards over their intended lifetime is the most effective and sustainable long-term approach (MfE, 2008). This approach is relevant to all coastal development situations, from completely undeveloped coastal margins to high-density urban areas.

A common approach where existing or proposed development is exposed to coastal hazards, is to apply information on potential coastal erosion in the form of coastal setbacks through a range of rules in planning documents, and, for inundation, specifying minimum floor and ground levels in land-development or engineering quality standards. In heavily developed areas, coastal hazard maps may be used simply for public education and awareness purposes, or to inform evacuation for storm-tide or tsunami warnings.

This guide focusses on approaches to defining coastal hazard zones as input to the provision of risk-based development setbacks. Other approaches for managing coastal hazards are outlined in the Ministry for Environment *Coastal Hazards and Climate Change A guide for Local Government* (MfE, 2008).

2.1.2 Consistency in terminology

In this guide, the following terminology is adopted:

- **Coastal hazard zones** are used to describe the present and potential future coastal hazard for a particular area. They are developed from a technical assessment conducted by a coastal hazard specialist. Depending on the level of assessment they can be used in some areas to act as an overarching trigger to require further coastal hazard investigation to be undertaken prior to any development, or if a more detailed quantitative assessment they can inform coastal development setbacks. A coastal hazard assessment cannot say precisely what will happen in the future but rather highlight areas potentially threatened by coastal hazards.
- **Coastal development setbacks** are planning tools to exclude or restrict beachfront development and land use within areas potential threatened by coastal hazards or to inform trigger points for the relocation of buildings. Rules most typically extend to control subdivision, earthworks and the construction of dwellings. In some cases, coastal development setbacks are applied as strict building exclusion zones, while in other cases, they limit the nature of building allowed or place caveats on new dwellings to acknowledge the risk.

A coastal development setback must therefore act to implement current coastal hazard knowledge, projections (and uncertainties) of future change, in a way that reflects the nature of the local environment, the current human uses, and the management and community aspirations for the area.

Coastal development setbacks can be based not only hazard information, but represent decisions on the management of different hazard types, the level of accepted residual risk (and therefore uncertainty) and the timeframes for planning implementation. Setbacks can also be defined by integrating with other coastal margin considerations, such as ecosystem, cultural and landscape values and public access.

When applied in the form of a development setback, information gathered in a coastal hazard study can have significant impacts on the use of often high value private land. Broadly held societal views place private property rights in high regard, and as such any restriction imposed tends to meet strong resistance.

The 2010 New Zealand Coastal Policy Statement (NZCPS) promotes a precautionary approach to planning new development, infrastructure and services to avoid coastal-hazard risks over the intended lifetime of the development. Identifying areas potentially threatened by coastal hazards to inform coastal development setbacks is a fundamental approach to effective and sustainable coastal hazard management, and contributes to all four key principles advocated within NZCPS and the Ministry for the Environment *Coastal hazards and climate change: A guidance manual for local government.*

Box 1 Key principles to be incorporated in to all aspects of Local Authority decision-making within coastal margins (Ministry for the Environment, 2008).

- **Precautionary approach:** A precautionary approach is adopted when making planning decisions relating to new development, and to changes to existing development within coastal margins. Decision-making takes account of the level of risk, utilises existing scientific knowledge and accounts for scientific uncertainties.
- **Progressive risk reduction:** New development is not exposed to, and does not increase the levels of, coastal hazard risks over their intended serviceable lifetime. Progressively, the levels of risk to existing development are reduced over time.
- **Coastal margin importance:** The dual role of natural coastal margins as *the* fundamental form of coastal defence and as an environmental, social and cultural resource is recognised in the decision-making processes and, consequently, natural coastal margins are secured and promoted.
- **Integrated, sustainable approach:** An integrated and sustainable approach to the management of development and coastal hazard risk is adopted, which contributes to the cultural, social and economic well-being of people and communities.

2.2 The importance of the journey

The process of defining coastal hazard zones and associated development setbacks is often complex, expensive, time consuming and iterative. There are a number of phases to any setback project, including scoping, design, calculation, review, mapping, community consultation, feedback, re-evaluation and implementation. Many coastal hazard setback projects receive the greatest resistance and are most prone to failure at the final stages of implementation. However, the resulting arguments typically centre on the early stages of the project, particularly the design. As outlined in the previous section, a common theme that came through in the consultations was that communication and cooperation between technical and planning staff was a major problem affecting effective setback design and application.

More effort at the outset to improved planning through careful forethought and clear communication in both the scoping stages, and throughout the project can greatly improve the likelihood of an efficient and effective process, Table 1.

2.2.1 Collaboration between technical and planning staff

Implementation of coastal hazard information into pragmatic and effective land use planning and policy requires effective communication and collaboration between technical (both council technical staff and any coastal hazard expert) and planning staff throughout the entire process:

- Technical practitioners must consider and communicate what can be realistically be achieved given the available data, information and financial resources. Where information is very limited, it can be impossible for any practitioner to quantify hazards into the future without significant uncertainties. These uncertainties need to be clearly communicated in a language suitable for a non-technical audience.

- Planner practitioners need to understand the limitations and uncertainties associated with predicting coastal hazards, its impact on a setback study, and how it may impact on the extent of planning control that can reasonably by enforced (and upheld in court if necessary).

Table 1 Key considerations in scoping a coastal hazard assessment (Adapted from Southgate and Brampton, 2001).

Consideration	Involvement
• Decide on the length of coast and period over which predictions are required, with a minimum of "at least 100 years" (NZCPS).	• Local Authority technical and planning staff, • Coastal hazard expert (possibly)
• Establish what data and information is available, what data gaps and further information required for the assessment.	• Local Authority technical and planning staff, • Coastal hazard expert
• Establish what types of results are required, what they are to be used for including identifying any potential limitations, and develop consensus on what outputs can be provided.	• Local Authority technical and planning staff, • Coastal hazard expert
• Decide on what processes are important in altering morphology or causing inundation within the section(s) of coast under consideration.	• Coastal hazard expert. • Potential input from Local Authority technical staff and local residents
• Decide on appropriate methodology, tools, climate change projections, range of uncertainties, and associated validation process.	• Coastal hazard expert • Local Authority technical staff
• Establish which aspects of the coastal system, management scenarios or sensitivities to coastal change drivers the tools need to test.	• Coastal hazard expert, • Local Authority technical staff
• Decide on how to interpret, synthesise and present the results.	• Local Authority technical and planning staff, • Coastal hazard expert • Local community (possibly)

The current level of development is an important consideration at this planning stage, and in turn the likely impact of the planned coastal setbacks on private use of land. Where this impact will be significant, the methodology behind coastal hazard setbacks needs to be very robust and the uncertainty reduced as far as possible. There is little value in a low budget, broad-scale study of coastal hazards if the resulting setbacks are to be used to apply severe restrictions to the use of existing sections.

2.2.2 Collaboration with local communities

Involving the community at a very early stage, and then throughout, a coastal hazard setback project is often of critical importance in the ease of acceptance by the community. This needs to include the wider community and what they value, not just the front row beach property owners.

The community will be more readily accepting of a setback where they have been informed and involved in the process from its earliest stages and invited to comment or contribute. Without such engagement with communities and other decision-makers, local authorities will tend to struggle in overcoming the many barriers and vested interests that can prevent successful coastal hazard risk reduction and adaptation (Rouse et al., 2011; Rouse & Blackett, 2011).

Furthermore, in many cases, long-term residents will hold valuable information about coastal processes and the history of hazards and human impacts in the local area. Integrating this local knowledge, and through open discussions with communities about the reasons for hazard setbacks and the methods used, there is less chance of major resistance at later stages of the process.

2.3 The process of defining development setbacks to incorporate coastal hazards

Defining coastal hazard zones that are applicable for at least 100 years is not an exact science. Nor can the methodologies used, and expertise available, predict exactly what will happen in the future. Even with very good information there is always a level of uncertainty in the final coastal hazard prediction. The magnitude of this uncertainty increases with the planning timeframe, and even more so given the influence of future climate change and sea-level rise.

The treatment of uncertainty in defining coastal hazard zones, and resulting setbacks is often a major source of difference between the results of different practitioners at the same location. The framework outlined in Figure 1 below, and discussed more fully in the following sections, aims to provide a process for a more consistent and transparent treatment of uncertainty and how it is communicated and incorporated within risk-based coastal land-use planning and development decision-making.

Box 2 Coastal hazard zones and setbacks

A **coastal hazard zone** does not constitute a "magical" safety zone immediately on one side of it, and a zone of "total hazard" or impending destruction on the other (Healy & Dean, 2000, Healy, 1993). Coastal erosion hazard is gradually reduced with distance from the coastline.

A **coastal hazard setback** therefore represents a chosen level of protection for a chosen planning period. Healy (1993) describes a coastal hazard setback as "*a line on the ground beyond which, on the balance of evidence, and in the light of scientific knowledge of the moment, it would be prudent to restrict (not necessarily completely avoid) development*".

Whilst land use planners and the public desire "certainty", it is impossible to put a line on a map to indicate that at some time in the future the landward side of the line is "safe" and the other seaward side "hazardous". Coastal erosion risk is gradually reduced with distance from the coastline (Healy, 1993).

The basic rationale applied within this guide is that:

1. **Coastal hazard zones** should more effectively encapsulate and present the inherent uncertainties,
2. to better inform **development setback lines** based on acceptable and appropriate levels of **risk**.

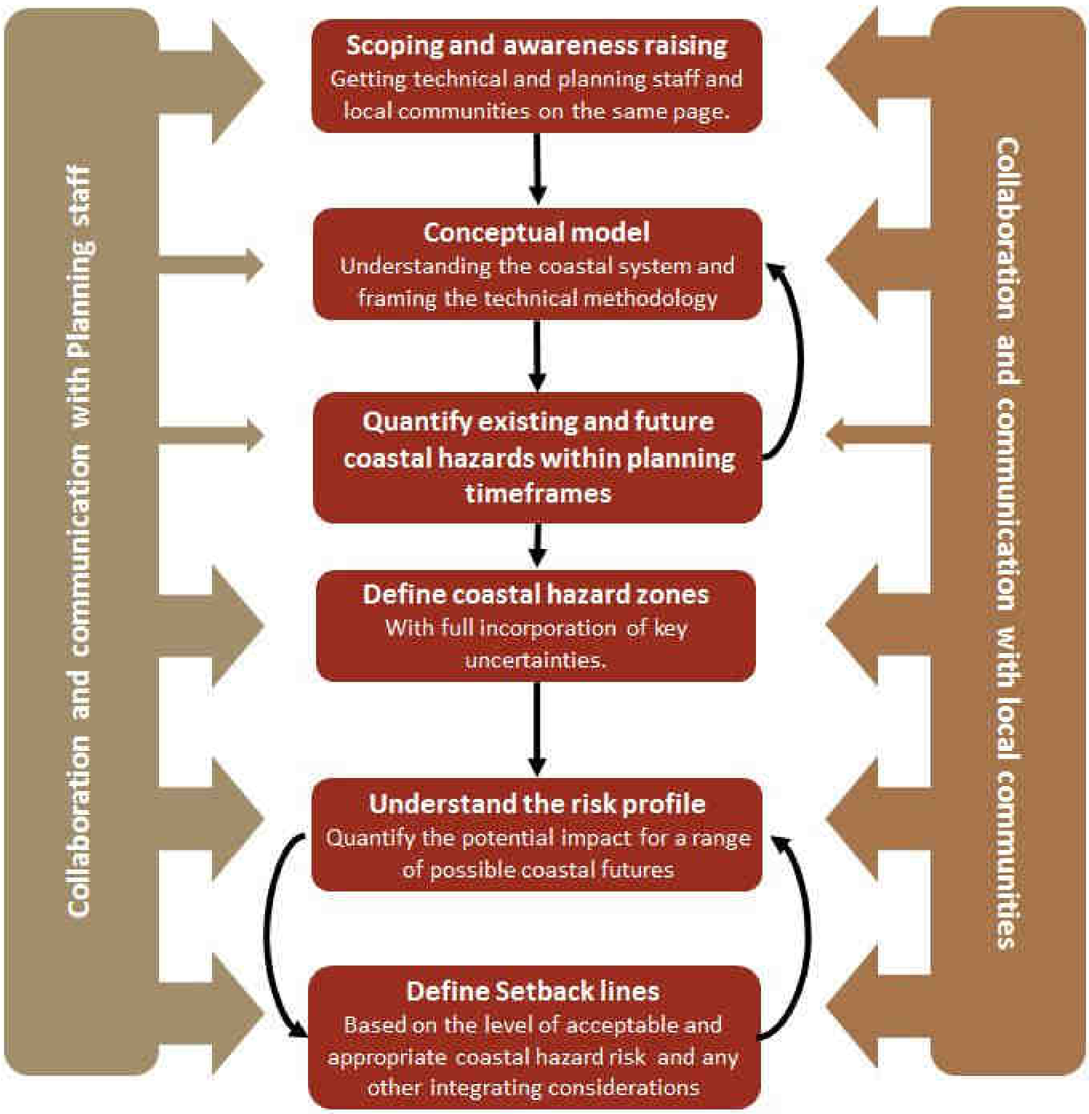


Figure 1: A basic framework for incorporating coastal hazard risk and associated uncertainties within development setbacks.

2.3.1 Monitoring and review

Coastal systems are complex and changeable, and projections of future change are commonly based on limited information. Ongoing monitoring of both coastal hazard events/shoreline change and of the performance of the hazard setback provides further information to refine and inform coastal setbacks. It is important that coastal hazard zones and the any resulting setbacks are periodically assessed and reviewed in response to coastal hazard events, ongoing development and new scientific information (e.g., new sea-level rise projections). These revisions are particularly important if major ongoing trends have been identified and implemented as part of these setbacks.

2.4 Key checklist for coastal hazard assessments

The following provides a checklist of good practice for coastal hazard assessments.

Box 3	Key checklist for coastal hazard assessments
1.	Key technical, planning and where relevant community stakeholders, have been involved in scoping the aims, objectives and intended outputs of the coastal hazard assessment, and at relevant times during the process of identifying coastal hazard zones.
2.	Available data for use in the assessment is identified at scoping stage, is adequate and appropriate for the intended application of the coastal hazard assessment, and any limitations identified.
3.	A conceptual model of the drivers, sources and pathways of coastal hazard and shoreline change processes is developed and used to aid scoping, facilitating communication and identifying knowledge gaps.
4.	Where numerical modelling approaches are to be utilized their use, within the context of the conceptual model is clearly defined; any limitations, range of validity, uncertainties and assumptions are specified; and as far as is possible the models are calibrated and verified.
5.	Uncertainty within each parameter or variable where it exists is captured and communicated and the impact on the final coastal change / inundation result clearly understood.
6.	A range of sea-level rise scenarios are assessed for the future timeframe under consideration and the sensitivity of the resulting coastal change / inundation ascertained.
7.	Estimates and projections of coastal hazards are referenced to a clearly defined vertical or baseline datum.
8.	Uncertainty is fully encapsulated within a derived coastal hazard zone and is clearly presented, in a non-technical manner.
9.	Mapping and presentation of results is produced at a scale appropriate for the level of approach adopted, the underpinning data and tools utilized, and the resulting application of the coastal hazard information.

3 Defining coastal inundation zones

3.1 Introduction

3.1.1 Purpose and overview

In the context of this guide, the fundamental purpose of a coastal inundation hazard study is to quantify the likelihood of occurrence (usually expressed in probabilistic terms) of extreme sea-levels at the shoreline and the resulting spatial extent and levels of sea water inundating low-lying coastal margins.

This section focuses primarily on storm-related coastal inundation. An outline of the section is shown in Figure 2.

The range of methods used to define tsunami-related inundation of coastal margins for land use planning decision-making are detailed in a recent publication *New Zealand's next top model: Integrating tsunami inundation modelling into land use planning* (Saunders et al., 2011). However, general information on broad scale tsunami hazard is summarised within this report for background purposes.

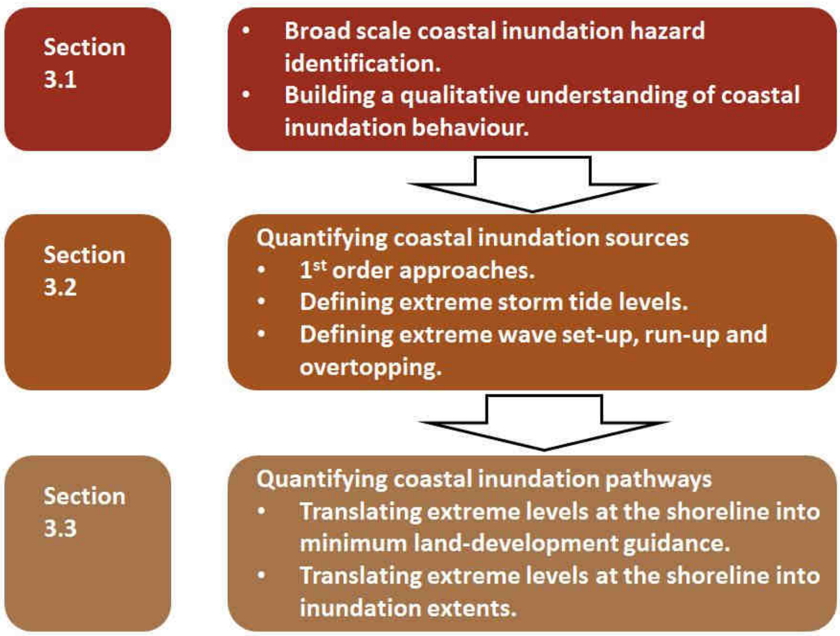


Figure 2 **Section overview**

Box 4 Annual exceedence probabilities and average recurrence intervals.

Large, rare episodic hazard events such as severe storms and tsunami have a low likelihood of occurrence, whereas frequently occurring events have a high likelihood of occurrence in any one year.

Extreme value analysis relates event magnitude to its likelihood of occurrence in a statistically robust way. Likelihood of occurrence tends to be expressed in terms of Annual Exceedence Probability (AEP) or Average Recurrence Interval (ARI).

'AEP' refers to the chance of a particular threshold (e.g., storm-tide level) being equalled or exceeded in any one year. It is defined either as a number between 0 and 1 or as a corresponding percentage. Common AEPs used in hazard assessment include 0.01 (or 1% AEP), which means that there is a 1% chance of an event of a given size or larger occurring this year, or any year. An AEP of 0.02 (or 2% AEP) means that there is a 2% chance of an event of a given size or larger occurring this year, or any year.

In general for annual exceedence probabilities of less than 0.1, the average recurrence interval for an event is approximately the reciprocal of the AEP. Hence an AEP of 0.1 (or 10%) would have an ARI of 10 years; and an AEP of 0.01 (or 1%) an ARI of 100 years.

The use of AEP to define the likelihood of hazard events is preferable to the use of return period terminology, which is often misused or misunderstood. It can lead to a false sense of security for non-technical people if there is not an equivalent statement qualifying the likelihood of a particular event occurring or being exceeded during a particular timeframe.

As a rule of thumb, there is approximately a 63% chance of an event with an AEP of 2% occurring in a 50-year timeframe, or a 1% AEP event occurring within a 100-year timeframe.

Further information on AEP's and ARI's is contained in Appendix 2.

3.1.2 Broad-scale coastal inundation hazard identification

A broad scale assessment of coastal inundation potential can provide useful guidance for coastal management where such information is lacking. Such assessments do not provide sufficient detail for land-use planning decisions but they can provide a "first stage" or "red flag" to guide further more detailed hazard assessments at priority locations.

A broad indication of areas where inundation may be an issue at a national scale, based on low-lying coastal margins are shown in the Figure 3 (left). Figure 3 (right) shows sections of the open coastline that are sensitive (relatively) to coastal inundation based on the national geomorphological classification.

At a national level relative tsunami hazard was summarised in the *Review of Tsunami Hazard and Risk in New Zealand* (Berryman, 2005). Average recurrence interval tsunami wave heights for 100 and 500 years are shown in Figure 4.

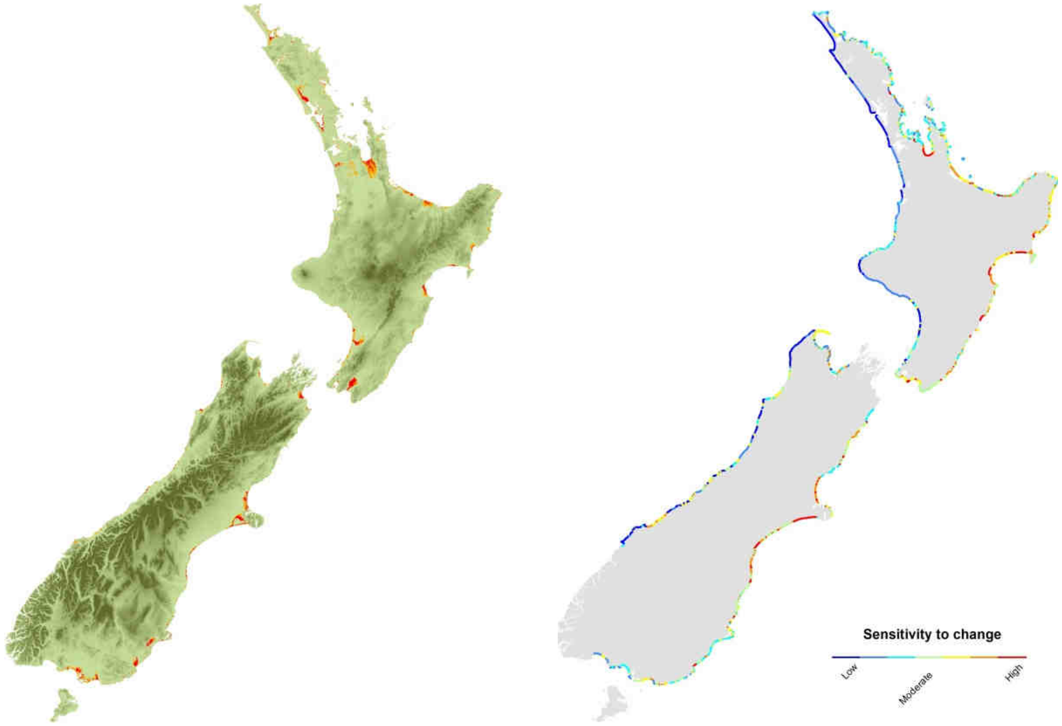


Figure 3: **Indicative areas that may be vulnerable to coastal inundation or drainage related problems due to storm events and sea-level rise (left) from MfE (2008). Draft open coast areas sensitive to coastal inundation based on a national geomorphological classification (right), (http://wrenz.niwa.co.nz/webmodel/coastal).**

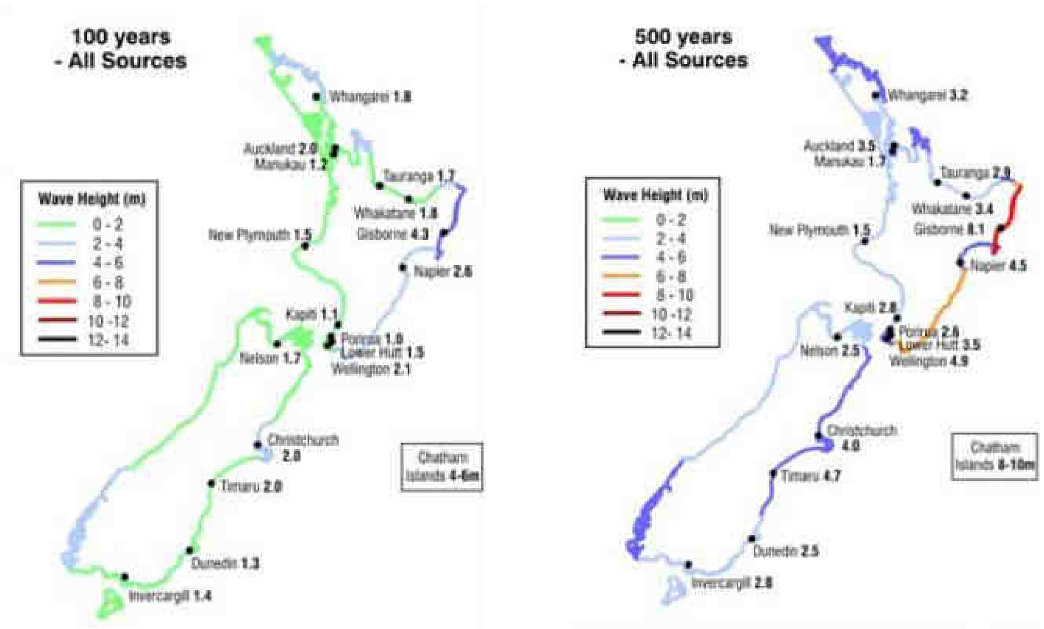


Figure 4 **Generalised estimate of tsunami hazard in New Zealand expressed as expected mean wave height above mean sea level at the shore for 100 and 500 year Average Recurrence Intervals. Significantly higher or lower water elevations may occur locally. These maps should not be used for site-specific assessments (Berryman, 2006).**

Typical data requirements:	•	Generally based on readily available historical and environmental information. A wide range of qualitative information can be useful including historic photographs and maps, previous reports, information from past storm events (e.g. newspaper records or the Historic Weather Events catalogue – www.hwe.niwa.co.nz), and anecdotal information from long-term residents.
	•	Field observations are useful to complement other forms of information.
Limitations:	•	Typically requires more detailed assessments to support land-use planning decision-making.
Application:	•	Identification of indicative locations or areas of coastline susceptible or potential susceptible to coastal inundation.
	•	Informing and raising public awareness of coastal hazard issues.

3.1.3 Building a qualitative understanding of coastal inundation behavior

Assessment of coastal inundation hazard due to coastal storm events (i.e., not including tsunami and river floods) needs to give consideration of (MfE, 2008):

- The interactions between the various coastal hazard drivers that can combine to produce inundation, the effects of climate change on these drivers, and how they influence inundation.
- The dynamic nature of inundation over land, particularly the mechanism of how seawater inundates a certain area (flood pathways) and the storage potential of a flood area relative to the volume of inundating water flowing in to the area, and drainage capacity of the area.
- The uncertainties associated with the assessment methods, data and information used.

The development of conceptual behavioral models for a section of coast (often referred to as coastal behavioral units, compartments or cells) helps frame the understanding of the natural functioning of the coastal system as well as the pattern of human use and development and its influences on that system. Conceptual models are concise and ideally visually-stimulating illustrations that use symbols or drawings to depict the important features, processes and management challenges within a section of coast that "behaves" in a generally similar way (OzCoast, 2012).

The Source-Pathway-Receptor-Consequence (SPRC) framework is one convenient way to consider the key drivers (and driver interactions), processes and controls on coastal inundation (both tsunami and storm-related) and how they impact on the range of the human and built environments within particular coastal margins (MfE, 2008). Example sources, pathways and receptors for coastal and tsunami inundation are shown in Table 2.

Box 5	Use and application of conceptual models

Conceptual models are useful because they (adapted from OZCoast, 2012):

- Facilitate communication. Conceptual models are a tool through which detailed technical concepts can be summarised in a non-technical way, and presented to end users such as environmental managers and other coastal zone stakeholders.
- Integrate knowledge across disciplines. Conceptual models provide a physical background upon which the understanding derived from various scientific disciplines can be integrated with the perspectives of other stakeholder groups for addressing management issues.
- Increase understanding. Conceptual models help users to understand the often complex processes in a system (e.g. how things work, what drives these things and major impacts) and demonstrate the links between them.
- Identify knowledge gaps. Conceptual models can help users to identify any gaps in scientific understanding, monitoring or management plans.
- Help with decision making and planning. Conceptual models can assist planners and stakeholders to better incorporate key coastal hazard considerations within land-use planning and other risk reduction approaches.
- Facilitate participation. Conceptual models can facilitate participation of local community stakeholders, and assist with interaction between different stakeholders and Local Authorities.

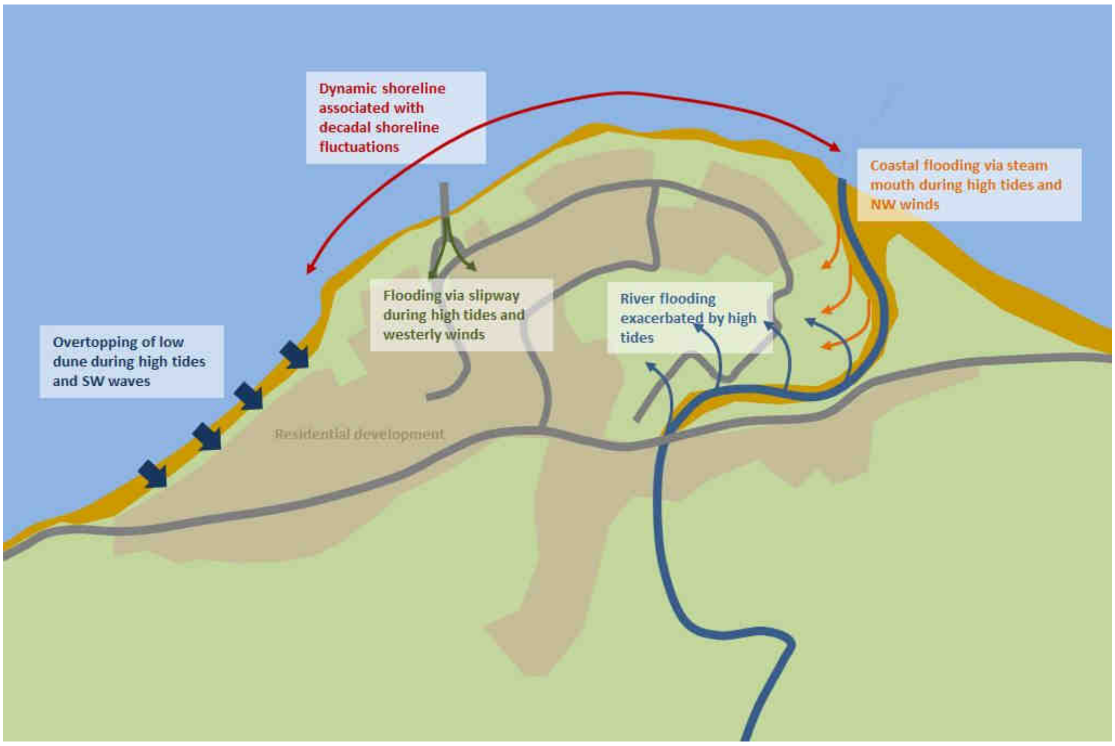


Figure 5 **Example of a basic conceptual model of coastal hazards on a small developed delta.**

Table 2 Example sources, pathways and receptors for coastal and tsunami inundation (MfE, 2008)

Hazard	Sources	Pathways	Receptors
Coastal inundation	• Spring high tides • Mean sea level fluctuations • Long-wave surging • Storm surge • Waves • River and urban drainage flows • Rainfall • Sea-level rise	• Direct inundation of low-lying coastal margins • Overtopping of dunes, coastal barrier or coastal defences • Breaching or overwashing of dunes, gravel barrier or coastal defences • Via beach access points and boat ramps • Inundation via estuary margins, river and stream mouths • Backed up stormwater systems	• People • Residential property • Commercial property • Essential services • Infrastructure • Cultural assets • Ecosystems • Landscape and natural character values
Tsunami	• Local source • Regional source • Distant source		

In terms of the sources or drivers, coastal inundation is rarely caused by one factor alone, it is normally due to some combination of tide level, storm surge and wave conditions (and in certain cases exacerbated by river or land drainage contributions or coastal erosion). These factors are typically correlated in some way but very rarely does an extreme high tide level coincide with both high storm surge and high wave conditions. Having an appreciation or understanding how these different drivers can combine in a statistical sense is important in assessing coastal inundation.

Box 6 Storm tide, wave set-up and wave run-up

In the context of this guide (MfE, 2008):

- Storm tide is the term used to describe the temporary rise in level of the sea offshore of the wave breaker zone. Storm tide is the combination of three components (mean level of the sea (which includes the effects of seasonal to long-period climate-related sea-level fluctuations and sea-level rise), the predicted tide at the time of the event, and the storm surge height).
- At the shoreline, the maximum vertical elevation reached by the sea is a combination of the wave set-up that is induced landward of the wave breaking zone and wave run-up (or swash). These act on top of the storm-tide level. Wave run-up is highly variable even over a short length of coast, varying according to the type of beach, the beach slope, the backshore features and presence of any coastal defence structure.

The extent and magnitude of inundation also depends on how the high storm tide and wave conditions (or tsunami wave) can inundate an area (the pathways available). This depends on the physical characteristics and topography of the upper parts of the beach or estuarine shoreline and immediate coastal hinterland. Typical flow pathways include:

- Direct inundation, where the storm-tide or wave set-up level exceeds the level of the land. This typically occurs where waves have not built up a coastal barrier, such as along estuarine and sheltered coastlines or along the margins of rivers, estuaries and streams or severely eroded coasts.
- Inundation due to the breaching of a barrier. This may be related to the breaching of a natural barrier such as a gravel ridge or narrow dune field (with low-lying land behind it) or a human-made defence such as a stopbank. Existing breaches that form public access-ways to beaches or boat ramps are also potential pathways.
- Overtopping of a barrier. Again this may be either a natural barrier such as a gravel ridge or narrow dune field or a human-made defence such as a stopbank. Overtopping typically occurs due to wave or swell conditions during a high tide or storm tide on more exposed open sections of coast

3.2 Quantifying coastal inundation sources

3.2.1 First order approaches to quantifying extreme storm tide, wave set-up or run-up levels

A commonly applied approach in New Zealand to establishing extreme storm tide, wave set-up and run-up levels (e.g. 1% and 2% AEP water levels), is based on a summation of various sea-level components. For an assumed 1% AEP level this is typically taken as the sum of: 1) the mean spring high water level, 2) an allowance for significant seasonal, El Niño Southern Oscillation / Inter-decadal Pacific Oscillation effects on raising mean level of the sea (typically assumed to be up to 0.25 m), 3) allowance for storm surge, 4) allowance for wave set-up and potentially wave run-up based on empirical approaches where extreme wave conditions have been assessed at the location, and 5) and for future levels, an allowance for sea-level rise.

This "building-block" approach usually sums large or maximum values for each sea-level component and therefore is typically conservative in its estimation and should not be presented as a probabilistic storm tide or wave run-up level.

In New Zealand storm-tide levels are dominated by the occurrence of very high tides, as unlike other parts of the world, storm surges are unlikely to exceed 1 m (Bell et al., 2000) with the largest recorded being 0.8 – 0.9 m. Whilst the various components combining to result in an extreme storm tide level are typically correlated in some way, very rarely does an extreme high-tide level coincide with both a high storm surge and high wave conditions, (Ramsay and Stephens, 2006). Simply assuming that an extreme sea level will always occur at the same time as extreme wave conditions will tend to overestimate inundation risk. This is discussed further in the section on the joint probabilities of extreme waves and water levels.

3.2.2 Defining extreme storm-tide levels

A suggested hierarchy of approaches is outlined to assess potential extreme storm tide levels along a regions coast and potential coastal inundation hazard depending on the level of detail required and the availability of appropriate data and tools. Figure 6 summarises the various approaches using different combinations of datasets and modelling tools, for different levels of detail of establishing extreme water levels and/or inland inundation extents.

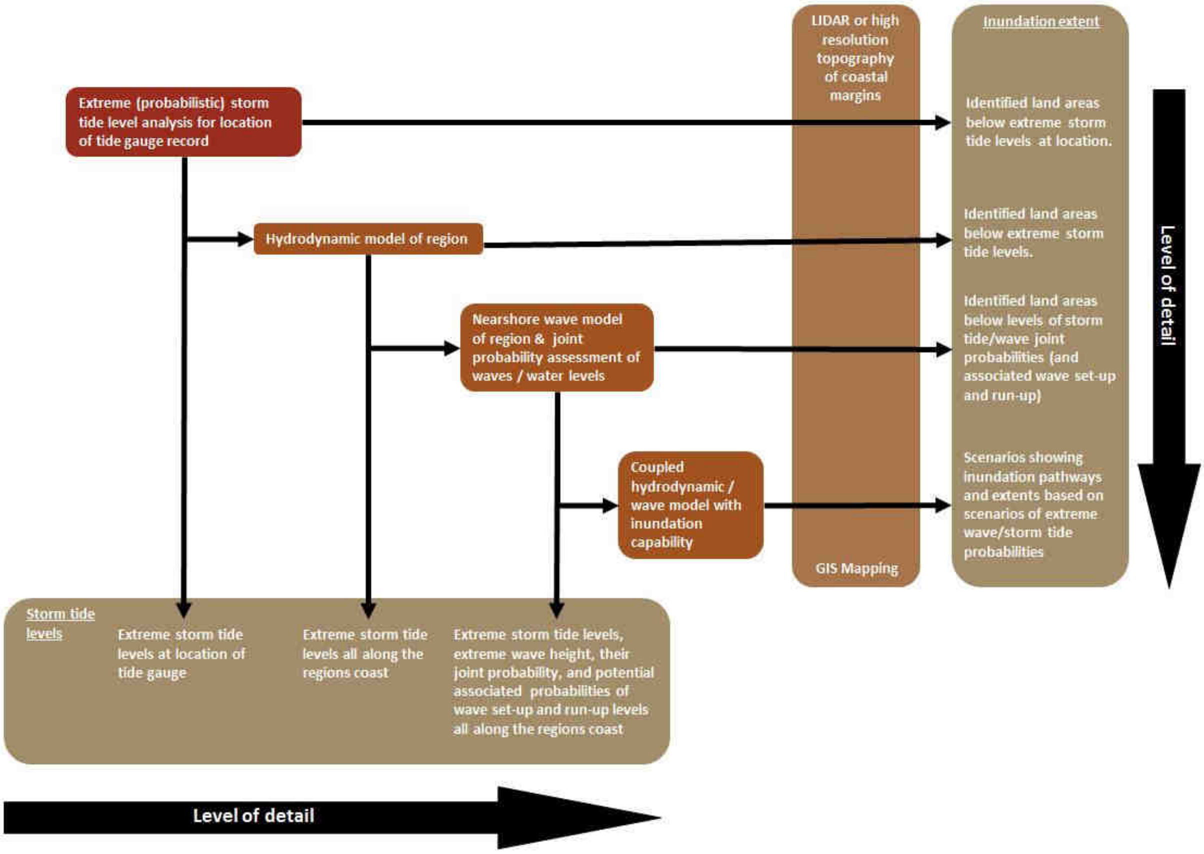


Figure 6 Summary of approaches at increasing level of detail for establishing extreme storm-tide levels along, and/or inland inundation extents for open coast situations.

In each of the approaches outlined below, the effects of climate change, such as sea-level rise or other changes on the drivers of coastal hazards (MfE, 2008) can be built into the assessment for different future time periods and levels of uncertainty.

Extreme storm-tide predictions from sea-level gauge records

Probabilistic estimates of extreme storm-tide levels are usually predicted by fitting a statistical extreme-value model (such as the generalised extreme value (GEV) or Generalised Pareto Distribution (GPD) model) to a subset of independent maxima from an existing sea-level record (Coles, 2001). In this way the very largest events in the record are extrapolated to estimate even larger events that might occur but have not been recorded over the usually limited duration of sea-level recordings.

Typical data requirements:	•	Hourly tide gauge records and if available information of historic storm tide events prior to the gauge record.
Limitations:	•	Single location in proximity to the gauge which may not be applicable over the coastline of a region
Extreme level outputs:	•	Extreme storm-tide levels for a range of annual exceedance probabilities commonly used for planning and design purposes (generally up to 1% AEP / 100 year ARI)

The accuracy of the extreme storm tide predictions depends on:

- The quality of the input data, including:
  - The accuracy of the measured or simulated sea level maxima (typically annual maxima for a GEV model or over a specified threshold "Peaks over Threshold" for a GPD model).
  - The occurrence and distribution of gaps in the record. Significant events may have occurred during these gaps.
  - Suitable historic coverage—the longer the available record the more reliable the estimates. Increased reliability results from improved statistical precision of the estimates and from decreased error associated with climate variability.

    For the GEV technique it is generally advised that extremes be predicted for recurrence intervals of no more than 3 – 5 times the record length as beyond this the associated margins of error become large. Therefore for a 1% AEP value to be derived, at the very least 20 year of data would be required.

    For the GPD method extremes can be predicted, from a statistical perspective, out to about 10 times the record length. However, care needs to be taken to ensure the influences of inter-annual and decadal variability on sea-levels are accommodated.
- The degree of fit between the "true" distribution of the sea levels, and the fitted statistical distribution (e.g., GEV or GPD model) used to extrapolate to the extreme values.

As extreme sea-levels around New Zealand are dominated by tide range, classical extreme-value analysis requires at least a number of decades (to encompass both a full 18.6 year period of the nodal tide epoch and 20-30 year full IPO cycle) of reliable sea-level records to predict out to 1% Annual Exceedance Probabilities (100 year Average Recurrence Interval). However, most sea-level records around New Zealand (Figure 7), other than at the main ports, are typically too short to robustly assess extreme storm tide levels out to 1% AEP levels using classical extreme level analysis techniques (Goring et al., 2010).

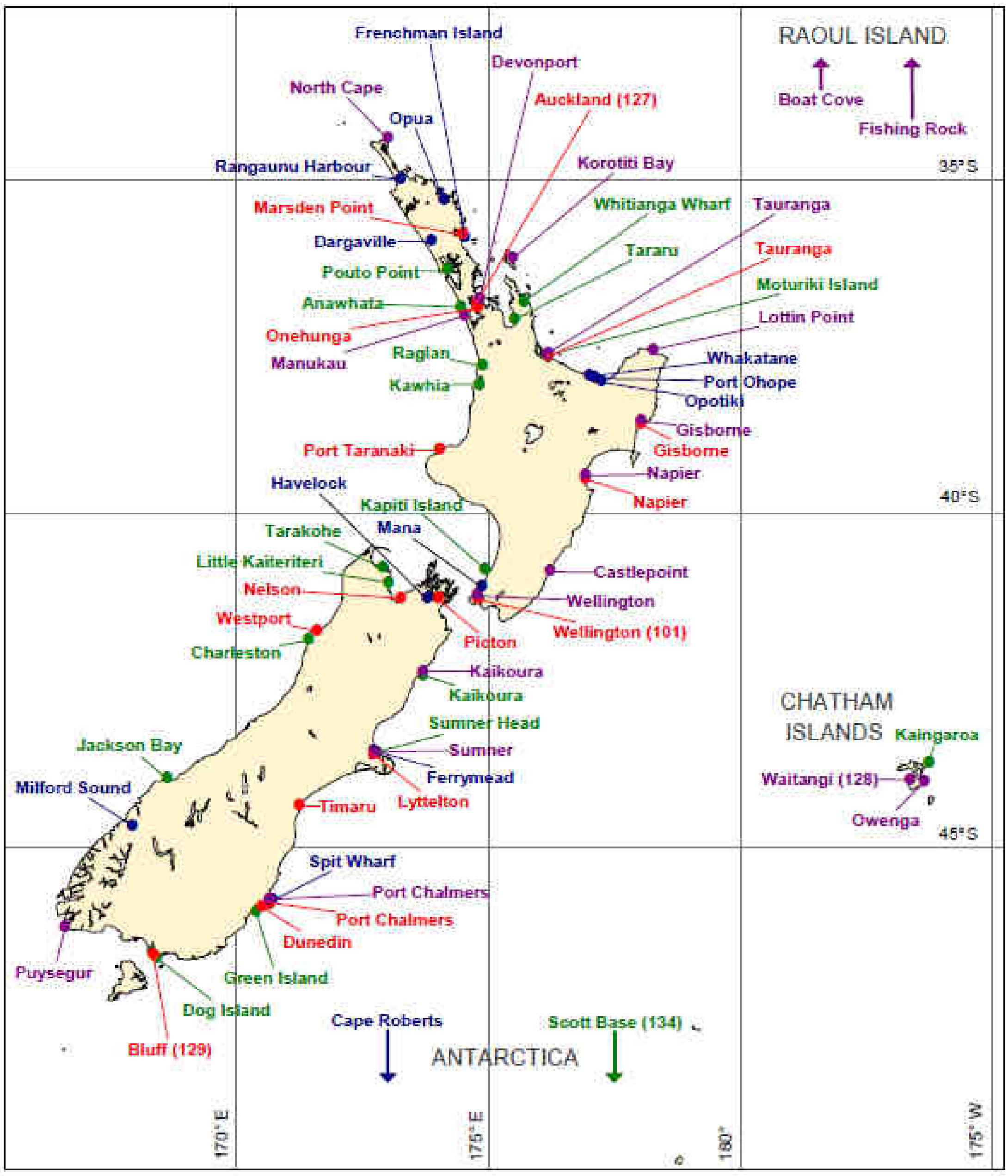


Figure 7 **Locations of known sea level records which may be suitable for extreme storm tide analysis. The major port sites are shown in red, open coast sites shown in green, GeoNETtsunami monitoring sites shown in purple and other sites (except four Tauranga Harbour gauges) shown in blue.**
Source: Land Information NZ and NIWA

In such situations alternative techniques need to be used to robustly derive probabilistic estimates of extreme sea levels from short data records. One such approach (Goring et al., 2010) essentially involves:

- Decomposing the available sea-level record in to its constituent components (e.g., tide, mean level of the sea, storm surge, annual cycle, and residual mean level of the sea (e.g., due to longer term climatic fluctuations). Other components, for example seiche if relevant, can also be incorporated. An important feature of the method is the ability to enhance the storm surge component from prior knowledge of historic storm-tide levels or modelling of likely extremes that lie outside the modern measured record.

- Using Monte Carlo simulation techniques, randomly re-combining the components to produce an annual series of sea levels at high tide from which an annual maximum is selected.
- Carrying out the simulation many thousands of times to generate a large dataset (many 1000s of years) of annual maximums from which more robust statistics of extreme sea level values can then be derived.

The robustness of the extreme value analysis can also be improved, and the range in tolerance levels in the extreme projections be reduced, where other historical storm tide levels that have been accurately observed are used to supplement the available digital sea-level record. This ensures the extreme sea level model includes all the largest known events (Figure 8).

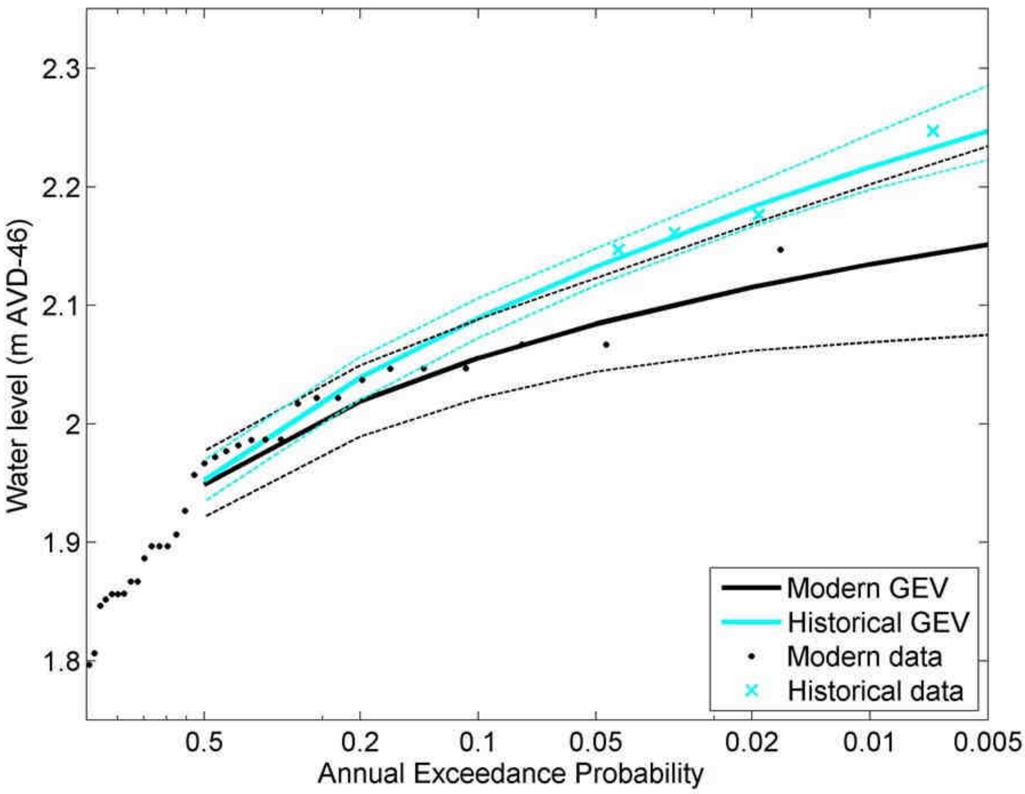


Figure 8 **Example of generalised extreme-value (GEV) model fits to 33 years of modern tide gauge data (black) and to the modern data supplemented by the historical data (blue). Dashed lines give 95% tolerance levels for the GEV fits (Ramsay et al., 2008).**

Irrespective of the methodology used it is essential that:

- Uncertainty levels on the extreme storm tide projections are clearly presented within any analysis (e.g., Figure 8).

- Projections are relative to a stated local or national (e.g. NZ Vertical Datum 2009) land vertical datum to avoid any confusion around what datum are used, and the datum used is clearly stated on all figures and tables. Note: Labels using "MSL Datum" or "Reduced Level (RL)" are ambiguous.
- For analysis of long sea-level records, it is necessary to remove any long-term trends such as sea-level rise before undertaking the analysis. It is important to state the year(s) used for the zero hinge point, as this is required when later adding on a sea-level rise component.

Present climate change information suggests that for New Zealand trends in storm-tide levels will be of a similar magnitude to trends in mean sea-level. Whilst non-stationary techniques are being developed to include variable sea-level rise rates into extreme value analysis, for now the pragmatic approach to accommodate sea-level rise is to simply add it to the extreme values (Figure 9).

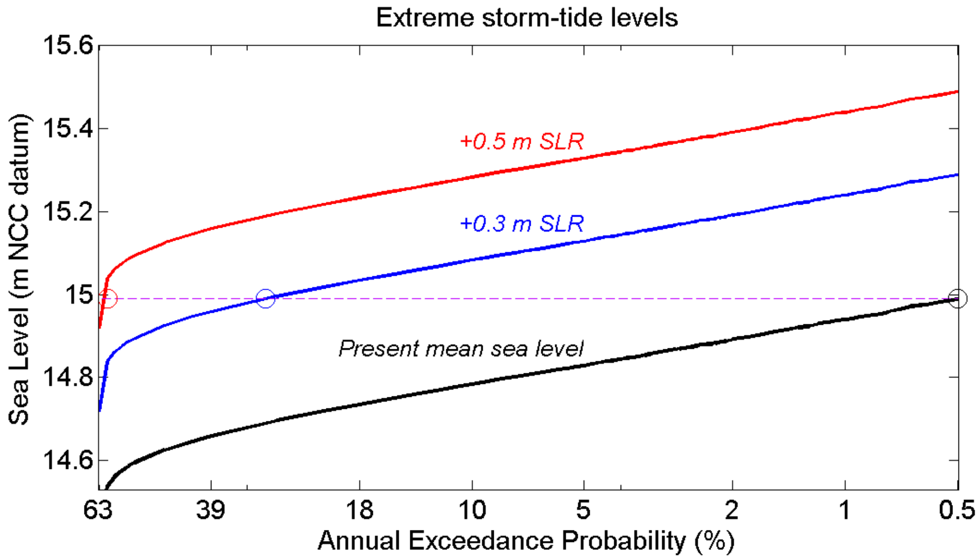


Figure 9 Comparison of extreme water levels for average recurrence intervals between 1 and 200 years for the present day (black) and with a 0.3 m (blue) and 0.5 m (red) rise in sea-level (Stephens and Bell, 2009).

Spatial variability in extreme storm-tide levels along a coastline

Sea-level data measured at a sea-level gauge can be analysed to provide extreme sea level estimates at that particular location. However, extreme sea levels do vary along a coastline, particularly in a harbour / estuarine environment. This is due to both:

- Changes in the tidal amplitude (i.e., in the upper reaches of estuaries and harbours the tide range is higher (amplified) than along the more open sections of coast).
- Changes in the relative contribution of the storm surge components.

Box 7 Sea-level rise guidance within a risk-assessment framework (Britton et al., 2012)

The MfE (2008) guidance manual Coastal hazards and climate change recommends for planning and decision timeframes out to the **2090's** (2090-2099):

1. a **base** value sea-level rise of **0.5 m relative to the 1980–1999 average** should be used, **along with**
2. **an assessment of potential consequences from a range of possible higher sea-level rises** (particularly where impacts are likely to have high consequence or where additional future adaptation options are limited). At the very least, all assessments should consider the consequences of a mean sea-level rise of **at least 0.8 m** relative to the 1980–1999 average. Guidance is provided in Table 2.2 (of the guidance manual) to assist this assessment.

Note: Table 2.2 in the MfE (2008) guidance manual covers a range of sea-level rise projections by 2100 with upper bounds from 0.8 m from IPCC (2007) to 1.0–1.4 m (based on three empirical studies from 2007 and 2008 described in the Table 2.2), to which values from more recent studies outlined in a Royal Society of New Zealand Emerging Issues paper could also be considered within the risk-based assessment. (Royal Society of New Zealand, 2010).

For longer planning and decision timeframes where, as a result of the particular decision, future adaptation options will be limited, an allowance for sea-level rise of 10 mm per year beyond 2100 is recommended (in addition to the above recommendation).

Commentary on the sea-level guidance:

The risk assessment should be based on a broad consideration of the potential consequences (direct impacts, loss of assets and amenity) from different sea-level rise magnitudes on a specific decision, objective or issue. The particular sea-level rise adopted in each case should be based on the acceptability of the potential consequences and likelihood of that sea-level rise (=risk) and the potential future adaptation costs that may be incurred, especially if sea-level rise is higher than anticipated.

Each risk assessment should also take into account the physical shore-type context (e.g., gravel, sandy or cliffed coasts) and the adjacent land-uses. In particular, upgrading existing development should be treated differently from new developments ('greenfields'), where risk avoidance and a precautionary approach are paramount (e.g., Policies 3(2) and 25(b) of the New Zealand Coastal Policy Statement (NZCPS), DoC 2010; see Appendix 1) along with the need to recognise the permanency of such developments and that sea levels will continue to rise for possibly several centuries. Therefore in undertaking a risk assessment and appraising future adaptation for greenfield developments, sea-level rises well over 0.8 m should be considered. The MfE guidance (MfE, 2008a), as it stands, recommends assessing a range of sea levels, starting any appraisal with a 0.5 m rise (by 2090s) and with the "at least 0.8 m" as a minimum higher sea-level rise to consider when assessing future consequences. Using this set of two benchmark values is therefore a minimum to consider, but assessments should not to be limited to those values.

Hence the risk assessment process, as recommended in the MfE guidance manual (MfE, 2008a), is an enduring approach, although it will need updating periodically in terms of planning timeframes. For example, the 2010 NZCPS requires assessments of hazards for "at least 100 years" (Policies 10(2)(a),24, 25). So already the range of sea-level rises that should be considered needs to take into account the presently recommended extension of 10 mm per year beyond 2100 e.g., the equivalent benchmarks **by 2115** (nominally the next 100 years relative to the 1980–1999 average) would be for an assessment starting at a **base value of 0.7 m** (equivalent to 0.5 m rise by 2090s) and **considering a range of possible higher values including at least a 1.0 m rise** (was a 0.8 m rise by 2090s). Both these 2115 values have been rounded to the nearest 10 centimetres, taking into account the present guidance is for the 2090s decade with mid-point at 2095.

If variability in tide and/or storm surge along a coastline, or within a harbour is likely to be significant this needs to be accounted for. Typically this requires a unique time-series of storm tides to be derived at a sufficient spatial resolution to capture this variability which is then analysed using extreme level analysis techniques.

It is impractical to measure sea level at a multitude of sites so a coastal hydrodynamic model is often used to characterise the variations in tidal amplification and storm surge. The model can then be used to translate the extreme assessment from the location of a long-term sea-level gauge to all the other sites of interest along a coastline (Figure 10).

Typical data requirements:	• Hourly tide gauge records and if available information of historic storm tide events prior to the gauge record. • Any other water level records in the domain of the hydrodynamic model (for calibration and validation). • Long time-series wind/pressure records from available anemometer stations in the region.
Model requirements	• Calibrated and verified 2D hydrodynamic model of the regions coastal area.
Extreme level outputs:	• Probabilistic storm-tide levels at specified locations along a regions coastline.

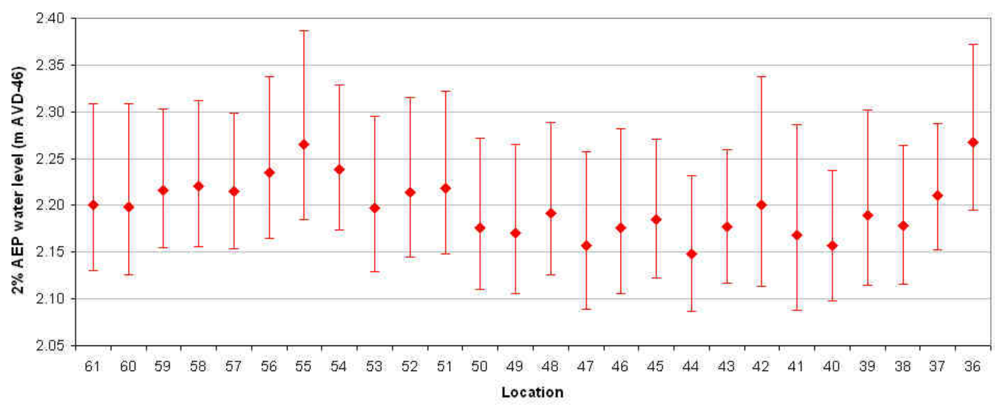


Figure 10 **Example of the variation in 2% AEP storm-tide levels along a section of the Waitemata Harbour coast of Auckland for the present day.** 5% to 95% tolerance levels are shown by the uncertainty bands (Ramsay et al., 2008).

In this context a hydrodynamic model can also be used to assess:

- Storm tide variability along the coast due to a historic storm event provided that some wind and barometric pressure observations are available for the event. For example the great 26 March 1936 cyclone has been simulated in Auckland for various studies based on observations of Barnett (1938). Replication of past severe storm events is often useful for verification and to put the severity of the event into probabilistic context.
- Any potential changes due to:

- Sea-level rise on tidal amplification variability.
- Changes in storm surge characteristics (either due to sea-level rise or where the sensitivity of extreme water levels due to possible changes in storm characteristics are incorporated), Figure 11.

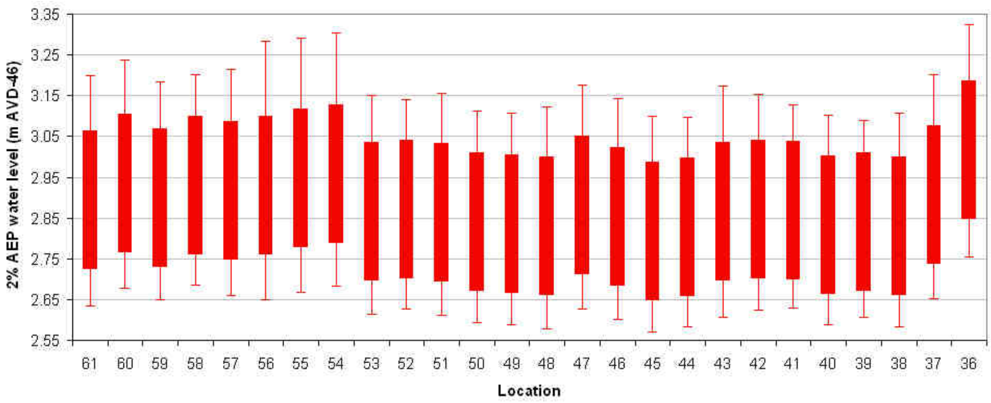


Figure 11 **Example of the variation in 2% AEP storm-tide level along a section of the Waitemata Harbour coast of Auckland accommodating a selected range of future sea-level rise.** The range shown by each bar represents the range in future sea-level rise assumed for the future time-period. 5% to 95% tolerance levels associated with the extreme analysis are shown by the uncertainty bands (Ramsay et al., 2008).

3.2.3 Defining extreme wave set-up, run-up levels and overtopping volumes

Where wave set-up, run-up or overtopping is an important component influencing inundation pathways or levels, both extreme storm tide levels *and* wave conditions will need to be considered.

The joint occurrence between tide and storm-surge is accounted for within any analysis of extreme storm-tide levels (discussed in the previous section). Extreme waves and water levels are also typically correlated in some way but very rarely does an extreme high tide level coincide with both an extreme storm surge and extreme wave conditions. Understanding the likelihood of large waves and large water levels occurring together is important to understanding potential wave set-up and run-up levels and overtopping volumes.

Deriving extreme wave conditions

Extreme wave conditions are typically derived for the same nearshore location(s) as the storm tide analysis. If joint probabilities of wave and water level occurrence are to be assessed this also needs the timeseries of both wave and water level data to be matched over the same time period.

Measured wave data is sparse around the coast of New Zealand and in most cases numerical models will need to be used to simulate datasets, or to extend them in time and space to enable an adequate assessment of extreme wave probabilities.

Typical data requirements:	• Hourly tide gauge records and if available information of historic storm tide events prior to the gauge record.. • Any other water level records in the coastal region of interest. • Long time-series wind/pressure records from available anemometer stations in the region. • Ideally an offshore or nearshore wave dataset, or a short term nearshore wave dataset (6 weeks or greater) for wave model calibration. • Offshore wave hindcast timeseries dataset (covering a number of decades). • Nearshore bathymetry (where possible) • Inter-tidal and coastal margin topography (from LiDAR if possible) • Typical beach profile data for sections of coast of interest.
Model requirements	• Calibrated and verified hydrodynamic model of for the regions coastline. • Calibrated nearshore wave model typically driven at offshore boundaries by wave hindcast timeseries dataset. • Empirical wave set-up, run-up and/or overtopping models.
Extreme level outputs:	• Probabilistic storm-tide levels at specified locations along a regions coastline. • Extreme significant wave heights (e.g., 2%, 1% Annual Exceedance Probabilities) at specified locations seaward of the wave breaking zone along the regions coastline. • Joint probabilities of extreme wave and water levels at specified locations along the regions coastline. • Probabilistic estimates of wave set-up and run-up levels for different coastlines or coastal defences.

To derive nearshore extreme wave conditions, a typical approach involves:

- An offshore hindcast of timeseries wave data of at least 20 years length (if 1% AEP wave conditions are to be estimated without significant error margins). There are a number of global/regional hindcast wave model datasets available around New Zealand with between 20 to 40 years of timeseries wave data, including the WASP dataset which also incorporates a futurecast of 30 years of wave conditions for two climate change scenarios.
- Calibration of extreme significant wave heights against any available offshore buoy or satellite data. Hindcast models typically underpredict the largest wave heights due to unresolved storm winds. Simply conducting an extreme analysis on a global hindcast wave dataset will underpredict the projected extreme wave conditions.
- The use of coastal area wave models which utilises the offshore hindcast wave data as boundary conditions and simulates the propagation of these waves to the region’s coastline, taking account of locally generated wave conditions due to local winds, and the various nearshore wave processes (A commonly used model for this

purpose is SWAN[1]). This is typically used to derive an equivalent time series of wave parameters at locations along the coastline, seaward of where waves tend to break.

It is good practice to also calibrate and verify wave conditions against measured wave data (for a minimum of at least 2 months but ideally several years to adequately calibrate extreme conditions) within the domain of the coastal area wave model.

- Once a timeseries of wave conditions has been derived at each location of interest, a statistical extreme-value model (such as the Generalised Pareto Distribution (GPD) model) is used to derive extreme statistics (e.g., 2%, 1% AEP significant wave heights).

  As with extreme analysis of water levels, error margins for the extreme significant wave height projections should be clearly presented.

Box 8 Wave and Storm Surge Projections (WASP)

Wave and Storm Surge Projections (WASP)

WASP was a Ministry of Science and Innovation funded project to produce a nationally consistent dataset of wave and storm surge information around New Zealand for:

- 40 year hindcast dataset (1960 to 2000).
- 30 year futurecast dataset (2070-2100) for the B1 and A2 climate change scenarios.

Data will be available around the entire coast of New Zealand to provide consistent "offshore" conditions to drive more detailed coastal storm surge and wave models. Data available includes:

- Hourly time series of tide, storm surge, significant wave height, wave period and wave direction.
- Summary statistics for the modelled variables, including distribution plots such as histograms, probability and cumulative distribution functions.
- Change in storm surge and/or significant wave height, due to climate change for A2 and B2 SRES climate scenarios.

More information can be found at: http://www.niwa.co.nz/our-science/coasts/research-projects/wasp.

The data can be accessed via Coastal Explorer: http://wrenz.niwa.co.nz/webmodel/coastal

Potential future climate change impacts on the wave climate, and hence extremes, can be assessed by:

- Using either the WASP dataset as boundary wave conditions to the coastal area wave modelling or by adjusting the current wave climate within the model and/or local wind conditions (MfE, 2008).

[1] SWAN – Simulating Waves Nearshore. http://www.swan.tudelft.nl/

- Creating a future wave timeseries for each location and carrying out the extreme value analysis as before.

Assessment of the joint probability of extreme waves and storm tide levels

Once extreme statistics have been derived for both storm tide and wave conditions at each location, joint probability techniques (Hawkes, 2002) can then be used to assess the interdependence between extreme waves and water levels. Correlations between high waves and high water levels can occur for two main reasons:

- Meteorological. However, since the astronomical (tide) component of storm tide is usually larger than the surge component, any such correlation may be modest.
- Depth-limited waves, where wave heights are dependent on the storm tide level. In this case the degree of dependency will depend on the depth of water where nearshore wave conditions were derived.

From these matching records of wave and water levels, joint probability contours for larger average recurrence intervals can be extrapolated. This produces a range of combinations of extreme wave and storm tide levels for different annual exceedence probabilities/annual recurrence intervals, (Figure 12), and for different scenarios of future sea-level rise/climate change impacts on wave conditions.

The curved contours in Figure 12 represent the locum of combinations of significant wave height and storm-tide sea level that produce the same annual exceedence probability. However, for each location there will be an optimum combination that produces the most set-up, run-up, overtopping or inundation.

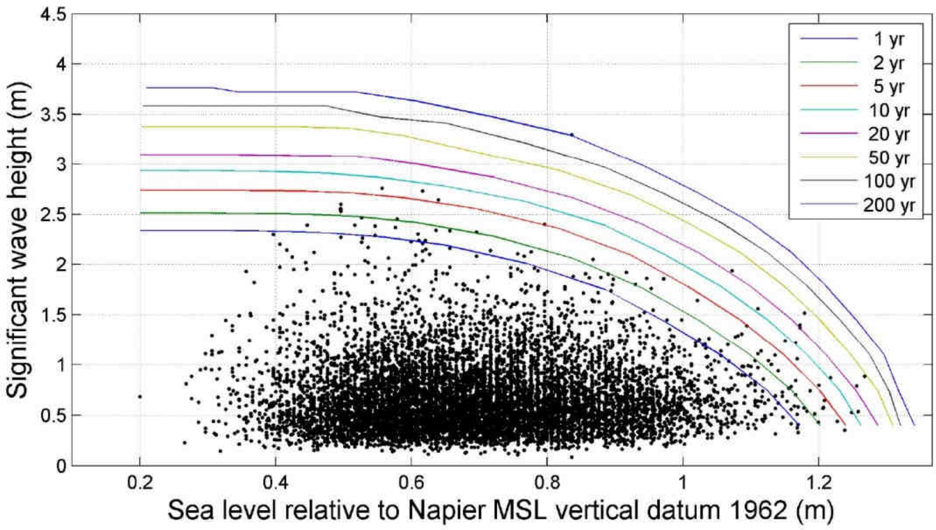


Figure 12 **Scatter plot of storm tide sea level and significant wave height with derived joint probability contours for a range of average recurrence intervals for a location in Hawke Bay (Gorman et al., 2009).**

Derivation of wave set-up and run-up levels and overtopping volumes

To derive probabilistic estimates of wave set-up and run-up levels and potential overtopping volumes there are two approaches that can pragmatically be adopted:

- Using the simulated time-series of storm tide and wave conditions at a particular location a corresponding time-series of set-up and run-up levels or overtopping volumes are calculated. An extreme value analysis is then conducted on the time-series dataset of each individual variable.
- For the range of wave/storm tide combinations for each joint probability contour the corresponding set-up and run-up levels or overtopping volumes are calculated and the maximum value for each variable from all the combinations for the particular joint probability contour selected.

For practical purposes, wave set-up and run-up levels are typically calculated using empirical formulae. For sand beaches there are a wide range of formulae available, less for gravel beaches. Most of the formulae take account of the significant wave height (or other wave height statistical parameter) and the wave period (or wave length) offshore from the breaker zone as well as information on the average beach slope.

It is difficult to provide specific guidance on what particular formulae to use as it depends on the characteristics of the location (for example some methods work better on steep beaches, others on gently sloping beaches, or are specific to rock revetments or sloping seawalls) and some judgement is required. However, the following comments are made:

- Some Local Authorities routinely survey run-up levels reached after severe storm events. Using storm-tide level and wave conditions from the event, different formulae can be assessed as to how well they replicate the recorded run-up levels.

- Where no data on run-up levels are available, a number of relevant equations should be incorporated to ascertain the potential variability in set-up and run-up from the use of different equations, and if necessary used to define uncertainty bounds.

- Care needs to be taken in applying set-up and run-up formulae, some separate out set-up and run-up components, other formulae for run-up incorporate both set-up and run-up.

Empirical approaches are also available to quantify indicative overtopping volumes (typically to an order of magnitude), particularly for a wide range of coastal defence structures, for example *Wave Overtopping of Sea Defences and related structures* (EUROTOP, 2007). Such approaches can be used to either define:

- Mean or peak wave overtopping rates.

- The total volume of water overtopping the barrier by integrated over the peak of the storm tide.

Box 9 Understanding the drivers of the 6 June 2012 damaging storm event, at Kina Point, Nelson.

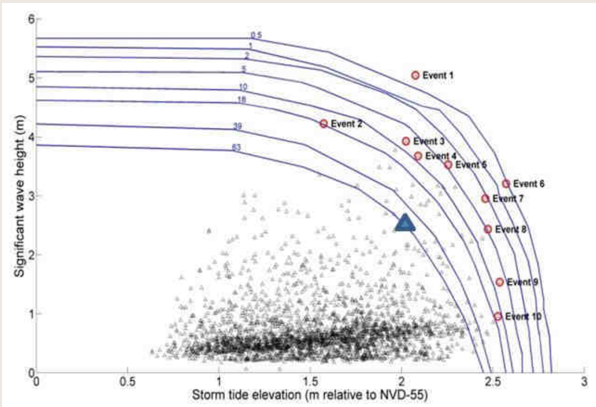
Along Kina Peninsula Road, adjacent to the Moutere Inlet in the Tasman region, there is a 300 metre long section which is squeezed between the beach and a high coastal cliff and is protected by a rock revetment.

A storm on 6 June 2012 caused substantial damage to the revetment and scoured a section of road carriageway (see photograph). Storm-surge, coinciding with a spring tide, was only about 0.16 m high arising from local barometric pressures of 990–992 hPa and north-east to easterly mean wind speeds of 11–13 m/s at Nelson Airport. The strong winds in Tasman Bay also generated a mix of sea and swell waves, exemplified by the photo.

Source: Tasman District Council

Significant wave heights measured off the Port of Nelson around the morning high tide were 2.4 m with an average period of 7–8 seconds, although the local sea had peaked earlier with a 3.3 m wave height around the early-morning low tide.

In terms of coastal inundation, the storm-tide level of 2.0 m NVD-55 for this damaging event was by no means extreme, compared to a mean estimate for a 2-year average recurrence interval (ARI) storm-tide level of ~2.5 m NVD-55 at Port Nelson.



Blue contour labels represent the joint Annual Exceedance Probability in % for each probability curve.

The Port has a similar tide range to Kina Peninsula. In terms of a joint-probability of both the significant wave height and storm-tide level, the 6 June 2012 event was only a 1-year combined ARI or 63% AEP (large blue triangle) according to the extreme value analysis shown in the joint-probability figure.

The degree of damage to the road didn't appear to match with this apparent low-level joint ARI occurrence. However, another sea-level gauge further north-west at Little Kaiteriteri, sampling at 1 minute intervals, recorded heights of "tsunami-like" long waves of 0.4 m at periods of 5–7 minutes between surges arising from offshore swell. Consequently, it was the mix of sea/swell waves compounded by the long-wave surging that provided the main damaging aspects, rather than the meagre storm-tide level reached.

This clearly illustrates that damage from coastal hazards can sometimes be due to a combination of several components (and not just the two drivers normally considered, short-period waves or swell and storm-tide levels). It also illustrates that it can be necessary to go back and reappraise the overall understanding, or conceptual model, of the sources of coastal inundation hazard.

Source: Goodhue et al, (2012).

3.3 Quantifying coastal inundation pathways

3.3.1 Translating extreme levels at the shoreline into minimum land-development guidance

Probabilistic storm tide, or storm tide plus wave set-up, levels at the shoreline can be used to assess the adequacy of, or to define requirements for, minimum land levels for development and/or minimum floor levels in council land development or engineering quality standards.

Where wave run-up is unlikely to significantly increase the potential depth of inundation in a low lying coastal margin (e.g. due to water overtopping a coastal berm), the minimum levels are generally based on the storm tide/wave set-up level defined at the shoreline, (Figure 13), sometimes with a specified freeboard added to account for uncertainties or other additional contributors of flooding such as heavy rainfall or stormwater drainage.

Whether wave set-up is incorporated depends on the particular situation:

- For open coast locations it will almost always need to be considered.
- In sheltered harbour and estuarine locations wave set-up may be insignificant but in small inlets or river mouths could be a significant driver of upstream water levels in combination with other storm-tide components.

Run-up levels may still need to be factored into planning considerations or engineering standards, over the immediate coastal barrier margins behind the beach. This is particularly relevant on open coast and where existing development or infrastructure is located very close to the shoreline.

Figure 13 Storm tide / wave set-up levels and resulting inundation levels where wave run-up and overtopping do not increase inundation levels above those resulting from other inundation pathways (for example estuary or river mouth, or storm water connection).

Where overtopping of a coastal barrier could raise inundation levels above the storm tide or wave set-up level (Figure 14), the magnitude of an increase in inundation level may need to quantified, for example be estimating the volume of water that could potentially overtopping the barrier over the peak of the storm tide. However, this also requires accurate information on the topography of the coastal margins (see next section).

Figure 14 **Overtopping of a coastal berm resulting in inundation levels that are greater than seaward storm tide or wave set-up levels.**

There are three other important considerations in translating extreme levels at the shoreline into minimum level guidance for land development:

- For practical implementation often a single level is defined in regional plans, policies or engineering standards. Where storm tide or the corresponding wave set-up levels vary (e.g. Figures 10 and 11) along a section of coast or the region:
  - If significant spatial variation occurs then different levels will need to be accommodated in different stretches of coast for a particular annual exceedence probability.
  - If the variation is low or modest, then one level may be suitable. However, in adopting a single level, consideration must be given to what effect this has on the resulting range of annual exceedence probability for that particular level all along the section of coast.
- Uncertainty in the extreme value analysis needs to be clearly defined and presented for consideration and accommodation within the minimum level considerations (Figure 15 and Figure 16).
- The corresponding future impacts of sea-level rise and any other climate change considerations on annual exccedence probability levels also need to be presented.

Following an assessment of future sea-level rise scenarios (MfE, 2008), it is important to capture the sensitivity or range in potential future annual exceedence probability levels due to the range in sea-level rise/climate change accommodated in the assessment (Figure 16).

Alternatively uncertainties associated with the rate of future sea-level rise can be used to estimate the potential range in timing of future sea-level exceedences of a tipping-point or trigger level, for a particular community, as shown by Figure 17.

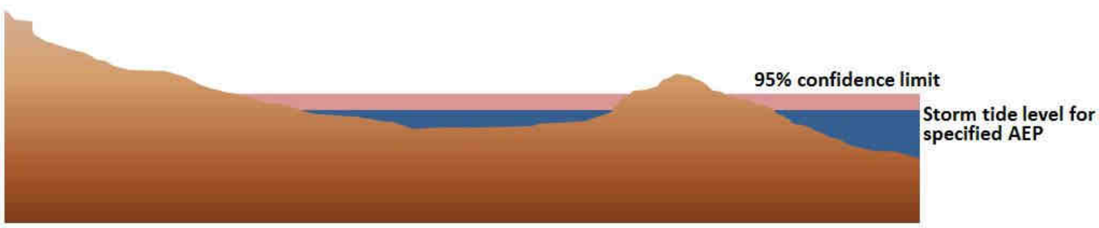


Figure 15 **Clear definition and presentation of uncertainty needs to be incorporated in any outputs to help non-technical staff incorporate it into any subsequent plans, policies or standards.**

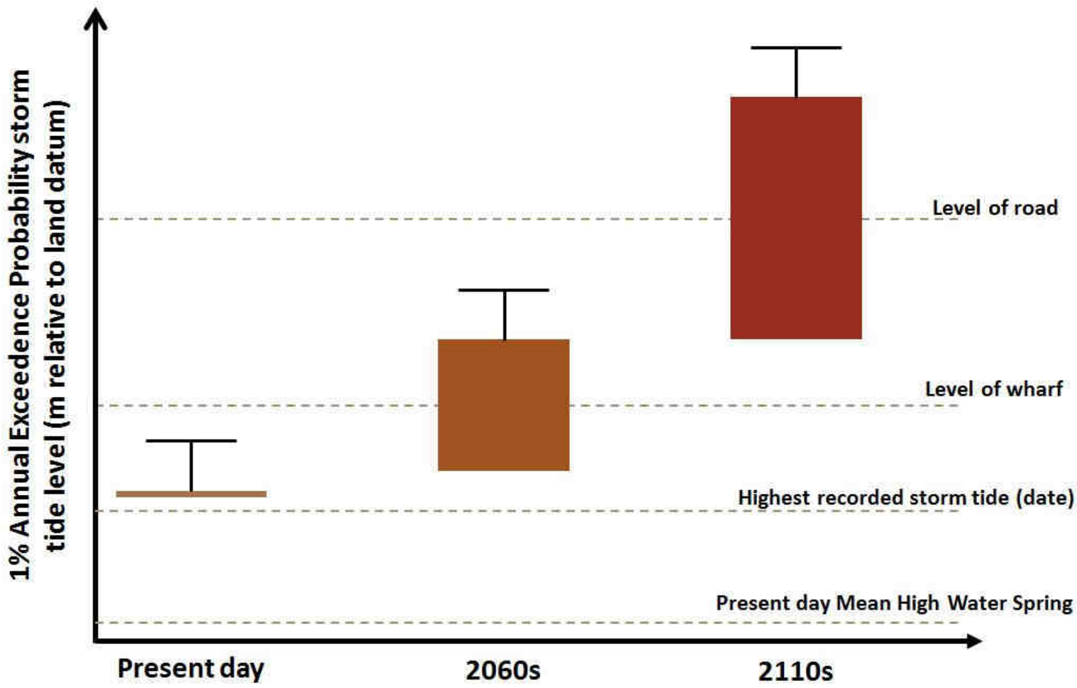


Figure 16: Example of a possible approach to present annual exceedence probability levels for the present day, and future scenarios incorporating a range of sea-level rise scenarios, with associated extreme value analysis 95% confidence limits and in the context of land levels of notable local features.

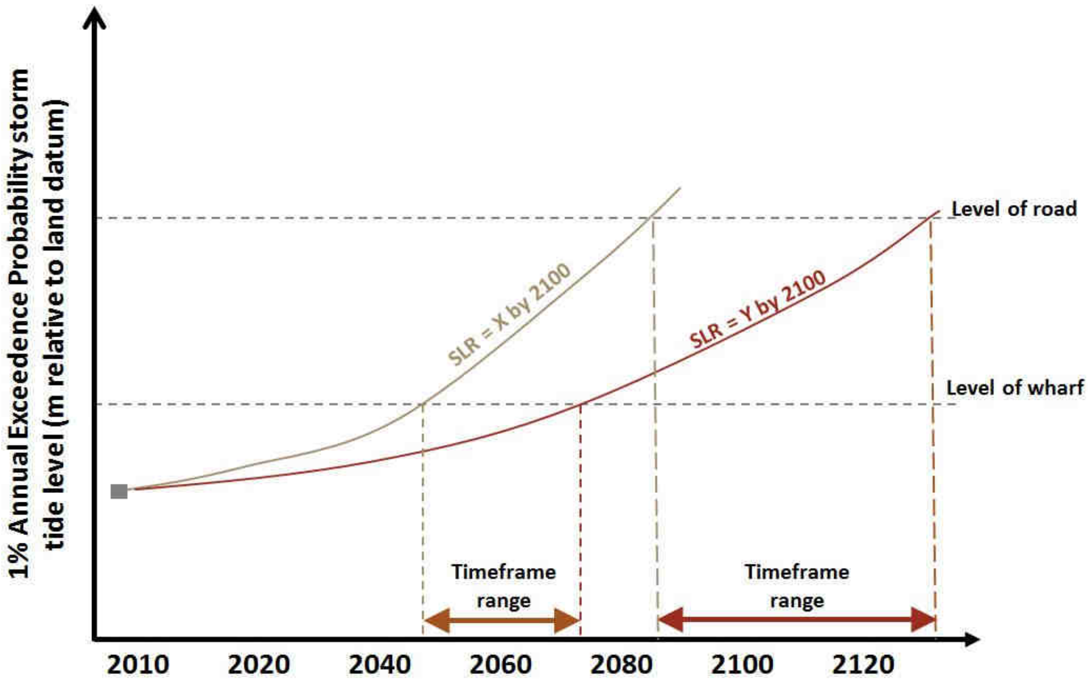


Figure 17: Example of an adaptive management approach that encapsulates uncertainties associated with the range of future sea-level rises within a planning timeframe in a time-varying 1% AEP storm tide level, showing the potential range of the timeframe it may take for sea-level rise to result in a corresponding future 1% AEP level, earlier if the faster sea-level rise rate occurs, later if sea-level rise rate is smaller.

In such analysis it is common for the types of information typically output to be presented as tables of numbers. Providing conceptual sketches and presenting the results in a pictorial or graphical context is important to help users understand the information and to put it in the context of critical levels (Figures 16 and 17). This is especially helpful for presenting uncertainties.

3.3.2 Translating extreme levels at the shoreline into inundation extents

Defining the areal extent of low-lying coastal margins at risk from coastal-related inundation, now and in to the future, provides a further level of information to help risk-based planning and decision-making and also requirements for evacuation if high inundation levels are forecast.

This also provides a more visually understandable characterisation of the potential hazard and what land, development, infrastructure or other values are potentially at risk and how this risk may change into the future due to either climate change or further development in areas prone to inundation hazards.

Availability of high resolution topography

To define areas of potential inundation for different annual exceedence probabilities requires a highly accurate representation of the topography of the coastal margins. This is particularly the case when mapping extreme water levels where inaccuracies of a decimetre or more can translate to variations in millions of dollars at risk.

In New Zealand extreme water levels are constrained by the tide range and magnitude of the storm surge component which often results in only a few centimetres difference in storm tide level, for a factor of ten or more decrease in annual exceedence probability (or ten times increase in ARI). Mapping a particular AEP level derived at the shoreline on topography to the nearest 1 m, 0.5 m or even 0.25 m contour would likely result in substantial over-estimation of the extent of inundation and hence risk, particularly if coastal margin slopes are very shallow. Where this is carried out it is suggested that this should not be specified with an AEP rating, rather an *indication* of inundation hazard extent and the caveats clearly communicated (if more accurate topography is not available).

Deriving a suitably accurate topography dataset can be achieved a number of ways, for example Ground Surveys or stereoscopic derivation from aerial photographs. However, it is the increasing availability of LiDAR[2] datasets for coastal regions, which provide very high

---

[2] Light Detection And Ranging – an airborne laser scanning system that determines ground levels at a very high density (often as little as 1-m spacing between measurements) along a lateral swathe of land underneath the track of the airplane. Most systems used in New Zealand collect data only on land above water levels, but systems are available that can also determine shallow water bathymetry levels in clear water. Vertical accuracy is typically better than ±0.15 m. Important note: When specifying LiDAR surveys for coastal inundation, insist that the surveys are done over low-tide periods, and on spring low tides if possible. Inter-tidal topography

(footnote continued)

quality datasets, that have enabled more accurate assessments of potential inundation extents and depths. This is achieved by overlaying the required sea level onto a digital elevation model surface created from the LiDAR data with a common vertical datum. The difference between the water level and the DEM provides an estimate of potential inundation extent and depth in the area.

Defining inundation extents and depths

The most commonly applied method to define inundation extents and depths is to simply apply the static extreme storm tide, and if available the additional, wave set-up level derived at the shoreline for a particular AEP and define an extent and depth over the coastal margins based on that level (Figure 13 and 18).

In many situations this "static" inundation approach will be a reasonably pragmatic approach and will likely provide a good indication of the potential extent of inundation for a particular AEP, given that in New Zealand, water level (and particularly high tide levels) tends to be the dominant factor controlling the magnitude of storm-induced inundation.

In presenting map-based inundation information the following considerations need to be taken in to account:

- The background maps have to display key information to locate the inundation extents:
  - If high resolution satellite imagery or aerial photography is available, this provides a good backdrop to locate community assets and dwellings relative to the inundation extent and depth information plotted. Care needs to be taken to plot at an appropriate scale: too low a scale it may be difficult to locate key features and there may be too much background information, too high a scale may convey an inappropriate high level of accuracy (e.g. individual properties inundated or not).
  - If background imagery is not available mapping relative to key roads and other key infrastructure features is useful (Figure 18)
- Mapping different AEP inundation levels enables a picture to quickly build up as how sensitive the coastal margin is to inundation. However, care needs to be given in not presenting too much information on a single map.
- When communicating the effects of climate change with communities, experience has shown in can be useful to focus on changes in inundation for a spring tide that will occur regularly (e.g. once a fortnight), rather than just an extreme case such as 1% AEP event.

---

greatly assists numerical modeling of inundation and for extracting beach slopes for assessing wave set-up and run-up.

- Mapping sections of coastal margin where there is a direct overland flow-path from the coast as distinct from other low-lying areas that are cut-off from a direct overland flowpath by slightly higher land (Figure 19).
- Present the impact of potential uncertainty limits in the extreme water level projections, or accuracy of the LiDAR data (or contours derived from the LiDAR data) may have on the potential area of inundation. Mapping such uncertainty is a useful way of conveying this uncertainty to non-technical colleagues but needs to be done in a clear and concise way. A suggested approach, which follows the practice suggested by Saunders et al (2011) for tsunami inundation mapping, is shown in Figure 19.

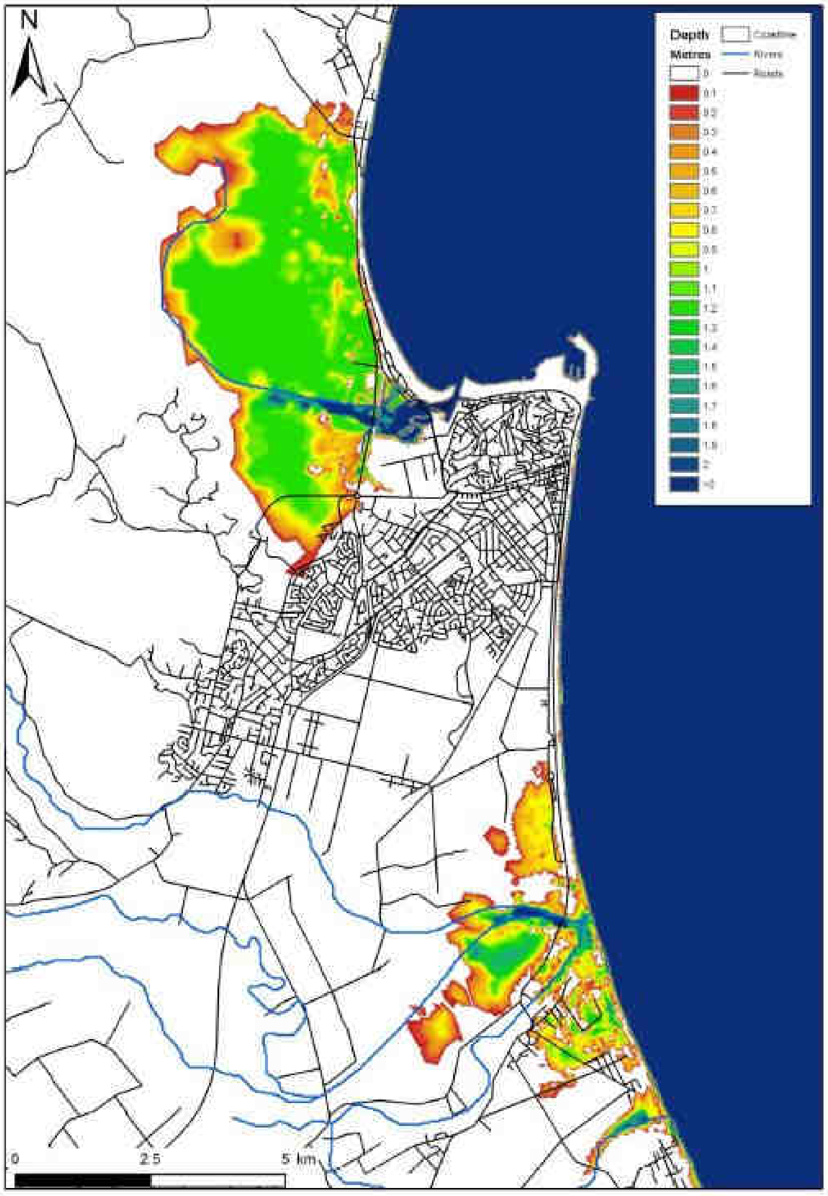


Figure 18 **Example of an inundation map showing extent and depths for a particular combined wave / storm tide scenario.**

Defining inundation pathways and other approaches

Where the above approach would potentially underestimate (or over-estimate) inundation levels or extent, additional consideration may need to be given as to how an area is inundated. Examples where this may need to be considered include:

- Where wave run-up and overtopping is a significant factor such as immediately behind relatively low coastal berms or coastal defences.
- Where inundation could potentially be due to, or significantly influenced by, a breach in a coastal barrier, for example a shingle ridge or constructed stopbank.
- Where there are multiple inundation pathways, for example multiple locations where overtopping is occurring, or multiple stream-mouths, public access or other openings in the coastal barrier.
- Where inundation extent may be influenced by a number of hazard sources, for example high river flows or extreme rainfall occurring at the same time as high storm tide/wave conditions

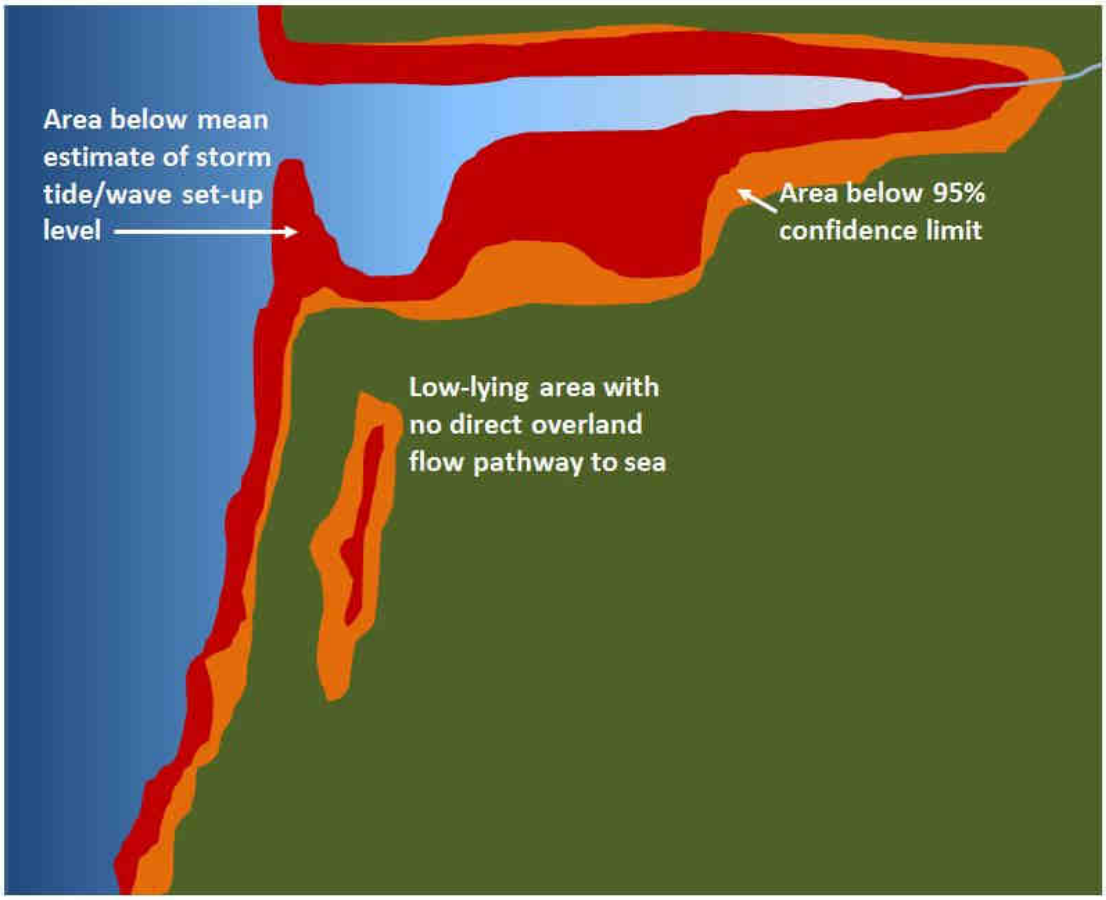


Figure 19 Example of incorporating uncertainty in to inundation mapping. The red area shows the land area likely to be below a particular mean estimate of an AEP level, the orange area the area below a less likely but possible upper confidence limit above the mean estimate (in this case 95%).

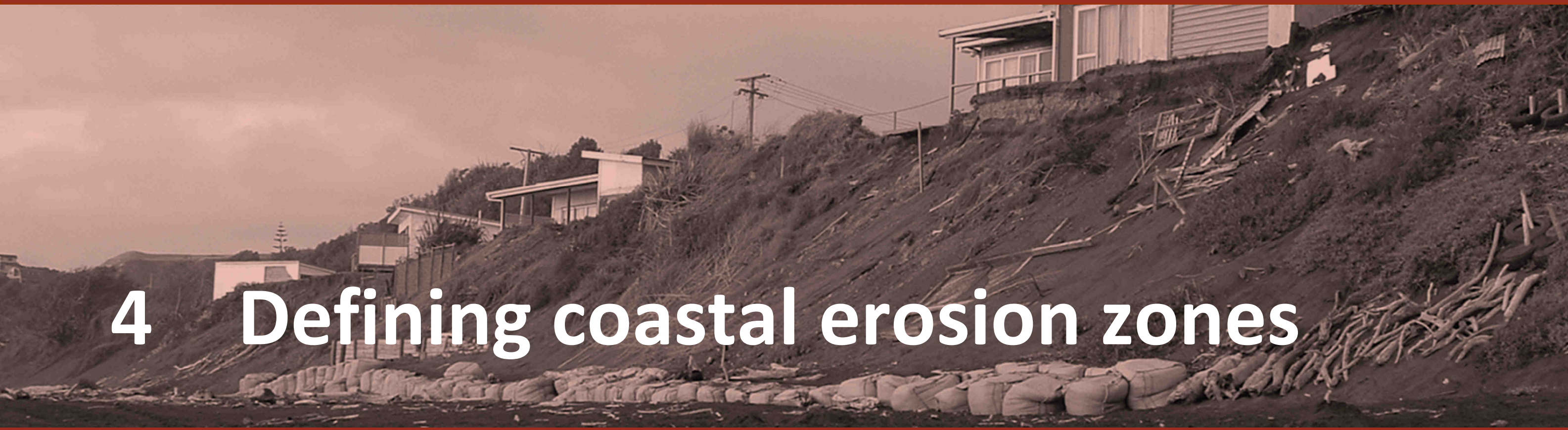
Where overtopping volumes can be defined (for example using empirical approaches integrated over the peak of the storm tide), the total, or additional, volume of water contributing to inundation can be quantified. This can then be added to the digital elevation model to define inundation extent and/or depths.

In more complex inundation situations, and where high resolution topography data such as LiDAR is available, it may be of use to define the direct overland flow pathways. This is typically done for a particular scenario (i.e. a particular combination of wave / water levels for a particular AEP) and can be done by either:

- Using GIS routing routines to map the various flow pathways from shoreline input information (storm tide levels, wave run-up or overtopping or breaches).
- Dynamic hydrodynamic modelling of overland flow pathways, again using shoreline derived information as input. Thus approach is well founded and typically used for detailed tsunami inundation mapping.

Such an approach can enable a more realistic representation of the extent and magnitude (depth, volume and duration) of inundation, particularly where there are multiple sources, or where inundation is due to a breach in a barrier.

Whilst it would be desirable to be able to use hydrodynamic models to simulate a particular storm tide / wave combination, the resulting wave set-up, run-up and overtopping at the shoreline, and the resulting coastal margin inundation, there remain research challenges in the dynamical simulation of nearshore wave / water level interactions. For sandy beaches with dune systems, recent models such as XBEACH (Roelvink et al., 2009, 2010) do provide opportunities to more realistically simulate swash zone hydrodynamics and associated beach and dune erosion, overwashing, breaching and hinterland inundation.



4 Defining coastal erosion zones

4.1 Introduction

4.1.1 Purpose

In the context of this guide, the fundamental purpose of a coastal erosion hazard study is to quantify the extent of potential shoreline or cliff change over a specified future timeframe as an input in to coastal margin development planning.

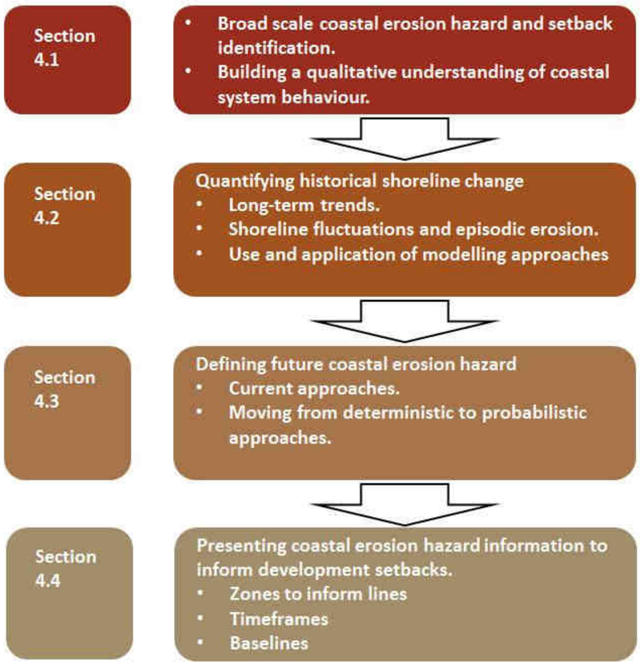


Figure 20 Section outline

4.1.2 Broad-scale coastal erosion hazard identification and setbacks

Identifying sections of coast exposed to coastal erosion

In many settings, particularly in areas where there is little development pressure, investment in detailed coastal hazard analysis is often not justifiable and tends to be conducted on an as-need basis when development is proposed. With the NZCPS approach to new development and increasing effects of climate change, there needs to be a change to a more pro-active approach to setbacks before development is ever considered to achieve more sustainable outcomes.

A broad scale assessment of coastal hazards can provide useful guidance for coastal management and at the very least should be conducted for the entire coast as a first cut. The onus is then on developers to prove otherwise. While such assessments do not provide sufficient detail or certainty to be defensible in the face of strong challenge, they provide useful hazard identification and prioritisation information. In many cases these assessments represent a "first stage" or "red flag" to guide further more detailed hazard assessments at priority locations.

At a basic level this can simply be a listing or basic map of known locations or sections of coast in the region that are susceptible to coastal hazards (for example Coastal Hazard Areas identified in the West Coast Regional Coastal Plan). The purpose is to highlight the existence of the hazard to inform both the public and land-use planning. This can "red flag" the need for specific investigation if development is proposed in these areas.

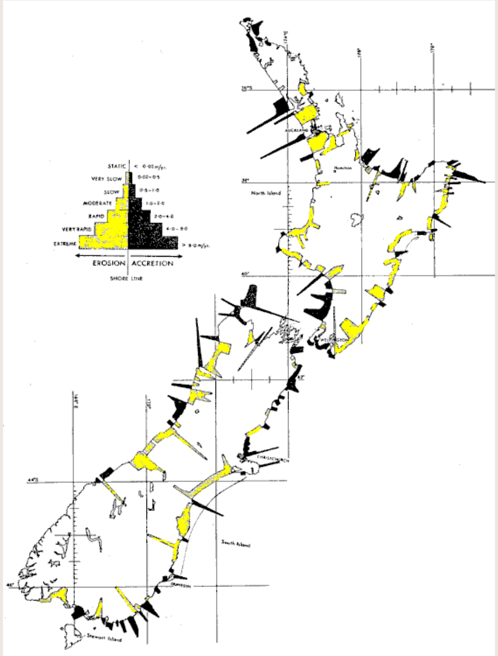
Such an approach can be based on some or all of the following:

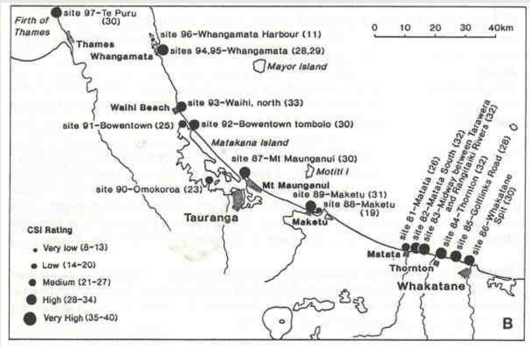
- Existing information and local knowledge
- Rapid visual survey of the coast undertaken by an experienced coastal hazard expert.
- Ranking of sections of coast susceptible to coastal hazards in a standardised way.

Typical data requirements:	• Generally based on readily available historical and environmental information. A wide range of qualitative information can be included such as historic photographs and maps, previous reports, information from past storm events (e.g. newspaper records), and anecdotal information from long-term residents. • Field observations are useful to complement other forms of information but should be interpreted carefully given it is a single, or limited, point in time to avoid serious misinterpretation of longer-term coastal change.
Limitations:	• Typically requires more detailed assessments to support land-use planning decision-making. • If it doesn't include predictions of future coastal change then limited to present-day hazard risk.
Application:	• Identification of indicative locations or areas of coastline susceptible or potential susceptible to coastal erosion. • Informing and raising public awareness of coastal hazard issues.

Box 10 Examples of broad scale shoreline change assessments

A national overview of historical rates of open coast erosion and accretion for the New Zealand coastline (ca. 1880 – 1980) was produced by Gibb (1978). This provides a general picture of erosion and accretion patterns and relative rates for most of the open coast sedimentary coastal margins but is now more than 30 years since this analysis was done.





Example of the Coastal Sensitivity Index (Gibb et al., 1992) for selected beaches in the Bay of Plenty. The index was based on eight variables and applied to 110 locations around New Zealand to rank coast susceptibility to coastal hazards (incorporating coastal change, storm wave run-up and tsunami). Each of the eight variables was scored from 1 to 5 based on a set of criteria for each variable, and the index derived from the sum of the scores. A five scale ranking was used ranging from very low to very high susceptibility to coastal hazards.

Draft relative sensitivity to future coastal change for open, sedimentary coasts (including climate change). This has been derived from a national geomorphological classification of the coast using only information that is available at a nationally consistent level. It incorporates components of beach sediment type, geomorphic setting, hinterland characteristics, shoreline stability, ratio of sea-level rise to high tide range, wave and storm surge exposure due to climate change. A multi-criteria analysis was used to assess the relative influence of the different parameters and derive the relative ranking.

Available from Coastal Explorer:

http://wrenz.niwa.co.nz/webmodel/coastal

Basic coastal erosion hazard setbacks

Arbitrary coastal hazard setback distances on beach coastlines are now less common in New Zealand, although they are still used in many other countries. Whilst such approaches recognise the need for development setback, a one-size-fits-all is rarely practical given the variability in rates and processes causing coastal change within a region or section of coast.

Nevertheless where no or limited information on coastal hazards is available, and in regions where Local Authority resources are limited, they can play a role for the purpose of:

- Informing and raising public awareness.
- Guiding general setback provisions in rural areas where no other specific provisions have been incorporated.

A further "red flag" as to when more detailed assessment may be required.

On cliff coastlines where erosion is a one-way landward process, in the absence of more specific investigations, a "red flag" zone can be simply defined as a width from the top edge of the cliff of:

- Twice the cliff height (where erosion of the toe of the cliff is slow (less than about 5 m / 100 years).
- Twice the cliff height plus allowance for ongoing retreat over the planning timeframe (based on the average historic rate of retreat) where the erosion rate is greater than the above.

4.1.3 Building a qualitative understanding of coastal system behavior

Quantifying how beach and cliff coastlines change, and how the patterns and rate of change may be influenced by climate change is extremely difficulty. Coastal change is a complex process where coastal and river hydrodynamics, morphology, geology, sediment supply/deposition and in some cases human modifications all interact over multiple timescales (MfE, 2008), Figure 21. Further complicating matters, these processes are subjected to both positive and negative feedbacks within the coastal system, again all of which operate on a number of different spatial and temporal scales, and are compounded at river, estuary or harbour entrances and associated spits. Assessment of future movement in estuary or harbour shorelines due to both climate and environmental human change are challenging.

There is no one methodology or model that accommodates all the spatial and temporal considerations required to estimate how a coastline may change in the future over the decadal to centennial timescales of relevance to land-use planning. Nor is the science of coastal processes and prediction at a level of understanding yet to incorporate all these interactions in a fully quantitative manner. Rather a range of tools, models and methods need to be applied within the context of expert judgment and drawing on similar analogues elsewhere (heuristic approach) to estimate long-term coastal change (Whitehouse et al., 2009).

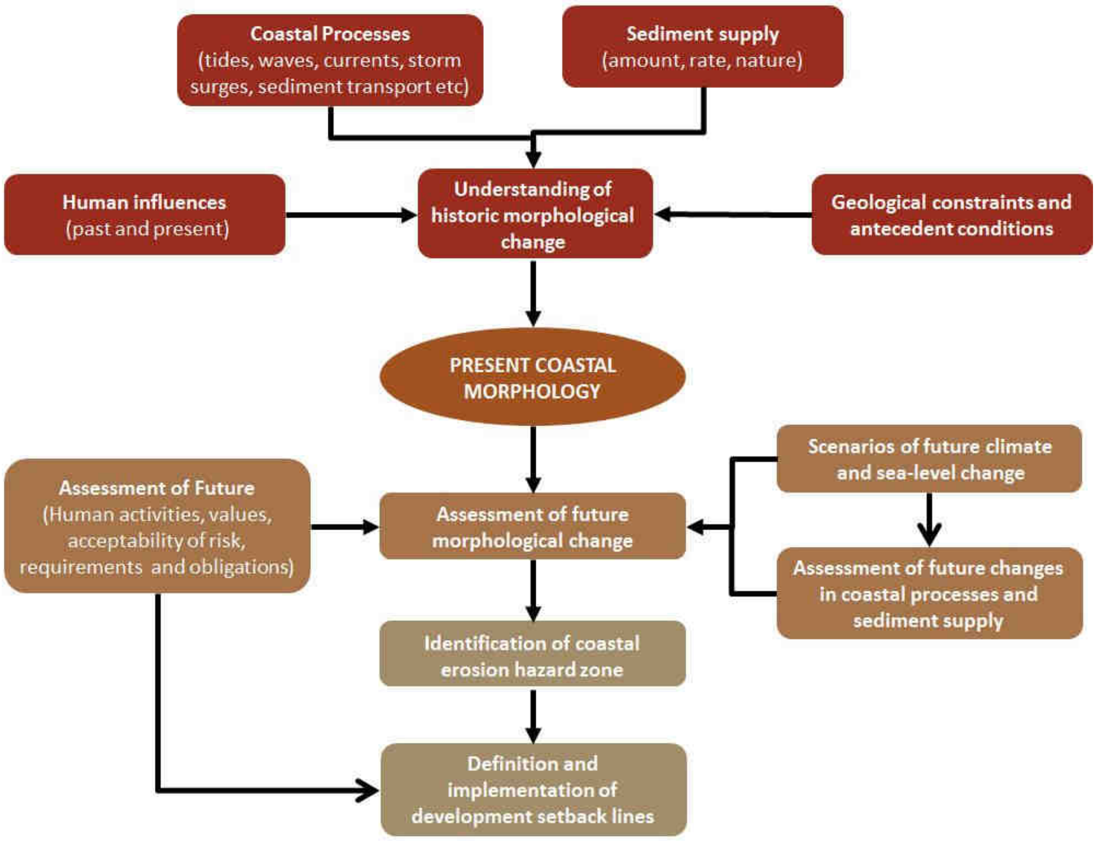


Figure 21 **Basic components of a coastal erosion hazard assessment relevant to the estimation of future areas potentially at risk from shoreline change as input to defining development setback zones.** Adapted from Pye and Blott, (2009).

As with coastal inundation, the development of conceptual behavioral models for a section of coast (often referred to as coastal or cliff behavioral units, compartments or cells) helps frame the understanding of the natural functioning of the coastal system as well as the pattern of human use and development and its influences on that system.

A conceptual model should aim to capture the key qualities of coastal-change behavior, giving qualitative insight into past shoreline changes and whether current shoreline behaviour and past changes are permanent, on-going or likely to reverse. In a coastal change context, it needs to capture what drives and controls both coastal planshape and cross-section profile response, including key sediment sources, pathways and losses, within the beach or cliff behavioural unit over differing timeframes.

Fundamentally a conceptual model forms the basis for the choice of methodology adopted and provides a critical interpretation of the outputs of the analysis (Whitehouse et al., 2009). A well-defined coastal behavioural model also provides a tool for assessing the implications of different management approaches.

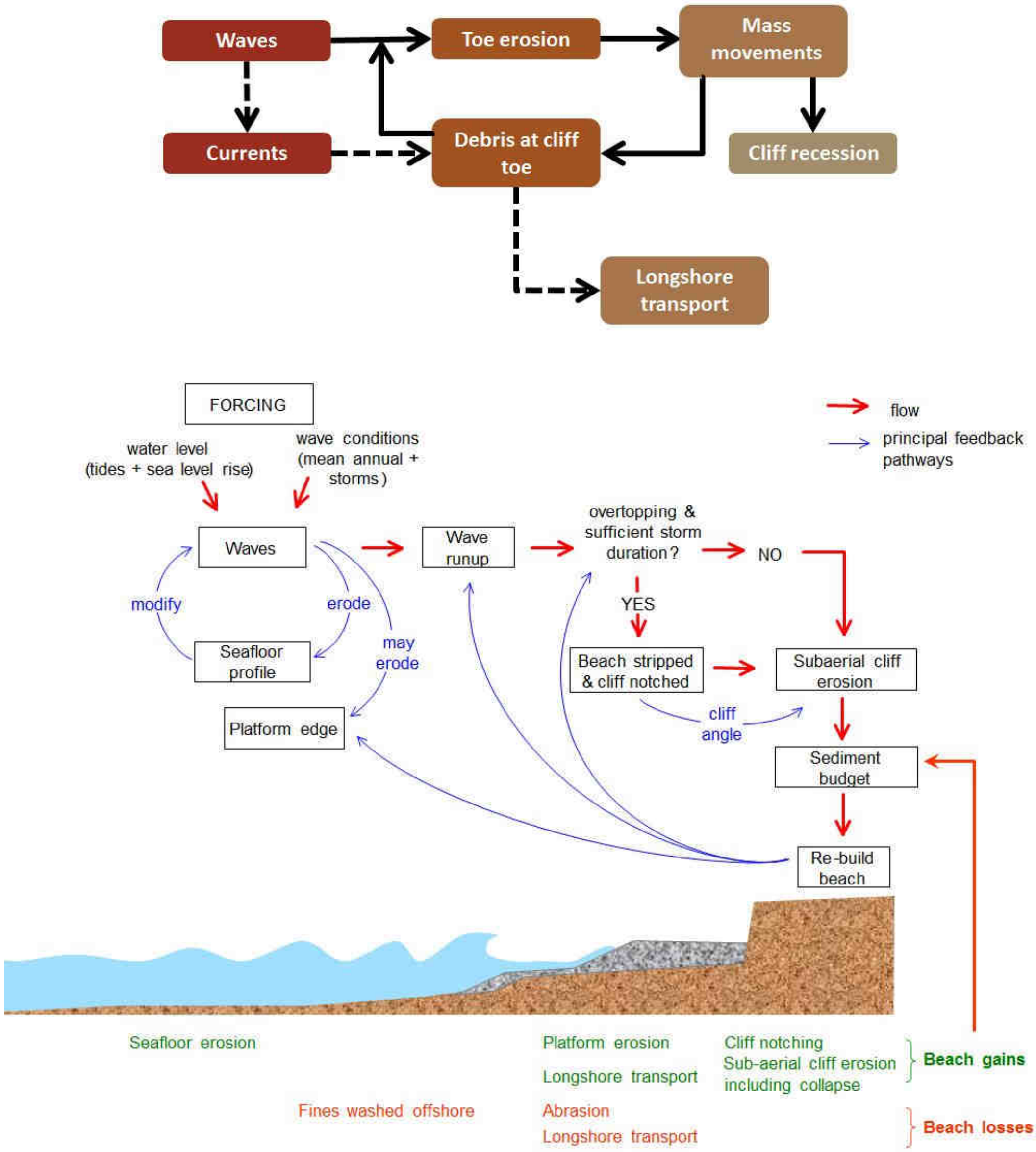


Figure 22 **Examples of a simple (top) and more detailed (bottom) conceptual model of cliff erosion processes in South Canterbury** (Courtesy Murray Hicks, NIWA).

4.2 Quantifying shoreline change

4.2.1 Introduction

Methods for assessing coastal change and prediction of future change in coastal morphology broadly fall in to three types (Whitehouse et al., 2009), Table 3.

In practice, all approaches typically straddle the boundaries between the general model types. No process-based models include all the physics involved in simulating morphological change with components relying on behavioural representations, and in many cases the potential for change of state will need to be considered in simulating long-term, large scale coastal behavior.

Table 3 Basic model types for assessing coastal morphological change (Whitehouse et al., 2009).

Model type	Key features
Behavioural models of coastal change	• Aims to reproduce observed behaviour of a feature of morphology, for example the position of the shoreline • Does not reproduce the physical processes that cause the observed changes • Assume future behaviour is similar to that of the past over which the model was calibrated. • Simple, quick and robust.
Process-based models	• Based on representations of physical processes. • Typically include forcing by waves and/or currents, a response in terms of sediment transport, and morphology updating. • Typically aim to simulate either cross-section profile or shoreline planshape change. • Assume that the feature or elements being modelled will be preserved and will not change state during the course of the modelling. • Modelling results often subject to a considerable degree of uncertainty. • Use requires a high level of specialised knowledge of science, engineering and management. • Computer resources often limit model simulations to short timeframes.
Change of state models.	• Used where there is a possibility of change of state, e.g., barrier breaching or inlet stability.

Furthermore, no one methodology or model accommodates all the spatial and temporal considerations typically required within a coastal hazard assessment (Figure 4). Hybrid approaches are a means of integrating methods or models that address different spatial or temporal scales.

The choice of a particular approach for a particular situation will be influenced by the physical characteristics of the environment, the severity of the current or potential hazard risk, the volume and form of data available, computer modelling resources, and (sometimes most significantly) available budget.

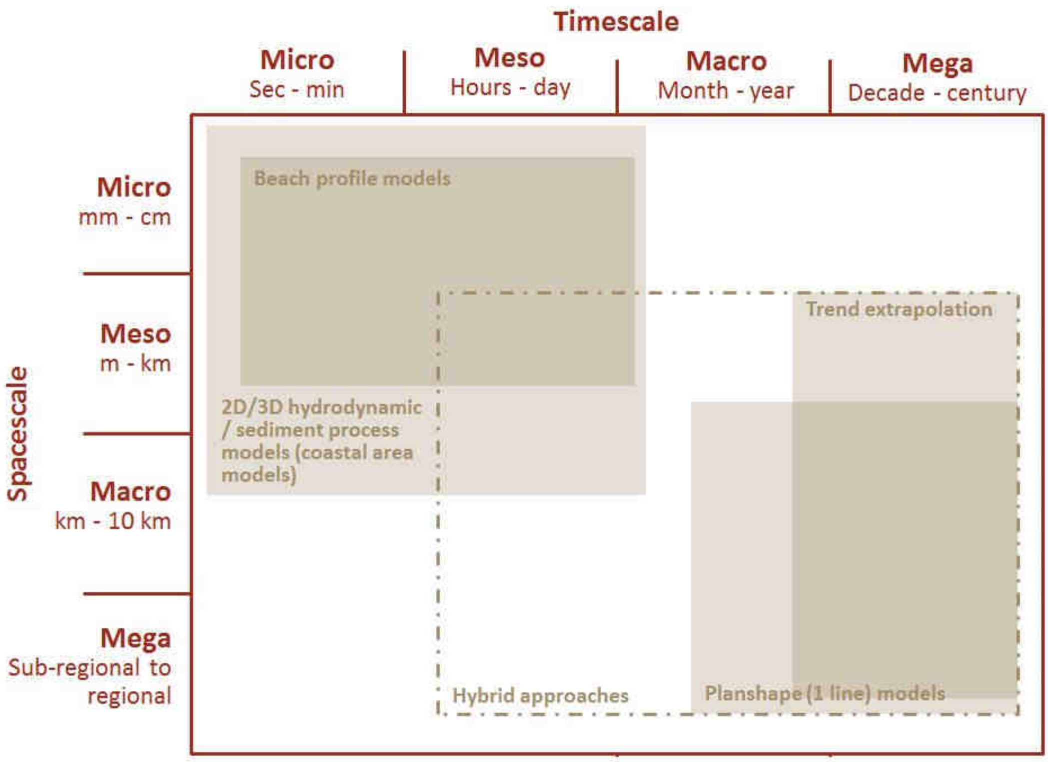


Figure 23 **Spatial and temporal classification of coastal morphological change models.** (Adapted from Larson, 2005).

4.2.2 Historical shoreline change

Most approaches to determining future coastal change adopted in New Zealand tend to focus on behavioural models, applied deterministically, to extrapolate past shoreline trends and fluctuations. Occasionally the approach is also supported by process-based models (typically to assess storm-related erosion extents). Approaches adopted also tend to focus on a profile, or profiles, perpendicular to the shoreline, with longshore sediment transport and its potential influence on planshape changes rarely considered in such analysis.

Over the timeframes of interest for developmental planning (e.g. 100 years), shoreline change is typically considered a combination of short-term fluctuations due to episodic events, medium term dynamic fluctuations, and long-term trends (Table 4 and Figure 24).

Dynamic fluctuations in the position of the shoreline can occur over timescales of hours to decades, and in some environments, centuries (Table 3). These movements are generally associated with open coast beach storm erosion and recovery, climatic cycles and near entrance estuary dynamics (Figure 25). The area over which a shoreline fluctuates is commonly referred to as the dynamic envelope.

Table 4 Timeframe components of coastal change and typically examples.

Change type	Typical examples	Type of coastline typically affected			
		Beach	Estuary / harbour shore	Tidal inlets & river mouths	Cliffs
Short-term storm erosion or cliff slope failure (< 5 years)	• Storm waves or sequences of storms	✓	✓	✓	✓
	• Spatial variability and rhythmic topography, such as sand bars and beach cusps	✓	✓	✓	✓
	• Cycles adjacent to tidal inlets and river mouths	✓	✓	✓	
	• Wave climate cycles – shoreline rotations or sediment "sloshing" back and forth along a coast.	✓	✓	✓	
Medium-term dynamic fluctuations (5 – 30 years)	• Climatic cycles usually associated with El Niño Southern Oscillation (2-5 years) and Interdecadal Pacific Oscillations (20 – 30 years)	✓	✓	✓	
	• Multi-year or decadal cycles of sand exchange between ebb delta and adjacent beaches	✓	✓	✓	
	• Sand/gravel slugs from rivers initiated by earthquakes, storms, major land-use change, or dredged-material disposal.	✓	✓	✓	
Long-term shoreline or cliff migration (> 30 years)	• Climate change and sea-level rise	✓	✓	✓	✓
	• Long-term shoreline adjustments	✓	✓	✓	✓
	• Tectonics or subsidence of large sediment basins	✓	✓	✓	✓
	• Natural or human-driven changes in littoral budget, e.g. dams on rivers or harbour breakwaters.	✓	✓	✓	

In many open coast (particularly sandy) beach and estuary/tidal entrances, short-term erosion and medium term dynamic shoreline fluctuations can represent a significant portion of the overall coastal erosion hazard, for example:

- Major storm events or sequences of storms where significant sand or gravel beach and/or dune erosion can be experienced as sand or gravel is redistributed offshore and/or alongshore. In quieter periods (weeks, months, years) between storms, sediment can return onshore rebuilding beach and dune levels.
- Broader climatic patterns and cycles (such as annual summer/winter storm patterns, El Niño Southern Oscillation and Inter-decadal Pacific Oscillation) can drive annual inter-annual and inter- decadal patterns of erosion and recovery or accretion. These changes can occur over periods of decades but do not necessarily represent a permanent change in average shoreline position (Bryan et al., 2008).

- In some coastal settings, dynamic shoreline change can occur over decades and even centuries, often related to episodic events, such as eathquakes or volcanoes, resulting in a “pulse” of sediment supply to the coast (e.g. West Coast North Island) or subsidence of the coastline to change the relative sea level, for example the coast south of Napier. These cycles can be difficult to identify and predict, but have important implications for managing local subdivision and development.

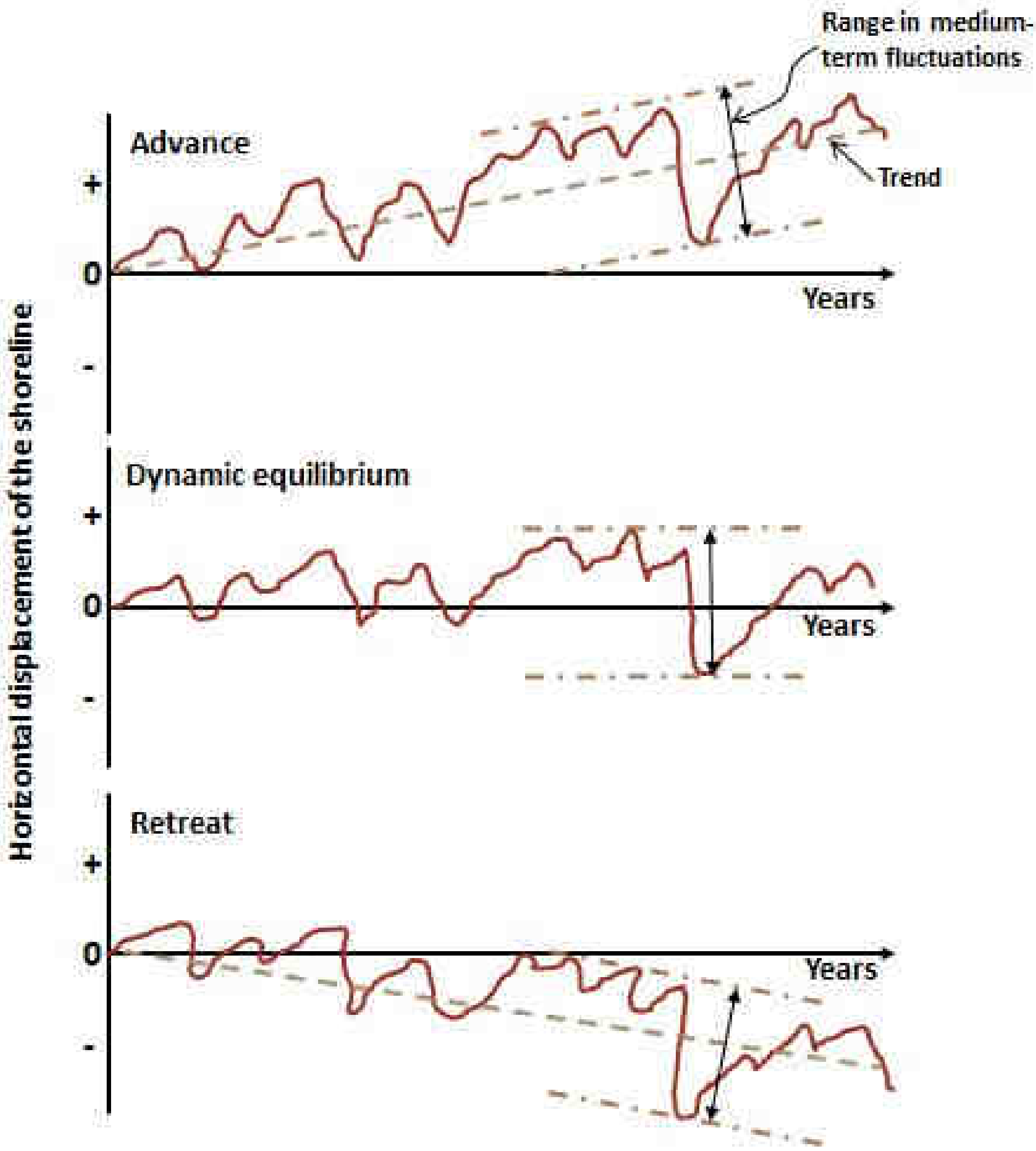


Figure 24 **Conceptual diagram showing both medium term fluctuations and trend in shoreline displacement for a prograding coast (top), dynamic equilibrium coast (middle) and retreating coast (bottom).** Adapted from Gibb and Aburn, 1986)**.**

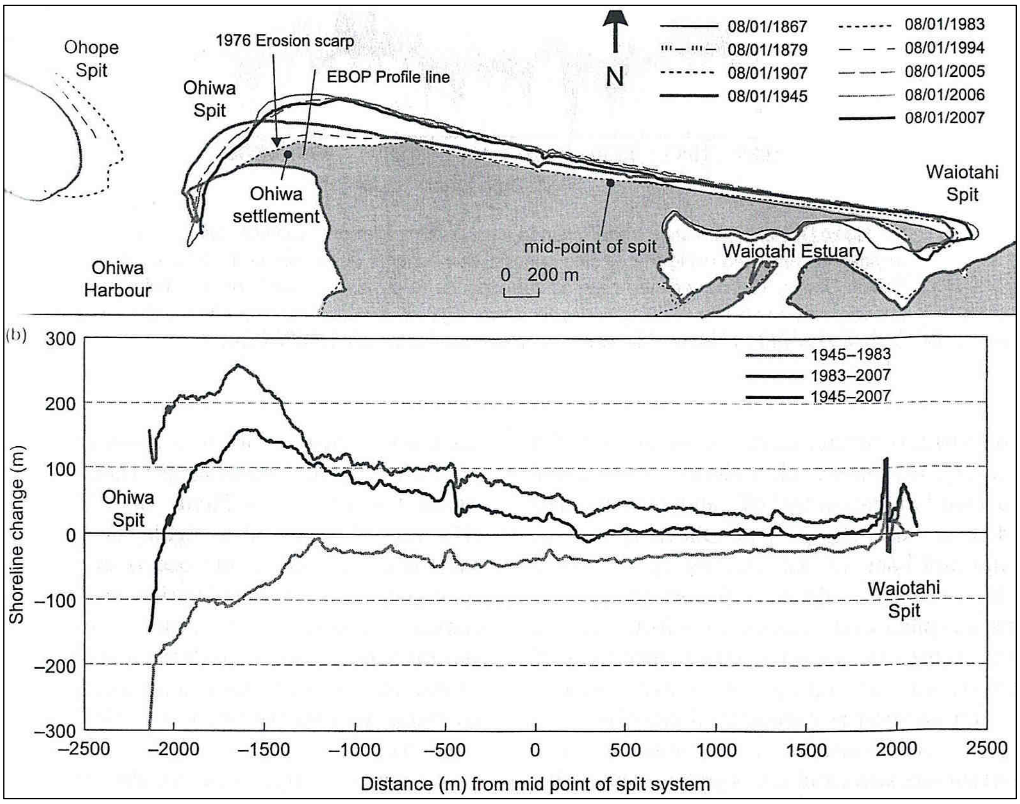


Figure 25 **Shoreline position between Ohiwa and Waitoahi spits. Top: Geo-referenced historic shorelines. Bottom: analysis of shoreline change a 1 m intervals along the coastline.** Adapted from Bryan et al, (2008).

Assessing long-term shoreline change trends

For the purpose of erosion hazard assessment, a long-term trend is defined as a progressive or net trend for shoreline change over the relevant planning horizon (typically 100+ years as required by the NZCPS, 2010).

For cliffed and some estuarine coasts, shoreline change tends to be a one-way erosion process. However, for many soft open coast shorelines and close to tidal inlets, there can be both landward and seaward movements in shoreline positions, over varying spatial and temporal timescales, and it can be difficult to reliably separate long-term trends from dynamic variability as:

- Dynamic variability is often large relevant to any long trends (Bryan et al., 2008).
- Many/most shoreline position records or even aerial photographs are of insufficient time period to accurately extract dynamic shoreline change from long term trends with any certainty.
- Shoreline change data is often inadequate, for example temporally sparse or irregular data, or different or ambiguous shoreline features captured in surveys (for example high tide line, dune toe, or vegetation line).
- Patterns of long-term change can be highly spatially variable.

If the available record is too short, the mis-interpretation of dynamic fluctuation as long-term shoreline change can result in significant error, particularly if rates of historic change are then used to project potential future change. Where dynamic fluctuations in shoreline position occur, identifying and separating long-term change from such fluctuations is critical if such information is to be used to define future coastal hazard zones.

Analysis of shoreline features extracted from historic aerial photographs, surveys and maps is the method most widely used in New Zealand to quantify long-term shoreline change and medium term fluctuations (Table 5). Note, old surveys typically captured mean high water and if used it is necessary to go back to the original survey books to verify how mean high water was defined. Analysis of beach profile datasets can also contribute where a sufficient length of dataset is available, but there are few such datasets with greater than 20 to 30 years of records.

Table 5 Typical data requirements for long term trend assessment and indicative positional errors.

Typical data requirements	Indicative positional error for shoreline features (± m)
Geo-rectified and ortho-rectified aerial photographs	Metres to 10s of metres
Geo-rectified and ortho-rectified high resolution satellite imagery.	Metres
Geo-rectified historic cadastral maps and surveys	10s of metres
Geo-rectified LiDAR data	Metres
Survey-grade Global Positioning System (GPS) equipment	Metres
Beach profile datasets	Metres

Given the normal paucity of historic shoreline data, separating long-term trends from medium term and/or episodic storm fluctuations based on the available data typically comes down to heuristic reasoning, ground-truthed against the conceptual model and qualitative information on past coastal change (for example surface and sub-surface geomorphic information, archaeological information, historic photographs, anecdotal accounts and from similar analogues elsewhere).

Shoreline change is typically assessed by mapping the position of consistent natural shoreline features within each image, map or survey. The features mapped will depend on the specific information contained on the imagery, maps or surveys available. It is preferable to use a consistent and easily defined features, such as a cliff edge, vegetation line or dune toe, or back of shingle berm, rather than one where there is the potential for further uncertainty as to how it was defined (such as a mean high tide mark or mean high water spring position).

In estuarine, tidal inlet and harbour situations, change in shoreline position is often driven by change in intertidal and sub-tidal morphology. Mapping change in intertidal areas, channel positions, and estuarine vegetation (for example mangroves) can assist in understanding morphological changes occurring in estuaries.

Mapping other features within the immediate coastal margins, such as infrastructure and buildings, is also useful to capture the amounts of human assets at potential risk from coastal hazards have also changed over the historical assessment period. In many cases it is the changes in human development that drive changes in coastal hazard risk rather than changes in hazard exposure.

With modern GIS tools, accurately geo-referencing historical imagery, maps and surveys, correcting any image distortions (ortho-rectification), and mapping the selected shoreline features is now a relatively straightforward exercise. Furthermore there are also specific GIS tools, such as the Digital Shoreline Analysis System (Thieler et al., 2009), for analysis of shoreline changes.

Box 11 Geo-rectification and ortho-rectification of aerial and satellite imagery

Where true distance measurements are to be made from aerial or satellite imagery or from historic surveys and maps, two correction processes are important. With the availability of GIS tools, such corrections are now more straightforward and image-related errors reduced.

- **Geo-rectification** is the digital alignment of an aerial or satellite image, map or survey plan with a number of corresponding control points on a baseline map or image. Control points can be known survey benchmarks or any common reference points on each image or map, such as road intersections.
- **Ortho-rectification** is the geometric correction of an aerial photograph or satellite image so that the spatial scale over the entire image is uniform and has the same lack of distortion as a map. The process removes distortions in the image introduced by topographic relief, lens distortion and camera tilt.

Where linear long-term trends can be derived from the datasets, the approaches used tend to be relatively simple:

- End point analysis: where an average trend is derived based on a direct comparison between the earliest and latest shoreline position. This method is limited in application and should only be applied to coastlines where:
  - There is little dynamic variability.
  - Trends are relatively consistent over time.
  - There is at least 50 years between the earliest and latest shoreline positions,
- Linear regression: where an average trend is derived from fitting a linear regression curve through a shoreline position dataset (typically measured from a defined common baseline). This is a preferable approach to end-point analysis but requires several reliable records of shoreline position over a period of time, ideally at least 50-100 years (Figure 26).

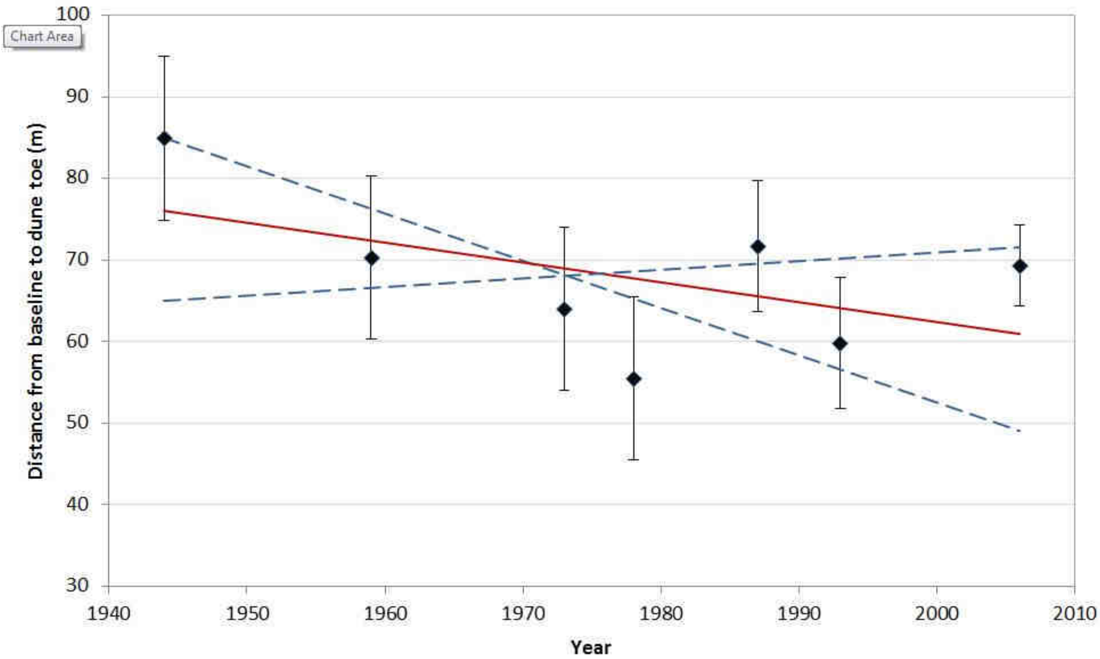


Figure 26 **Linear long-term trend for a single location from seven sets of aerial photographs.** The black points show the derived position of the dune toe relative to a baseline, the error bars the associated measurement/scale error for each of the datasets. The red line shows the average linear regression, with the dotted blue lines the maximum and minimum change rate taking into account the data uncertainties.

Irrespective of methodology used, good practice process in determining a long-term trend includes that:

- The trend is considered in the context of any short and medium-term dynamics. The data used needs to adequately represent the different states of the shoreline, and is not heavily weighted toward a particular shoreline state (due to the temporal coverage of the data), and therefore suggest and apparent trend that may not be accurate. Ensuring that results from analysis of datasets concur with the conceptual understanding of the coastal system.

- The length of the dataset used to calculate long-term trends should be in excess of 50 years and ideally be at least equivalent to the length of the intended planning period as well as being longer than any known cycles/patterns of shoreline change.

- Aerial and satellite imagery, survey and map information are properly geo-rectified and where necessary ortho-rectified. The process undertaken to properly position historic datasets against a common base map or image, and to correct image distortions, should be clearly defined.

- The baseline from which all shoreline feature measurements are made is clearly defined.

- Consistent natural features are captured from each of the historic datasets (such as the cliff edge, vegetation line or dune toe).

- Where significant medium-term dynamic variability exists, the impact of this variability in the context of the total period of the historic shoreline dataset needs to be clearly outlined and the potential impact this may have on long-term trends defined.

- Potential longshore variability in shoreline change information is presented and communicated in the context of a section of coast, such as along a beach or cliff behavioural unit, rather than just focussing on change at a single location (Figure 27).

- No significant change of state has occurred during the period of the analysis that has a significant impact on the rate of shoreline change. For example, large changes in river or nearshore sediment supply due to earthquakes, catchment land–use change or damming or rivers, coastal defences or other coastal structures, beach nourishment, dredging or nearshore sand extraction. In such cases more specific analysis of the temporal changes in the inputs, distribution and losses of sediments to and within the coastal systems needs to be considered.

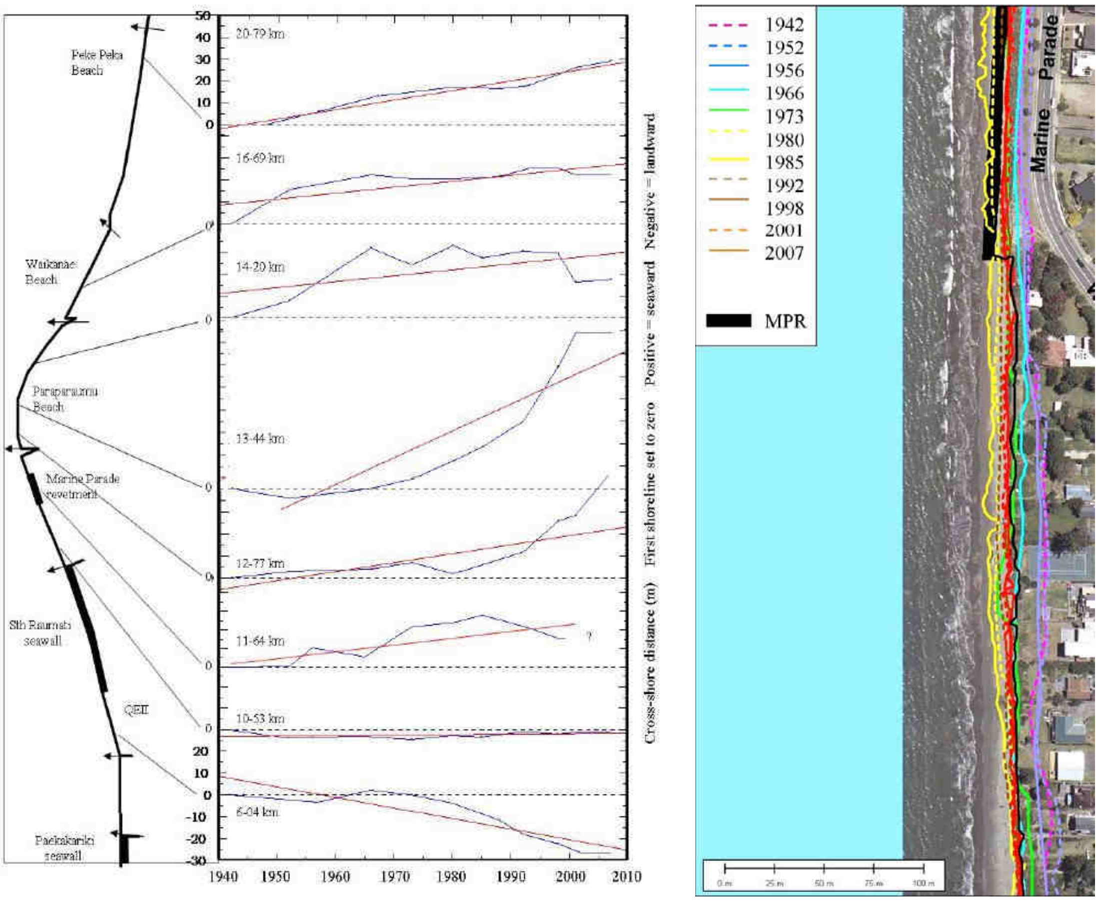


Figure 27 **Example of linear shoreline change trends for various points (left), and shoreline position at various times between 1942 and 2007 for a section of the Kapiti coast.** Source: Shand (2010).

Shoreline fluctuations and episodic storm erosion from past measurements

A range of methodologies are commonly employed, depending on the particular physical situation, the key drivers and temporal and spatial nature of shoreline fluctuations. Typically this aims to ascertain the "maximum likely fluctuation".

Where historic shoreline information is available direct analysis of measured data is commonly used to define potential shoreline position variability:

- Analysis of shoreline position features extracted from aerial or satellite imagery, historic surveys and maps: where a number of reliable records of shoreline position are available within the period of available records an assessment of potential dynamic fluctuations based on the variability around the long-term trend can be made.
- Analysis of beach profile data: where the horizontal variability of a particular level (such as the dune toe or Mean High Water Spring level) is assessed from a long-term beach profile dataset. Depending on the length and frequency of the beach profile record, different temporal fluctuations may be able to be identified. However, in practical application where total or "maximum likely variability" is required to be identified from beach profile dataset a number of assumptions are typically made including:
    - Over a long time period (decades), variations in the position of the shoreline are assumed to be normally distributed around the long-term trend.
    - An estimate of the likely range of shoreline position fluctuation is often assumed to be three times the standard deviation of the observed data.
    - As the beach profile or shoreline position data only provides a snapshot at a particular point of time which may not capture shoreline extremes, some expert judgement and factor of safety is often applied.

Whilst analysis of existing datasets, such as those above, provide a reasonable baseline to define an indicative magnitude of shoreline variability there are significant limitations:

- Beach profile datasets in New Zealand are generally neither long enough and/or frequent enough (annually is generally too sparse but can give an indication) to adequately capture the scale of variability.
- Beach profile measurements would need to capture both the major storm profile changes as well the more frequent small to mid-range erosion events to adequately fit a statistical distribution. The commonly made statistical assumptions, outlined above, are a judgement call and may not be robust, but an explanation should at least be documented

However, such data can provide calibration and verification for modelling approaches to assess shoreline change.

Modelling approaches to defining shoreline fluctuations and episodic storm erosion

For open-coast beaches there are a range of modelling techniques used to simulate either profile or planshape shoreline change for a range of different temporal and spatial scales (Figure 23). There is no one approach that will simulate all the processes with a classification of some examples of the common modelling types shown in Figure 28 and outlined further below.

In selecting appropriate models to use consideration needs to be given as to what results are actually required from the model. For example, is it just simply to gain an order of magnitude understanding of potential shoreline fluctuation or storm erosion, or to develop a more detailed understanding of the various processes contributing to shoreline change and the impact potential future changes in these processes may have on future shoreline change.

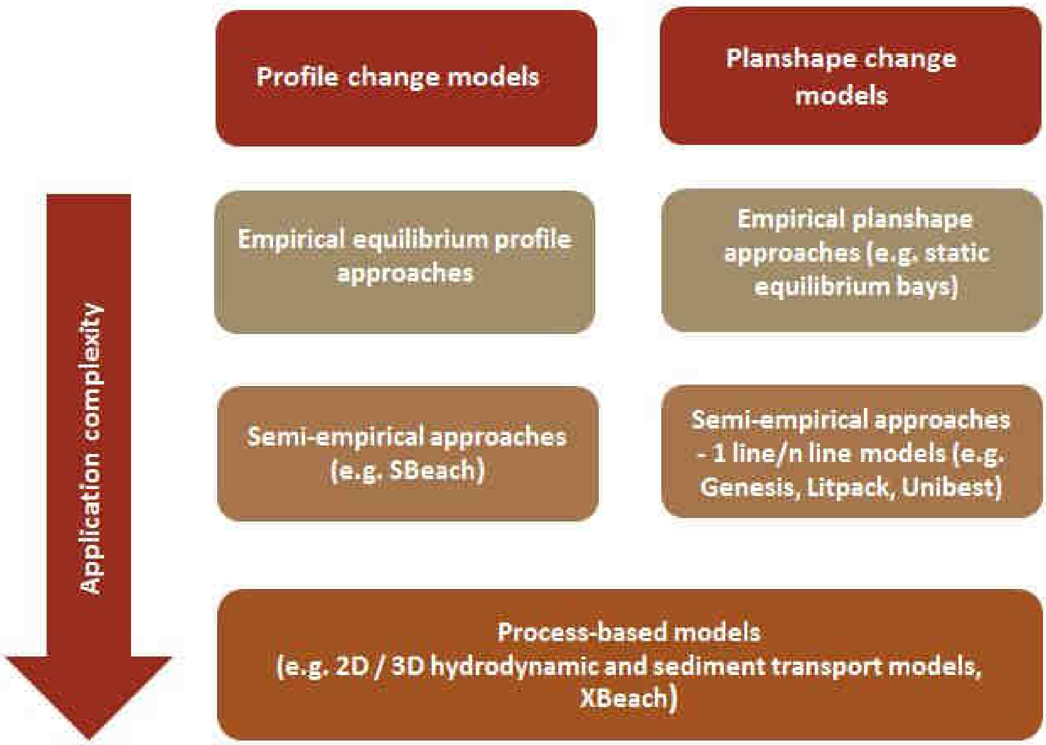


Figure 28 Examples of model types used to assess shoreline changes

The most complex model is not necessarily always the best option. Indeed in general terms the best model option is typically one where it has been effectively calibrated and verified for a particular coast, for example against measured shoreline change or beach profile datasets. Where models are to be used in a shoreline change assessment, calibration and verification should always be a fundamental component. If calibration and verification are not possible then model results should can only treated as indicative to an order of magnitude of the coastal response and used with caution.

Box 12	Model calibration and verification

- **Calibration** is the process of tuning the model to provide the best fit to measurements over the same period
- **Verification** involves leaving the calibrated model parameters untouched and running the model for a different period to assess goodness of fit to measurements.

There are many different examples of the types of models outlined below, developed for different physical situations or ranges of validity. In using and applying any models for shoreline change assessment the following must be clearly communicated:

- What the models are to be used for and why the modelling approach selected is appropriate, in the context of the conceptual understanding of coastline under consideration.
- What assumptions are being made, limitations, range of validity and uncertainties there are for the models used and associated impacts on the intended use of the models.
- How sensitive model predictions are to each model parameter and which ones are the most sensitive.
- How the models were calibrated and verified and associated implications for the intended use of the models including any limitations.
- Model predictions are presented with uncertainty bounds where possible.
- Whether there is the potential for a change of state, for example a dune or shingle barrier being breached, and the implications this may have on model use and the potential outputs.

Behavioural or empirical models

Behavioural or empirical models simulate beach profile or shoreline planshape position change without attempting to simulate the key processes that cause the change. The models are simple and quick to implement and where calibrated/verified and used within the range of validity the expressions were developed for, can be robust. However, such models produce a final result without any information of the evolution of the process and typically assume that any future response is similar to the behaviour that the model has been calibrated with (Whitehouse et al., 2009).

Common examples of model types include:

- Geometric profile models for maximum sand beach or dune recession due to the storm tide level (Komar et al., 1999, 2001). This is a widely used and simple approach to estimate the maximum extent of foredune retreat. The model translates the existing beach/dune form landward in response to elevated storm water levels according to the relationship shown in Figure 29.

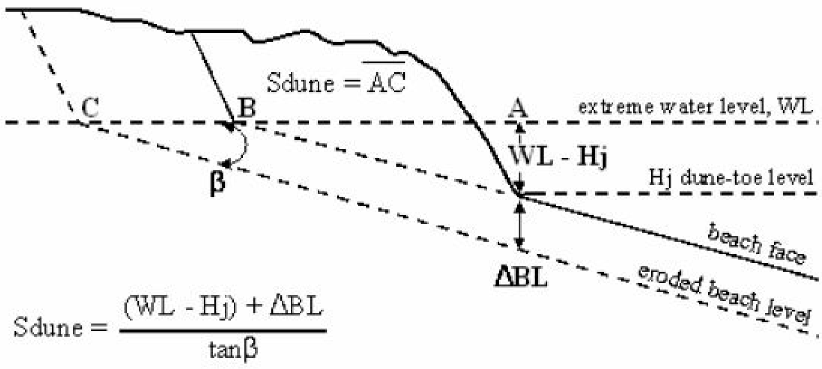


Figure 29 Geometric foredune erosion model (Komer et al, 1999, 2001).

Where:

- Sdune is the maximum extent of foredune retreat due to storm erosion;
- WL is the storm tide level during the storm event;
- Hj is the elevation of the toe of dune at the start of the storm;
- ΔBL is a vertical shift in the beach profile that can result from the presence of a rip current, in effect a safety factor;
- tanβ is the beach slope.

The model assumes that erosion is not limited by storm duration and can continue to the limit of wave run-up. If the method is calibrated against storm cut profiles in the beach profile record, it can provide a very useful estimate of the extreme erosion possible at that site. This method is generally considered to be relatively precautionary as it estimates maximum possible erosion for a particular storm tide level (see Section 3) rather than the erosion that is likely to occur given that most storms are limited in duration.

- Sand beach/dune or shingle beach equilibrium profile response models. For sand beaches and dune systems there are a wide number of models that use the concept of an equilibrium profile in response to a defined storm condition (for example the DUROS model (Vellinga, 1986; van Gent et al., 2008)). The typical approach used in equilibrium profile response models is summarised in Figure 30.

  For gravel and shingle beaches, the SHINGLE model (Powell, 1990) provides an estimate of the dynamic equilibrium beach profile that will form for the same input storm-related hydrodynamic boundary conditions and beach parameters as outlined in Figure 30. Further approaches are outlined in Stripling et al, (2008).

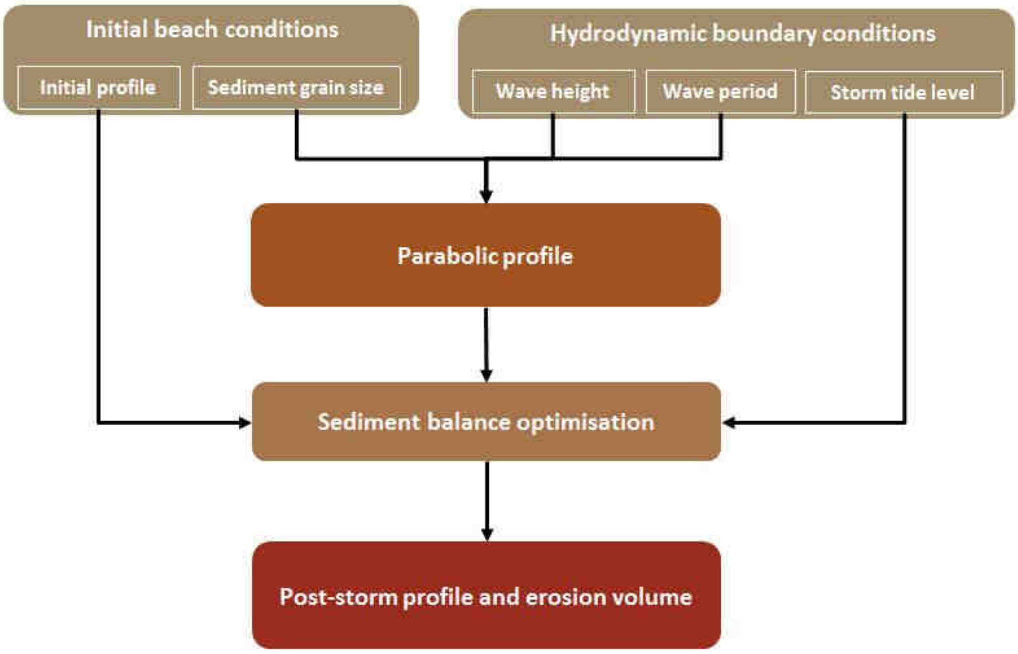


Figure 30 Typical input requirements and process for equilibrium profile response models

These approaches again typically assume that storm duration is not limited and that there is conservation of beach volume across the profile. As all these models have typically developed from a limited number of field or physical model measurements, care also needs to be taken to ensure the models are used and applied within their specific range of operating conditions.

- Equilibrium planshape models. For pocket and headland bay beaches where a curved beach shoreline is bound by a rocky outcrop or headland or where offshore rock reefs or structures influence the lee planshape of a beach, a wide range of expressions have been developed to characterise the curvature of the beach in response to the predominant incident wave direction (see Whitehouse et al., 2009 for a summary). The most commonly applied approach is parabolic shape equation (Hsu and Evans, 1989) which links the shoreline shape to the influence of the headland or engineering structure on wave diffraction. Where mean wave direction is known to vary, from year to year or due to varying climatic conditions, such as ENSO, a simple estimate of the variation in average shoreline planshape position (not storm erosion position) can be made.

- Tidal inlet / estuarine empirical models: There are a wide range of empirical techniques typically developed to assess long-term (decades to century) tidal inlet stability in relation to mouth cross-sectional area and the volume of water entering and leaving the estuary or inlet (tidal prism) which influences tidal inlet sediment flushing ability. The approaches are typically known as regime relationships and assume that the estuary will achieve some form of dynamic equilibrium and that this equilibrium relationship can be described (Pethick and Lowe, 2000). These approaches can provide a useful foundation to understanding the relative influence of different processes and the sensitivity to major natural perturbations including inferring the possible effects of sea-level rise (Whitehouse et al., 2009). A wide range of approaches are available and the choice of approach used must be based around a sound understanding (conceptual model) of the hydrodynamic and sedimentary processes occurring. A review of many of the approaches are provided in EMPHASIS (2000) and in a New Zealand context by Hume and Herdendorf (1988), Hume (1991) for tidal inlets.

Semi-empirical models

Semi-empirical models attempt to simulate, using empirical approaches, the key physical processes resulting in beach profile or shoreline planshape position change. They tend to be more versatile than empirical approaches outlined above as they include more of the variables influencing beach changes and more realistic representation of the change processes.

- Beach profile models. Beach profile models extend across the dune/beach perpendicular to the shoreline and assume longshore uniformity. A commonly used model of this type is *SBEACH* (Larson et al., 2004). Such models typically quantify beach profile response under storm conditions due to cross-shore sediment transport and unlike purely empirical approaches can account for the influence of the initial beach profile and storm duration on the resultant profile response. In some cases they can also simulate the storm-related movements of nearshore sand bars.

  Such models generally include empirical representation of various nearshore wave processes, such as wave shoaling, wave energy loss due to breaking and bottom friction and resulting cross-shore wave-induced currents and sediment transport. They can incorporate tidal currents and in some cases provide estimates of the cross-shore distribution of longshore transport. If properly calibrated such models can provide realistic representation of storm erosion response but are not capable of simulating post-storm beach recovery and should only be used to assess episodic storm response.
- Beach planshape models. Beach planshape models aim to simulate the longshore position of a particular beach contour (1-line model) over a spatial scale of kilometres to 10s of kilometres and temporal scale of years to decades. They typically assume a constant beach profile, although some have been extended to model a number of different contours, known as n-line models. Planshape models simulate the longshore transport of beach sediment (sand or shingle, but assume a single beach sediment size) due to wave action and the effect that this has on the position of the shoreline (or simulated beach contour). They typically require an input timeseries of directional wave conditions, ideally over a period of a number of decades, at an offshore model boundary (e.g., from wave hindcasting, see Section 3)

and normally have some basic nearshore wave transformation capabilities to the point of wave breaking on the beach, for example wave refraction and shoaling.

Such models can be used to assess:

- The potential variation in beach position over a number of decades.
- Gross and net longshore sediment transport rates.
- Sensitivity of beach profile position to changes in key sediment sources (e.g. cliff erosion or river input) or changes in wave climate.
- The effectiveness of beach nourishment or the influence of engineering structures, such as groynes, seawalls and offshore breakwaters, on beach response. The effects of such structures are typically represented empirically within such models.

As with all other models, the model parameters need to be calibrated and this is typically achieved by comparing simulated beach planshape change with available shoreline position of beach profile data over the same time period. A commonly applied model is *GENESIS* (Hanson and Kraus, 1989) but there are a wide range of similar commercially available models of this type.

Where determining open coast sediment budgets is important, planshape models are often used in conjunction with other models (such as hydrodynamic models – see below) to develop an understanding of inputs, redistribution and outputs of sediment from a beach or coastal unit.

Process-based models

Process models aim to describe the various physical processes and interactions occurring as a means of simulating, in the context of this report, morphological changes to specified hydrodynamic conditions.

Process-based two dimensional (depth averaged) and three dimensional hydrodynamic and sediment transport models are frequently used to understand detailed short-term (tidal cycles to months) hydrodynamic patterns and associated mud or sand sediment transport pathways, erosion and accretion of intertidal and subtidal estuarine and coastal areas. Hydrodynamic modelling can involve separate current-velocity and wave modelling to provide input to a sediment-transport model but increasingly coupled current/wave modelling is becoming more tractable.

Coastal area models have been used to determine longer-term morphological change (years to decades) but the computational requirements, typical limitations in calibration and verification, and assumptions and simplification that often need to be made to simulate long timeframes can introduce considerable uncertainties. The use and application of such models in such a context therefore needs to be carried out by very experienced coastal modellers.

For beach response there are few process-based morphodynamic models that are robust enough to simulate the range of dynamic responses of beach systems to storm events. *XBEACH* (Roelvink et al., 2009, 2010) is a recently available two-dimensional coastal area model which:

- Simulates wave propagation, far infragravity waves and mean flow, sediment transport and morphological changes of the nearshore area, beaches, dunes and backbarrier during storms.
- Can be used by defining particular input hydrodynamic conditions (e.g. a particular storm event) or driven by boundary timeseries conditions from wave and storm tide models or datasets.
- Enables the evolution of seabed and shoreline morphology to be updated within the model simulation and can simulate the overwashing and breaching of beach barrier sections.
- Can be used in either profile or coastal area (i.e. 2 dimensional) mode.

As the model solves coupled 2D horizontal equations for wave propagation, flow, sediment transport and bottom changes, for varying (spectral) wave and flow boundary conditions it can account for variation in long waves caused by wave grouping. This can be responsible for most of the swash waves that actually hit the dune front or overtop it. Because of this innovation, and if adequately calibrated, XBeach should be able to more robustly model the development of the dune erosion profile and to predict when a dune or beach barrier will start overwashing and breaching.

The application of all the above models to define potential shoreline variability and storm-related erosion extents is typically done in a deterministic manner. Assumptions tend to be made where, for example maximum storm erosion is based on the largest measured historical event, or modelled using a particular historic storm event (for example Cyclones Fergus and Drena are commonly used for north-east coastlines of the North Island). However, this tends to be a limitation as it excludes the potential for two or more independent but closely spaced events. For example, where two events of equal magnitude occur closely together, the resulting erosion is typically greater than if they were separated by months or years and the beach had time to recover between the two events (Callaghan et al, 2008).

4.3 Defining future coastal erosion hazard

4.3.1 Current approaches

Many different approaches have been adopted by New Zealand practitioners to predict potential future coastal erosion hazard. Despite a variety of terminology used, all are typically a variation of the same general approach involving a simple addition of some or all of the following components:

- Extrapolation of the calculated long-term erosion rate over the future planning timeframe.
- Maximum assumed potential storm erosion and/or other fluctuations.
- A dune, cliff or other setback factor.
- Additional retreat of the shoreline due to sea-level rise or other climate change influence.
- A factor of safety which is typically used to incorporate uncertainties in the methodology and is usually defined based on heuristic reasoning.

Dune, cliff or other setback factors

In addition to the long term erosion, storm erosion and other short to medium term fluctuations typically defined from analysis of measured data or numerical modelling, most practitioners also apply some form of "dune" or stable slope factor:

- For dune coasts this provides sufficient additional width to provide for the unconsolidated nature of the sediments and the tendency for a facetted dune face to erode to a stable angle following storm erosion. This factor has traditionally been calculated by observing the natural angle of repose of loose sand or applying a universal value (typically approximately 30 degrees).
- For gravel or shingle beaches this is often related to width to the beach crest position or the backshore of the beach crest.
- For cliffs this is often related to the cliff height and is based on the geomorphological nature of the cliffs and angle of stable slope after episodic failure events.

Incorporating the impacts of sea-level rise

The response of a shoreline to climate change will primarily depend on sea-level rise, the wave climate, and for beaches, the sediment budget (the ongoing supply, redistribution and losses of sediments).

Application of a well-constructed conceptual model of the coastal or cliff behavioural unit can also help frame an understanding of the potential influence that sea-level rise and/or other climate factors will have on the future cross-sectional profile and planshape response of a section of coast (Box 13). Similar types of coast will not always respond in the same way and consideration needs to be given to not just change in the hazard drivers (which can include non-coastal-related drivers such as rainfall changes affecting the geotechnical response of cliffs) but for example also to:

- Potential changes in state (for example overstepping of a gravel barrier), and interactions with other coastal hazards such as inundation (see Section 3).
- Specific impacts of potential changes in beach (and dune) sediment budgets (Pye et al., 2007).

Understanding coastal morphological response to climate change and sea-level rise is limited, other than in very general terms. This is reflected in the simple empirical methodologies typically applied to account for the effect that sea-level rise will have on shoreline change. For sand and gravel beaches these approaches generally assume that sea-level rise will cause an additional landward movement of the beach profile (relative to any existing lateral movements in the beach profile if no sea-level rise was occurring).

Box 12 Examples of a hazard zone formula for a beach (Tonkin & Taylor, 2004)

Hz = (ST + SE)sf + DS + SL + LT x T

Where:

Hz =Coastal erosion hazard width for a specific future planning timeframe, T

ST = Horizontal magnitude of short-term erosion fluctuation

SE = Horizontal magnitude of storm erosion

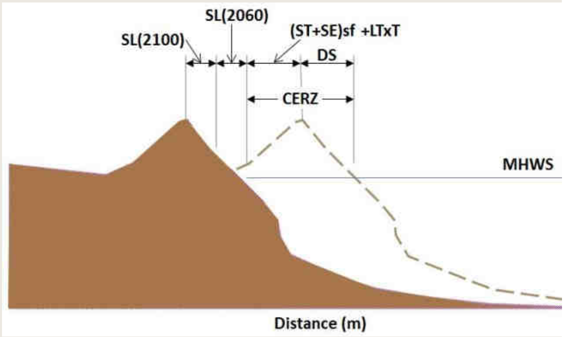
Sf = Safety factor

SL = The additional retreat associated with a particular sea-level rise over the planning timeframe.

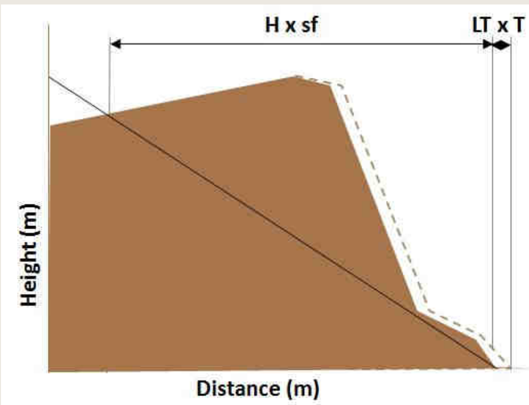
DS =Dune setback factor

LT = Long term erosion trend

T = Future planning timeframe, e.g. 100 years



Example of a hazard zone formula for a cliff



Hz = H x sf + LT x T

Where:

Hz = Coastal erosion hazard width for a specific future planning timeframe, T

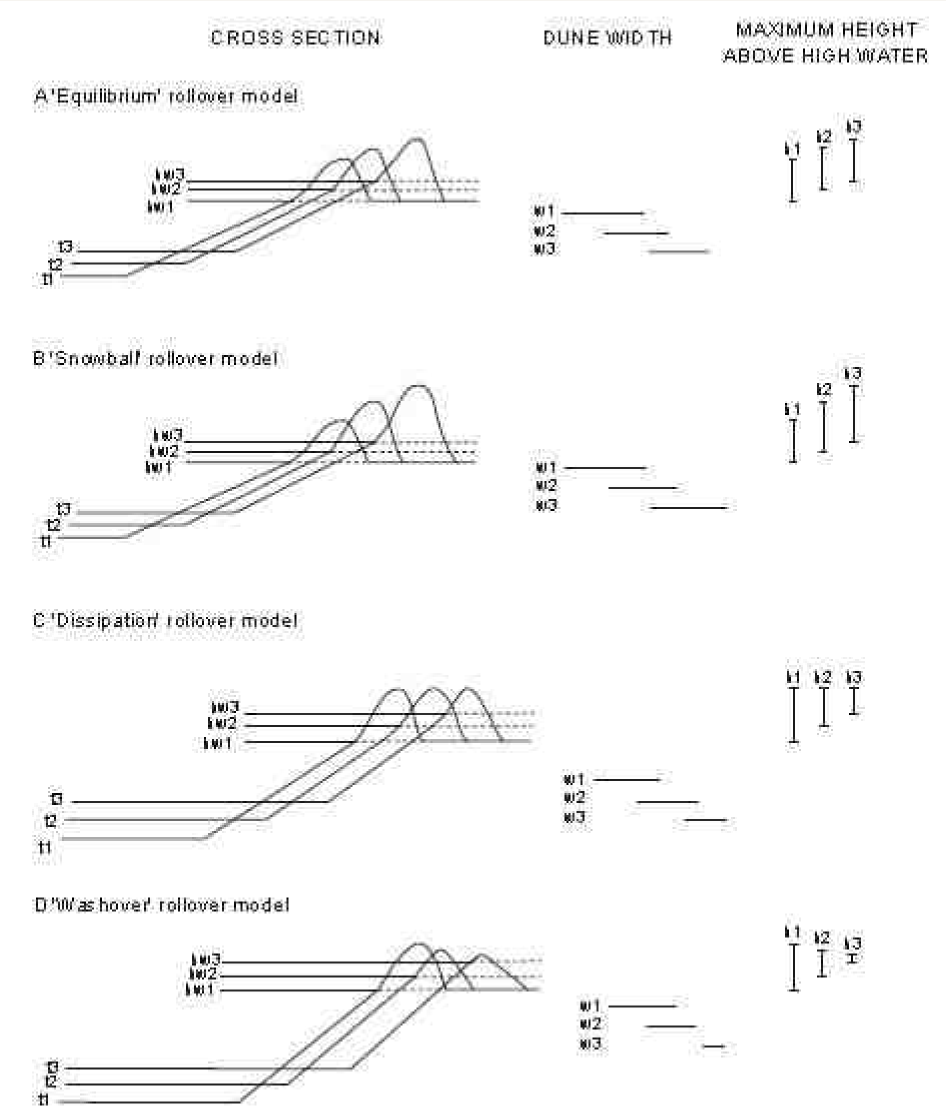
H = Vertical height of the cliff

Sf = Safety factor

LT = Long term erosion trend

T = Future planning timeframe, e.g. 100 years

Box 13 Schematic coastal dune development scenarios under rising sea level, sediment budget and shoreline recession conditions (Pye et al., 2007).



Model	Beach sediment budget	Dune sediment budget	Dune height above high water level	Dune width
Equilibrium rollover	Strongly -ve	+ve	Constant	Constant
Snowball rollover	Strongly -ve	Strongly +ve	Increases	Increases
Dissipation rollover	-ve	Neutral / slightly +ve	Decreases	Decreases
Washover rollover	-ve	-ve	Significant decrease	Significant decrease

The most common approach is typically based on the "Bruun Rule" which is applicable to open-coast sandy beaches, Figure 31, (Bruun, 1962). It describes the cross-shore response of a beach to sea level rise. The Bruun Rule suggests that landward of the closure depth of a beach (the closure depth being the seaward limit of significant wave driven sediment transport) that the beach will adjust its equilibrium profile relative to the still water level by eroding the upper, landward end of the profile to provide sediments to the nearshore so that the seabed can elevate in direct proportion to the rate of sea level rise. The approach has been modified many times to account for different physical situations, for example to account for both mainland and barrier beaches and to allow for net gains and losses in sediment.

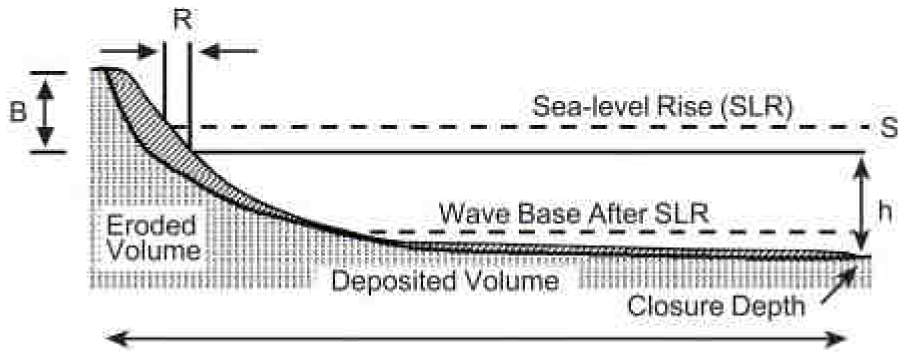


Figure 31 Basic concept of beach profile response to sea-level rise suggested by the standard Bruun Rule.

The many limitations and assumptions associated with the Bruun Rule include:

- No consideration of longshore sediment transport or gain or loss of sediment to the beach system.
- The shore profile is considered entirely beach, and there are no lithological controls
- The wave climate is steady and consequently the (average equilibrium) beach profile does not change.
- The magnitude of retreat suggested by the Bruun Rule is very sensitive to the slope of the beach and the estimated closure depth.

Other common empirical beach profile approaches to estimate the potential impact of sea-level rise on beach long-term mean beach/dune change include the geometric foredune erosion model (Komer et al, 1999, 2001) for sand beach / dune systems, and the SHINGLE model (Powell, 1990) for shingle beaches, both described above, and the Shoreline Translation Model (Cowell et al., 1992) which enables factors such as substrates of varying physical resistance and stratigraphic complexity, open sediment budgets and time dependent shoreface evolution to be incorporated.

These techniques are open to much criticism and at best provide a generally pragmatic precautionary approach for open coast beach systems to incorporating the potential effects of sea-level rise on long-term mean beach change.

In selecting, using and applying an approach to incorporate sea-level rise considerations for shoreline change, the following must be clearly considered and communicated:

- A range of sea-level scenarios need to be assessed and the sensitivity of the model predictions ascertained.
- The methodologies selected need to be informed by a conceptual understanding of how the beach system may change with sea-level rise and climate change.
- Where appropriate a range of methodologies should be investigated and applied the variability in response considered.
- What assumptions are being made, limitations, range of validity and uncertainties there are for the methodologies used and associated impacts on the intended use of the approaches.

In many cases, the methodologies applied often indicate that erosion predicted to occur in response to sea-level rise will be the largest single component influencing the magnitude of future coastal erosion.

4.3.2 Moving from deterministic predictions to probabilistic projections

Current approaches to defining uncertainties

The final component in current approaches to defining future coastal erosion hazard is a "factor of safety" which tends to be a "catch all" for uncertainties in the prediction methodology. Such uncertainties can arise from:

- Uncertainty in the data used.
- Uncertainty in modelling the various components of beach response.
- Uncertainty in future climate change and sea-level rise.

The recognition and treatment of uncertainty is typically a key source of variance between coastal erosion hazard predictions developed by different coastal hazard practitioners for the same environment. Typically, uncertainty is provided for in one of three ways:

- Direct application of a multiplication factor of safety to some or all of the setback terms.
- Detailed calculations of error for each setback term.
- Application of precaution throughout process (e.g. taking maximum likely values for each factor rather than averages).

It is this treatment of uncertainty that is a primary cause of the many conflicts that occur around defining coastal erosion hazard zones and associated development setbacks. This, and the continued reliance on deterministic approaches used to predict future coastal erosion hazard typically suffer from:

- A lack of transparency in the treatment of uncertainty.
- Predictions expressed precisely and without caveats related to the underlying uncertainties (Cowell et al., 2006).

Box 14 Deterministic and probabilistic approaches

- **Deterministic approaches** make predictions that have a single outcome albeit in practice with some associated error. The underlying assumption is that with better models or better data increasingly accurate predictions can be made.
- **Probabilistic (stochastic) approaches** provide a range of projections with associated probabilities. The approach recognises there will always be inherent uncertainties associated with projections and provides a much more transparent way of capturing and presenting such uncertainty.

Quantifying uncertainty to underpin risk-based decision-making

It is now well recognised that quantification of this uncertainty can bring much richer level of information to underpin decision-making, and is crucial where a risk-based approach to hazard decision-making is required, as it is in New Zealand.

A wide range of procedures for managing uncertainty have been around for many years. Whilst these procedures are well established and utilised in some aspects of coastal management, for example in assessing coastal storm-related inundation (Section 3), the uptake and application within the predictions of coastal change has been much less forthcoming, both in New Zealand and elsewhere.

The approach outlined below aims to build on the current deterministic approach commonly used in New Zealand, and the expertise and experience held by practitioners, to determine future coastal change, but to apply it within a pragmatic stochastic (probabilistic) way, as described by Cowell et al., (2006). The general approach is outlined below:

- Uncertainty is captured in each parameter or variable where it exists as individual probability distributions.
- These probability distributions can be derived either directly from analysis of data where it exists, from simple heuristic reasoning based on experience, or a combination of the two. At the most basic level a simple triangular distribution can be defined that contains a best estimate and lower and upper bounds of the parameter (i.e. it assumes that the actual value lies somewhere within the bounding range).
- The peak of each distribution (i.e. the most probable value of a parameter or variable) corresponds to the calibrated, or “best” estimate of the parameter or variable in the deterministic approach.
- Simulation techniques, such as Monte Carlo methods, are then used to repeat sample each of the probability distributions of each input variable to generate many thousands of possible outcomes from which probabilities of the different outcomes (coastal erosion hazard) are derived.

The process is summarised in Figure 32.

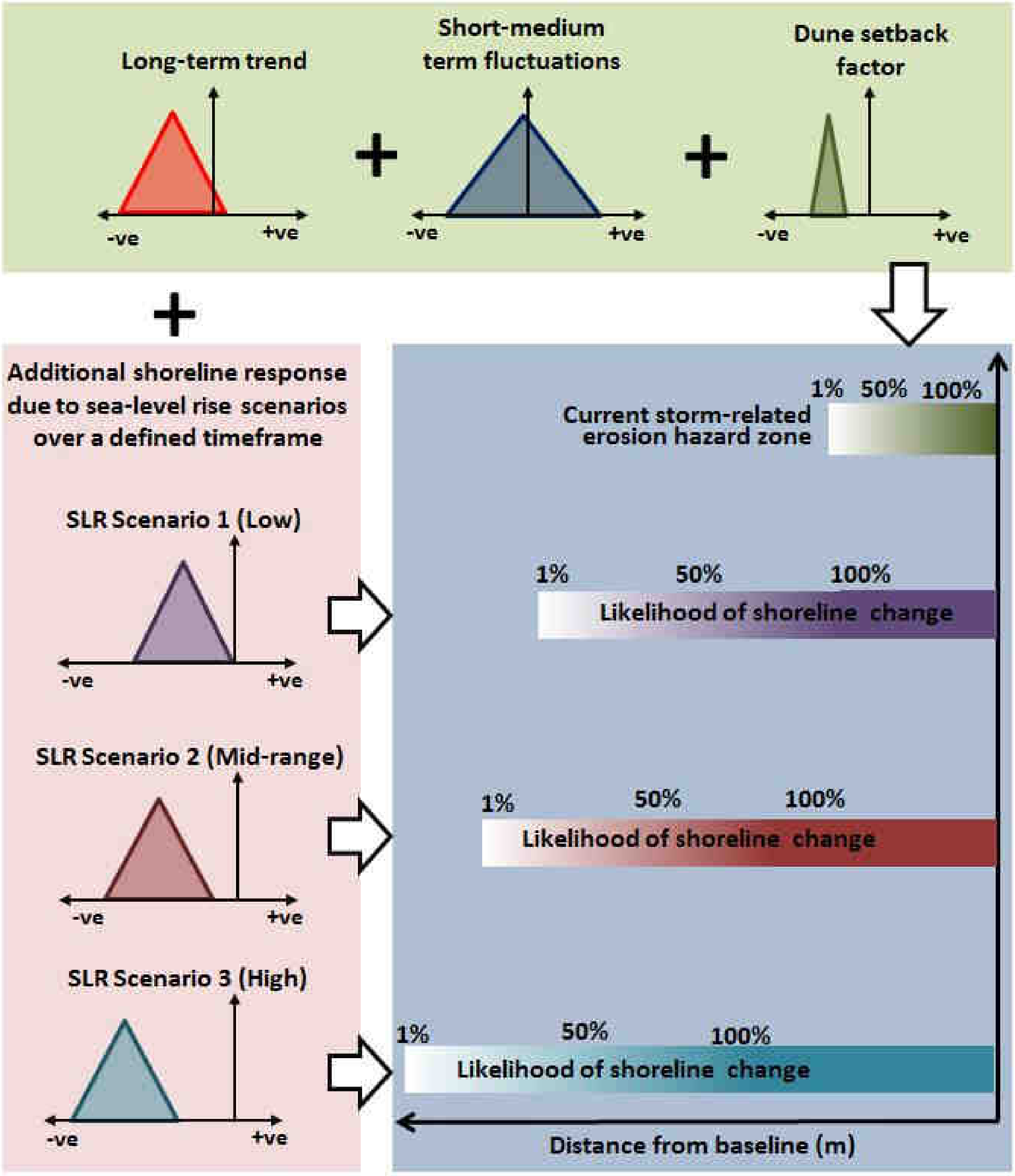


Figure 32 **Conceptual approach to defining a probabilistic coastal erosion hazard zone.** Each probability distribution for each component is sampled many times to generate many thousands of possible outcomes from which probabilities of the different outcomes (coastal erosion hazard) are derived. Note: 1) The baseline for each component needs to be clearly defined and consistent. 2) The probability distributions are represented by triangular distributions for demonstration purpose only.

Cowell et al, (2006) summarise key benefits of the approach as:

1. It is computationally more efficient than sensitivity analysis as it allows simultaneous variation in any or all of the parameter values.

2. It places the modelling approach in the most useful and conventional context for understanding uncertainty, i.e. in terms of probability (and hence consideration of risk).

3. It provides best estimates (a central tendency in the output), analogous to those obtained from deterministic models coupled but captures the associated underlying uncertainties in a clear and transparent way.

Examples of possible ways to incorporate parameter uncertainty in the various components of coastal erosion hazard assessment are outlined below.

Long-term erosion rates

Where long-term rates have been derived from analysis of historic shoreline position data, a simply derived probability distribution can be derived to encapsulate the potential measurement and other errors in the shoreline position and their resulting impact on the range of potential long-term trend (for example as shown in Figure 26).

Storm erosion and fluctuations

Whilst heuristic reasoning can be used to estimate the probability distribution of storm and/or short-medium term fluctuations around a long-term shoreline trend (for example assuming three times the standard deviation of a normal distribution derived from beach profile data), there are recent methods available that have attempted to develop more robust probabilistic approaches to understanding storm-related erosion. This can reduce the limitations and assumptions that are commonly made around maximum potential storm erosion and incorporate considerations such as storm-spacing.

The approaches are based upon the availability of wave and water level datasets and the ability to carry out robust extreme value probabilistic assessments, including the probabilistic dependencies between different parameters (for example wave heights and storm-tide levels, see Section 3), of these datasets. The steps involved in one approach, Callaghan et al., (2008), are outlined below:

1. Identify meteorological independent storm events from the wave and water level record.
2. Fit extreme value distributions to wave height and storm duration (marginal distributions).
3. Fit the dependency distribution between wave height and storm duration.
4. Fit the wave period and peak tidal anomaly conditional distributions.
5. Determine the empirical distributions for wave direction.
6. Fit a non-homogeneous Poisson distribution to the spacing between storms.
7. Simulate the wave climate using the fitted distributions including storm spacing.
8. Estimate extreme values of beach erosion from the simulated wave climate.

The approach above used an empirical equilibrium profile approach (Kriebel and Dean, 1993), calibrated against a long beach profile dataset, to estimate beach profile response (Step 8) This was an acknowledged limitation, with other subsequent similar approaches, (e.g. Corbella and Stretch, 2012) using also using semi-empirical (SBEACH) and process models (XBEACH) with improved results. The output from such an approach is a probabilistic assessment of the average recurrence interval of beach erosion change (and associated confidence limits). The approach can also readily assess the sensitivity of extreme beach erosion due to potential impacts of climate change impacts on storm conditions, for example by utilising the WASP wave and storm-surge dataset (see Section 3). Similar approaches can also be applied in the application of planshape modelling (Zacharioudaki, 2009; Zacharioudaki and Reeve, 2010).

Dune or slope stability factor

Where potential variability in the dune or slope stability factor exists, this can also be represented as a distribution, either based on beach profile data, or based on heuristic reasoning.

Additional profile response due to sea-level rise

Uncertainty exists both from:

- The range in magnitude of sea-level rise that could occur over the 100 year planning timeframes and beyond.
- The parameters within the methodologies (and the basic methodologies themselves) typically used to characterise the additional impact that sea-level rise will have on shoreline change.

Whilst attempts have been made to define a probability distribution for future sea-level rise over a specified timeframe based on a reasoned approach from a variety of sea-level rise projection studies, the present full potential range of future sea-level rise will likely have a very large impact in the resulting uncertainty captured within any coastal hazard erosion forecast.

Rather than trying to encapsulate this within a probability distribution it is recommended that a scenario-based approach, for a likely mid-range of assumed sea-level rises over the planning timeframe, as advocated within Ministry for the Environment (2008) guidance manual on *Coastal hazards and climate change* (See Box 7) be adopted (for example Figure 33).

Where simple empirical beach profile approaches (e.g. Bruun Rule) are used to estimate the potential impact of sea-level rise on beach long-term mean beach/dune or cliff change, heuristic reasoning can be used to define upper and lower bounds and simplified probability distribution, for example in defining the closure depth for a beach, (which can be defined by a range of expressions (Hallermeier, 1981)), or capturing the variability in beach slope.

Given the sensitivity of both these two parameters on the resulting landward change in the shoreline profile, the use of the Bruun Rule is likely to result in significant uncertainty in shoreline response. Approaches that adopt the Bruun Rule will be conservative and should be considered a first order approach, even within the probabilistic framework outlined above.

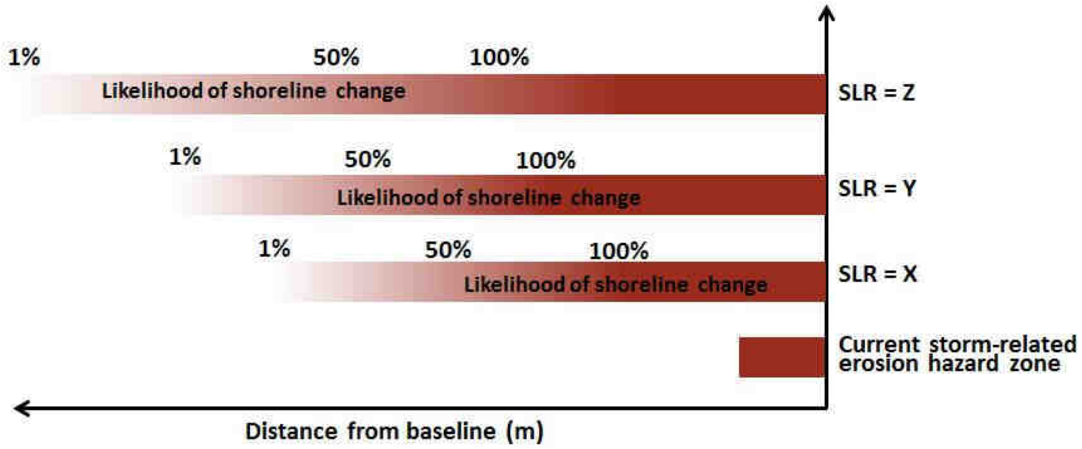


Figure 33 Conceptual example showing the sensitivity of three different sea-level rise scenarios for a particular planning timeframe on coastal erosion hazard where all other uncertainties have been encapsulated in a stochastic manner.

Beyond the Bruun Rule

Whilst estimation of future potential shoreline change using Bruun Rule, and associated approaches, have been accepted by the Environment Court, the above probabilistic approach still is still limited by the uncertainties associated with the approach.

The probabilistic approach suggested outlined above (Cowell et al., 2008; Callaghan et al., 2008) has been developed further to estimate coastal recession due to sea-level rise along an open beach/dune coastline (Ranasinghe et al. 2012). The approach is outlined below:

1. Generate a 110-year (1990-2100) time series of storms using data derived joint probability distributions of storm characteristics within a Monte Carlo simulation (Callaghan et al. 2008).
2. Using IPCC projections, estimate the sea-level rise at the time each storm occurs.
3. For each storm, estimate dune recession using the process based dune impact model presented by Larson et al. (2004) while allowing for dune recovery between storms.
4. Estimate the final dune position by temporally averaging the dune toe position in the last 2 years of the simulation.
5. Subtract the initial dune toe position from the final dune toe position to estimate dune recession between 1990 and 2100.
6. Repeat steps 1 to 5 until exceedance probabilities greater than 0.01% converge.

The advantage of the approach is that the uncertainty associated with the estimates is likely to be less than that associated with Bruun Rule type estimates. It also describes the physical processes of dune/shoreline recession due to consideration of both wave and water level conditions and enables the sensitivity of the estimates due to potential future wave and storm surge change to be assessed, e.g. through use of the WASP dataset (Box 8).

Similar probabilistic approaches can be adopted for assessing future cliff recession (Lee, 2002).

Planshape and sediment budgets

Where wave driven longshore transport is a critical factor influencing shoreline change, or there is the potential for significant changes in key beach sediment sources, beach planshape models (Figure 34) are commonly used to investigate potential sensitivity or impact on longshore planshape change:

- For example with the availability of the Wave and Storm Surge Projections (WASP) dataset (see Section 3.2.3) as boundary wave conditions to a coastal area wave modelling or by adjusting the current wave climate within the model and/or local wind conditions (MfE, 2008), an assessment can be made as to the potential impacts of wave climate change on shoreline longshore positions change and variability.

- Assessing changes in key sediment supply, e.g. from fluvial sources, can be complex and require a detailed assessment. It may require significant field measurements or scenario modelling, such as catchment modelling of changes in flow and sediment run-off under different climate change scenarios as input to the planshape modelling.

Estuarine shorelines

Rates of change on estuarine shorelines can be highly variable and extremely complex. The effect of sea level rise on estuarine shorelines will depend on the interrelationship between estuary topography, tidal prism volume and estuary sediment supply and storage, and sediment interactions with the adjacent open coast. In general sedimentation rates in most North Island estuaries have been sufficient to counter the present rise in sea level. It is more likely that the future acceleration of sea level rise will exceed natural sedimentation rates. With a rise in relative water level, the frequency of inundation events will rise and the potential for shoreline wave exposure will be increased, potentially driving an increase in erosion. Estuaries with a relatives small tide range will be more vulnerable to sea level rise effects. In areas that currently experience occasional inundation, erosion may be rapid as this inundation becomes frequent and eventually permanent. Where the landward retreat of the high water mark is constrained due to morphology, geology or coastal defences, intertidal ecosystems may be reduced and potentially “squeezed” out.

Increases in tidal prism and freshwater runoff may generate significant increases in tidal flows, resulting in scour in main channel and tidal entrance areas. Again indicative guidance can be provided from empirical techniques of tidal inlet stability (e.g., Hume, 1991). However, river, harbour and estuary mouths and inlets are naturally highly dynamic, making it very difficult to predict the response of such environments to climate change with any certainty (Hicks and Hume, 1996; Hicks et al., 1999).

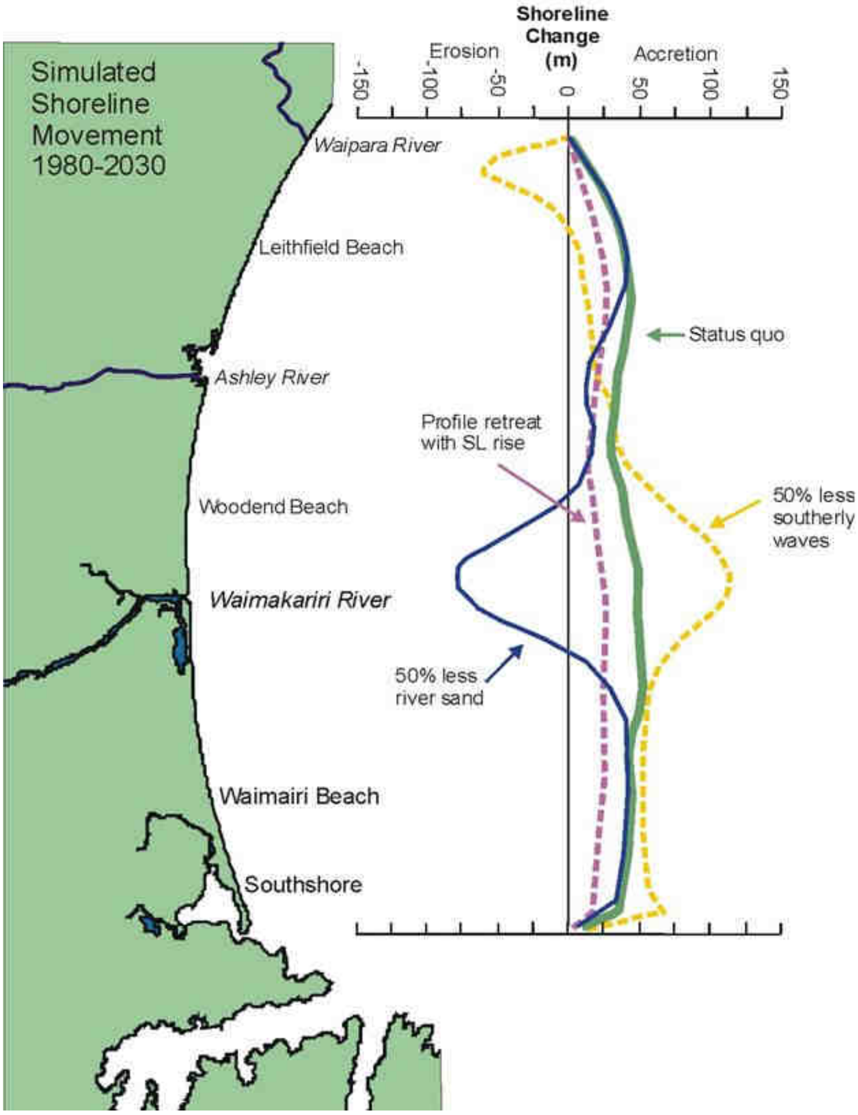


Figure 34 **Example of planshape shoreline change in Pegasus Bay under different wave, river sediment supply, and sea-level rise scenarios.** Source: M. Hicks, NIWA**.**

4.4 Presenting coastal erosion hazard information to inform development setbacks

4.4.1 Future timeframes

The New Zealand Coastal Policy Statement (2010) requires that coastal hazard identification is undertaken with a timeframe of at least 100 years. There is therefore an obligation by councils to apply this timeframe in defining coastal erosion zones.

Once the methodology for defining future potential coastal erosion zones has been set up, it can be relatively quick and straightforward to derive coastal hazard zones for other potential timeframes (assuming there are no changes in state). This can provide additional useful information to help inform decision-making, including consideration of:

- Potentially longer timeframes than 100 years (given essentially the permanency of key infrastructure and sub-division). However, the magnitude of uncertainty increases with planning timeframe, and even more so given the influence of future climate change and sea-level rise.
- Comparison of the evolution of the potential coastal erosion hazard with time (for example a zone with a 1% change of being affected by erosion over the next 50 years (low risk), may have a 50% of being affected over 100 years (possible risk), (Figure 12).
- How frequently the coastal erosion hazard assessment will be updated to ensure the "at least 100 years" intention of the NZCPS is adhered to.

4.4.2 Baselines

Every coastal erosion zone and development setback must be mapped relative to some form of baseline. This should typically be the same baseline as is used in the hazard assessment, for example the toe of dune, edge of vegetation line or cliff edge at a particular point in time (often defined from the most recent aerial photograph or high resolution satellite image).

Clear definition of a baseline is particularly important where:

- Development setbacks are presented in council plans as specified distances rather than shown visually on maps.
- How the development setback is going to be practically applied through the planning mechanisms.

Baseline must be linked to and represent the data on which the setbacks are based on to ensure no double counting or loss of intended setback width:

- Moving baseline: Where the setback is expressed as a distance from the current toe of dune, cliff edge (or other geomorphic feature), the actual location of a proposed setback will move over time as the shoreline undergoes long term or dynamic change. Where the shoreline is prone to significant dynamic change, an inconsistent level of protection is enforced to each new dwelling or development and is generally not appropriate. This approach may be appropriate where long-term erosion is relatively consistent, with minimal dynamic fluctuation (e.g., cliff sites). In this case, a moving baseline will provide a relatively constant level of protection over time.
- Fixed Toe of dune/vegetation/cliff line. The most commonly applied setback baseline is a historically (often the most recent) mapped toe of dune/cliff or vegetation line. With modern GIS tools the baseline can clearly be defined.
- Mean High Water Spring (MHWS) line. This line can be applied as a fixed or moving baseline as described above. The line can be determined by field mapping or by using elevation data from surveying or LiDAR. The horizontal location of a MHWS mark is highly changeable and harder to define, generally making it less suitable as a

baseline. The use of this baseline must also carefully consider the methods for determination of the setback. If the setback calculations have been based on movements of a dune toe, it would be inappropriate and inaccurate to then present them relatively to a MHWS mark.

4.4.3 Zones to inform lines

How coastal erosion hazard information is presented is vitally important for effective development setback decision-making. It is one where there needs to be a shift in current practices to enable a more transparent process and to reduce the political and community conflicts that commonly occur.

Current approaches to presenting coastal erosion hazard information tends to present both the coastal erosion hazard information and the derived setback in the form of one feature, typically a line, or a series of lines on a map, for example representing an area of immediate coastal erosion hazard and the erosion hazard over the next 50 and 100 years (Healy, 2005). Whilst this provides a precise outcome (a defined line on a map) that is typically desired by decision-makers, it presents a precision in the context of the erosion hazard that is not justifiable as it does not communicate the associated uncertainties that are inherent in these future predictions. As discussed above, this frequently leads to the misunderstanding where a coastal hazard zone is considered to "constitute a "magical" safety zone immediately on one side of it, and a zone of "total hazard" or impending destruction on the other" (Healy, 1993).

Rather, as discussed in the previous section, the presentation of coastal erosion hazard information must be able to encapsulate that:

- Coastal erosion hazard reduces with distance from the coastline.
- Predictions of future coastal erosion hazard incorporate considerable uncertainty.
- Uncertainty of future coastal erosion hazard predictions increases with increasing timeframe of the prediction.
- This uncertainty needs to be clearly presented to, and understood by all, that make decisions from coastal erosion hazard information.

Both zones and lines are required. Presenting coastal erosion hazard information and defined development setbacks are two distinct steps that need to be presented individually where:

- Coastal erosion hazard is presented as a zone that fully encapsulates the range of probabilities of erosion occurring over a specified future timeframe.
- Development setbacks are presented as a line that is derived from:
    - A consideration and acceptability of likelihood or erosion occurring within a specific timeframe, and
    - The resulting potential risks (and acceptability of these risks based on community, planning and management aspirations) to existing or potential assets and values located within this coastal hazard zone.

- Any other coastal margin considerations, such as ecosystem, cultural and landscape values and public access that may need to be incorporated in to the development setback.

It also recognises that that different stakeholders need to be involved in the above two steps. Defining the coastal erosion hazard zones is the responsibility of the coastal hazard expert, whereas determining development setback lines, even if they are purely based on coastal erosion hazard considerations, is a process that needs to involve a wider range of development decision-makers, planners and potentially the coastal communities. They need to understand these uncertainties if they are to make informed, risk-based decisions.

This also removes the often confused approach to using and applying different setback lines in that decisions can be made purely on the level and acceptability of risk, for example:

- Where there is only a low level of use and development in an area, one setback line may be appropriate and more easily implemented based on a defined or accepted likelihood or erosion occurring within a specific timeframe.
- In other areas it may be more appropriate for staged or graduated control to be defined based on the relative level of risk (for example different defined setback lines for major infrastructure or subdivision compared to individual properties).

4.4.4 Presentation of results

Mapping and presentation of results needs to be produced in a format that is understandable, typically by a non-technical audience, and a produced at a scale appropriate for the level of approach adopted, the underpinning data and tools utilized, and the resulting application of the coastal hazard information.

Presentation approaches can include (Lee, 2002):

- Tabular form
- Graphical form:
  - Probability density functions of cliff/shoreline position at a given time
  - Probability density functions for the time required for cliff/shoreline recession to reach a given point.
- Map form:
  - The best estimate of cliff/shoreline position after a given time including confidence limits and prediction limits.
  - A zoning based on the cumulative probability distribution of cliff recession over a given time, e.g. Figure 35 (note zone divisions are arbitrary and can be varied to suit the purpose).

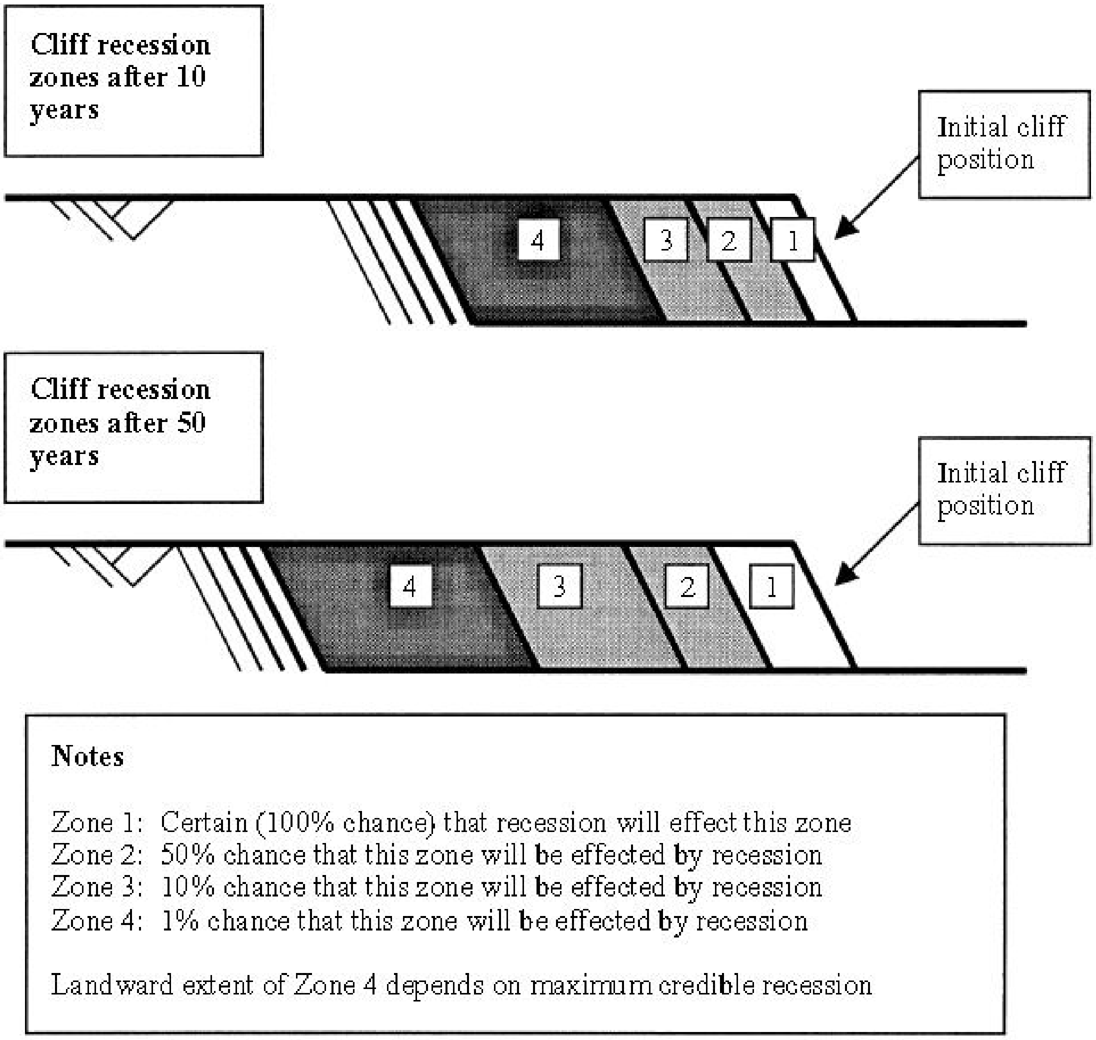
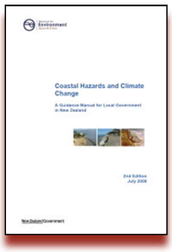


Figure 35 Example of zoning of the cumulative probability of cliff recession over two given timeframes.
Source: Lee (2002).

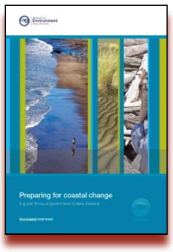
5 Resources

This guide has been written to sit alongside and support various Ministry for the Environment coastal hazard-related guidance, and recent guidance on incorporating risk assessment in to climate change adaptation including developing and implementing strategic plans for coastal adaptation to climate change.



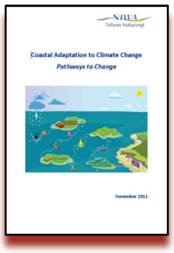
MfE. (2008). *Coastal Hazards and Climate Change. A Guidance Manual for Local Government in New Zealand.* This guidance is a comprehensive technical report which is updated after each IPCC assessment.

http://www.mfe.govt.nz/publications/climate/coastal-hazards-climate-changeguidance-manual/



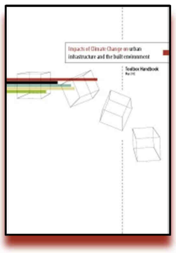
MfE. (2009). *Preparing for Coastal Change: A Guide for Local Government in New Zealand.* (Blue book). This is a summary of the MfE (2008) guidance.

http://www.mfe.govt.nz/publications/climate/preparing-for-coastal-changeguide- for-local-govt/index.html



Britton, R., Dahm, J., Rouse, H., Hume, T., Bell, R., Blackett, P. (2012). *Coastal Adaptation to Climate Change. Pathways to change.* Development of necessary information and tools to enable adaptation by communities, in tandem with central and local government, to the impacts of climate change in the coastal environment.

http://www.niwa.co.nz/our-science/coasts/research-projects/coastal-adaption-to-climate-change



NIWA, MWH, GNS and BRANZ (2012). Impacts of Climate Change on Urban Infrastructure and the Built Environment. This is a set of guidance and decision tools that can be used by urban council staff and policy makers to reduce the potential adverse effects of climate change.

http://www.niwa.co.nz/climate/urban-impacts-toolbox

6 References

Auckland Regional Council (2000). Coastal Hazard Strategy: Coastal Erosion Management Manual. Auckland Regional Council Technical Publication 130. Auckland.

Barnett, M.A.F. (1938). The cyclonic storms in Northern New Zealand. Department of Scientific and Industrial Research. Meteorological Office Note No. 22.

Bell, R. G., Goring, D. G. & de Lange, W. P. (2000). Sea-level change and storm surges in the context of climate change. IPENZ Transactions, 27(1), 1- 10.

Berryman, K. (ed) (2005). Review of Tsunami Hazard and Risk in New Zealand. GNS Science Client Report 2004/104.

Blackett, P., Hume, T. (2006). Community involvement in coastal hazard mitigation: An initial scoping of processes and pitfalls. NIWA Client Report HAM2006-083, June 2006.

Britton, R., Dahm, J., Rouse, H., Hume, T., Bell, R., Blackett, P. (2012). Coastal Adaptation to Climate Change. Pathways to change. NIWA Report for MSI contract C01X0802.

Bruun, P. (1962). Sea-level rise as a cause of shore erosion. American Society of Civil engineering Proceedings, Journal of waterways and Harbors Division, 88: pp. 117-130.

Bruun, P. (1988). The Bruun rule of erosion by sea-level rise: a discussion on large-scale two- and three-dimensional usages. Journal of Coastal Research, 4: pp. 627-648.

Bryan, K.R., Kench, P.S., Hart, D.E. (2008). Multi-decadal coastal change in New Zealand: Evidence, mechanisms and implications. New Zealand Geographer 64, 117-18.

Callaghan, D.P., Nielsen, P., Short, A., Ranasinghe, R. (2008). Statistical simulation of wave climate and extreme beach erosion. Coastal Engineering 55, 375–390.

Coles, S. (2001). An introduction to statistical modelling of extreme values. Springer. London; New York.

Corbella, S., Stretch, D.D. (2008) Predicting coastal erosion trends using non-stationary statistics and process-based models. Coastal Engineering 70, 40–49.

Cowell, P.J., Roy, P.S., Jones, R.A. (1992). Shoreline translation model: computer simulations of coastal sand body response to sea-level rise. Mathematics and computers in simulation. 33, 603-608.

Cowell, P.J., Thom, B.G., Jones, R.A., Everts, C.H., Simanovic, D. (2006). Management of uncertainity in predicting climate change impacts on beaches. Journal of Coastal Research. 22, 232-245.

Dahm, J., Gibberd, B. (2009). Coromandel Beaches – Coastal Hazards. Review of primary development setback at selected beaches. Report prepared for Thames Coromandel District Council. October, 2009.

Department of Conservation (2010). New Zealand Coastal Policy Statement 2010. Wellington.

EMPHASYS Consortium. (2000). A guide to prediction of morphological change within estuarine systems, Version 1B, produced by the EMPHASYS consortium for MAFF project FD1401, Estuaries Research Programme, Phase 1, December 2000. Report TR 114, HR Wallingford. Download from http://www.hrwallingford.co.uk/projects/ERP/index.html

Gibb, J.G., (1978). Rates of coastal erosion and accretion in New Zealand. New Zealand Journal of Marine and Freshwater Research 12(4), 429-456.

Gibb, J.G., Aburn, J.H. (1986). Shoreline fluctuations and an assessment of a coastal hazard zone along Pauanui Beach, Eastern Coromandel Peninsula, New Zealand. Water and Soil Technical Publication No. 27. 48p.

Gibb, J., Sheffield, A., Foster, G. (1992). A Standardised Coastal Sensitivity Index Based on an Initial Framework for Physical Coastal Hazards Information; Science & Research Series No. 55. Department of Conservation.

Goodhue, N.G.; Stephens, S.A.; Gorman, R.M. (2012). Combined wave and storm tide hazard for southern Tasman Bay. Client Report to Nelson City Council No. HAM2012-087. 41 p.

Gordon, D., Fraser, R. (2005). Pilot Report of Proposed Coastal Hazard Indicators. Environment Bay of Plenty, Environmental Publication 2005/21.

Gordon, D. (2006). Confirmed Hazard Risk Indicators. Environment Bay of Plenty, Environmental Publication 2006/05.

Goring, D. G.; Stephens, S. A.; Bell, R. G. ; Pearson, C. P. (2010) Estimation of Extreme Sea Levels in a Tide-Dominated Environment using Short Data Records. Journal of Waterway, Port, Coastal and Ocean Engineering, 137 (3), 150-159.

Gorman, R.M.; Gillibrand, P.A.; Stephens, S.A.; Arnold, J.; Kohout, A.; Bell, R.G. (2009). Inundation due to combined storm surge, tides and waves in Hawke Bay. NIWA Client Report No. HAM2009-020, March 2009.

Hallermeier, R.J (1981). A profile zonation for seasonal sand beaches from wave climate. Coastal Engineering, 4, 253-277.

Hanson, H., Kraus, N.C. (1989). GENESIS: Generalised Model for Simulating Shoreline Change. US Corps of Engineers, Vicksburg. 247pp

Hawkes, P. J., Gouldby, B. R., Tawn, J. A., Owen, M.W. (2002). The joint probability of waves and water levels in coastal engineering design. Journal of Hydraulic Research 40: 241-251.

Healy, T.R. (1993). Coastal erosion, setback determination and recommendations for the management of the Waihi-Bowentown and Pukehina beach and dunes. A report to the Western Bay of Plenty District Council. September 1993. 55pp.

Healy, T.R., Dean, R. (2000). Methodology for delineation of coastal hazard zone and development setback for open duned coasts. Chapter 19 in J.B. Herbich (ed). Handbook of Coastal and Ocean Engineering. McGaw-Hill, 19.1-19.30.

Healy, T.R. (2005). Holistic or zoned approach to coastal hazard setbacks on open duned coasts? Solutions to coastal disasters 2005, American Society of Civil Engineers, 395-402.

Hicks, D. M., Hume, T.M. (1996). Morphology and size of ebb-tidal deltas at natural inlets on open-sea and pocket-bay coasts, North Island, New Zealand. Journal of Coastal Research, 8(2), 355-375.

Hicks, D.M., Hume, T.M., Swales, A., Green, M.O. (1999). Magnitudes, spatial extent, time scales and causes of shoreline change adjacent to an ebb tidal delta, Katikati Inlet, New Zealand. Journal of Coastal Research. 15, 220-240.

Hsu, J.R.C., Evans, C. (1989). Parabolic bay shapes and applications, Proceedings of Institution of Civil Engineers, Part 2, 87, 557-570.

Hume, T.M., Herdendorf, C.F. (1988). A geomorphic classificationor estuaries and its application to coastal resource management – A New Zealand example. Journal of Ocean and Shoreline Management. 11, 249-274

Hume, T.M. (1991). Empirical stability relationships for estuarine waterways and equations for stable channel design. Journal of Coastal Research 7(4): 1097–1112.

Kriebel D.L., Dean R.G. (1993). Convolution method for time-dependent beach-profile response. J Waterw Port Coast Ocean Eng 119(2):204–226

Komar, P.D., McDougal, W.G., Marra, J.J., Ruggiero, P., (1999). The rational analysis of setback distances: Applications to the Oregon coast: Shore & Beach, v. 67, p. 41-49.Komar et al (2001).

Komar, P.D., McDougal, W.M., Marra, J.J. and Ruggiero, P. (2001). The rational analysis of setback distances: Applications to the Oregon Coast. Journal of Coastal Research 17, 407–419.

Larson, M., Erikson, L., Hanson, H. (2004). An analytical model to predict dune erosion due to wave impact. Coastal Engineering 51, 675– 696.

Larson, M., 2005. Numerical modeling. In: Schwartz, M. (Editor), Encyclopedia of Coastal Science, pp. 730-733.

Lee, E.M. (2002). Soft cliffs. Prediction of recession rates and erosion control techniques. DEFRA/Environment Agency Flood and Coastal Defence R&D Programme. R&D Project FD2403/1302.

Ministry for the Environment (2008). Coastal Hazards and Climate Change. A Guidance Manual for Local Government in New Zealand. 2nd edition Revised by Ramsay, D., and Bell, R. (NIWA) Prepared for the Ministry for the Environment. Wellington. viii +127p.

Ministry for the Environment (2009). Preparing for Coastal Change: A Guide for Local Government in New Zealand. Ministry for the Environment. Wellington.

OzCoast (2012). Conceptual models of Australian estuaries and coastal waterways http://www.ozcoasts.gov.au/conceptual_mods/introduction.jsp.

Pethick, J., Lowe, J. (2000). Predicting the shape and future evolution of estuaries. Chapter 13 in EMPHASYS Consortium (2000). Modelling estuary morphology and processes. Final Report. Research by the EMPHASYS Consortium for MAFF Project FD 1401. Report TR 111. HR Wallingford, UK.

Powell K.A. (1990) Predicting short term profile response for shingle beaches. Hydraulics Research Report SR219.

EUROTOP. (2007). Wave Overtopping of Sea Defences and Related Structures: Assessment Manual. Environment Agency (EA), Expertise Netwerk Waterkeren (ENW), Kuratorium für Forschung im Küsteningenieurwesen (KFKI), www.overtopping-manual.com.

Pye, K., Blott, S.J. (2009). Coastal Change in Suffolk on Decadal to Centennial Timescales. Internal Research Report IR638, Kenneth Pye Associates Ltd, Crowthorne.

Pye, K., Saye, S.E., Blott, S.J. (2007). Sand Dune Processes and Management for Flood and Coastal Defence. Part 2. Sand Dune Processes and Morphology. Joint Defra/Environment Agency Flood and Coastal Erosion Risk Management R & D Programme, R & D Technical report FD1302/TR.

Ramsay, D., Stephens, S. (2006). Double trouble: How often do large waves occur with high water levels? Coastal News. 32: pp. 4-5. Published by the New Zealand Coastal Society.

Ramsay, D.L., Stephens, S.A., Oldman, J., Altenberger, A. (2008) Review of rainfall intensity curves and sea levels in Manukau City. Part 2: Sea levels. NIWA Client Report HAM2008-168, January 2008.

Ranasinghe, R., Callaghan, D., Stive, M.J.F. (2012). Estimating coastal recession duer to sea-level rise: beyond the Bruun rule. Climatic Change 110, 561-574.

Roelvink, D., Reniers, A., van Dongeren, A., van Thiel de Vries, J., McCall, R., Lescinski, J. (2009). Modelling storm impacts on beaches, dunes and barrier islands. Coastal Engineering 56 1133–1152.

Roelvink, D., Reniers, A., van Dongeren, A., van Thiel de Vries, J., McCall, R., Lescinski, J. (2010). XBeach model description and manual. Unesco-IHE Institute for Water Education, Deltares and Delft University of Technology. June 21, 2010.

Rouse, H.L., Blackett, P., Hume, T.M., Bell, R.G., Ramsay, D., Rickard, D., Smith, E., Dahm, J., Wishart, P., Singleton, P., Pickett, V. (2011). Engaging with communities on coastal adaptation to climate changes: Whitianga experience. NIWA Internal report, CHC2011-095.

Rouse, H.L. Blackett, P. (2011). Coastal Adaptation to Climate Change: Engaging communities - making it work. NIWA Report for MSI contract C01X0802.

Saunders, W.S.A., Prasetya, G., Leonard, G.S. (2011). New Zealand's next top model: Integrating tsunami inu8ndation modelling into land-use planning. GNS Science Miscellaneous Series 34. 42p.

Shand, R.D. (2010) Marine Parade Revetment Erosion Update and Management Programme. A report prepared for the Kapiti Coast District Council. Client Report 2010-09CRep, August 2010.

Southgate, H.N., Brampton, A.H. (2001). Coastal Morphology Modelling: A Guide to Model Selection and Usage. HR Wallingford Report SR570, June 2001.

Stephens, S.A., Bell, R.G. (2009). Review of Nelson City minimum ground level requirements in relation to coastal inundation and sea-level rise. NIWA Client Report HAM2009–124 prepared for Nelson City Council and Envirolink Fund (NZ Foundation for Research Science and Technology). 58 p. http://www.envirolink.govt.nz/Envirolink-reports/ {Report ID: 731}

Stripling, S., Bradbury, A.P., Cope, S.N., Brampton, A.H. (2008). Understanding barrier beaches. Joint Defra/Environment Agency Flood and Coastal Erosion Risk Management R&D Programme Technical Report FD1924/TR. Internet: available from http://sciencesearch.defra.gov.uk/Document.aspx?Document=FD1924_7426_TRP.pdf.

Thieler, E.R., Himmelstoss, E.A., Zichichi, J.L., Ergul, A. (2009), Digital Shoreline Analysis System (DSAS) version 4.0—An ArcGIS extension for calculating shoreline change: U.S. Geological Survey Open-File Report 2008-1278. Available online at http://pubs.usgs.gov/of/2008/1278/.

Tonking and Taylor Ltd (2004). Regional coastal hazard assessment: Volume 1. Assessment. Report for Hawkes Bay Regional Council, Reference Number 20514, February 2004.

Van Gent, M., Coeveld, E.M., De Vroeg, H. and Van de Graaf, J. (2007). Dune erosion prediction methods incorporating effects of wave periods. Coastal Sediments 2007, ASCE, 612-625.

Vellinga, P. (1986): Beach and dune erosion during storm surges: Ph.D. thesis Delft University of Technology.

Whitehouse, R., Balson, P., Brampton, A., Blott, S., Burningham, H., Cooper, N., French, J., Guthrie, G., Hanson, S., Nicholls, R., Pearson, S., Pye, K., Rossington, K., Sutherland, J., Walkden, M. (2009) Characterisation and Prediction of Large Scale, Long Term Change of Coastal Geomorphological Behaviours: Final Science Report. Environment Agency Science Report, Environment Agency, Bristol

Zacharioudaki, A., Reeve, D.E. (2010). A note on the numerical solution of the one-line model, Environmental Modeling and Software, 25, p802-807.

Zacharioudaki, A. (2008). Mathematical modelling of shoreline evolution under climate change. PhD thesis, Faculty of Technology, School of Engineering, University of Plymouth, 259 pp.

7 Appendix 1 Legislative framework

District and Unitary Regional Councils have a duty of care under the Resource Management Act (RMA) to “avoid, remedy and mitigate” adverse effects of the use and development of land and the CMA (respectively), including the avoidance or mitigation of natural hazards. Section 106 allows a consent authority to refuse subdivision consent if it considers the land is likely to be subject to erosion or inundation from any source or where subsequent use could accelerate or worsen the impact of such hazards.

The Building Act (1991) further requires a Territorial Authority to refuse to grant a building permit where land is subject to, or is likely to be subject to, erosion or inundation, or if building work itself is likely to accelerate, worsen or results in erosion or inundation. Where the council’s jurisdiction covers an area of coastline, coastal hazards are frequently at the forefront of natural hazard management challenges.

The New Zealand Coastal Policy Statement (2010) contains policies that enact the purpose of the RMA in relation to the coastal environment of New Zealand. One of its objectives (Objective 5) is *to ensure that coastal hazard risks, taking account of climate change, are managed by*:

- Locating new development away from areas prone to such risks;
- Considering responses, including managed retreat, for existing development in this situation, and
- Protecting or restoring natural defences to coastal hazards.

Policy 24 of the NZCPS (2010) specifically requires councils to identify areas in the coastal environment that are potentially affected by coastal hazards (including tsunami), with particular priority given to those areas at high risk. Hazard risk is to be assessed over at least 100 years, having regard to:

- Physical drivers and processes that cause coastal change including sea level rise.
- Short term and long term natural dynamic fluctuations of erosion and accretion.
- Geomorphological character.
- The potential for inundation of the coastal environment, taking into account potential sources, inundation pathways and overland extent.

- ☐ Cumulative effects of sea-level rise, storm surge and wave height under storm conditions.
- ☐ Influences that humans have had or are having on the coast.
- ☐ The extent and permanence of built development.
- ☐ The effects of climate change on:
  - The matters above.
  - Storm frequency, intensity and surges.
  - Coastal sediment dynamics.

Councils are then required (Policies 25, 26 and 27 NZCPS (2010)) to avoid increasing the risk of harm from coastal hazards in affected areas through careful management of subdivision, land use and coastal protection works. The most common approach where existing or proposed development is at risk from coastal hazards, is to apply the above information in the form of coastal setbacks through a range of rules in planning documents.

8 Appendix 2 Average Recurrence Intervals and Annual Exceedence Probabilities

Extreme events that only happen occasionally are expressed in terms of their **average recurrence intervals** (ARI), sometimes referred to as return period, or **annual exceedence probability** (AEP).

The Average Recurrence Interval is a measure or rarity. It is defined as the average time, normally in years, between subsequent events that exceed a given magnitude threshold (such as high waves or high sea levels). The higher the ARI, the rarer the event.

Annual exceedence probabilities (AEPs) are expressed as a number between 0 and 1 or as a percentage (0 – 100%). The smaller the AEP, the less likely that the particular event will occur in any one year. For example a sea level with a 2% AEP (or 0.02) means that there is a 2% chance in any one year of that sea level being equalled or exceeded.

ARI and AEP are related by the following:

$$AEP \ = 1 - \exp\left(\frac{-1}{ARI}\right)$$

$$ARI \ = \frac{-1}{log_e(1-AEP)}$$

which, for an ARI greater than about 10 years, simplifies to approximately: AEP = 1 / ARI.

So an AEP of 2% (0.02) is equivalent to a 50 year average recurrence interval. Common ARIs and their equivalent AEPs are summarised below

AEP (0 – 1)	AEP (%)	ARI (Years)
0.01	1% chance of occurring in any one year	100
0.02	2% chance of occurring in any one year	50
0.05	5% chance of occurring in any one year	20
0.10	9.5% chance of occurring in any one year	10
0.18	18% chance of occurring in any one year	5
0.39	39% chance of occurring in any one year	2

Over a particular period of time (for example a structure design life or planning timeframe) the likelihood (%) of an extreme event occurring within a given time period is summarised in the table below.

Annual exceedence probability	Design Life – time horizon (years)								
	2	5	10	20	50	100	200	500	1000
0.39	75%	97%	100%	100%	100%	100%	100%	100%	100%
0.18	36%	67%	89%	99%	100%	100%	100%	100%	100%
0.10	19%	41%	65%	88%	99%	100%	100%	100%	100%
0.05	4%	10%	18%	33%	64%	87%	98%	100%	100%
0.01	2%	5%	10%	18%	39%	63%	87%	99%	100%
0.005	1%	2%	5%	10%	22%	39%	63%	92%	100%
0.002	<1%	1%	2%	4%	10%	18%	33%	63%	100%

The chance that an event in % terms with a given average recurrence interval will occur within the design life can be summarised in a number of ways, for example using terminology such as in the table below.

Rating	Percentage chance that an event with a given average recurrence interval will occur within the design life
Almost certain	>85%
Likely	60% - 84%
Possible	36% - 59%
Unlikely	16% - 35%
Rare	< 15%

Hence an event with an AEP of 0.1 (10%) has a 41% chance of occurring over a 5 year period, i.e. it is ***possible*** that it will occur.

Whereas the same event (AEP = 0.1) has a 99% chance of occurring over a period of 50 years, i.e. it is ***almost certain*** to occur.