Coastal Hazard Assessment in the Auckland Region

Guideline document 2021/010

July 2022, Updated

aucklandcouncil.govt.nz

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ISSN 2230-4541 (Print)

ISSN 2230-455X (Online)

ISBN 978-1-99-100288-4 (Print)

ISBN 978-1-99-100289-1 (PDF)

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Recommended citation:

Carpenter, N (2021). Coastal hazard assessment in the Auckland region. Auckland Council guideline document, GD2021/010

Acknowledgements

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Thanks are extended to technical experts who contributed to the review of this document including Richard Reinen-Hamill (Tonkin and Taylor).

List of abbreviations

Abbreviation	Definition
AC	Auckland Council
AEP	Annual Exceedance Probability
ARI	Average Recurrence Interval
ASCIE	Area Susceptible to Coastal Instability and/or Erosion
AUP	Auckland Unitary Plan
CHA	Coastal Hazard Assessment
GD	Guideline Document
ENSO	El Nino Southern Oscillation
IPO	Interdecadal Pacific Oscillation
MfE	Ministry for the Environment
MHWS	Mean High Water Springs
GIS	Geographic Information Systems
TRs	Technical Reports
NZCPS	New Zealand Coastal Policy Statement

List of units and equation nomenclature

	Unit	Description
B	m	Height of berm or dune crest
d_*	m	Depth of closure
DS	m	Dune Stability
h_{cr}	m	Height of rock layer of cliff
h_{cs}	m	Height of soil layer of cliff
LT	m/yr	Long term erosion rate
LT_F	m/yr	Potential future cliff toe retreat rate including sea-level rise effects
LT_H	m/yr	Long term historic rate of retreat
m	-	Response factor
Mt	m	Medium term fluctuations
S	m/year	Sea level rise
S_F	m/year	Future sea level rise
S_H	m/year	Historic sea level rise
SL	m	Horizontal shoreline retreat due to accelerated sea level rise
ST	m	Short term change
T	years	Timeframe
$\tan\alpha r$	degrees	Slope of the rock layer of cliff
$\tan\alpha s$	degrees	Slope of the soil layer of cliff

List of definitions

Term	Definition
Coastal erosion	The removal of the material forming the land due to natural processes, resulting in the coastline moving inland over time. It is a complex process caused by factors including wave energy, changes to sediment availability and land use, and sea-level rise. Although some types of shorelines (e.g. beaches) may undergo short-term periods of erosion but then recover (i.e. build out again), other types of shorelines (e.g. cliffs) continuously erode with no cycle of recovery.
Coastal inundation	The flooding of normally dry land by the sea, particularly during storms. This is often a temporary situation which reverses when the storm has passed, although rising sea levels will increase the frequency of flood events and cause some permanent inundation.
Natural hazard	A natural event with the potential to have a negative impact on people or things we value.
Risk	The effect of uncertainty on objectives (ISO 31000).
Slope instability	The episodic movement of land (typically as a landslide) resulting from the loss of support caused by coastal erosion.

Contents

Figures

1.0 Introduction

Coastal erosion and flooding are natural processes. They become hazards when they adversely impact people or the social, economic, environmental and cultural values of our coastline.

To support the sustainable future growth and development of Auckland, it is important that accurate assessments of potential coastal hazard risks are completed. The results should be used to ensure any identified risks are appropriately avoided, remedied, or mitigated as required by the Auckland Unitary Plan and to follow best practice asset management within the coastal zone.

1.1 Aim of the Guideline

Coastal hazards assessments are required to understand the potential effects of coastal hazards to inform a range of decision making for Auckland Council, including:

- Development controls when land is identified as being within the coastal hazard areas in the Auckland Unitary Plan (referred to in the Plan as the '*coastal erosion hazard area*', the '*coastal storm inundation 1% annual exceedance probability [AEP] area*' and the '*coastal storm inundation 1% annual exceedance probability [AEP] plus 1 m sea level rise area'*).
- The acquisition and vesting of esplanade reserves and strips to Auckland Council to ensure an appropriate buffer against coastal hazards is maintained, as well as the ability to provide for public access and amenity along the coast, over time.
- The associated acquisition and vesting of coastal assets including coastal protection structures to protect land or development (e.g. rock revetments, seawalls, dune planting) to confirm their appropriateness, potential risks and potential ongoing maintenance costs.
- Identification of long-term coastal hazards over at least 100 years, including sea-level rise, as required by the New Zealand Coastal Policy Statement (NZCPS) for coastal adaptation planning.
- Asset management planning of Auckland Council's coastal assets including coastal protection structures and coastal amenity structures.

1.2 Scope and application of the Guideline

This guideline primarily focuses on the production of site-specific coastal hazard assessments for coastal erosion and coastal inundation, as required by (but not limited to) the Auckland Unitary Plan E36.9 Special Information Requirements. By following this guidance, the user should be able to replicate a consistent coastal hazard assessment report structure and apply Auckland Council's recommended methodologies for assessing the extent of any coastal hazards. Assessment of the tsunami hazard is out of scope within this guidance document.

The guidance is structured as follows:

- Section 2 outlines a list of key information Auckland Council requires to make informed decisions, and sets out a recommended report structure so that the hazard assessments are presented in a consistent format
- Section 3 expands on the information requirements for each section of the coastal hazard assessment
- Section 4 provides detail on Auckland Council's recommended methodologies to assess coastal hazards.

1.3 How to use this Guideline

How you should use this guideline will depend on your existing knowledge of coastal hazard assessment criteria. If you are an experienced coastal practitioner, you should use this document as a guide to Auckland Council's expectations so that your assessment aligns with its current, best available, coastal hazards information. It is critical that the specific parameters and recommended methodologies are applied in your site-specific assessment.

If you are less experienced and/or have limited knowledge in this area, it is recommended that an experienced coastal engineer/scientist (or geotechnical engineer for coastal cliff assessments) is engaged to complete the coastal hazards assessment. However, this document provides reference material to support the completion of a robust coastal hazard assessment including the approach and information requirements.

1.4 Need for this Guideline

Auckland Unitary Plan's Chapter E36 'Natural Hazards and Flooding' requires the completion of Hazard Risk Assessments when a subdivision, use or development requiring resource consent is proposed to be undertaken on land which may be subject to natural hazards. This includes land in the coastal erosion hazard area, coastal storm inundation 1% AEP area and the 1% AEP plus 1 m sea-level rise area. While the special information requirements of Chapter E36 provide an outline of the requirements for a Hazard Risk Assessment, the Plan does not provide detailed methodologies for the assessment of specific hazards.

To assess coastal erosion and inundation hazards, methodologies vary with both the coastal geomorphology in question and our increasing understanding of the influence of coastal processes. To ensure that assessments to support resource consent applications are accurate and follow current best practice, Auckland Council has developed this guide to outline our expectations of how the format should look and what it should contain.

Coastal hazard assessments that do not follow the guidelines set out below are unlikely to provide sufficient detail or confidence in the extent of potential coastal hazards and long-term risk. This will likely result in the need for extensive revision to the original assessment or completion of a repeat assessment.

1.5 How this Guideline was developed

This document has been developed by considering the challenges that have arisen when reviewing hazard risk assessments since the Auckland Unitary Plan became operative, alongside best available technical information, national policy, and guidance.

Auckland's best available coastal erosion and inundation hazard information is currently provided in the following technical reports:

- *Predicting Auckland's Exposure to Coastal Instability and Erosion* (Roberts et al, 2020)
- *Auckland's Exposure to Coastal Inundation by Storm Tides and Waves* (Carpenter et al, 2020)

These reports include extensive literature reviews of current national and international science to assist in assessing Auckland's coastal hazard risk at a regional scale. To ensure consistency in approach, methodologies recommended in this guideline align with those applied in the technical reports. Application at a site-specific scale will enable a more detailed and accurate understanding of the extent of any potential hazards.

This guideline also gives effect to the New Zealand Coastal Policy Statement (2010) and considers the guidance provided by the Ministry for the Environment's ‘'*Coastal Hazards and Climate Change Guidance for Local Government*' (2017).

1.6 Exclusions

This guidance focusses on the assessment of coastal erosion and coastal inundation hazards. While tsunami is also considered a coastal hazard, it is not included within the scope of this guidance as it is a low frequency, high magnitude event which is generally addressed through emergency management measures rather than land use planning.

1.7 Mana whenua values

The coast holds intrinsic value to Māori who should be considered within any resource consent application or coastal modification. The values of mana whenua as kaitiaki of the land and coast, and how they can be maintained for future generations should be considered within the coastal hazard assessment and engagement undertaken with mana whenua within the wider application as required.

2.0 Structure of coastal hazard assessments

For resource consent applications on land identified within a coastal hazard area, the Auckland Unitary Plan Special Information Requirements of Chapter E36.9 sets out information that should be included in a hazard risk assessment report. The level of information required should be proportionate to the nature and risk presented by the hazard. Where appropriate, it should also reflect the scale, nature, and location of the proposed activity. Consistent with the requirements of the New Zealand Coastal Policy Statement (2010), the assessment should include consideration of the effects of climate change over at least a 100-year timeframe.

To assist with the development of 'fit for purpose' coastal hazard assessments, set out below is Auckland Council's required report structure (to be amended as appropriate). Details for each chapter are further outlined in Section 3.

1) Introduction
2) Background/site context
    a) Geographic location and proposed development
    b) Identification and analysis of existing coastal structures
    c) Historic shoreline change
3) Geomorphic setting
    a) Geology and geomorphology
    b) Topography
    c) Bathymetry
    d) Beach characteristics
4) Coastal processes
    a) Wind and wave climate
    b) Water levels including current mean high water springs
    c) Large scale processes
5) Coastal hazards assessment
    a) Coastal inundation (where appropriate)
    b) Coastal erosion (where appropriate)
6) Risk assessment
7) Hazard avoidance, remediation, and mitigation
8) Conclusions and recommendations
9) References
10) Appendices
    a) Input parameters and calculations

3.0 Content guidance

3.1 Introduction

The purpose of the report and the application's context shall be clearly stated prior to undertaking an assessment of the site's coastal hazards.

3.2 Background

This chapter shall provide context and sufficient background information about the site being assessed including:

a) Geographic location and proposed development: Clearly introduce the site, the type of activity being undertaken and its potential vulnerability to natural hazards.

b) Identification and analysis of existing coastal structures: Identification of any coastal structures (if present), their associated condition, consent status and/or any approved as-built plans. Coastal structures include coastal defence structures (e.g. seawalls) or coastal amenity structures (e.g. boat ramps and jetties). This information will provide an indication of any perceived coastal management issues at the site and identify any structures intended to be vested to Auckland Council in relation to the proposal (where applicable).

c) Historic shoreline change: Provide an analysis of historic shoreline movement (including reclamation) by assessing historic aerial photography, survey plans or past studies. The information shall be used to inform the historic long-term retreat rate within the later coastal erosion hazard assessment.

3.3 Geomorphic setting

At a high level, coastal hazards are influenced by two factors:

1) The controlling geomorphology; and
2) The driving coastal processes.

This section shall provide an initial overview of the geomorphic controls influencing the site with respect to the coastal hazard being assessed, including:

a) Geology and geomorphology: Provide an understanding of the underlying composition of the site which can inform its erosive potential. For coastal cliffs, this should also include any geological exposures and geomorphic characteristics including the height and slope angle of the rock and soil layer of cliffs (to inform later predictions of coastal erosion).

b) Topography: Outline the landform of the site. On low lying sites this may indicate if the site is potentially exposed to coastal inundation. Contrastingly, for coastal cliffs, this will inform the cliff height to again inform later predictions of coastal erosion.

c) **Bathymetry:** Outline the offshore environment which may be required to inform the seaward location of the depth of closure for sediment transport when assessing beach erosion.

d) **Beach characteristics:** If a fronting beach is present, this section can include the type and source of sediment and its profile to inform beach erosion calculations.

3.4 Coastal processes

This section shall provide an overview of driving coastal processes at the site including:

a) **Wind and wave climate:** Provide an understanding of exposure to wave energy at the site through consideration of fetch distances, wind direction and wind speed to inform wind wave characteristics and extreme wave heights. At sites exposed to ferry wake, this shall also be quantified as part of the assessment.

b) **Water levels:** Outline normal, extreme and future water levels at the site to identify the present-day position of Mean High Water Springs (MHWS), the degree of wave energy reaching the backshore (as waves are depth limited) and potential coastal inundation risk. Key water level components for consideration include:

   - Astronomical tides
   - Storm surge and wave processes
   - Medium-term fluctuations (including ENSO[1] or IPO[2] effects, sediment fluctuations)
   - Long-term changes in sea-level

   A key consideration in the development and vesting of land is the location of the MHWS. Indicative tidal levels of the area can be obtained from literature including the LINZ Nautical Almanac and the report '*Development of an Updated Coastal Marine Area Boundary for the Auckland Region*' (NIWA, 2012). However, to determine cadastral or administrative boundaries, a recent (within 3 years of the application date or more recently if there have been noticeable changes) topographic survey should be undertaken to accurately plot the present-day location of MHWS-10[3] at the site. As noted by LINZ, there is no single method that can be used to establish this boundary, which should be determined by a chartered surveyor after considering the individual characteristics of the site.

c) **Large-scale processes:** To conclude this section, commentary of large-scale coastal processes such as near-shore currents and long-shore drift may also be required.

[1] El Nino-Southern Oscillation

[2] Interdecadal Pacific Oscillation

[3] Height exceeded by 10% of all high tides

3.5 Coastal hazard assessment

Coastal hazards include coastal inundation and coastal erosion (of both beaches and cliffs), along with the ongoing changing risk presented by the future impacts of climate change including sea-level rise. As a result, the site-specific hazard assessment needs to consider the coastal hazards the site is exposed to and assess their future impact over at least the next 100 years, in alignment with the New Zealand Coastal Policy Statement (2010). For Auckland Council to undertake an accurate and detailed review, presented hazard areas should include 30-, 50- and 100+ year timeframes, and the RCP8.5 and RCP8.5 H+ sea-level rise projections. As noted by the MfE (2017) guidance, RCP8.5 H+ over more than 100 years should be considered as part of a first pass/screening assessment for the avoidance of hazard risk. With respect to these timeframes, Auckland Council considers it prudent to round-up to the nearest decade (e.g. 2130 for at least 100 years).

Given that coasts are dynamic environments, a range of methodologies to assess coastal hazards are available. Section 4 details the methodologies that Auckland Council recommends are applied in the assessment along with key parameters to be included.

3.6 Risk assessment

A risk assessment of the proposed activity shall be undertaken, informed by the site-specific coastal hazard assessment. This shall include:

a) A summary of the type, frequency, and scale of the coastal hazard including consideration of climate change projections over the life of the proposed development, or, if considering land use change, at least 100 years.

b) The type of activity being undertaken, and its exposure to coastal hazards.

c) The consequences of a coastal hazard event in relation to the proposed activity and the people likely to be involved in that activity and whether adverse effects on the development will be temporary or permanent.

d) The potential effects on public safety, other people and property.

e) Any exacerbation of existing coastal hazard risks or creation of new natural hazard risks as a result of the proposed activity. Exacerbating the risk includes:

   - Increasing the number of ‘receptors’ (e.g. people or properties) within a hazard zone;
   - Locating receptors so that hazard impacts become more probable or future hazards become more imminent; or
   - Constructing structures or interfering with natural processes in a way that exacerbates the hazard, e.g. increasing wave run-up, disrupting sediment transport or supply.

f) Whether any building, structure or activity located on land subject to natural hazards near the coast can be relocated in the event of severe coastal erosion or coastal inundation.

g) The risks associated with mitigation options (e.g. sea walls, fill, dune planting etc.) if they fail, or consents are not renewed.

3.7 Hazard avoidance, remediation, and mitigation

Based on the findings of the coastal hazard assessment and risk assessment, this section shall summarise the results and present relevant coastal hazard areas shown as an overlay on site plans in relation to the proposed activity, and the proposed esplanade reserve/strip (if applicable). Cross-sections shall also be provided including reference elevations, location of MHWS-10, and the coastal hazard zones.

This information shall be used by the applicant to consider:

a) Site layout and management to avoid or mitigate the adverse effects of natural hazards, including effects on people, property and access and exit during a natural hazard event.

b) The ability to use non-structural solutions, such as planting or the retention or enhancement of natural landform buffers to avoid, remedy or mitigate the hazard, rather than hard engineering solutions or protection structures.

c) The design and construction of buildings and structures to mitigate the effects of natural hazards.

d) The effect of structures used to mitigate hazards on landscape/ coastal/ vegetation/ cultural values and public access.

e) The duration of consent and how this may limit the exposure for more, or less, vulnerable activities to the effects of natural hazards including the effects of climate change.

f) Any measures and/or plans proposed to mitigate the natural hazards, or the effects of the natural hazards and the risks associated with relying on that mitigation.

3.8 Conclusions and recommendations

This chapter shall clearly summarise the findings of the coastal hazard assessment and any subsequent recommendations for future risk management. The report shall end with a series of clear and concise conclusions and recommendations.

3.9 References

A reference list is required to clearly demonstrate where information used to inform the Coastal Hazard Assessment has been sourced from.

3.10 Appendices

The appendices shall include a summary of all input parameters applied and supporting calculations to determine the area susceptible to coastal instability and erosion, or the coastal inundation level (including freeboard).

4.0 Recommended coastal hazard assessment methodologies

A range of methodologies to assess coastal hazards are available. This section details the methodologies required by Auckland Council for inclusion within the coastal hazard assessment, along with key parameters and factors that shall be included.

The methodologies are in alignment with Auckland Council's most recent technical reports which will be used as a baseline for screening coastal hazard risk. For further information on the methodologies below, please refer to the following reports on Auckland Council's Knowledge Auckland web page:

- *Predicting Auckland's Exposure to Coastal Instability and Erosion* (Roberts et al, 2020)
- *Auckland's Exposure to Coastal Inundation by Storm Tides and Waves* (Carpenter et al, 2020).

4.1 Coastal inundation

For low lying land, an assessment of present and future coastal inundation risk is required to inform a range of factors including floor levels for habitable development, any potential exposure of assets and an initial indication of appropriate crest heights of coastal structures.

The first confirmation of the site's potential exposure to coastal inundation can be made through Auckland Council's Online Geomaps: (https://geomapspublic.aucklandcouncil.govt.nz/viewer/index.html) by selecting the Environment theme – Emergency Management – Coastal Inundation (1% AEP). Exposure of the site at the '1% AEP' and '1% AEP plus 1 m sea-level rise' shall be considered in alignment with the Auckland Unitary Plan (Operative in Part).

Following confirmation of whether the site is spatially exposed to coastal inundation, the assessment shall include consideration of the following factors in determining overall water levels:

- **Mean High Water Springs:** Present day MHWS-10 at the site (as discussed in Section 3.4) and the impact of future sea-level rise (see below).
- **Extreme sea-levels as a result of coastal storm surge:** 1% AEP, otherwise known as the 100-year Average Recurrence Interval (ARI) storm surge, shall be specified. This extreme water level is in alignment with the Auckland Unitary Plan.

  Auckland Council's best available information in relation to extreme sea-levels shall be referenced as outlined in Carpenter et al (2020).
- **Wave set-up:** For open coasts, the increase in extreme water level as a result of wave set-up shall also be considered in addition to storm surge. This is the increase in sea-level within the surf-zone caused by the release of wave energy. Wave set-up values are also specified in the above referenced report and shall be included where appropriate.

- **Freeboard:** Is applied to account for additional factors that may not be captured by the coastal inundation scenario, including wave run-up and wave overtopping on coastal margins, and to incorporate potential uncertainty in modelled extreme water levels.

  Freeboard allowances are typically applied to 'habitable' dwellings and are dependent on the proposed usage/vulnerability of the activity (e.g. retirement homes are considered a more vulnerable activity, see Auckland Unitary Plan definition of 'more vulnerable activities'), exposure of the site (e.g. situated on the open coast) and confidence in flood level predictions.

  The Building Code Clause E1 Surface Water sets a freeboard level of 500 mm where surface water has a depth of 100 mm or more. While this level is focussed on the impact of waves generated by vehicles, Auckland Council considers this allowance best practice to account for the above factors.

  The MfE Guidance identifies a probable maximum run-up of 30 m inland from the dune crest, beach berm or seawall that can be applied as a wave run-up setback. Alternatively, inclusion of a 0.5 m wave run-up allowance is recommended.

  Considering the above, a site-specific freeboard allowance shall be calculated and applied (where applicable).

- **Sea-level rise:** The Auckland Unitary Plan provides for 1 m of sea-level rise, based on best available information at the time of Auckland Unitary Plan development. Considering the New Zealand Coastal Policy Statement requirement to consider at least a 100-year timeframe, the Auckland Unitary Plan also requires consideration of longer-term sea-level rise impacts. The latter should consider the most up-to-date climate change and sea-level rise information. More up-to-date sea-level rise projections are currently provided in the MfE *Coastal Hazards and Climate Change Guidance* (MfE, 2017), including minimum transitional sea-level rise allowances for use in a range of planning instruments (Table 12, MfE guidance).

  Further updated sea-level rise projections are also available in the latest Intergovernmental Panel on Climate Change sixth assessment report (IPCC, 2021). It is anticipated this will be incorporated into the next iteration of MfE guidance.

For more complex flood systems (e.g. low lying land on estuaries or land also exposed to catchment flooding), site-specific hydrodynamic modelling to gain a more detailed understanding of inundation levels and extent across the site may be required.

4.2 Coastal erosion

Coastal erosion is the process of removal of material at the shoreline. A differentiation can be made between soft shoreline erosion (e.g. beaches and dunes) and hard shoreline erosion (e.g. coastal cliffs). This guidance addresses both processes in turn.

The recommended methodologies below can be applied both deterministically or probabilistically. The deterministic approach prescribes set values to each given parameter and the resulting area susceptible to erosion is fully determined by these values. In contrast, the probabilistic approach recognises potential uncertainties within each parameter and incorporates randomness into the results. Final calculated hazard susceptibility areas can be aligned to probabilities of exceedance. The approach adopted by the Coastal Hazard Assessment should reflect the scale and nature of the activity proposed and be clearly articulated within the assessment.

4.2.1 Beach erosion

Beach erosion can be defined as the landward translation of the beach and occurs because of short-term fluctuations in the beach profile along with longer term trends. The process is typically influenced by sediment supply being insufficient to replace that removed by hydraulic action. A range of methodologies are available to predict beach erosion over time, dependent on the site-specific conditions at the area being assessed.

For this guidance, Auckland Council requires the application of the methodologies presented in *Predicting Auckland's Exposure to Coastal Instability and Erosion* (Roberts et al, 2020) for unconsolidated beach shorelines on Auckland's open coast and harbour beaches, as described in Equations 1 and 2 below, and schematised in Figure 1:

$$Current\ ASCIE_{Beach} = ST + DS$$

Equation 1

$$Future\ ASCIE_{Beach} = (LT \times T) + SL + (ST) + DS + MT$$

Equation 2

Where:

$ASCIE_{Beach}$	=	Area of beach susceptible to instability and erosion
ST	=	**Short Term Changes** (m) This factor describes short-term changes in the horizontal shoreline position related to storm erosion (storm cut) due to a singular or a cluster of storm events or fluctuations in sediment supply and demand, beach rotation and cyclical changes in wave climate. It should be derived from existing information sources outlined in the introductory sections of the coastal hazard assessment or from interpolation/judgement from adjacent or similar beaches where limited data is available for the subject area.
DS	=	**Dune Stability** (m) This is the horizontal distance from the base of the eroded dune to the dune crest at a stable angle of repose (m). It is recommended that this factor is measured directly or based on the height of the dune crest relative to the toe of the dune multiplied by 32° (the typical stable angle of sand).

MT	=	**Medium Term Fluctuations** (m) This allows for shoreline fluctuations on a decadal timeframe due to ENSO or IPO effects, or decadal fluctuations in the sediment budget (which are not reflected by the long-term changes). Note that this parameter may be omitted for beaches that do not experience significant medium-term fluctuations.
LT	=	**Long-Term Erosion Rate** (m/yr) This factor should consider all horizontal movement of the coast based on data (historic aerial photography, past surveys, existing studies) or expert judgement, excluding medium term fluctuations (see above).
T	=	**Timeframe (years)** As previously noted, in alignment with the New Zealand Coastal Policy Statement, Auckland Council requires the assessment over at least a 100-year timeframe.
SL	=	**Horizontal Shoreline Retreat Due to Accelerated Sea-Level Rise** This describes the geometric response model where, as sea level rises, the equilibrium beach profile is moved upward and landward conserving its mass and shape. The most well-known of these response models is known as the Bruun Rule (Bruun, 1962, 1988) and is described by the following equation: $SL = \frac{L_*}{(B+d_*)} S$ *Equation 3* Where: L* = Extent of the seabed influenced by wave action, calculated by the horizontal distance from the shoreline to the offshore position of d* d* = depth of closure (theoretical maximum depth of sediment exchange) e.g. as determined through the method of Hallermeier (1981) B = height of the berm or dune crest within the eroded backshore S = Sea-level rise. The increase in water level from present day to T as a result of climate change.

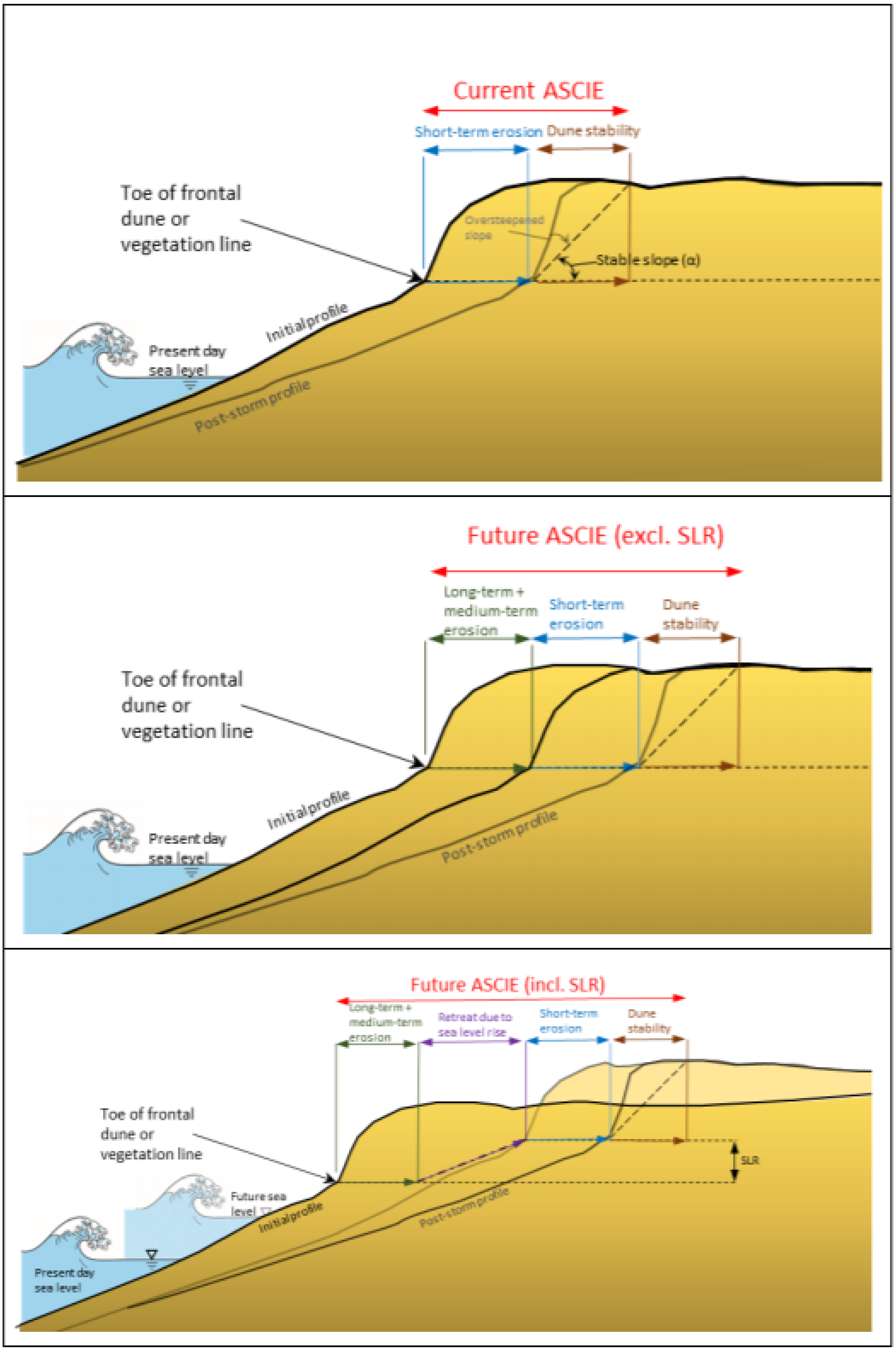

Figure 1: Definition sketch for areas susceptible to coastal instability and/or erosion on unconsolidated open coast beaches over time (including with future sea-level rise). Source: Roberts et al (2020)

4.2.2 Cliff erosion and instability

The erosion processes associated with consolidated cliff coastlines are highly complex and can be affected by a wide range of geotechnical, sub-aerial, marine, meteorological and biological factors. As a result, a variety of methodologies may be applied to predict future rates of cliff retreat. Consistent with the above section, the methodologies applied in Roberts et al (2020) are required to be applied on a site-specific basis. The calculation of areas susceptible to coastal erosion and instability shall consider two key components:

- **Toe erosion** – gradual retreat of the cliff toe caused by weathering and marine processes
- **Cliff instability** – episodic instability events causing the cliff slope to fail to a more stable angle.

The model describing these components is outlined in Equations 4 and 5 below:

$$Cliff\ Toe\ Erosion = LT_F \times T$$

Equation 4

$$Cliff\ Instability = \left(\frac{hc_r}{Tan\alpha_r}\right) + \left(\frac{hc_s}{Tan\alpha_s}\right)$$

Equation 5

When calculating the area susceptible to erosion and instability over time, the above components are used to predict the current and future area susceptible to coastal instability and erosion (ASCIE) as outlined below and schematised in Figure 2:

$$Current\ ASCIE = \left(\frac{hc_r}{tan\alpha_r}\right) + \left(\frac{hc_s}{tan\alpha_s}\right)$$

Equation 6

$$Future\ ASCIE = (LT_F \times T) + \left(\frac{hc_r}{tan\alpha_r}\right) + \left(\frac{hc_s}{tan\alpha_s}\right)$$

Equation 7

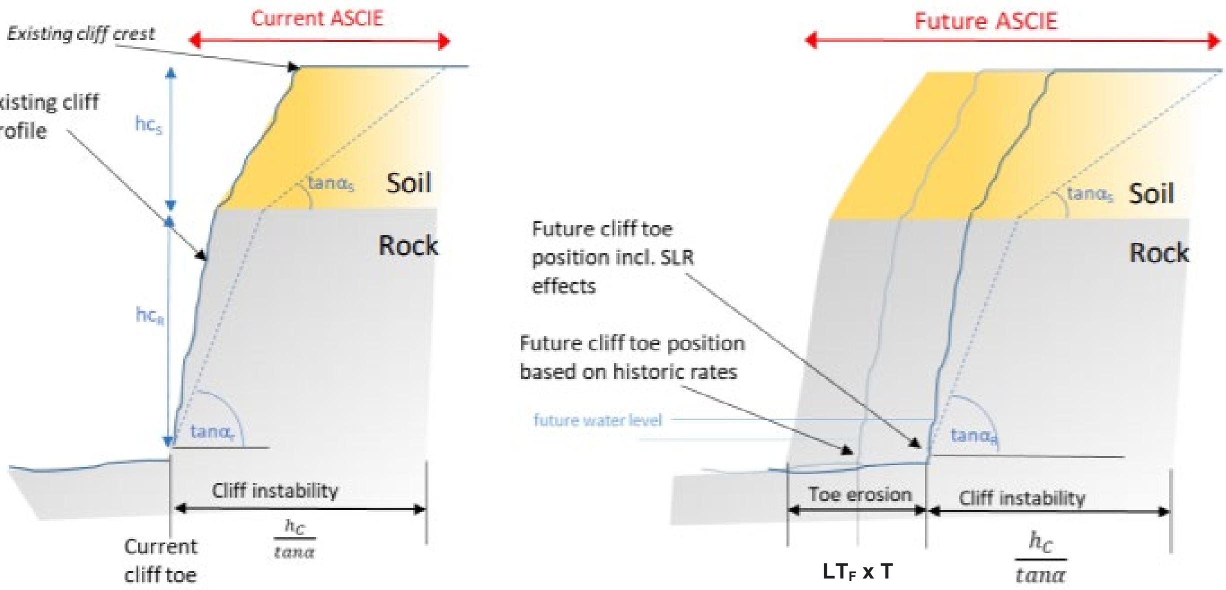

Figure 2: Definition sketch of areas susceptible to coastal instability and erosion on cliff shorelines

Where:

LT_H	=	**Historic Long-Term Rate of Retreat (m/yr)** This parameter should take into account the historic regression rate of the cliff based on data (historic aerial photography, past surveys, existing studies).
T	=	**Timeframe (years)** In alignment with the New Zealand Coastal Policy Statement, Auckland Council requires the assessment of at least a 100-year timeframe.
Hc_r	=	**Height of the rock layer of the cliff (m)** As obtained from survey data associated with the application or Auckland Council's online geodatabase.
Hc_s	=	**Height of the soil layer of the cliff (m)**
α_r	=	**Cliff slope angle of the rock layer (degrees)** The characteristic slope angle of the cliff surface measured from the horizontal (typically controlled by the cliffs lithology and structure). This angle varies according to the likelihood of failure considered.
α_s	=	**Cliff slope angle of the soil layer (degrees)**
LT_F	=	**Potential future cliff toe retreat rate due to sea-level rise effects** A number of methods have been used to describe the gradual recession of the cliff due to sea-level rise effects (Defra, 2002, Walkden and Dickson, 2008). In alignment with Auckland Council (2021) it is recommended that the model of Ashton et al (2011) is applied, where S_F and S_H are the future and historical rates of sea level rise, respectively and m is the coefficient describing the response of the cliff to sea-level rise.

$$LT_F = LT_H(\frac{S_F}{S_H})^m$$

Equation 8

The response factor (*m coefficient*) is described by Ashton et al (2011) in Figure 3 below. In summary:

- An instantaneous response (m = 1) is where the rate of future recession is directly proportional to the increase in SLR. An instant response is typical of unconsolidated or weakly consolidated shorelines.
- No feedback (m = 0) indicates that wave influence is negligible, and weathering dominates.
- Negative/damped feedback system (m = 0.5) is considered the most likely response of consolidated soft-rock shorelines, where rates of recession are slowed by development of a shore platform.
- Inverse feedback (m < 0) indicating a reduction in recession with increasing sea levels. This could occur when erosion is influenced by factors such as bio-erosion is controlled by bio-erosion or the wave impact regime, which could be modified by additional submergence.

The negative/damped feedback system is considered the most appropriate for Auckland Geologies. Auckland Council (2021) identifies appropriate m values to apply for all Auckland's main geological types.

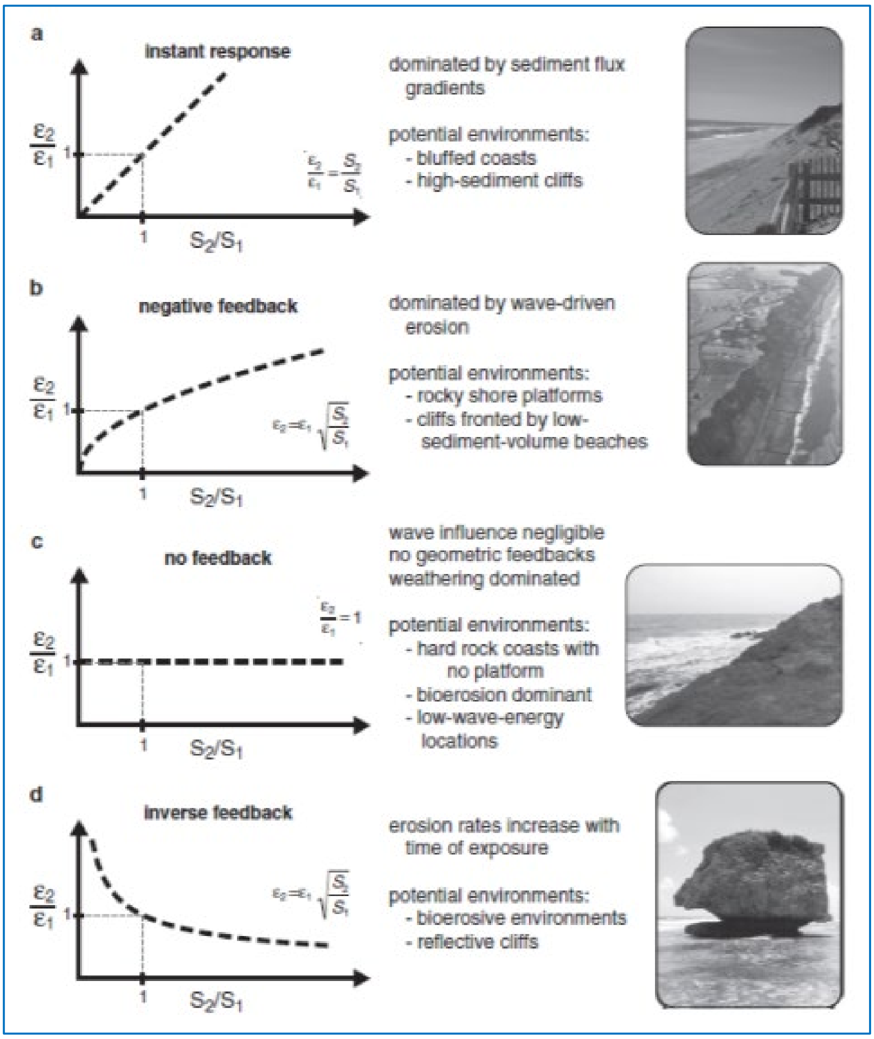

Figure 3: Possible modes of cliff response to SLR

(adapted from Ashton et al., 2011), with E1 = historical long-term rate, E2 = future long-term rate, S1 = historical SLR and S2 = future SLR

5.0 References

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6.0 Appendices

6.1 Appendix A

Recommended Report Contents

1) Introduction
2) Background/site context
    a) Geographic location and proposed development
    b) Identification of existing coastal structures
    c) Historic shoreline change
3) Geomorphic setting
    a) Geology and geomorphology
    b) Topography
    c) Bathymetry
    d) Beach characteristics
4) Coastal processes
    a) Wind and wave climate
    b) Water levels including current mean high water springs
    c) Large scale processes
5) Coastal hazards assessment
    d) Coastal inundation
    e) Coastal erosion
6) Risk assessment
7) Hazard avoidance, remediation, and mitigation
8) Conclusions and recommendations
9) References
10) Appendices
    a) Input parameters and calculations

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