Appendix 1: Relevant legislation

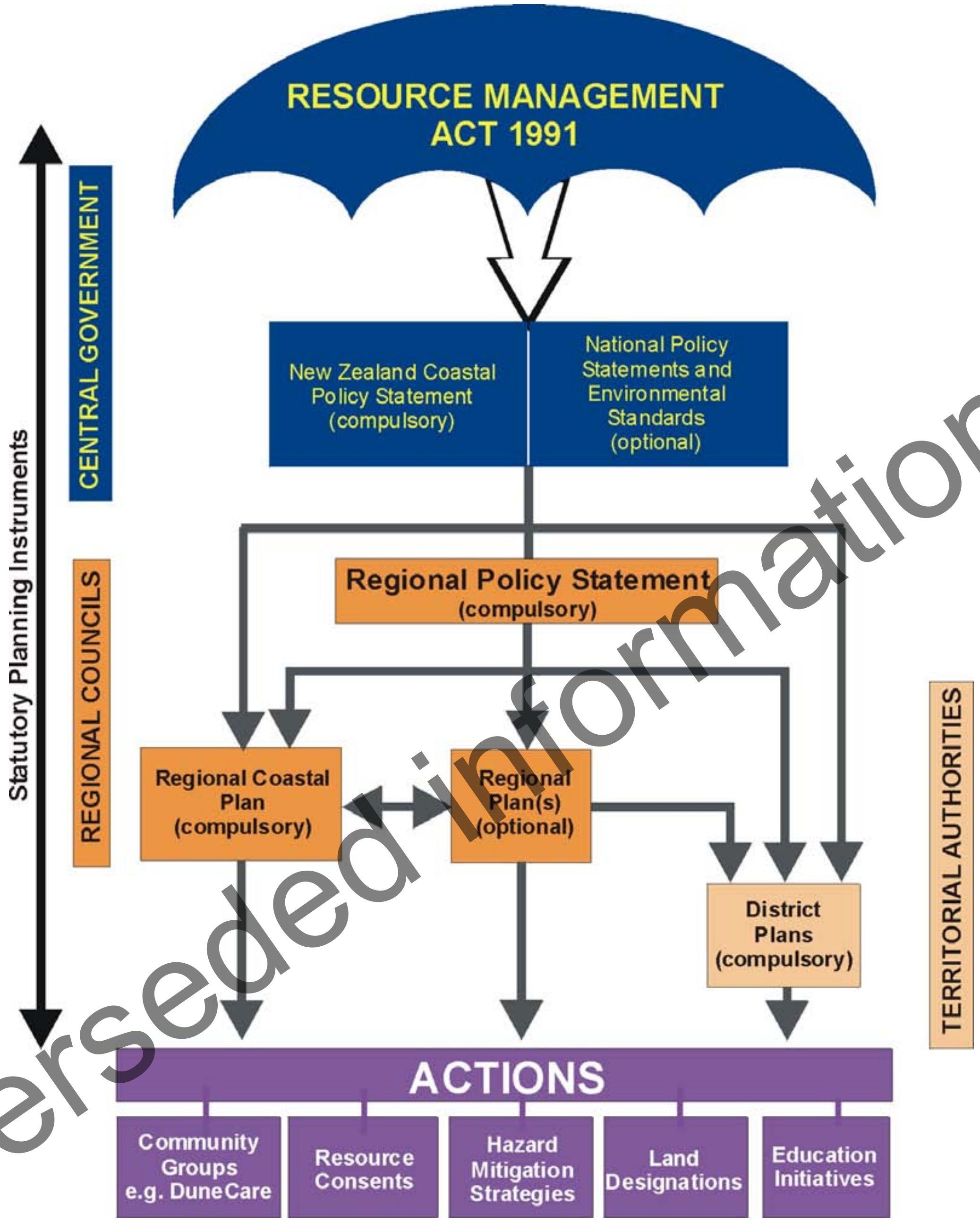

Figure A1.1: Hierarchy of Resource Management Act 1991 provisions.

Resource Management Act

Although coastal management is singled out in the Act, there is no specific part within the Act which deals with it.

Regional coastal plans focus on the sustainable management of natural and physical resources within the coastal marine area (below mean high water springs). Other regional plans can address natural resources, in particular land, (air) and water above mean high water springs, air quality and land management.

District Plans contain management provisions from a district perspective. Under the RMA, District Councils have particular responsibilities for the management of land above mean high water springs, including for subdivision, use and development. District Plans are required to not be inconsistent with the NZCPS, RPS and Regional Coastal Plan.

The issue of hazard management within District and Regional planning documents was considered in the case of Canterbury Regional Council v Banks Peninsula District Council in which McKay J. Court of Appeal noted that

> *It is true, … that natural hazard is not defined as being the consequence of the occurrence, but as the occurrence itself which has or potentially has the adverse consequence. What can be avoided or mitigated, however, is not the occurrence but its effect. Neither in s 30 nor in s 31 are the words "effects of" used in connection with "natural hazards". This is for the simple reason that they would be otiose*[20]*, as the definition of "natural hazard" incorporates a reference to effects. The word "effects" would also be inappropriate in respect of s 30(1)(c)(i)-(iii). It is unnecessary and inappropriate to explain the language by reference to some subtle distinction between the respective functions of regional councils and territorial authorities.*
>
> *It follows that the control of the use of land for the avoidance of (sic) mitigation of natural hazards is within the powers of both regional councils and territorial authorities. There will no doubt be occasions where such matters need to be dealt with on a regional basis, and occasions where this is not necessary, or where interim or additional steps need to be taken by the territorial authority. Any controls imposed can be tested by appeal to the (Environment Court), and inconsistencies are precluded by s 75(2).*

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[20] Functionless.

Building Act

The relationship between the BA and RMA is considered in sections 68(2A) (regional rules) and 76(2A) (district rules) of the RMA, which states:

> *"Notwithstanding section 7(2) of the Building Act 1991, rules may be made under this section, for the protection of other property (as defined in section 2 of that Act) from the effects of surface water, which require persons undertaking building work to achieve performance criteria additional to or more restrictive than those specified in the building code in force under that Act."*

A corresponding reference is also contained within the Functional Requirement E.1.2, and corresponding Performance Standards of the Building Code. The reference in the Building Code is to 'surface water resulting from an *event*', which ensures that causes of flooding not associated with a storm, such as high tides, are to be taken into account. These events do not specifically refer to climate change events, and instead rely on such events having a 10 percent or 2 percent probability of occurring annually. The provisions will therefore, not protect property from coastal climate change hazards in the future.

Other provisions relevant to coastal hazards are outlined in section 30 and 36 of the Building Act. Section 30 of the BA addresses Land Information Memoranda and enables information to be made available to the purchaser at the time of sale on *potential erosion, avulsion, falling debris, subsidence, slippage, alluvium, or inundation,* that is not otherwise apparent in District Plans. Such provisions could include future coastal hazards likely to result from climate change until such time as more prescriptive criteria (such as through district plan provisions) are able to be established.

Section 36 of the BA notes that a territorial authority is required to refuse to grant a building consent for work on unstable land unless the authority is satisfied that the work will not increase the instability. A building consent granted for such land must be noted on the certificate of title.

In Arkinstall v Wairoa DC [1998] NZRMA 428, noted [1998] BRM Gazette 117, the Court accepted that s 36(2) BA91 was a more appropriate way to deal with concern about erosion, than requiring a covenant under s 108(2)(d) RMA91 to the effect that the only building allowed on the site must be relocatable. The Court adopted the reasoning of Hammond J in Coromandel Peninsula Watchdog Inc v Hauraki DC [1997] 1 NZLR 557, noted [1997] BRM Gazette 53, at p 566.

In many cases it has been argued that controls under the RMA do not need to be applied because the Building Act regulates building in areas subject to natural hazards. This argument has been rejected. In *Bay of Plenty Regional Council v Western Bay of*

Plenty District A27/02 the Court noted that both Acts regulate building in zones subject to natural hazards according to each Act’s purpose. The RMA contains a wider environmental perspective than the Building Act (“sustainable management”). Generally the RMA provisions will be invoked initially and the Building Act will follow. In *Lowry Bay Residents Association v Eastern Bays Little Penguin Foundation Inc* W 45/01 (Judge Kenderdine presiding) the Court firmly rejected the argument that the potential of the proposed facility to be affected by severe storms, salt deposits and spray drift was not relevant because design of buildings is a matter dealt with under the Building Act. The Court expressed surprise that the development had been approved for an area demonstrably subject to coastal hazards.

Local Government Act 2002

This Act requires stopped roads along the margins of the coast (along Mean High Water Springs) to be vested in Council as esplanade reserves. The Local Government Act 1974 also establishes the means by which Council may collect financial contributions for funding the acquisition, maintenance and development of reserves.

Section 650A1(i) of the Local Government Amendment (No 2) Act allows for district councils to undertake various works in the coastal environment including the erection and maintenance of: quays, docks, piers, wharves, jetties, launching ramps, and any other works for ‘*the improvement, protection, management, or utilisation of waters within its district (subject to the controls established by the RMA)*’.

Civil Defence Emergency Management Act 2002

As part of the comprehensive approach to civil defence emergency management (CDEM), all hazards, not only natural hazards, must be taken into consideration.

The CDEMA requires CDEM Groups to form and prepare Civil Defence Emergency Management Plans by June 2005. CDEM Groups are cross-boundary, regional groupings of which all the region’s local authorities are represented by their mayors.

The CDEM plans must state and provide for:

- the local authorities that have united to establish the CDEM Group;
- the hazards and risks to be managed by the Group;
- the civil defence emergency management necessary to manage the hazards and risks;
- the objectives of the plan and the relationship of each objective to the National Civil Defence Emergency Management Strategy;

- the apportionment between local authorities of liability for the provision of financial and other resources for the activities of the Group, and the basis for that apportionment;

- the arrangements for declaring a state of emergency in the area of the Group;

- the arrangements for co-operation and co-ordination with other Groups.

Reserves Act

The Reserves Act also enables the formation of esplanade reserves and eplanade strips (in accordance with the purposes outlined in the RMA) where land adjoins the coast. The key difference between these two provisions being that esplanade strips are not fixed in position but maintain their position relative to the coast (or other body of water), even if the coast moves. Unlike esplanade reserves, which can only be created in the circumstances outlined in the RMA, esplanade strips can also be created by voluntary agreement.

While the Reserves Act is based on public use and access, often reserve areas are used to provide buffers of coastal land through managed retreat, or adaptation responses where coastal hazards have been identified. Without explicit reference to buffer functions in a reserve management plan, it is questionable whether reserve areas can be treated in this way by TAs, because their buffering function may impact upon their specified use for reserve or open space recreation reserve.

The eight classifications of reserves differ in their degree of protection and public access rights.

Private Property Rights

RMA case law on property rights has clearly established that property rights are subject to RMA procedures.

The most important case on ‘property rights’ in this context is *Falkner v Gisborne District Council* [1995] 3 NZLR 622 (Barker J, High Court Gisborne). In that case it was held that a common law right to protect ones property from the sea must be subject to the procedures under the RMA.

In *Bay of Plenty Regional Council v Western Bay of Plenty District Council* A 27/02 (Judge Bollard presiding) the Court noted that the even if private property owners are prepared to accept the risk of a hazard, the council still has responsibility to control the use of ‘at risk’ land.

In *Skinner v Tauranga District Council* A 163/02 (Judge Bollard presiding) economic evidence was put forward of the decrease in property values if rules restricting development were included in the plan. However the Court said this was not sufficient to override the need for the council to plan ahead for coastal hazard risks.

In summary, arguments about overriding property rights, and residents who are prepared to accept the risk, have not succeeded.

Appendix 2: Hazard drivers and the effects of climate change

A2.1 Hazard drivers

A2.1.1 Sea-level fluctuations

Fluctuations in the mean level of the sea (after taking out the influence of tides) are an important component to consider when assessing the risk of coastal inundation, and to a lesser extent coastal erosion. The predominant timescales at which sea-level fluctuations occur at are:

- days to weeks (storms and winds);
- seasons (annual heating and cooling cycle by the sun on the ocean surface);
- interannual (3 to 5 year El Niño-Southern Oscillation[21] cycles);
- interdecadal (20 to 30 year Interdecadal Pacific Oscillation[22] cycles).

Besides the general long-term trend in rising sea level under past and future climate-change, climate change will also modify all of the above fluctuations in sea level to a greater or lesser extent.

Presently, the actual mean level of the sea can fluctuate by up to ±0.25 m when all the longer-period sea-level cycles of at least 6 months are included, but without considering storm effects or climate-change trends.

Seasonal variability over a year from thermal heating and cooling can amount to around ±0.04 m on average, but up to ±0.08 m in some years, with the maximum usually occurring between January to April.

ENSO-driven fluctuations in sea level at Mount Maunganui (Figure A2.1) approach ±0.12 m, with the highest sea levels occurring during La Niña episodes. This behaviour pattern is typical of both east and west coasts.

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[21] Cycle of alternate El Niño and La Niña episodes that govern climate and sea-level variations around the Pacific and Indian Oceans—commonly called the El Niño–Southern Oscillation or ENSO system.

[22] Longer "El-Niño–like" 20–30 year cycles of alternate positive and negative phases that effect the wider Pacific Ocean region, abbreviated as IPO. Since 1998 the IPO has been negative.

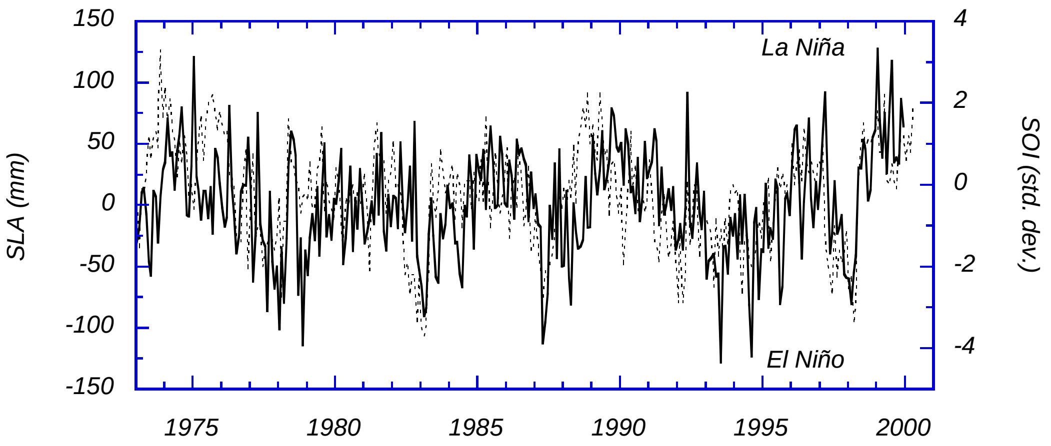

Figure A2.1: Mean sea-level anomaly (SLA) from Mt. Maunganui, after removing tides and the mean annual cycle, compared with the Southern Oscillation Index or SOI (dotted line) over the 27-year period 1973–2000. Positive values of SOI indicate La Niña conditions.

The IPO signal at 20–30 year cycles is clearly seen in New Zealand's longest sea-level record from the Port of Auckland shown in Fig A2.2. The IPO facilitates sea-level fluctuations of up to ±0.05 m, as indicated by the moving-average line, with the higher sea levels being recorded during the negative phase of the IPO.

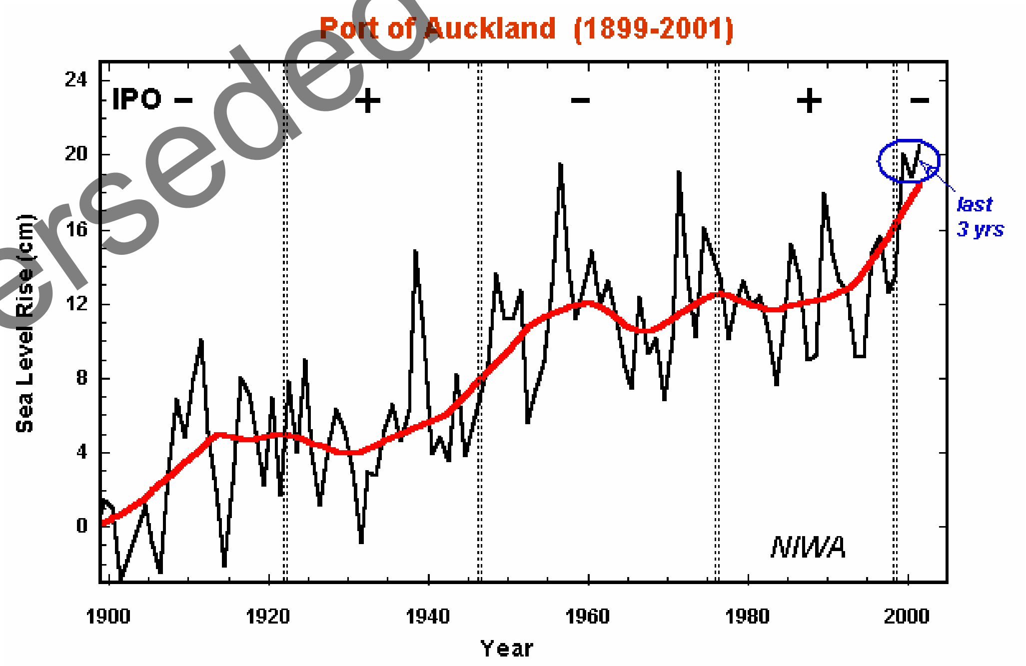

Figure A2.2: Annual fluctuations and the 20-year moving-average (thick red line) for mean-annual sea level from the Port of Auckland, compared with the positive and negative cycles of the IPO. [Note: the overall linear trend in historic sea-level rise is +0.16 m/century.]

A2.1.2 Tides

Timing and height of the tide is an important determinant for whether coastal or river-flood inundation from a storm will occur in a particular coastal area. Tidal currents are also an important process in shifting supplies of sediment via sandbars or deltas into and out of estuary and river entrances, feeding or starving the adjacent coastal beach systems. Consequently, tides are part of the coastal hazard equation (along with river sediment exports, coastal wave climate, and alongshore sediment drift) as to why the end of sand spits such as Ohiwa, Mokau, and South Brighton are vulnerable to excessive erosion or accretion. The delicate balance between these hazard drivers at river and estuary entrances has major implications for managing coastal erosion, increasingly so as climate change effects increase.

Tides are generated by gravitational forces exerted by both the Sun and Moon on the Earth's oceans. Ocean tide waves then propagate onto the continental shelf and into estuaries and harbours, being modified by wave refraction (where the tidal wave slows down and increases in tide range as the water becomes shallower), friction from the seabed, and constrictions such as estuary entrances, river mouths and straits.

As tide height is a critical component of any coastal inundation event, an upper-limit tide level is needed for a risk assessment (see inset box on assessing inundation levels in Section 4.4.2). One such upper level that is widely available is mean high water spring (MHWS)[23]. MHWS traditionally is computed as the long-term average of the highest high tide that occurs just after every New and Full Moon, called spring tides. Normally only around 10–12% of high tides would exceed the MHWS mark.

While MHWS is a simple concept and widely available, New Zealand tides along the central-eastern coasts don't easily fit with the traditional MHWS definition. For example, at Kaikoura over 50% of high tides exceed the MHWS level. The reason is there is little difference between the fortnightly neap and spring tides along the central-eastern region. Instead, the highest tides occur once a month (27.5 days), when the Moon's elliptical orbit takes it closest to the Earth (i.e., when the Moon is in its perigee). Therefore in estuaries and open coast locations from Christchurch to East Cape, a better 'hazard' definition of the peak monthly tides is to use a 'pragmatical' MHWS, such that only 10–12% of local high tides exceed it, or use the perigean-spring tide level. These different types of MHWS level may be able to be obtained from NIWA or the regional council.

Knowledge of the frequency distribution of high-tide heights (Figure A2.3) can also provide a useful context in assessing the coastal inundation risk over several decades and also to calculate a 'pragmatical' MHWS level for central-eastern coasts.

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[23] MHWS for Standard Ports is at: http://www.hydro.linz.govt.nz/tides/info/tideinfo5.asp and for some Secondary Ports at: http://www.hydro.linz.govt.nz/tides/secports/index.asp

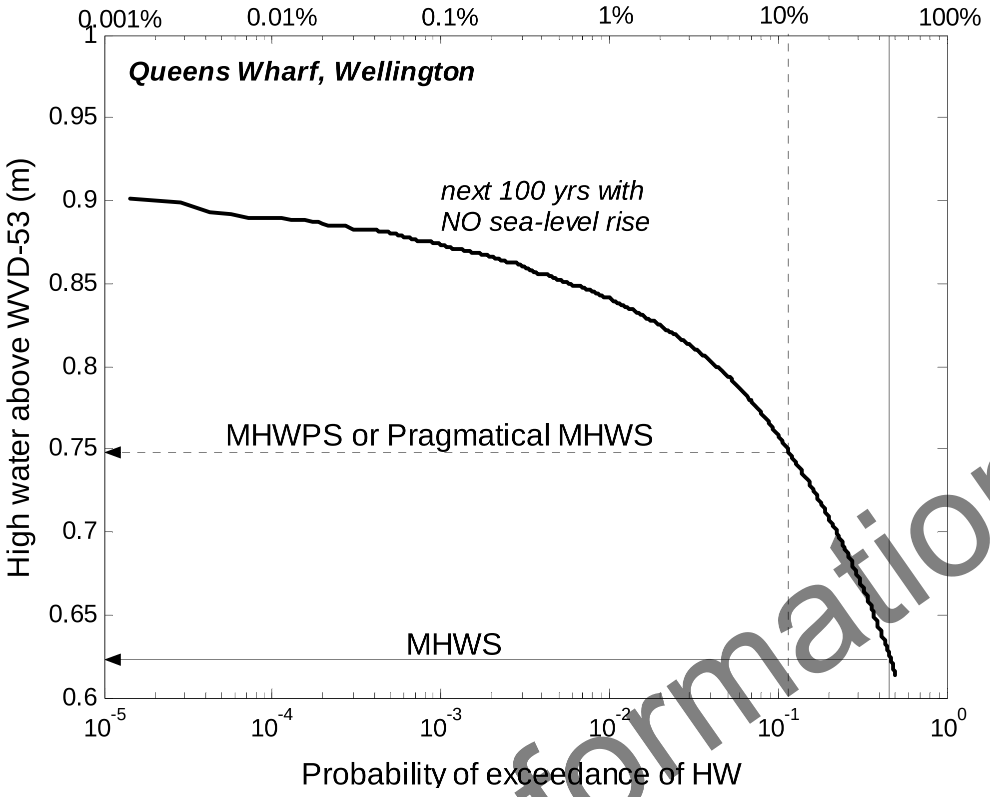


Figure A2.3: Example probability-of-exceedance plot of predicted high water (HW) heights over the next 100 years for Queens Wharf (Wellington), excluding storm and global-warming effects. The traditional MHWS level in Wellington is 0.62 m, but it is exceeded by 46% of all high waters. A 'pragmatical' or the mean high water perigean-spring (MHWPS) level, which is 0.13 m higher than MHWS, is only exceeded by 11% of all high waters. The peak predicted tide height for the next 100 years is another 0.15 m above the 'pragmatical' MHWS.

A2.1.3 Storms and adverse-weather patterns

Storms or sustained adverse weather patterns are the most well-known cause of coastal hazards. The effects can be sub-divided into:

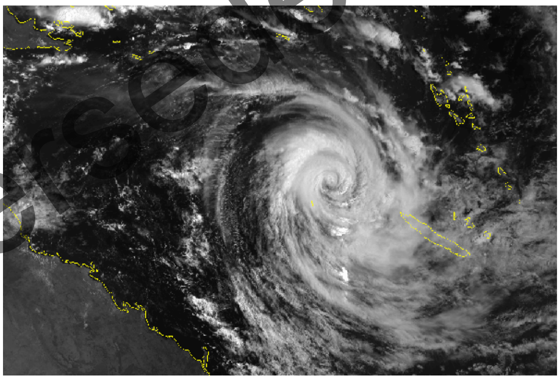
- weather-related causes that directly impact the coast:

    - ► severe meteorological events, such as extra-tropical cyclones (see Case Study below) or mid-latitude depressions, where strong winds cause damaging waves, strong currents and storm tides, and low barometric pressure further intensifies storm tides;
    - ► adverse-wind patterns over extended periods that contribute to chronic coastal erosion (or at the other end of the spectrum, chronic accretion) through movement of sediment up- or down-coast or offshore/onshore;

- weather-related causes that operate in the hinterland, but indirectly affect the coast:
  - severe storms producing heavy rainfall that cause rivers to flood, ultimately inundating low-lying coastal areas near river mouths and in estuaries, particularly during high tides, or changing geomorphological conditions at river mouths or along beach fronts that make coastal areas more susceptible to erosion/inundation;
  - storm events can deliver fresh sediment sources to coastal and estuarine systems via rivers;
  - adverse weather patterns, such as drought periods or El Niño episodes that produce westerly winds, when sediment supply to east-coast areas reduces, and vice-versa in La Niña conditions.

Waves and storm tides are discussed separately below, with inputs needed for the risk assessment process.

CASE STUDY: Ex-tropical cyclones—Cyclone *Drena* passed New Caledonia on 7 January 1997 en-route to New Zealand (see photo). Nearer New Zealand it re-intensified as an ex-tropical cyclone.



Cyclone *Drena* off New Caledonia on 7 January 1997. [*Photo: courtesy of NOAA]*

The storm hit both North and South Islands from 9 to 12 January with heavy rain, gale force winds, low pressure (990 hPa) and coincided with large tides that exceeded mean high water perigean-spring tides. *Drena* caused large 'storm tides' that lead to coastal inundation of properties in Moanataiari suburb of Thames (30 houses), New Plymouth and Nelson (Ruby Bay). On average, northern New Zealand is affected by one extra-tropical cyclone per year.

Waves and swell

New Zealand's location in the open ocean between the strong westerly wind or 'roaring forties' belt (45–60°S) and the mid-latitude high pressure belt (30°S) means that the coast is exposed to one of the highest energy wave regimes in the world. The wind-generated waves observed at the coast represent the combination of locally generated (wind-sea) and distantly generated (swell) waves. In most northern and central regions, the local wind generated component tends to dominate, particularly during extreme storm conditions. However, there have been occurrences on otherwise fair-weather days of swell riding on the back of high tides causing coastal inundation through coastal barrier overtopping (Figure A2.4).

Figure A2.4: Coastal inundation at East Clive, south of Napier, in August 1974 caused by swell (right) on the back of very high tides overtopping the gravel coastal barrier and causing coastal inundation (left).

A consistent New Zealand-wide wave climate for the 20-year period 1979 to 1998 has been developed by NIWA.[24] The results are summarised in Figure A2.5 in terms of the 20-year average of the significant wave height H_{av}. (Note: *significant wave height* is a term used by engineers and scientists to embrace the higher bracket of all individual wave heights that occur over a period—usually over a 15 to 20 minute period—being the average height of the highest 33% of wave heights). The pattern of the 20-year average for significant wave height in Fig. A2.5 is only a general guide to open-coast wave exposure in assessing the coastal hazards, as many coastal localities have a degree of sheltering from deepwater waves in particular directions due to headlands or islands.

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[24] Gorman, R.M.; Bryan, K.R.; Laing, A.K. (2003). A wave hindcast for the New Zealand region–Deep water wave climate. *NZ Journal of Marine and Freshwater Research Vol. 37(3)*, in press.

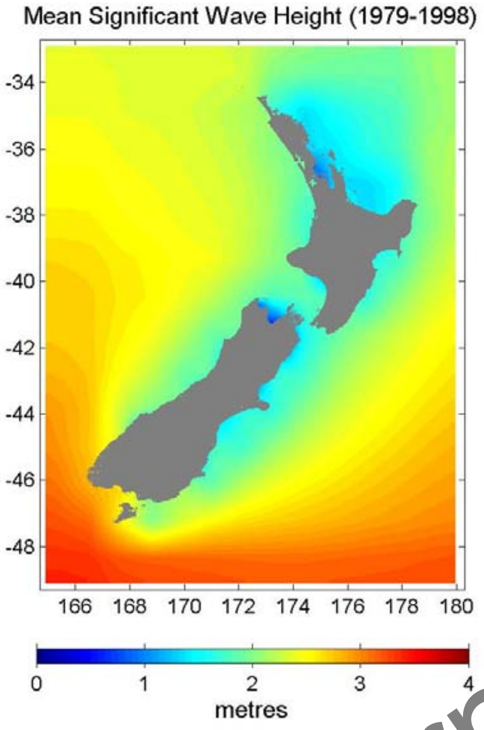

Figure A2.5: 20-year average of the significant wave height (H_{av}) around New Zealand, based on a deep-water wave model. Note: results are only approximate in coastal areas.

New Zealand can been subdivided into 4 major zones in terms of open-coast wave exposure for a broadly-based risk assessment. These zones are categorized by the range of the long-term mean for significant wave height (H_{av}), the average wave period between wave crests (T_{av}), and prevailing compass directions from where waves approach:

a) South-facing coasts, Fiordland to Catlins, South Island—an extremely high-energy wave zone (mean H_{av} =3–4 m; T_{av}=10–12 sec; SW–W). Waves are typically steep, indicating a zone of active wave generation, but also contain a sizable swell component from the Southern Ocean.

b) Western New Zealand coasts—a fairly high energy wave zone (mean H_{av} =2–3 m; T_{av}=6–8 sec; SW–W). The waves are steep and respond to the regular passage of weather systems across the Tasman Sea.

c) Eastern New Zealand up to East Cape—a moderate-energy wave zone (mean H_{av} =1.5–3 m; T_{av}=6–9 sec; S), due to sheltering from prevailing westerly winds by the New Zealand landmass. Wave steepness is variable, indicating a mixed swell and local sea environment.

d) North-eastern North Island (East Cape to North Cape)—a low-energy lee shore (mean H_{av} =1–2 m; T_{av}=5–7 sec, N–E). Wave steepness is variable. Highest waves occur during extra-tropical cyclones, or as swell that is generated by Pacific cyclones well out to the north-east of the North Island.

In all areas, waves are about 50% higher in the winter season compared with the summer.

During severe storms, waves can reach much higher levels than these long-term average wave heights, and therefore contribute to coastal inundation and/or coastal erosion. One example of extreme waves occurred during the *Wahine* storm on the 10 April 1968, when the significant wave height (*H*) exceeded 8 m and maximum wave heights reached 13 m off the south Wellington coast. Similar wave conditions also occurred along the south Wellington coast on Waitangi Day in 2002. The Wahine Storm also generated significant wave heights of up to 9.9m in the Bay of Plenty, and significant wave heights of 9.0m with a maximum wave height of 10.5m were recorded off Tauranga during Cyclone Fergus (1996) when average wind speeds reached 30 knots and gusts reached 64 knots.

At present there is no reliable set of extreme wave height statistics around the entire New Zealand coast. A consistent set of wave height statistics for different open-coast regions is currently being developed by NIWA from the 20-year wave climate study. Waves change in character from deep water to the nearshore due to wave breaking, refraction, defraction and shoaling. The processes are complex and site- specific, requiring consideration by an experienced coastal engineer or scientist.

In estuaries and harbours, waves are mostly generated by local winds and the crest height they can reach is limited by the wind fetch. Fetch is the distance downwind of continuous open water, with long fetches allowing the wind to build up larger waves. Wind waves in estuaries and harbours can still cause erosion and inundations hazards, particularly during very high tides or concurrent with a high storm-surge level from the open sea.

Waves contribute to coastal inundation hazards by three consecutive processes:

- wave set-up—after incoming waves break, the average level of the water inside the surf zone to the beach is set-up higher than the sea level offshore from the breaker zone;
- wave run-up—extra height elevation is reached as the broken waves run up the beach and adjacent coastal barrier (natural or artificial) until the wave energy is finally expended by friction and gravity; and
- overtopping—if wave run-up reaches the crest of the coastal barrier or defence structure, then seawater will spill over and flood land and properties behind the barrier. Also if the depth and velocity of overtopping wave-flow across the top of the coastal barrier are

sufficiently high, the momentum of the flow can inflict considerable damage to coastal properties and cause injuries to people.

The factors that affect wave set-up are essentially the offshore wave height and wave period, together with the nearshore seabed slope. These factors may be similar over large stretches of coast in the district, which is why wave set-up is often included in the storm-tide level. In contrast, wave run-up at any coastal locality is usually quite site specific—factors such as beach slope, roughness (sand, gravel or large rocks), wave height, exposure to ocean swell, how close inshore waves can penetrate before breaking, and whether the shoreline is bounded by dunes, seawalls, or low cliffs, or worse, unbounded. In most cases, wave run-up calculations require assistance from coastal specialists, but for the purpose of a screening risk-assessment process, an indicative formula is given for typical natural sandy or estuary beaches (but not modified shorelines).

Wave set-up, run-up and overtopping can be assessed using various formulae and nomographs for wave set-up and run-up in the *Shore Protection Manual* (US Army Corps of Engineers 1984), or the recently completed Coastal Engineering Manual (US Army Corps of Engineers, 2003).

For coastlines with coastal protection works or cliffs terminating in ocean water with no intertidal buffer, wave run-up will be higher than for beach areas which assist dissipation, as large waves can approach much closer to the shoreline before breaking.

Waves also play a major role in causing coastal erosion, by de-stabilising and moving large quantities of sediment back and forth between the beach and nearshore bars, or moving sediments along the coast in the down-drift direction. Run-up/run-down, overtopping and cliff toe-attack by waves are other mechanisms for erosion. Waves approaching the coast at an angle to the shoreline will generate sediment drift down-coast of the approaching waves. Erosion can occur in this situation, especially if the drift is predominantly in one direction when any structure or natural feature traps sediment behind it, 'starving' the down-drift coast. Gentle swell and more quiescent waves following a storm usually assist in 're-stocking' a beach by slowly combing sediment back onto the beach, helping it to recover. Sequencing of moderate to severe storms that generate high wave activity is also an important factor in the susceptibility of a beach or cliff to severe coastal erosion.

Storm surge and storm tides

Storm surges are temporary increases in coastal and estuary water levels associated with severe storms. Storm surge is a combination of two processes:

- strong persistent winds that 'pile up' water against the coast; and
- low barometric pressure allows sea level in a region to rise above the pre-storm sea level, known as the 'inverted-barometer' effect. (Cause: low atmospheric

pressure means the weight of air above the sea is reduced, allowing the sea level to temporarily rise above normal levels).

The mix of both the wind and inverted-barometer contributions can vary widely, but typically would be around 50:50 for extreme events. A storm surge can last from several hours to a few days, and can extend along at least 100 km of coast. In New Zealand, the most severe storms could generate storm-surge heights to just over 1 m above the predicted tide level. A New-Zealand wide default storm-surge height of 0.9 m can be used for the risk assessment process if local upper-limit values are not known.

The storm-surge hazard for a local coastal community depends on the total level reached by the sea at any shoreline location at any time. Therefore it is important to account for the normal ocean tide and the wave conditions at the time of the storm surge. The combined total sea level (storm surge + high tide + wave set-up) that could impact the coast is called the '**storm tide**', and is the term used in this Guidance Manual as the storm driver for coastal inundation hazards. As discussed in the previous section, wave run-up must be added to the storm-tide to estimate the total storm-driven elevation of the sea that could impact coastal properties or infrastructure.

The likelihood of coastal inundation relates to the joint probability of a storm response (random chance) coinciding with reasonably high tides. Though tides are well described, storm-surge measurements around New Zealand are limited, which makes it difficult to carry out a rigorous return-period analysis of the likelihood of coastal inundation from storm tides around the New Zealand coast. In the interim, the combination of an equivalent MHWS or MWHPS high tide level and a default value of a 0.9 m storm surge, along with estimates of wave set-up and wave run-up will provide a realistic severe storm-tide 'event'.

A high storm tide in isolation does not necessarily imply that coastal erosion will take place, but the potential for erosion increases as waves are able to mobilise sediments further up towards the back-beach or the toe of coastal cliffs or dunes.

CASE STUDY: Worst North Island storm-tide events of last century—The impact of the *Wahine* storm (ex-tropical cyclone *Giselle*) on the Bay of Plenty produced a storm tide of around a 75-year return period. Barometric pressure fell to 963 hPa accompanied by winds gusting to 90 knots, producing a 0.9 m storm surge at the Port of Tauranga (inside Tauranga Harbour). Fortunately it coincided with neap tides.

Large seas of up to 10 m whipped up by ex-tropical cyclone *Giselle* (Wahine storm) off Mt Maunganui on 10 April 1968. [*Photo: Tauranga Harbour Board engineer*]

The biggest storm-tide events last century occurred close together in 1936. The Great Cyclone of 1–2 Feb 1936, with barometric pressures down to 970 hPa and ferocious winds, on the back of a very high perigean-spring tide, caused widespread coastal inundation damage along the east coast of the North Island. Coastal roads were washed away, a house fell into the sea at Te Kaha, while the sea swamped houses 100 metres inland at Castlepoint when the sea broached the coastal dunes.[25] A month later on 25–26 March 1936, an easterly gale produced by a low depression combined with extremely high 100-year high tides. This event caused extensive sea-flooding of the Hauraki Plains and some low-lying areas of Auckland.

A2.1.4 Earthquakes and undersea landslides and volcanoes (tsunami)

Geological processes operating on or within the seafloor can cause coastal hazards in the form of a tsunami. *Tsunami* is a Japanese word meaning ‘harbour wave or waves’, because these long waves only amplify and become obvious in coastal waters. Tsunami are generated by large earthquakes (generally Magnitude >7) that rupture the seafloor, submarine landslides (which may or may not be caused by earthquake shaking), undersea volcanic eruptions, or from large coastal cliff slides into the sea. In terms of risk and emergency management, tsunami exceeding 1 m in height at the coast are considered to be a significant hazard requiring a Civil Defence response, while a tsunami exceeding 10 m height would be catastrophic. Considering all historic and known prehistoric tsunami events recorded anywhere in New Zealand, the average return periods for 1, 5, and 10 m wave heights occuring somewhere on the New Zealand coast are approximately 8, 18 and 53 years.[26] For example, tsunami of approximately 10 m height are believed to have occurred in 1947 (north of Gisborne) and 1868 (Chatham Islands).

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[25] Brenstrum, E. (1998). *The New Zealand Weather Book*. Craig Potton Publishing, Nelson.

[26] de Lange, W.P.; Fraser, R. (1999). Overview of tsunami hazard in New Zealand. *Tephra Vol. 17*, p. 3–9.

It is helpful to categorise tsunami into two types according to their source region because their characteristics and risk profiles differ:

- *local* tsunami—generated on New Zealand's continental shelf, where active offshore faults, undersea volcanoes or steep/unstable continental slopes or large coastal bluffs are present. Local tsunami are characterised by short periods between wave crests, could reach large heights (>10 m) over short stretches of coast, but die away reasonably quickly. [NZ risk areas ☞ *East-coast North Island (Northland to Wairarapa), Kaikoura, Southland, Fiordland/Westland, Greater Cook Strait*[27]];

- *remote* tsunami—generated beyond New Zealand's continental shelf, with the predominant risk from South America. Remote tsunami waves have longer periods, more limited in maximum wave height at the coast than local tsunami (e.g., up to 5–10 m), impact wide stretches of coast and can persist for several days. [NZ risk areas ☞ *entire east coast, Southland, Greater Cook Strait*].

The best available source of information on tsunami risk in the New Zealand context is the October 1999 issue of *Tephra* published by the Ministry of Civil Defence and Emergency Management. This information is about to be updated in Goff et al. (2003). However, much further work is needed to build in the risk of local tsunami in different parts of New Zealand, and the knowledge that tsunami comprising different wave periods will resonate or amplify in different parts of our coastline. In the interim, approximate return periods for different magnitudes of maximum vertical tsunami height (to be superimposed on the local tide and sea level) are listed in Table A2.1 and shown in Figure A2.6. Dr Willem de Lange is currently revising this information.

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[27] Includes Cook Strait, Marlborough, South Taranaki Bight and Tasman/Golden Bays.

Table A2.1: Return periods (years) for specified tsunami heights determined for a selection of New Zealand major and minor ports. These results should be treated with caution as the data used to derive the distributions are of limited quality. The results are based mainly on remote tsunami data. [*Source*: de Lange & Fraser (1999)].

Tsunami return periods (yrs)				
	Tsunami height (m)			
Location	**1.0**	**2.5**	**5.0**	**10.0**
Whangarei	179	930	14,500	3,510,000
Auckland	85	427	6,280	1,360,000
Tauranga	80	322	3,300	345,000
Gisborne	44	67	135	556
Napier	56	97	243	1,540
Wanganui	79	147	414	3,260
Wellington	40	119	728	27,200
Lyttelton	35	52	101	376
Timaru	63	130	439	5,010
Dunedin	125	1075	39,000	51,000,000

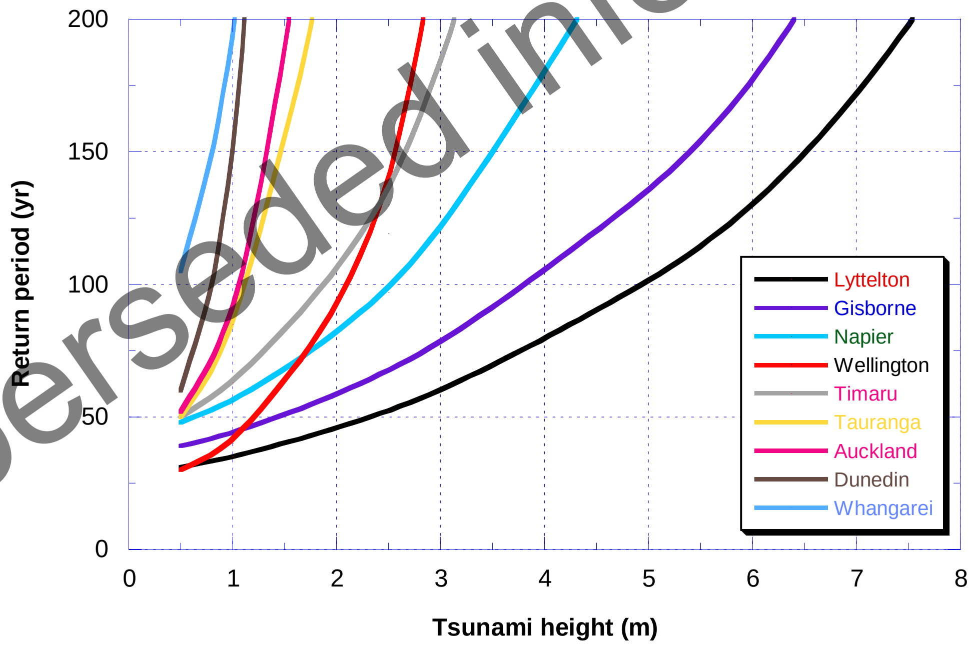

Figure A2.6: **Return-period distributions for major ports around New Zealand, based on the data in Table A2.1. Clearly Lyttelton and Gisborne areas have the highest likelihood. [*Source*: de Lange & Fraser (1999)].**

A2.2 Impacts of climate change on coastal hazard drivers

Climate change due to global warming will have a profound effect on coastal communities and environments. However, climate change won't introduce any 'new' coastal hazards—instead it will impact on existing coastal hazards through changes to hazard drivers. In very general terms, localities that are currently subject to occasional coastal hazards, are likely to suffer increased risks with a warming climate, while areas that are currently in a delicate balance may begin to experience more damaging coastal hazards in future.

A2.2.1 Climate change effects on sea level

There is no doubt that future sea-level rise due to increased global warming will contribute to a worsening situation with respect to coastal hazards. As shown by the overall trend in Figure A2.3 for sea-level data from the Port of Auckland (and similarly for our other main ports), sea level has been steadily rising around the New Zealand coastline at a national average of about +0.16 m/century, with a ±0.04 m/century variation between the four main ports (Auckland, Wellington, Lyttelton, Dunedin)[28]. (This rise is also evidenced by the fact that older MSL survey datums established in the 1940-50's around New Zealand are now several cm's below the current mean level of the sea.) The variations between the main ports in the linear trend in sea level are mainly accounted for by different rates of land subsidence or uplift and the quality of the historic data.

The long historic records from New Zealand ports demonstrate clearly that sea level is rising–so far in a linear fashion. However, as global warming becomes established and the oceans begin to warm, the rise in sea level is projected to accelerate in the near future. Global sea-level rise projections for the rest of this century have been issued by the Intergovernmental Panel on Climate Change (IPCC) in their Third Assessment Report.[29]

Although there are variations in sea-level rise around the world, mainly due to differences in vertical land movement (uplift or subsidence), research in the New Zealand region indicates that, at this stage, the IPCC (2001) global projections for sea-level rise are reasonable estimates to use for New Zealand. One exception may be Canterbury, where the historic relative sea-level rise is a little higher, around 0.2 m per century (based on Port of Lyttelton records), indicating a small degree of subsidence is occurring. However, until further land-movement assessments are complete, the NZ-

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[28] Prof J. Hannah (Univ. of Otago, pers. com.-publication pending).

[29] IPCC (2001). Climate Change 2001: The scientific basis. Technical Summary of the Working Group I report, contributing to the Third Assessment Report of IPCC. Available at: http://www.grida.no/climate/ipcc_tar/wg1/index.htm

wide average should be used. Further research continues on sea-level variability in our regional oceans, as well as GPS[30] measurements on vertical land movements.

Figure A2.7 combines the historic relative sea-level rise of 0.16 m per century at Auckland over the past 100 years (which is close to the global-average of around 0.18 m per century) with the projected accelerating sea-level rise to 2100 due to global warming from IPCC(2001). The uncertainty bands increase towards the end of this century due to uncertainties in the science and modelling, and also the uncertainty about what the world's socio-economic systems (including use of fossil fuels) will look like in 100 years time. The historic annual mean sea-level fluctuations from Figure A2.2 are also plotted in Figure A2.7, illustrating the extent to which sea level can fluctuate from year-to-year about the long-term trend (see Section A2.1.2).

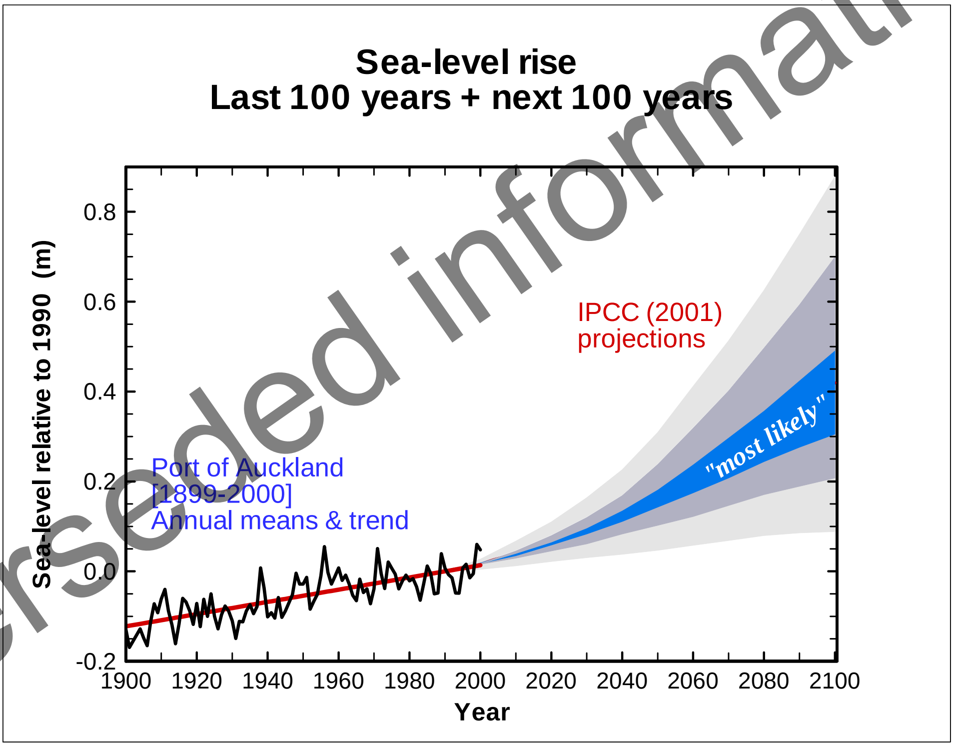

Figure A2.7: Relative sea-level trend (linear) for Auckland since 1899 (red), superimposed on the annual variability in the mean level of the sea (black), spliced with the predicted IPCC (2001) projections for global sea-level rise from 1990 up to 2100. The middle 'most likely' (blue) zone spans the range of average estimates produced by a range of climate-ocean models. The least likely estimates (high and low) are the lightest-coloured zones. (Note: sea level has been plotted relative to the 1990 sea level, which for Auckland was 1.840 m above gauge datum.)

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[30] Global Positioning System: a few NZ coastal sites have a GPS mounted permanently recording height and horizontal movement. http://www.gns.cri.nz/what/earthact/crustal/contgps.html

Recommended sea-level rises to use in the risk assessment process are listed in Table A2.2, along with the various uncertainty ranges.

IPCC have only issued formal projections on sea-level rise to the year 2100. However, for long-term planning in coastal areas it is important to note that IPCC expect sea level will continue to rise for several centuries, even if greenhouse gas emissions are stabilised. This is due to the long lag times needed for the deep oceans to respond to ocean surface heating and the expected contributions from the massive Antarctica and Greenland ice sheets after 2100.

Table A2.2: Projections of future sea-level rise (SLR) for New Zealand above 1990 mean sea level. Values in blue-shaded row are recommended for use in the risk assessment process.

Scenario	**Climate factors**	**SLR by 2050 (m)**	**SLR by 2100 (m)**
Recommended NZ sea-level rise magnitudes		0.2	0.5
IPCC–2001 'Most-likely' mid-range [Figure A2.7]	Averages of climate models & socio-economic scenarios	0.14–0.18	0.31–0.49
IPCC–2001 Outer ranges [Figure A2.7]	Intermediate zones	0.10–0.24	0.21–0.70
	Upper & lower extreme zones	0.05–0.31	0.09–0.88
Average historic NZ trend continues (0.16 m/century)	No change in sea-level trend over the 1900's	0.08	0.16

Note: 'Most-likely' projections and uncertainty ranges (Figure A2.7) for future global sea-level rise (SLR) by 2050 and 2100 from IPCC (2001), compared with a continuance of the NZ-average rise in relative sea level from 1900's with no acceleration. Suggested 'most-likely' SLR projections to work with are shaded in blue.

CASE STUDY: Interaction of tides and sea-level rise at Wellington**—**The effect of a rising sea level can be illustrated by Figure A2.8, using the present exceedance curve for high tides in Wellington (Figure A2.3). At present, the maximum high-water level is 0.9 m above datum at Wellington (lower curve). With a projected 0.2 m rise in sea level by 2050, this present maximum high-water mark will be exceeded by 22% of all high tides (follow arrows on Fig A2.8). After a projected 0.5 m rise in sea level by 2100, that same present-day mark will be exceeded by 99.9% of all high tides. This illustrates the rapid rise in the likelihood of extreme high tides exceeding a given level, which in turn will increase the likelihood of storm tides or tsunami exceeding a specified datum level.

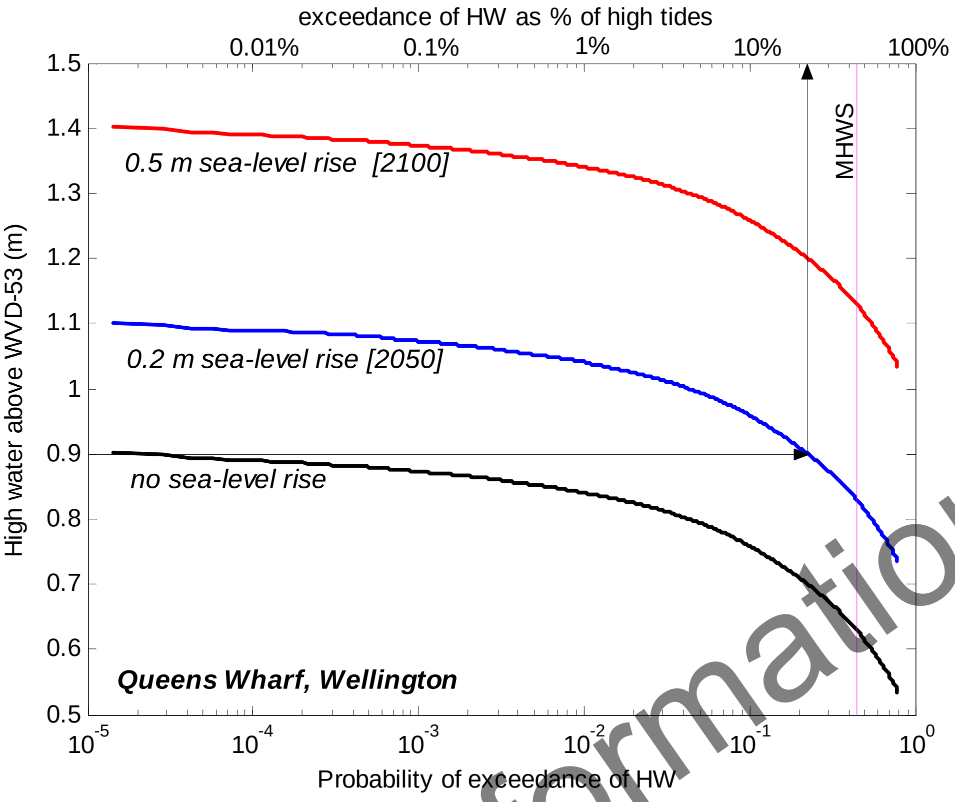

Figure A2.8: Example probability-of-exceedance curves for High Water (HW) based on 100-years of tidal predictions at Queens Wharf (Wellington), illustrating the effect of sea-level rise on the increased frequency of the present-day maximum high water level being exceeded (in this case 0.9 m above datum).

A2.2.2 Climate change effects on storms

New Zealand is subject to storms that originate from either the tropics (ex-tropical cyclones) or mid-latitudes (mid-Tasman depressions, southerly gales and fronts).[31]

The IPCC Third Assessment indicates that by 2100 it is likely that in some regions the peak wind intensities in tropical cyclones may increase by 5–10%. Tropical cyclones change their characteristics by the time they reach New Zealand, evolving into ex-tropical cyclones, and tend to affect mainly northern and eastern coastlines of the North Island and central eastern regions (Wellington, North Canterbury). During La Niña episodes, ex-tropical cyclones tend to track more directly southwards towards New Zealand, while during El Niño episodes, they tend to track more south-easterly. However, during both ENSO episodes, the frequency of occurrence is still about 1 severe ex-tropical cyclone per year that reaches New Zealand. Climate models discussed in the Overview Guidance Note show an El Niño-like change in the overall mean state of the tropical Pacific over the next 50 years. Whether or not this decreases

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[31] Revell, M. (2003). Weather systems that produce floods and gales. *Tephra, Vol. 20*, p. 2–6. Ministry of Civil Defence & Emergency Management, Wellington.

the likelihood of severe ex-tropical cyclones reaching central New Zealand is not clear, but northern regions will likely continue being impacted with a similar frequency of about 1 severe event per year. With warmer air and sea temperatures, the moist processes that govern the development and associated winds of an ex-tropical cyclone may lead to an increase in wind intensity during severe events.

Mid-latitude storms are discussed in detail in the Overview Guidance Note. "Storminess" is likely to increase in the Southern Hemisphere this century, but it is not yet possible to say whether this would mean more intense storms or a higher frequency of passing cold fronts, or a combination of these. Also regional changes over New Zealand may vary considerably from this projection for the Southern Hemisphere.

A2.2.3 Climate change effects on ocean currents, winds, and waves

Global ocean-atmosphere climate models do not include enough detail to show the narrow ocean currents that flow over the continental shelf around New Zealand. At a broad scale, there may be little change to the northern warm-water currents that flow down the eastern North Island, but increased westerlies to the south of New Zealand may accelerate the cold Antarctic Circumpolar Current, as discussed by the Overview Guidance Note.

With global warming, the average westerly wind component across New Zealand is suggested to increase by approximately 10% of its current mean value in the next 50 years.[32] However, changes to the average state of winds doesn't easily translate into what changes we might experience in extreme winds. Strong winds are associated with intense convection (expected to increase in a warmer atmosphere) and with intense low-pressure systems (see above section), so an increase in severe wind hazards could occur, as discussed in the companion guidance manual to this document "Climate Change Effects and Impacts Assessment".

Due to the short length and paucity of historic wave measurements around New Zealand, changes in wave patterns associated with global warming are not easily discerned. Increased westerlies (as described above) would affect the ocean wave climate around New Zealand, especially in southern and western coastlines. Coastal regions exposed to prevailing westerly and south-westerly winds would be subject to an increase in the frequency of heavy seas and swell that would add to the effects of higher sea levels. Waves generated by extreme storms could also increase if storm intensity increases with climate change.

A2.2.4 Climate change effects on sediment supply to the coast

Sediment is "food" to open-coast systems, so the effects of climate change on factors that affect the supply of sediment to the coastal/estuarine regions is critical to the

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[32] Mullan, B.; Bowen, M.; Chiswell, S. (2001). The crystal ball: model predictions of future climate. *NIWA Water & Atmosphere Vol. 9*: p. 10–11.

assessment of future coastal erosion hazards. Important factors that affect coastal sediment budgets are: the availability of offshore sediments to be moved onshore; changes in wave and wind climate; foredune and cliff stability; changes in river and catchment supply of sediment, abrasion; and carbonate production from ground-down shells.

Possible climate-change outlooks for wind and wave patterns (described in the previous section) will also affect different erosion and deposition processes along the coast, such as increased erosion of foredunes, gravel barriers and cliffs during extreme events, and loss or gain of sediments from the shoreline by wind blow or higher waves reaching the deeper seabed sediments more often.

Increasing sea levels will increase the tidal prism (volume of water that comes in and out each tide) in estuaries bordered by low-lying land areas, where the higher seas can encroach onto a wider area (if not bounded). This change in tidal prism is likely to alter the tidal current patterns at estuary and harbour entrances, including higher current speeds, which could alter the formation and movement of sand bars. Such changes induced at tidal entrances and estuary/river mouths may well cause further detrimental erosion on the adjacent shorelines either side of these entrances, given that these areas, such as the end of sand spits, have always been highly dynamic with marked shoreline shifts (e.g., see Ohiwa Spit photo in Fig. 1.1, where the shoreline has fluctuated within a range of around 200 m).

Changes to run-off from rivers and catchments could also markedly affect sediment delivery to the coast, provided the rivers are not already constrained by dams. A warmer atmosphere can hold more moisture, so the potential for heavier extreme rainfall (and hence higher river/sediment flows) certainly exists. The Overview Guidance Note indicates that a particular storm scenario, under a 2°C change in temperature and a 10% increase in wind speed, could result in a 16% increase in both maximum and catchment-averaged rainfall. Various modelling studies suggest that heavy rainfall events will occur more frequently in New Zealand over this century, but the likely size of this change is not yet very certain. Even less certain is how sediment delivery to the coast for different regions will respond to not only heavier, more intense rainfall events, but also greater frequencies and persistence of drought events in eastern areas, or growing urbanisation (hardening) of catchments.

A2.2.5 Climate change effects on coastal erosion

The previous section described the various perturbations from climate change that could individually impact on the supply of sediment to coastal and estuary shorelines—some may deliver more sediment to the coast, while others will reduce supply. Adding together the effects of these perturbations (pluses and minuses) plus the potential future changes in dynamics of shoreline behaviour, whether they be sandy shores, cliffs or estuarine shores, poses a real challenge in trying to produce credible predictions of trends in coastal erosion for the next 50+ years.

On sandy shores, it is generally anticipated that future sea level rise is likely to bring an increase in rates of shoreline erosion for eroding beaches, while stable to slightly-accreting beaches may begin to erode. This expectation is behind the intuitive reasoning that lies behind the so-called 'Bruun Rule' (Bruun, 1962, 1988), which was developed as a simple predictor of shoreline retreat. Bruun's model balances sediment in the beach with that in the nearshore seabed profile in response to sea-level rise. The model predicts that, as sea level rises, there will be an adjustment in the shape of the seabed and beach profile, resulting in (Fig. A2.9): (a) a shoreward displacement of a beach as the backshore is eroded; (b) movement of this eroded sediment being equal in volume to sediment deposited on the near offshore seabed; and (c) a rise of the near offshore seabed as a result of this deposition, equal in height to the sea-level rise.

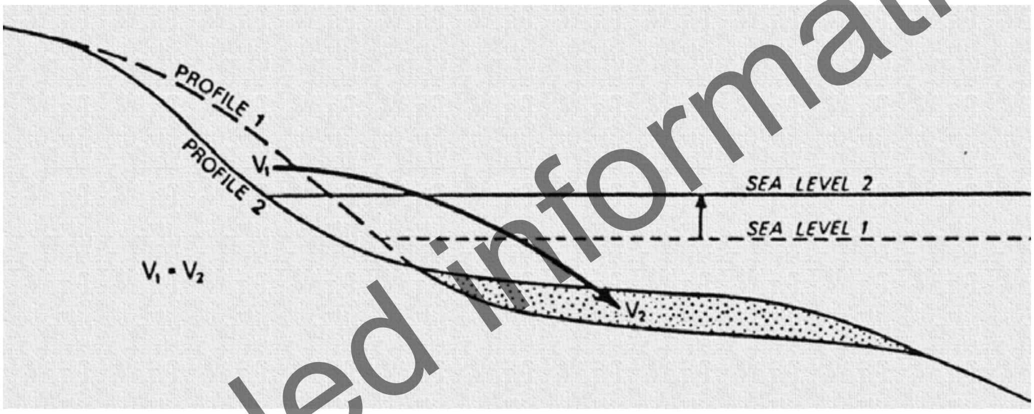

Fig. A2.9: Schematic of the Bruun Rule: response of the beach/nearshore profile to a relative sea-level rise, based on a shift from one state of *equilibrium* profile to another, where the volume V_1 of sediment lost from the backshore is conserved in the two-dimensional profile by being deposited offshore (V_2), but results in a retreat of the backshore.

Because of its simplicity, the Bruun Rule is often used in the management and long-term planning for coastal margins under a rising sea-level scenario. For typical beach profiles in New Zealand, the Bruun Rule predicts horizontal shoreline retreat rates at between 10 to 100 times the vertical sea-level rise rate. Details of how to use the Bruun Rule can be found in Bruun (1962, 1988), most coastal textbooks (e.g., Komar, 1997; Douglas et al., 2001), or refer to the ARC Coastal Erosion Handbook (ARC, 2000) for various methods of estimating coastal erosion hazard zones. However, before applying this method, it is important to understand the assumptions and limitations of the Bruun Rule. In particular, the model:

- describes the general overall shape (an equilibrium or statistical average profile), which will vary with storm events;

- applies to a two-dimensional *equilibrium* profile, wherein there is no longshore drift and the sediment volume is conserved within the cross-shore profile;

- is sensitive to selecting the distance offshore, and hence water depth, particularly the outer boundary of the active beach-nearshore profile (sometimes called the profile *closure depth*);

- can not be applied where site-specific factors for long-term erosion or accretion exist, such as in the vicinity of port breakwaters, groynes, channel dredging and dammed rivers, or to beaches near the entrance to rivers and estuaries;

- does not imply the sea-level rise itself actually causes erosion; rather, increased sea level enables high-energy storm waves to attack further up the beach and transport sand offshore. By inference, such a situation does not apply to flat intertidal beaches in estuaries, where shoreline retreat can be dominated by *inundation* from a higher sea level, not just erosion (loss of sediment), and waves can only impact the beach at high spring tides;

- was developed for sandy beaches (Bruun, 1988). It does not readily describe the response of mixed shingle/sand beaches, muddy coasts and cliffs.

Recent articles and papers continue to debate the relative merits and applicability of the Bruun Rule, especially if applied locally at a site rather than regionally or near tidal inlets (e.g., Pilkey and Cooper, 2004; Zhang et al., 2004; Stive, 2004).

For coastal cliffs, coastal retreat accompanying sea level rise depends on factors that are not directly related to the actions of the sea, such as rock types, hydro-geological processes and slope stability. Coastal cliffs can be categorised according to their composition on a scale from hard to soft. Erosion of *hard* rock or *semi-hard* cliffs (e.g. Waitemata Group cliffs in North Shore City) is mainly by way of weathering, mass slumping or slab failure, with undercutting of the toe by wave action only a secondary factor (Moon and de Lange, 2003). Any future alteration in erosion rates of these types of cliffs is more likely to be impacted by climate-change effects on hydrological "drivers" (e.g., soil moisture, heavy rainfall, droughts, groundwater) rather than sea-level rise, except where cliffs are quite low. On the other hand, *soft* coastal cliffs comprising clays or unconsolidated gravels are more likely to undergo massive slope failure that is more directly linked to undercutting at the toe by wave action. In these cases, future sea-level rise is likely to facilitate higher wave energy at the toe of the cliff, provided the shore platform is narrow[33], thereby potentially accelerating cliff erosion in tandem with climate-change impacts on hydrological processes. Further guidance on coastal cliff processes and hazard management are available in ARC (2000), Moon & de Lange (2003) and Glassey et al. (2003).

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[33] Note: wide, shallow shore platforms at the base of cliffs provide a dissipative environment for incoming waves, considerably reducing the energy of waves impacting on the cliff face, even with moderate rises in sea level.

Appendix 3: The response of different coastline types to coastal hazards

A3.1 Open-coast sand beaches

A sand beach system generally comprises compartments such as dunes, the backshore (normally not reached by tide), the intertidal beach (foreshore) and sand in the shallow nearshore, including the nearshore bar (where most of the wave breaking occurs). Sand is exchanged between these compartments by the wind and waves. Sand exchange between the dunes and the beach is retarded by the growth of vegetation, which traps material. Sand can also be delivered to the beaches by rivers and streams, from cliff erosion, from neighbouring coastal areas by wave-driven littoral drift, from the breakdown of shells, and reworked ashore from offshore seabed sediments.

Prior to human intervention, sand dunes on beaches provided good buffers against both coastal inundation and erosion hazards. Where dunes have been removed by development there is little natural defence (or 'buffer') against coastal erosion and inundation. Developments behind the foredune also prevent the dune from migrating landward (even temporarily); hence on a beach experiencing long-term erosion, the size of the natural buffer is continually reducing.

Removing vegetation leaves bare sand, which is prone to wind erosion. Removing native sand-binding species and replacing them with introduced sand binders, predominantly marram, produces a higher and steeper 'dunescape' which can cause 'blowouts'.

In some open coast locations, the foredune has been removed completely. These 'foreshore only' systems have little natural protection against erosion and inundation. As a consequence, coastal protection measures are often installed, including seawalls or rock revetments. These structures often do not dissipate the energy of wave run up. Instead they cause increased turbulence at the toe of the structure, which in turn causes increased scour and beach lowering. They also prevent the foreshore migrating landward to capture additional sediment, and in some locations have resulted in the total loss of the beach (e.g., Sumner, Christchurch).

Sand spits and sand barriers warrant special consideration from a coastal hazards perspective, particularly when they are narrow. New Zealand has many examples e.g., Ohope/Ohiwa, Omaha, and South Brighton. The end of the sand spit or barrier is very transient, even under normal tidal conditions, but particularly during storms and at times of river floods. Sand spits are among the most dynamic and changeable landforms found on the planet.

Beach and dune erosion is exacerbated locally at stream mouths or stormwater outlets due to both direct erosion as the stream meanders with time, and indirectly because the high water table in the beach sediments makes them more susceptible to erosion.

Long term and storm-induced erosion (sandy beaches)

At longer time scales, slow rates of shoreline change (0 to 1 m/yr) are most common. Rates of long-term erosion greater than 2 m/yr are less common, and long-term rates greater than 5 m/yr are rare (except for sand spits). Although over the long term there may be little change in shoreline position, movements over medium-term timescales (e.g., a couple of years up to decades) can be large and rapid. The most noticeable place where this occurs is on sand spits, where movements of hundreds of metres can occur in a matter of years. For example, the end of the Brighton Spit in Christchurch retreated 500 m in 9 years between 1940 and 1949. Coastal erosion of sandy beaches is also often serious with ‘foreshore only’ beaches that are tightly squeezed or ‘bounded’ by development or coastal protection works.

Short-term erosion occurs as a result of individual storm events, or multiple storm events over periods of weeks or a few months. These short-term responses need to be added to the long-term changes to assess total susceptibility to erosion.

Inundation caused by storms

Sand beach foreshores tend to be very flat, with slopes of 1:20 to 1:50 being common. Depending whether the beach has recently been in an erosional or accretion phase, the upper limit of these foreshores tend to be in the order of 2 to 4 m above MSL. Even in an accreted state, moderate storm run-up will run over the foreshore to the sand dunes or what ever lies behind the foreshore. Therefore ‘foreshore only’ shorelines are very vulnerable to coastal inundation.

Sand dunes are much steeper than the foreshore, so run-up onto dunes is generally less than on the foreshore. Nevertheless, run-up on dunes can reach more than 6 m above MSL. It is also important to determine whether ‘blowouts’ are present along the dune, since wave run-up can surge through these gaps and flood low-lying areas behind the dunes.

Figure A3.1: Waves overtopping the shingle/sand barrier at East Clive, south of Napier, during a storm in August 1974. [*Source*: Ministry of Works and Development collection, Napier.]

In situations where beaches are bounded by hard artificial structures, protection from coastal inundation is dependent on the height, slope and type of structure. In general, the lack of dissipation of energy from these structures results in higher wave run-up than would occur on natural beach materials.

Inundation and erosion caused by tsunami

Our understanding of the effects of tsunami is less than that for storm effects, simply because we have had less modern experience with moderate to strong tsunami. Note: small tsunami are relatively frequent (see Appendix 2). However, the greatest impact of tsunami inundation and erosion will be felt on low-lying margins behind sand beaches, gravel ridges and around estuaries and inlets. For sand beaches and gravel ridges, tsunami will run-up the beach to elevations well in excess of the offshore tsunami wave height. Also for a tsunami event with wave heights over 2 to 5 m, the sheer volume in each wave crest and the speed with which the water moves (up to 35–40 km/h) will cause erosion of dunes and beach ridges that will be more extreme than in storm events. Hence the greatest vulnerability is to low lying hinterlands behind narrow coastal barriers of less than 10 m in elevation.

A3.2 Open coast gravel beaches

There are two types of gravel beaches, one where a distinct upper-beach ridge separates the foreshore and the backshore, and the other where the beach consists of only a foreshore slope. The material on gravel beaches is transported only by wave run-up processes, hence these beaches tend to be narrower and lower than sand beaches (where wind processes are also important for beach building). As a consequence, the height of the gravel ridge is limited by the magnitude of past storm wave run-up and the supply of sediment available to build the ridge.

In many locations, there is insufficient material to build a ridge to the full height reached by storm run-up. In these circumstances, storm waves overtop the barrier, resulting in inundation of the low-lying hinterland. Overtopping also results in gravel being 'rolled over' the ridge crest, resulting in the landward retreat of the whole beach profile. In this erosion process, beach volumes are retained, but beach heights are lowered, resulting in the potential for the process to be repeated more frequently.

In locations where stopbanks have been constructed, these have often been buried by the retreating beach ridge, rendering them ineffective. This results in greater offshore sediment losses and increased run-up, accelerating beach retreat and further increasing the risk of inundation. Along the Seadown coast, north of Timaru, three rows of stopbanks have been buried by the retreating gravel barrier over the last 70 years.

Because of the high permeability of gravel beach ridges, flow directly through the beach face can also occur, often causing the crest to 'blow out' as the landward face of the crest is undermined.

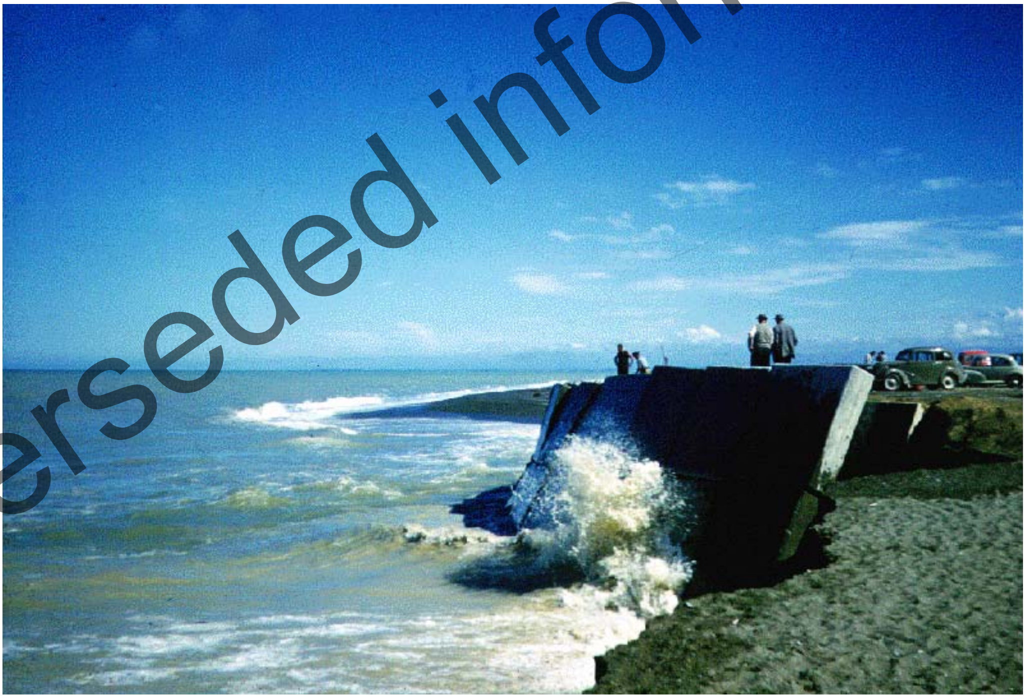

Figure A3.2: Attempted armouring of the gravel/sand beach at the mouth of the Orari River, South Canterbury (late 1950s). (*Source*: D. Todd).

'Foreshore only' gravel beaches occur where the beach has insufficient width for the development of a ridge profile. Where there is insufficient width or elevation to provide the required level of protection, artificial barriers such as seawalls or rock revetments are often constructed at the back of the beach. An example of this is the protection works on State Highway One along parts of the Kaikoura coast. This artificial ‘bounding’ of the beach often results in decreased dissipation of storm wave run-up and increased turbulence at the toe of the structure, which in turn causes increased scour and beach lowering in front of the structure, further reducing the effective width of the nature buffer system. Ultimately, protection of the shoreline against erosion and inundation becomes totally dependent on the artificial structure.

Gravelly spits enclose shallow elongated lagoons at the mouths of rivers in some locations (e.g., Ashburton River). These low narrow spits are built by wave-driven up-coast drift and are very unstable. They are overtopped in large seas, and during floods the river will burst through the spit (barrier) and straight out to sea.

Because gravel beaches are steeper and coarser than sand beaches, run-up should theoretically be less than for sand beaches. However, there are many examples of gravel ridges up to 6 m high being overtopped by storm wave run-up. The reduction in ridge crest elevation as a result of these failures results in large areas of hinterland being exposed to greater inundation hazards. A storm in South Canterbury in July 2001 resulted in over 1100 hectares of land being inundated by a combination of overtopping and beach failure.

Figure A3.3: Damage caused to a coastal property at Haumoana (Hawke’s Bay) by waves overtopping the gravel barrier in the Easter storm of 3–4 April 2002, assisted by high perigean-spring tides. [*Source*: Hawkes Bay Regional Council].

A3.3 Cliffed coastline

Where the rocks of cliffs are hard and strong, such as the metamorphic cliffs of Fiordland or the hard volcanic rocks of the Banks Peninsula and parts of the Auckland coast, the susceptibility to erosion at management timescales is very low. However, with softer sedimentary rocks the rates of cliff retreat are often up to 1 m/yr, and where the rocks are poorly compacted, badly weathered, closely jointed, sheared, or faulted, long-term retreat can be 2 m/yr.

Erosion generally occurs during storms when elevated sea levels and large waves attack the base of the cliff, resulting in undermining and failure. Cliffs also erode slowly under wetting and drying processes.

Many sea cliffs, particularly those formed in harder rocks, have either inter-tidal wave cut shore platforms at the base of the cliff or nearshore reefs. These platforms can modify vulnerability to erosion by either reducing wave heights at the shore, or possibility focusing wave energy to one spot. Soft coast cliffs, particularly alluvial outwash fans, may have beach deposits at the base of the cliff, which can reduce the frequency and intensity of wave run-up attacking the cliff face, hence reducing their vulnerability to erosion.

Other processes that can affect the stability of cliffs are vegetation cover (positively or negatively), rainfall runoff, stormwater discharges and seismic instability.

A3.4 Estuaries

In many situations, rural and urban development has occurred right up to the edges of estuaries, and the shore have been bunded, removing the important transitional area at the margin of the estuary. As a result, coastal hazards exist around many estuaries.

In estuaries where processes are driven largely by the tides and river inflows, the hazards of flooding and erosion will be greatest at the mouth and in the headwaters. Inundation is maximised when the estuary is surrounded by low-lying land and extreme tides combine with river floods. While wave energy is inhibited inside most estuaries, erosion of estuary banks still occurs, particularly in the soft sediments often found around the margins of low-lying estuaries. Changes in the location of channels can also result in significant erosion of estuary banks. In many cases, urban and farming development of the margins of these shallow estuaries has resulted in artificial barriers being placed around the edges of estuaries, to provide protection against both inundation and erosion. Large estuaries (e.g., Manukau Harbour) have fetches great enough that winds generate sizeable waves that attack the shoreline. Ocean swell can enter the mouths of large estuaries at high tide and erode the shore (e.g., Kaipara Harbour).

Erosion

The long-term movements of estuary shorelines are generally poorly recorded and difficult to quantify. However, estuary shorelines are generally less vulnerable to erosion than open coast shorelines, due to the low energy of the erosion drivers present. Also, in general, sedimentation rates in the main basins of estuaries have been keeping pace, or surpassing, the contemporary rates of sea level rise of about 2 mm/yr. As a consequence, estuaries do not have sediment deficit. Therefore significant long-term erosion of estuary shorelines is mainly limited to changes in channel patterns in the estuary, the causes of which are complex.

Inundation

Flooding of low-lying coastal land about the shores of estuaries is common, particularly where wetlands have been reclaimed for farmland and the ability to accommodate additional water in the shallow basins is limited. Although wave heights inside estuaries are often limited due to the shallow water depths and short fetch lengths, waves can make a significant contribution to inundation when strong winds combine with extreme water levels. Ocean waves overtopping narrow sand or gravel barriers can also significantly increase water levels in lagoons.

Tsunami

For large inlets, the topography may increase the amplitude of the incoming tsunami waves, due to resonance. For example, it is believed that amplification in Lyttelton Harbour during a 1960 tsunami resulted in higher tsunami elevations that on the open coast. Tsunami can also scour the entrances of tidal inlets, causing long-term changes in the tidal compartment.