Coastal Systems & Sea Level Rise

What to look for in the future

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Te Hunga Takutai o Aotearoa
NEW ZEALAND COASTAL SOCIETY

The New Zealand Coastal Society was inaugurated in 1992 'to promote and advance sustainable management of the coastal environment'. The society provides a forum for those with a genuine interest in the coastal zone to communicate amongst themselves and with the public. The society currently has over 300 members based in New Zealand and overseas, including representatives from a wide range of coastal science, engineering and planning disciplines, employed in the consulting industry; local, regional and central government; research centres; and universities.

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Foreword Paul Klinac, NZCS Chair

As part of the New Zealand Coastal Society's work to promote and advance knowledge and understanding of the coastal zone, this special publication, which is the fourth in the series, presents an insight as to how our coastal systems have and can be expected to behave in response to past and future sea level rise.

It is intended to complement the existing and rapidly growing knowledge base on climate change impacts, with the aim of conveying that diverse coastal systems behave in different ways, and this needs to be considered and understood by practitioners addressing coastal planning, management and engineering issues.

Articles in this publication seek to contribute to the existing literature by focusing on coastal systems, evolution, response, and – importantly – Māori perspectives on environmental change. The assembled authors are some of New Zealand's leading scientists and engineers, with roles including the education and training of our next generation of coastal managers, and they are thanked for their considered contributions and support of this publication. My special thanks are also extended to the New Zealand Coastal Society committee who have been involved with the preparation, guidance and publication of this special publication.

This publication was supported by a New Zealand Coastal Society webinar in November 2020, where selected authors also presented their research. This interactive webinar replaced what would have been our society's annual conference, which was disrupted by the global impacts of Covid-19. A recording of this webinar has been made freely available via the New Zealand Coastal Society website (www.coastalsociety.org.nz), and I encourage you to view this in support of this publication.

Waimakariri River mouth, Canterbury (Photo: Charles Hendtlass)

Introduction

Lucy Brake

Kapiti Island beach (Photo: Department of Conservation)

Sea level rise (SLR) is of special interest to NZCS members, as well as to the wider public in Aotearoa New Zealand, as it will increasingly impact on our way of life and the environments around us. Understanding and predicting coastline evolution under SLR is increasingly a priority. This Special Publication fills a gap in our knowledge about the response of coastal systems to SLR, to support improved management of our very special coastal environment.

New Zealand is part of international forums and agreements that respond to climate change challenges, one of which is rising sea levels. This means we have access to some of the latest knowledge on global and national SLR predictions. MFE guidance issued in 2017, based on the Intergovernmental Panel on Climate Change (IPCC) 2014 report, projects that by 2120 absolute mean sea levels will be between 0.55 and 1.36 m above mean 1986 to 2005 levels. The actual rise largely depends on our global greenhouse emissions pathway and the non-linear response of the polar ice sheets to warming above a tipping point. Up to 2060 there is more certainty in projections, with a New Zealand region absolute mean SLR expected to total between 0.3 and 0.5 m. In addition to rising sea levels, climate change is predicted to result in an increase in the frequency of occurrence and intensity of future storms, and that coastal inundation and erosion will be both more frequent and widespread relative to the present day.

What happens going forward depends on how our understanding of climate systems and sea level response changes, on improvements made to the predictive models and whether greenhouse gas emission targets are met. The most recent work described in the *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate*, released in September 2019, revises SLR projections upwards adding urgency to our response to rising sea levels.

But before we delve into the science there is a perspective that is an umbrella to all of these components which has been explored by Dan Hikuroa. Mātauranga Māori and its role in coastal management is 'a rich, vast body of takutai knowledge that significantly extends the temporal range of variability and change and also different perspectives on planning and management.' His chapter on the Māori perspective acknowledges that 'it does not seek universality – there can be more than one vision – and it embraces that variability, seeing it as a strength', so draws mainly from widely accepted versions to outline this viewpoint from a cultural perspective.

An overarching nationwide programme which has a major influence on how we manage the impacts of SLR is the NZ SeaRise Programme. A team of experts in this field examine the current state of knowledge about global and local SLR and how the NZ SeaRise Programme is updating our national projections to incorporate state-of-the-art information regarding future response of Earth's large ice sheets and local non-climatic influences. These local projections will be used to help make local decisions to inform adaptation. One of the key points they emphasise is that the NZ Coastal Hazard Guidance should be followed and that the projections in the NZ Coastal Hazard Guidance are 'based on previous global assessments (Kopp et al., 2014) and indicate that sea level could rise by as much as 1.2 m by 2100 under high emissions scenarios'. However, they note that these projections do not include local influences, such as vertical land movement due to tectonics or land compaction that may worsen or offset the effects of SLR.

In the context of understanding and possibly predicting coastline evolution under SLR, modelling is our most useful tool. A team of scientists investigate how over the past few years the nearshore research community has proposed a number of models to simulate coastal change. They explain that the models can be broadly categorised as '*process-based*, when the model attempts to simulate as many processes as deemed important, and *data-driven*, when the model entirely relies on local observations'. Through their research it is highlighted that some of the models are widely available but their applicability and predictive skills are often questioned.

With these first chapters providing some overarching perspectives on SLR effects on coastal systems, the remaining chapters explore some of the diverse environments that occur in New Zealand: sand beaches, gravel beaches, cliffs, coastal hydrosystems and estuaries. With that diversity comes a wide range of responses to SLR, and an equally interesting range of scientific approaches for assessing them.

Sandy beaches are one of this country's most iconic coastal features, from the top of the North Island to the bottom of the South Island. Karin Bryan and Giovanni Coco provide a perspective on how sandy beaches evolve, through sand being stored around New Zealand in beachface and dune systems, in the active nearshore region (the zone of breaking waves), in estuaries and embayments, and on the continental shelf. They explain that sand storage is continuously affected by the balance between sources, such as rivers and cliff erosion, and sinks which can range from loss to the deep sea, permanent removal through incorporation into the sedimentary record, and removal through resource extraction. They outline how all of these pathways will be affected to different degrees by SLR, 'either through a gradual change in processes, or through changes to the occurrence and duration of events'. In this chapter these effects are explored in more detail, differentiating between the effects for which we have both greater and diminished certainty.

Whilst gravel beaches are fairly common in New Zealand, they are rare throughout the world. This means that there is limited information about the impacts on gravel beach processes as a result of SLR. Derek Todd and Kate MacDonald explain how the 'literature on gravel beach dynamics is limited and their responses to SLR has been assessed only in general terms. Notably, there is no commonly accepted method or approach available to quantify the predicted effects of SLR on gravel beaches as there is with sand beaches.' This means that there are challenges to understanding and quantifying the risk to these environments from SLR. In this chapter, they evaluate various existing geometric models that have been developed for, or could be used on gravel beaches, and assess how well they replicate the processes known to be acting on gravel beaches along the Canterbury coast.

A broad range of coastal cliff lithologies and geometries occur around the country, and these are subject to a wide range of erosion rates based on their geological makeup. Mark Dickson and Catriona Thompson offer a wide overview of the possible effects of SLR on coastal cliff erosion in New Zealand. They explain that the topic of SLR and cliff erosion is associated with a 'high level of scientific uncertainty owing to the inherent variability of the physical environment, including localised lithological erosion controls and limitations in our understanding of the physical drivers of cliff erosion'. This chapter focuses on describing processes 'related to SLR that influence cliff-toe erosion, which can subsequently promote slope failure', and to provide coastal practitioners with a broad overview of the possible effects of SLR on cliff erosion.

Coastal hydrosystems comprise a diverse set of environments at the interface of terrestrial and marine systems that span a gradient from near-coast freshwater lakes and wetlands though to fully marine systems. Terry Hume and Deirdre Hart explain how SLR and climate change will affect different types of hydrosystem classes through changes to hydrodynamic forcing from river inputs (flows, water volumes and sediment volumes), ocean inputs (tidal reach, tidal prism and wave climate) and the longshore transport of sediment. They use this 'physical process lens' to discuss the potential responses of different coastal hydrosystem types to our changing climate and sea level rise. They also refer to the influence of other human-induced changes and a range of coastal management implications.

The final chapter describes how estuaries have naturally evolved over thousands over years, but that in the last 150 years or so, human activities have significantly changed the estuarine environments around New Zealand. Andrew Swales and Rob Bell outline how the future climate change impacts on estuaries are all influenced by the ongoing SLR. They point out that 'these multiple pressures, from both catchment and the sea, will magnify the issues and pressures already facing New Zealand's estuaries and lowland brackish habitats over the coming decades'. They also review the potential impacts of SLR on the biophysical environments of New Zealand's estuaries and lowland brackish habitats and set out an adaptive pathways approach to enable adaptation.

This Special Publication highlights the complexity and dynamic nature of New Zealand's coastal environment. There are diverse systems and impacts at play, which are consequences of sedimentary characteristics, geological setting and hydrodynamic climate. In addition, human influence is impacting how our coastlines are now evolving. Through the different chapters we take a look at the science behind how these different coastal environments and systems operate, their likely response to SLR and climate change and what needs to be considered to progress our thinking in terms of research, planning, engineering and management.

Mātauranga Māori and its role in coastal management

Dan Hikuroa

Tauranga (Cape Foulwind), Westport (Photo: Dan Hikuroa)

'Angi angi ki te wakarua, Angi angi ki te mawaki; Taku aho ka tangi wiwi nei; Taku aho ka tangi wawa; Taku aho kai iria ka mate, Tu ana he wata mano wai. Manowa mai hoki, Te watu wiwia, Te watu rawea, Te watu ko ronga ta, au ni ka wai atu ki moana, ka wainga Waka nene a Maui Waka nene a-ka-tau, He Hirihiringa mo te hutinga a te ao.'

'Blow gently from the wakarua, Blow gently from the mawaki; My line let it pull straight; My line let it pull strong; My line, it is pulled, It has caught, It has come. The land is gained, The land is in the hand, The land long waited for, The boasting of Maui, His great land, For which he went to sea, His boasting, it is caught.' (from Taylor, 1855).

This is the karakia Māui recited to haul up Te Ika a Māui, the Fish of Māui, the North Island of New Zealand, using the sacred magic jawbone he had acquired from his ancestress Muri-Ranga-Whenua as a hook and his own blood as bait. His canoe, Te Waka a Māui, is the South Island; Te Punga a Māui, the anchor stone, Stewart Island; Te Taumanu o te Waka a Māui, the seat or thwart, Kaikōura Peninsula. Hence, land was drawn out of the ocean and so at their interface we have coasts – takutai.

A brief history of Aotearoa New Zealand

Aotearoa New Zealand* has been settled in many waves of migration, with our identity and nation built around two main bodies of knowledge – mātauranga and science. Both provide an understanding of our whenua, our land and our moana, our oceans, harbours and estuaries, and where the two meet – our takutai.

After the Polynesian ancestors of Māori settled in Aotearoa New Zealand many centuries ago (Hikuroa, 2017), they brought with them vast navigation, ocean, tropical ecosystem, weather and storm knowledge, and systems for testing and adding to existing knowledge, and creating new knowledge. Distinct groups emerged (today, about 40 iwi and hundreds of hapū) that built their identity from landscapes, waterscapes and coastscapes. A fundamental underpinning of the knowledge bases and knowledge systems is that change is guaranteed, is anticipated, hence the systems were structured to observe, record and codify change as it occurred. Other key and intertwined underpinning principles were that of reciprocity, responsibility and relationships. These form the foundation of what we call today kaitiakitanga – the practices we undertake to fulfill our responsibility to uphold the principle of intergenerational sustainability. Kaitiakitanga is understood as managing human relationships with the environment, not managing the environment.

Although drawing from all available knowledge is our moral and ethical responsibility, I also believe that in so doing we will reach the best decisions. While the rest of the chapters will discuss scientific understandings of how different coastal systems behave in different ways, and how these should be considered in the planning, management and engineering components, this chapter will focus on mātauranga Māori and its role. In particular, within mātauranga Māori is a rich, vast body of takutai knowledge that significantly extends the temporal range of variability and change and also different perspectives on planning and management. One of the features of mātauranga Māori is that it does not seek universality – there can be more than one version – and it embraces that variability, seeing it as a strength. What does that look like? What does that mean? The multiple names and hence explanations for the South Island – Te Wai Pounamu and Te Waka a Māui for instance is what it can look like. What this means is that the observations,

* Aotearoa is one Māori name for New Zealand's North Island, but commonly used when referring to New Zealand overall.

interpretations and knowledge that informs those different names is likely vast and varied, affording us the opportunity to learn from the widest range of knowledge available. Noting there are many places with more than one name, it is highly likely that much salient coastscape information can be found therein. Acknowledging that there is no one universal set of mātauranga Māori, just like there is not one Māori perspective, I will draw mainly from widely accepted versions. I further acknowledge therefore that there will be different versions I haven't included herein, not because they are wrong, or less important, but because those are for others to tell.

Mātauranga Māori

Over time Māori developed a detailed knowledge of their natural environment (King et al., 2017), including local takutai. Hitherto mostly ignored or disregarded by the science and engineering community because it seemed to be myth or legend, fantastic and implausible, mātauranga Māori is generated using techniques consistent with the scientific method, but also includes culture and values and is explained according to a Māori world view (Hikuroa, 2017). Building on mātauranga Māori – a taonga tuku iho (treasured gift handed down through generations) – through observations and local experience, the practice of mātauranga included the recording and classification of knowledge into various forms including stories, songs, place-names and narratives. It also included methods to test and, when necessary, update knowledge.

Pūrākau

Pūrākau comprise environmental knowledge codified in story form and are an integral part of mātauranga. They are deliberately constructed explanations of landscapes,

Figure 1. Aotearoa New Zealand, aligned according to a Māori worldview, with the head of Te Ika a Maui upwards.

seascapes, coastscapes and associated phenomena, consistent with a Māori world-view, many record environmental change. Place names also contain valuable takutai knowledge and information. In customary Māori society, pūrākau were fundamental to understanding and making sense of the world.

In Te Ao Māori (Māori world), people are simply one strand in the relational networks known as whakapapa, linked in a kinship-based relationship with everything through their shared descent from Papatūānuku (Earth Mother) and Ranginui (Sky Father) (Salmond, 2014; Hikuroa, 2017). All mātauranga is understood within that whakapapa, relational framing. Accordingly, although there is much mātauranga of the takutai, and hence relevant to this Special Publication, it needs to be viewed first through that whakapapa lens, and then engaged with respectfully and appropriately.

A Māori worldview of Aotearoa New Zealand is demonstrated in Figure 1. This view doesn't change the shape of the takutai, doesn't change the processes that occur in the takutai, it just changes the orientation, and is another example of 'more than one version'. Neither version is wrong.

Because of the growing recognition of pūrākau as place-based repositories of accurate takutai information, the scientific community and Māori are increasingly working together to elucidate risks and anticipated coastal change. Despite this progress, there is still much more that could be done.

'Based on a long and close association with the land and its resources, Māori have developed a detailed knowledge of local natural hazards. This includes oral histories and traditions that *record past catastrophic hazard events, place names that designate areas that are high hazard risk, and environmental indicators that inform about the safety and viability of activities linked to changes in the environment*. Māori Environmental Knowledge [knowledge of local environmental features and processes] is a valuable and neglected area of information on natural hazards and provides a unique source of expertise that can contribute to contemporary natural hazards management and mitigation in New Zealand.' King et al. (2007, p. 59).

In Te Ao Māori, tangata whenua, the local people (tangata) born of the land (whenua), had a role as kaitiaki of their lands, waters, and physical and cultural environments they draw their identity from. Kaitiakitanga is a responsibility to maintain the wellbeing of people and environment. Contemporary kaitiakitanga can be understood as implementation of mātauranga-informed decisions and management (Clapcott et al., 2018; Paul-Burke et al., 2018) to achieve intergenerational sustainability.

In Aotearoa New Zealand we have novel laws that consider both scientific and indigenous worldviews, emphasising the human and non-human elements of landscapes and waterscapes and interconnectivity – Te Urewera Act 2014 and Te Awa Tupua Act 2017. Building on the latter Brierley et al. (2018) posit that rivers have rights to be rivers. In their Te Mana o te Wai Report to Hon Minister David Parker, the Kahui Wai Māori (2019) are very clear there is a hierarchy of obligations and the first obligation is to protect the health and mauri of the water. These laws acknowledge the integrity of both science and mātauranga Māori and resultant policies provide opportunities for coastal scientists, technicians, practitioners and Māori communities to act as advocates for the takutai. They also align with an Earth Systems Science, a trans-disciplinary, systems-based approach focused upon sustainability as an outcome, which acknowledges that changes in the environment result from interactions among the air, water and living things and that the Earth behaves as a system in which oceans, atmosphere and land, and the living and non-living parts therein, are all connected. An Earth Systems Science approach seeks to understand, predict and work with natural systems, as opposed to taking a command-and-control approach. Accordingly, Earth Systems Science has much in common with Kaitiakitanga.

One understanding of the origins and dynamic processes forming and interacting with Aotearoa New Zealand and our takutai – coasts, as introduced above, stems from the exploits of Māui. Māui's older brothers had continually refused to let him come fishing with them, so early one morning he hid in their canoe. After Māui's brothers had paddled far out to sea to start fishing, he emerged from his hiding place. Māui drew out his fishing line, which was imbued with strength through karakia and to which was attached the jawbone of Muri-Ranga-Whenua, his ancestress. He hooked the home of Tonga-nui/Tongo-nui, grandson of Tangaroa, deity of the ocean and began to pull in the huge fish. So immense was the fish that he had to recite a karakia to assist in raising it to the surface. Other versions have Māui calling the fish Ranga Whenua, Haha Whenua or Hahau Whenua, however no matter which version you prefer, once caught, the fish was called Te Ika a Māui – The Fish of Māui – the North Island.

When considered as a pūrākau (codified oral history) there is some physical evidence to support the hauling of a giant fish out of the sea – the shape is broadly that of a whai (ray) or pātiki (flounder). Te Upoko o te Ika, the head of the fish, is the southern part of the North Island, some say at Turakirae Head, with the upper jaw being Rongorongo and the lower jaw at Te Rimurapa (north and south heads of Wellington Harbour respectively), another version has Turakirae and Matakitaki a Kupe (Cape Palliser) as the jaws. The salt water eye of the fish is Whanganui-a-Tara, Wellington Harbour and the fresh water eye is Wairarapa (Lake). Te Hiku o te Ika, the tail of the fish, is Muriwhenua, the Far North, Te Tara o te Ika – the barb – is Coromandel Peninsula, Ngā Pakau o te Ika – the fins, are at East Cape and New Plymouth respectively, Te Pito o te Ika is Taupo, and the axial ranges are Ngā Tuara o te Ika – the spines or backbone. Once the fish was caught, the hook, Te Matau a Māui, instantly transformed into land now forming the coast of Hawkes Bay, and Te Kauae a Māui, Māui's jawbone, is Cape Kidnappers. There are also marine fossils found throughout Te Ika a Māui, including right in the middle of the island, indicating that at some stage what is now land was once beneath the ocean. Te Waka a Māui, the South Island, is broadly the shape of a waka, listing to the east. The northern region is Te Tauihu – the prow, and the southern region Te Taurapa – the stern.

However, to truly grasp the meaning of Te Ika a Māui we must draw also from earlier Polynesian navigation knowledge. Māori used stars to navigate from the tropics to Aotearoa New Zealand. One constellation is Te Mātau a Māui – the hook of Māui, also known as Scorpius. During the optimum season for sailing to Aotearoa Te Matau a Māui is aligned vertically. As you sail toward it, the hook appears on the horizon, with more and more of it appearing, and as you get closer and closer, first a glimpse of land, then more and more land, before finally, Te Mātau a Māui has 'pulled' Te Ika a Māui out of Te Moana Nui a Kiwa (Pacific Ocean). The Māui pūrākau is a codification framework for making sense of the many observations detailed above, consistent with a Māori worldview.

In another pūrākau that discusses the various responses of Ranginui and Papatūānuku's children after they separated their Sky father and Earth mother whom were locked together in a loving embrace, we can also see reference to processes in the takutai. The children dismissed Tu-matauenga's (guardian of humankind and war) initial suggestion to kill them, instead resolving to separate them. Tāwhiri-mātea (guardian of winds and storms) had not shared his opinion during the discussion, but after Tāne-mahuta (guardian of forests) separated his parents, his feelings were revealed – he was enraged. After wreaking havoc on Tāne-mahuta he turned his attention to Tangaroa (guardian of sea life) and Kiwa (guardian of the sea), where he heaped up waves as high as cliffs, churned the sea to whirlpools and battled the tides. Tangaroa took flight in terror from his usual home, the shores, and hid in the ocean depths, where Tāwhiri-mātea could not reach him. As Tangaroa was about to leave the shores, his grandchildren consulted together as to how they might save themselves. Ikatere, the father of fish, and Tutewanawana, the father of lizards and reptiles, could not agree where it was best to go to escape the storms. Tutewanawana and his party, shouting into the wind, followed one and some followed the other, and so they fled in two parties. Those of Tutewanawana hid themselves on land, and those of Ikatere in the sea. This is what is called, in the ancient traditions of our people, 'The Separation of Tāwhiri-mātea'. Hence Tangaroa, angered that some of his offspring deserted him and were sheltered by the forests, has ever since made war on Tāne-mahuta, so the sea is forever eating at the edges of the land.

Taniwha

Taniwha are widely known as supernatural creatures, similar to serpents and dragons in other cultures, however they are also a form of pūrākau that can have varied meanings. They could take the shape of animals such as sharks, eels, dolphins, octopuses, or even logs. In one tradition the taniwha Pane-iraira took the shape of a whale, and swam with the Tainui canoe from Hawai'ki to Aotearoa. Most usually associated with water, they reside in many places including the ocean, harbours, rivers, lakes and caves. They are seen variously as dangerous, predatory beings and as highly respected kaitiaki (protective guardians) of people and places. Exploits of taniwha include eating and killing people, kidnapping women and eating or inundating land. Pomare and Cowan (1930) record a pūrākau concerning a taniwha, Rapa-roa, that lived in a cave at the base of cliffs at Honipaka, on the Kawhia coast. A local chief, Haumia lived nearby in Taungatara pa and he made a maara kumara (kumara garden) at Honipaka. Every year Rapa-roa created large waves that inundated Haumia's gardens, ruining the entire crop. Determined to stop Rapa-roa, one day Haumia convinced Rapa-roa to go out sea, and once Rapa-roa had left he filled in his home with sand and rocks. Without a home Rapa-roa died.

In Matatā, Bay of Plenty, a taniwha in the form of a ngārara (lizard) resides in the Waitepuru Stream. Debris-flow and flood events cause the lower part of the stream to overrun its banks and carve new channels, moving back and forth over centuries – just like a flicking tail. In 2005 during extreme weather, the debris flows wiped out several roads, damaged nearly a hundred homes, many of which were completely destroyed, and caused tens of millions in damage. However it was noticeable that marae in the area were unaffected. This is because of a pūrākau of the Waitepuru Stream, that presents the ngārara, its tributaries in the form of the body (tinana), limbs (waewae) and flicking tail (hiku) and warns 'beware the flicking tail of the ngārara'. The Waitepuru ngārara pūrākau is simultaneously metaphorical and literal incorporating local Māori knowledge of geomorphology with disaster risk reduction – it is both the evidence and policy, and decisions about where to build and where not to build marae were made based on it (Hikuroa, 2017).

Another less well-known understanding is that taniwha are our kaitiaki – our guardians. When taniwha are acknowledged and accorded appropriate respect, they keep you safe. One example is Tuhirangi, whom Kupe the legendary explorer left in Te Moana a Raukawa (Cook Strait), to guide and protect canoes in the area (Keane, 2007). Another example is Karu-tahi. Ngāti Naho voiced concerns that a section of the Waikato expressway being constructed near Meremere in 2002 would encroach upon the lair of Karu-tahi. After consultation the route was slightly altered. Just over a year after construction, a flood engulfed the lair of Karu-tahi, but the re-design ensured the expressway was not threatened (Jones et al., 2020). Practically, if you know about a taniwha and how it manifests and behaves, if you take precautionary action based on that knowledge, the taniwha serves to reduce disaster risk, its presence acting simultaneously as a warning sign and hence as a guardian.

Maramataka

The maramataka is the Māori stellar, lunar and environmental calendar used to mark time, seasons and as a guide for activities such as fishing, planting and harvesting. Each lunar month was represented by a star or stars, and the nights within each month had general guides for activities, that varied in specificity through the months and seasons. The maramataka is not fixed and static, it is dynamic, and when it was taught to the next generations, the method was a combination of authority teaching and experiential learning – the maramataka was lived and practiced (Hikuroa, 2017). Importantly, a critical component of the teaching and learning process was to continually test the knowledge, to ensure that it was still valid. This continuous testing derives from an understanding that in natural cycles, change is the only constant. Accordingly, practised maramataka are both accurate and precise. By interacting closely with local environments and processes over time, Māori developed a detailed knowledge of biophysical indicators or tohu (King et al., 2005). Through these layers of the past, tohu provide access to the memories of Māori ancestors and the state of the environment in their time. They can therefore be used to signal, monitor and forecast changes in the natural environment. Due to the regular, detailed observations that form a key aspect of maramataka, it is likely that maramataka practitioners will be some of the first to notice environmental change in our takutai.

Pūrākau and maramataka are frameworks by which Māori understand and comprehend the takutai – add to and test that knowledge, share it within generations, and pass it down through the generations. Pūrākau and maramataka comprise knowledge critically verified and updated through time and therefore can be both accurate and precise.

Working with Māori communities

Mātauranga Māori is taonga tuku iho, it is not freely available to be accessed by anyone. Māori communities are the kaitiaki of the mātauranga, so it is imperative that coastal scientists and practitioners work with them in respectful, reciprocal and responsible ways. Excellent examples are works led by Darren King (King and Skipper, 2006; King et al., 2007; King and Goff, 2010). Further guidance can be found in Wilkinson (2020). One approach documented therein is the IBRLA – Initiation, Benefits, Representation, Legitimation and Accountability framework (Bishop, 1996). In this framework, mātauranga Māori is respected and upheld, collaboration is facilitated, security for the researcher is provided when including mātauranga Māori, while maintaining the integrity of the scientific method. Another is the He Awa Whiria (Braided rivers) framework (MacFarlane and MacFarlane, 2018) that recognises two streams of knowledge – science and mātauranga Māori, allowing the two knowledge streams to operate both independently and collaboratively, and like a braided river, the streams may diverge, converge, and meander, but ultimately, they both flow in the same direction and towards the same goal (Wilkinson et al., 2020).

Conclusions

This chapter has shown the origins, nature, breadth and depth of mātauranga Māori and hence its value as a repository of takutai information. Pūrākau and maramataka are a key source of takutai knowledge, showing broad understandings in those of Māui, Tawhirimatea, Tangaroa, and Tāne-mahuta, and specificity in maramataka and taniwha. In cases where taniwha are known we can anticipate the effects of sea-level rise and increased storm intensity to be acutely seen and experienced, and even utilise warning systems and implement disaster risk reduction. Many Māori place names will hold salient takutai information. Kaitiakitanga is a mātauranga Māori informed approach relevant to the takutai and the challenges we face. Similar to an Earth Systems view, kaitiakitanga seeks to work with the environment, not command and control it, by managing our relationships with the environment and what we do in the takutai.

As we explore how different coastal systems behave in different ways, and how these should be considered in the planning, management and engineering components, weaving mātauranga Māori with science will yield significant mutual benefits to Aotearoa New Zealand.

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Te tai pari o Aotearoa – Future sea level rise around New Zealand's dynamic coastline

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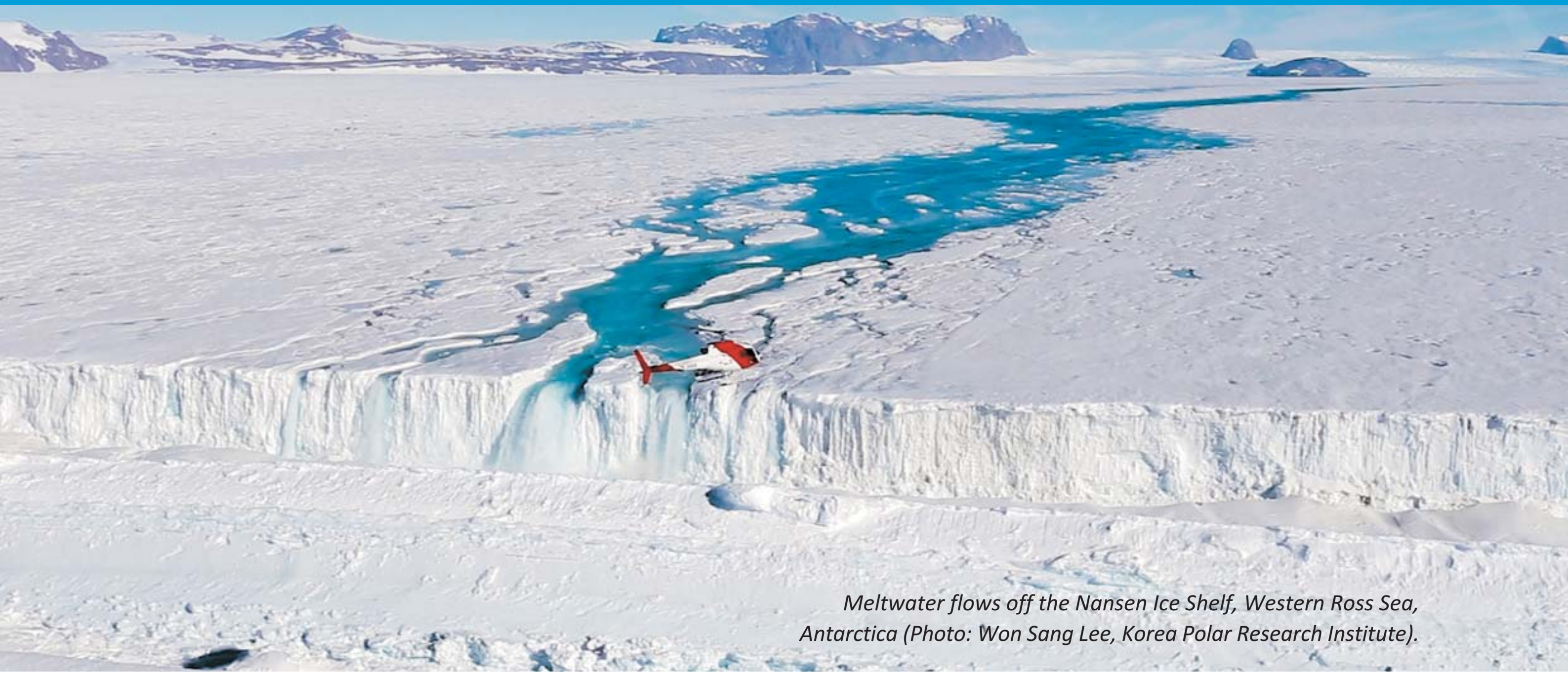

Meltwater flows off the Nansen Ice Shelf, Western Ross Sea, Antarctica (Photo: Won Sang Lee, Korea Polar Research Institute).

Introduction

Our planet is warming as greenhouse gas concentrations in Earth's atmosphere continue to increase. The warmer temperatures are causing sea level to rise as warming oceans expand and water from melting glaciers, ice caps and ice sheets flows into the sea. These rising seas will impact the things we value including private and public infrastructure and our coastal environment, much of which defines us as a nation. At risk will be dunes, coastal wetlands, estuaries, beaches, shellfish, fish nursery habitats like seagrass, groundwater and artesian water quality, and coastal habitats that provide storm surge protection and act as rich carbon sinks.

However, projecting just how much and how fast sea level will rise is difficult and this makes it challenging for us to plan into the future. This difficulty is mostly because we don't know enough about Antarctica's ice sheets nor how global emissions will track this century. Understanding Antarctica's likely contribution to future global sea level rise (SLR), and projecting sea level change around Aotearoa, is a major focus of the NZ SeaRise Programme (www.searise.nz/about) – a multi-million-dollar Endeavour Research Programme supported by our Ministry of Business, Innovation, and Employment (MBIE).

Uncertainty in Antarctic ice sheet response is not the only challenge. There is also public ambiguity and confusion regarding some aspects of climate change, SLR, and the widening uncertainty in future projections. As part of a public engagement workstream of the NZ SeaRise Programme, we surveyed 1000 New Zealanders to find out what they understood about SLR. Our survey showed that most people were correct in understanding that SLR in Aotearoa New Zealand could reach 1 m by 2100, or up to 2 m under a worst-case scenario. But it also showed that some people significantly overestimated how high sea level could reach, checking the survey boxes for 5 m, 8 m, 12 m, or even '15 m or more' of SLR. Thankfully, these higher amounts of SLR by 2100 are not physically possible, but a 1 m rise will still cause a lot of issues.

It's important that people have access to the right information – if they underestimate SLR there is a risk that our communities won't take the measures that are needed to adapt. But the same thing can happen if people overestimate SLR – research shows that overestimating the risk can lead to feelings of helplessness and a lack of willingness to act.

Our goal is to provide the public with the best location-specific information about current and future SLR – so that people can plan for the SLR that cannot be avoided, prepare for a range of uncertain future SLR, and act to avoid the higher SLR scenarios through deep carbon emission reductions.

In this chapter we outline the current state of knowledge regarding global and local SLR. We emphasise that New Zealanders should follow the New Zealand Coastal Hazard Guidance (Ministry for the Environment, 2017). Projections in the guidance are based on previous global assessments (Kopp et al., 2014) and indicate that sea level could rise by as much as 1.2 m by 2100 under high emissions scenarios. However, these projections do not include local influences such as vertical land movement due to tectonics, land compaction, or sediment accumulation.

The NZ SeaRise Programme is updating our national projections to incorporate state-of-the-art information regarding future response of Earth's large ice sheets and local non-climatic influences. These local projections will be used to help make local decisions to inform adaptation.

Sea level rise since 1900

Global mean sea level has risen approximately 18 cm since 1900 (Frederikse et al., 2020). For Aotearoa New Zealand, the observed local SLR averaged across our four main ports (Auckland/Tāmaki Makaurau, Wellington/Te Whanganui-a-Tara, Lyttleton/Ōhinehou, and Dunedin/Ōtepoti) is 21 ± 0.6 cm from 1900-2018 (MfE/StatsNZ, 2019). Whereas 20 cm may not seem like a lot, this historical rise in sea level has increased the frequency of coastal flooding events around the world (Lin et al., 2016) (see Figure 1) and future SLR will amplify this impact (Paulik et al., 2020).

Approximately two-thirds of the historical rise in sea level is due to an increase in ocean water mass as fresh water from melting ice sheets and glaciers enters the sea. The remaining third is due to expansion of the ocean as it warms. While the average rate of SLR through this time interval is 1.56 ± 0.33 mm yr^{-1} (Frederikse et al., 2020), measurements from satellites indicate SLR has accelerated over the past 25 years (Nerem et al., 2018) and that the current rate of rise is approximately 3 ± 0.4 mm yr^{-1}. Similarly, from the gauge records at our four main ports, the rate of rise in mean sea level has doubled since 1960 (MfE/Stats NZ, 2019). The most likely cause for this acceleration is an increase in the rate of mass loss from Earth's mountain glaciers and large ice sheets (Hock et al., 2019; Rignot et al., 2019; Velicogna et al., 2014).

The most recent Intergovernmental Panel on Climate Change (IPCC) projections show global mean sea level will 'likely' (17%-83%)* rise between 29 cm and 1.1 m above a late 20th century baseline by 2100, depending on the greenhouse gas emissions pathway we follow (Oppenheimer et al., 2019). Whereas these projections primarily rely on outputs from process-based models, it is important to note that sea level will rise approximately 65 cm by 2100 if we simply extrapolate the observed rate of current acceleration (Nerem et al., 2018). We also emphasise that sea level will continue to rise well beyond 2100 for several centuries – albeit at a rate of rise tied intricately to how global emissions track. Evidence shows we must act now to reduce our greenhouse gas emissions and mitigate future warming and associated impacts.

* In the calibrated language of IPCC, 'likely' means a one-third probability that SLR by 2100 may lie outside the 'likely' range.

Sea level rise is not uniform

Unlike a uniform increase in water height that occurs as water is added to a bathtub, SLR varies across geographic location and over time – SLR at any specific location can depart markedly from the global average. So, while global mean sea level (GMSL) projections help us understand the total magnitude of change, they do not offer estimates that are always relevant at a local scale.

Local Sea Level (LSL) is the sea level experienced at a specific point on a coastline and has obvious relevance when it comes to planning and adapting to inevitable change. LSL is influenced by a range of complex climate change related processes including: ice sheet melt, oceanographic processes (including changing currents and thermal expansion), glacier and ice cap melt, and changes in land water storage (including both natural and human controlled mechanisms). Non-climatic geodynamic processes also influence LSL and include instantaneous changes in Earth's gravity field and rotation, and vertical land movement due to tectonics, sediment compaction, and glacial isostatic adjustment (or GIA, which is an ongoing response to previous episodes of ice sheet growth and retreat) (see Figure 2). Vertical land movement is particularly important in New Zealand as our nation sits across the active boundary between the Pacific and Australian plates. NZ SeaRise is integrating the latest understanding regarding these processes at global, regional, and local levels to generate Local Sea Level projections around the entire New Zealand coastline.

Ice sheet melt

Most of the fresh water on our planet's surface is locked up in the ice sheets on Greenland and Antarctica. The Greenland Ice Sheet contains enough ice to raise sea level by 7.4 m (Morlighem et al., 2017) while the Antarctic Ice Sheet holds enough frozen water to raise sea level by 58 m (Fretwell et al., 2013). The Greenland Ice Sheet is currently losing mass at approximately twice the pace of the Antarctic Ice Sheet and has already contributed approximately 5.2 cm of SLR since 1900 (Frederikse et al., 2020). However,

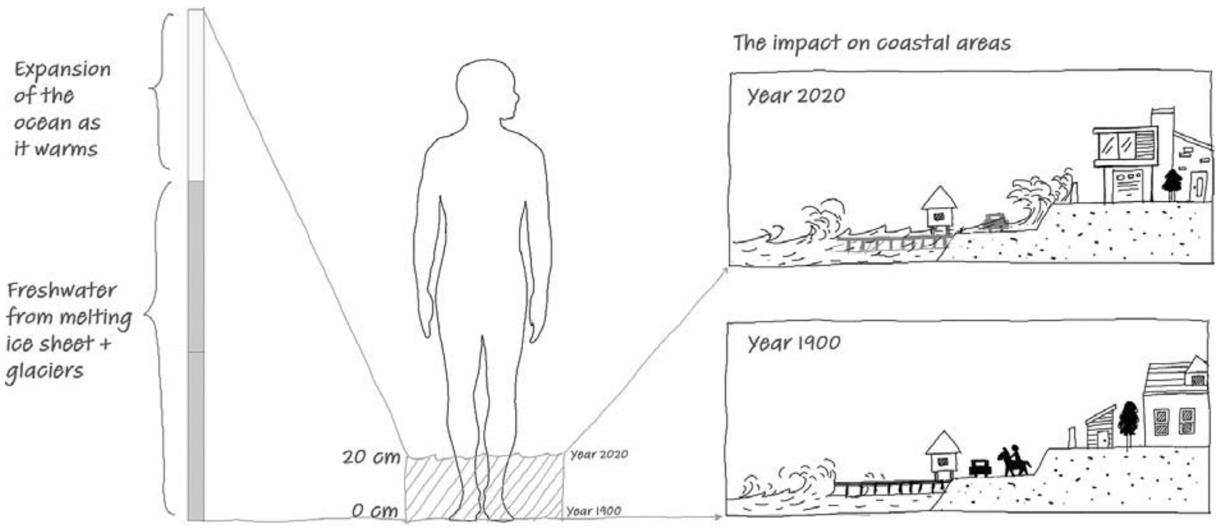

Figure 1: Sea level has risen by approximately 20 cm since 1900 causing an increase in the frequency of coastal flooding around the world. Future sea level rise will exacerbate this trend towards increased incidents and impacts or coastal flooding (Graphic: Katy Kelly, GNS Science).

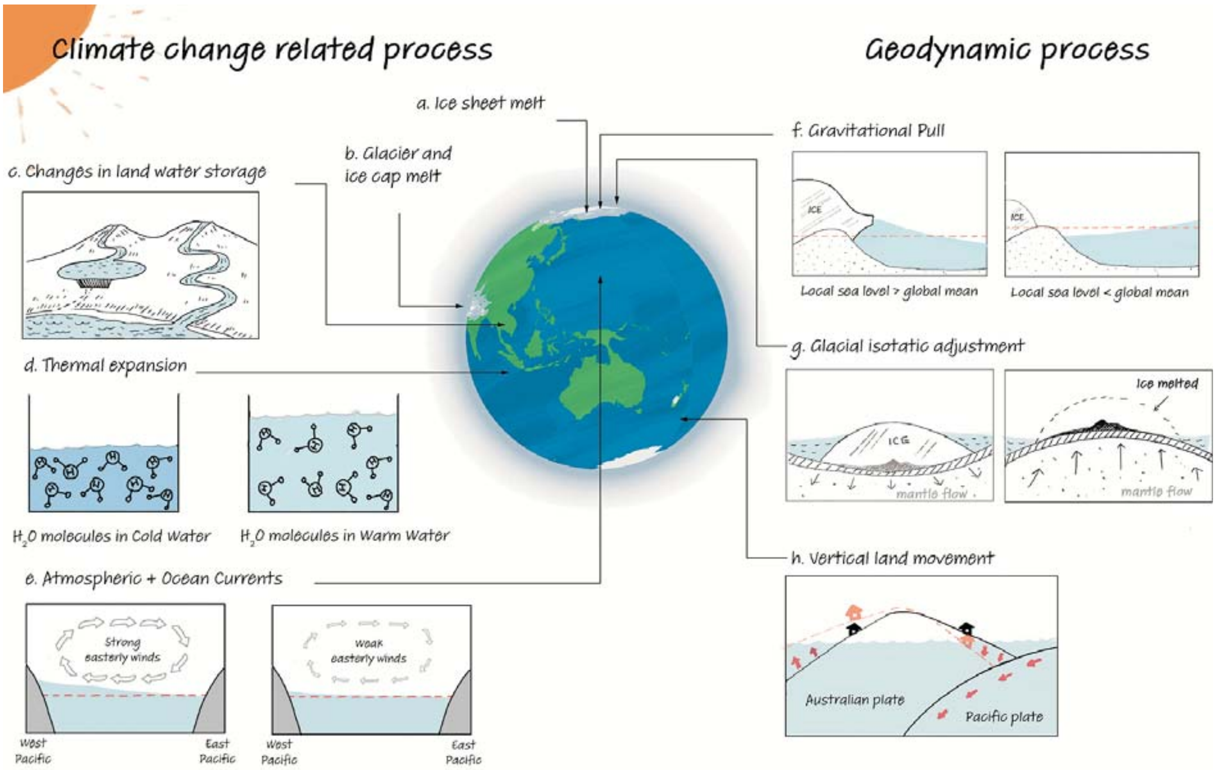

Figure 2: Processes that influence mean and local sea level. Each process is discussed in this chapter (Graphic: Katy Kelly, GNS Science).

large regions of the Antarctic Ice Sheet sit on ground below sea level and are vulnerable to ocean warming.

Whether Earth's ice sheets grow or shrink is determined by the balance between ice mass gain and mass loss (see Figures 3a and 3b). Ice sheets typically gain mass when snow falls and accumulates across inland regions and lose mass as ice and snow melts at their margins. Whereas the Antarctic Ice Sheet is currently gaining mass in some regions, the overall mass balance is negative (Rignot et al., 2019). The West Antarctic Ice Sheet is losing significant mass in areas where the ice is connected to the ocean.

Ice flow in many of these regions is accelerating as buttressing ice shelves, that provide resistive stress to the flow of the ice sheet towards the ocean, melt and thin due to warm ocean water flowing up and across Antarctica's continental shelves. When the ice shelves thin the grounded ice behind them flows faster, causing more thinning, which in turn allows previously grounded ice to float, forcing the grounding zone to retreat inland (see Figures 3a and 3b). This process speeds up, and may be unstoppable, in areas where the bedrock surface beneath the ice sheet slopes inwards toward the centre of the ice sheet (retrograde slope), as it does under much of the West Antarctic Ice Sheet. This process of Marine Ice Sheet Instability can lead to runaway retreat as the ice flux across the grounding zone increases and surface mass accumulation feeding the ice shelf margin remains stable or decreases. Science suggests we may reach a tipping point if global mean temperatures warm by 2°C, at which point positive feedbacks and dynamic processes such as Marine Ice Sheet Instability produce rates of SLR at least an order of magnitude greater than those observed now (Pattyn, 2018) and cause ice loss for centuries to come (Golledge et al., 2015).

Despite our ever-improving understanding of ice sheet dynamics, difficulties associated with modelling polar ice sheet response to climate change remains the largest source of uncertainty in sea level projections. One of the primary objectives of the NZ SeaRise Programme and the related Antarctic Ice Dynamics Project in the Antarctic Science Platform (http://antarcticscienceplatform.org.nz), is to generate new constraints on ice sheet behaviour from historical records. These constraints are used to test and improve ice flow models that are commonly used to predict how the Greenland and Antarctic ice sheets change as air and ocean temperatures increase. So far, these models have differed significantly in their projections of future ice sheet contributions to the global sea level. To help address this issue, the recent Ice Sheet Model Intercomparison Project 6 (ISMIP6) sought to understand these differences and improve model performance by using the most up-to-date atmospheric and oceanic influences from state-of-the-art climate models. This international effort, which brought together ice, ocean and atmosphere scientists, has generated new estimates of how much Earth's melting ice sheets could contribute to global sea level change by 2100. If greenhouse gas emissions continue apace, the Greenland and Antarctic ice sheets could together contribute more than 44 cm of global SLR – and that's beyond the amount that has already been set in motion by Earth's warming climate (Goelzer et al., 2020; Seroussi et al., 2020).

ISMIP6 investigated two different greenhouse gas emissions scenarios to predict SLR between 2015 and 2100: one with carbon emissions increasing rapidly, and another with lower emissions. In the high emissions scenario, the models show that melting of the Greenland Ice Sheet leads to an additional global SLR of about 9 cm by 2100. In the lower emissions scenario, the ice loss would raise global sea level by about 3 cm. This rise in sea level is on top of the anticipated future increase due to Greenland Ice Sheet melt that will occur because of warming that has already occurred since pre-industrial times. Previous studies have estimated that 'locked

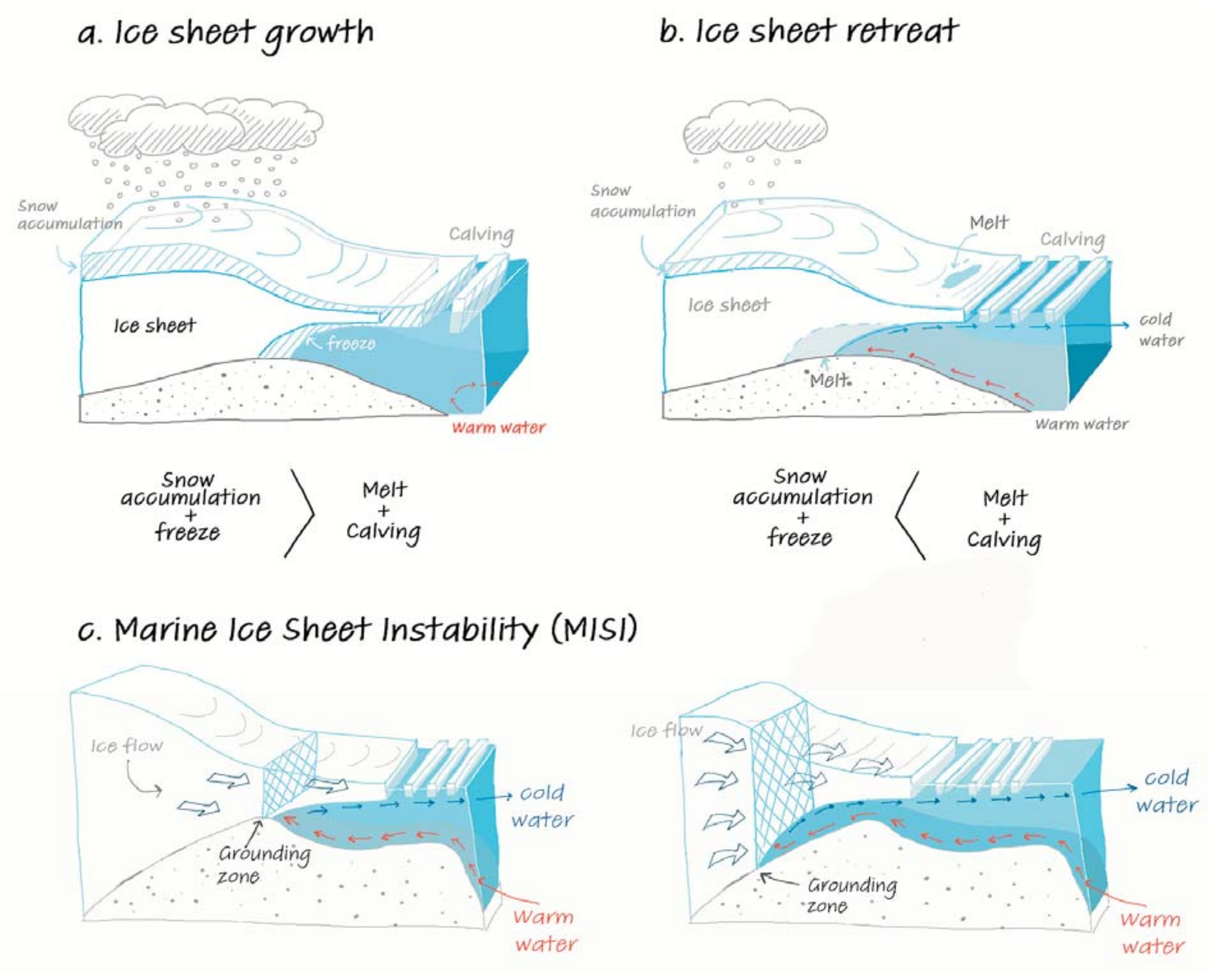

Figure 3: Processes that influence ice sheet advance (a) and retreat (b) (mass balance); (c) Marine Ice Sheet Instability can contribute to ice sheet collapse even when climatic warming slows or stops causing an unstoppable commitment to future sea level rise (Graphic: Katy Kelly, GNS Science).

in' contribution to global SLR by 2100 to be about 6 mm for the Greenland Ice Sheet. The models also indicate that the ice mass loss is largely from melting on the surface of the ice sheet.

In contrast to Greenland, ice loss from the Antarctic Ice Sheet is more difficult to predict. In West Antarctica, warm ocean currents erode the bottom of large floating ice shelves, causing loss; while the vast East Antarctic ice sheet may gain mass, as warmer temperatures cause increased snowfall. This results in a greater range of future possibilities, from ice sheet growth that decreases sea level by 7.8 cm to ice sheet melt that increases sea level by 30 cm by 2100. Ice sheet projections show the greatest loss in West Antarctica, where melting ice may cause up to 18 cm of SLR by 2100 under the warmest conditions. The main cause of the differences between the Antarctic Ice Sheet model projections is the melting underneath the floating ice shelves that surround Antarctica (see Figures 3 and 4). Many of the models underestimate modern melt rates at the base of ice shelves. Better understanding of ocean circulation underneath the ice shelves is therefore critical for improving these ice flow models. But for now, we need to live with, and adopt adaptive approaches to work with, the uncertainty.

Oceanographic processes

Increasing temperatures generally cause materials to become less dense and therefore increase the material's volume per unit of mass. When this process of thermal expansion occurs in the world's oceans, sea level increases even when the water mass remains constant. The world's oceans have absorbed 93% of the increase in heat in the climate system, and approximately one-third of the observed increase in sea level since 1900 is due to thermal expansion of the ocean (Frederikse et al., 2020).

Regional sea level is affected by variations in atmospheric and oceanic circulation. Wind stress is the main driver of changes in regional ocean height and these changes are connected to climate modes including El Niño/Southern Oscillation (2 to 4 year cycles), Pacific Decadal Oscillation (20 to 30 year cycles), and the Southern Annular Mode ('see-saw' of air mass between mid and southern latitudes). Differential heating and freshening of layers in the ocean also influence variations in global sea surface height. Together, these factors can cause regional sea level trends as much as four times the rate of global mean sea level (GMSL). Perhaps nowhere is this effect more apparent than the Western Tropical Pacific, where satellite altimetry indicates sea level is rising at a rate over 1 cm yr^{-1} (Zhang and Church, 2012) (the current trend in GMSL is approximately 3 mm yr^{-1}) (see Figure 5).

Glacier and ice cap melt

Glaciers (outside of Antarctica and Greenland) have been the largest contributor to SLR over most of the twentieth century (Frederikse et al., 2020) and are expected to continue

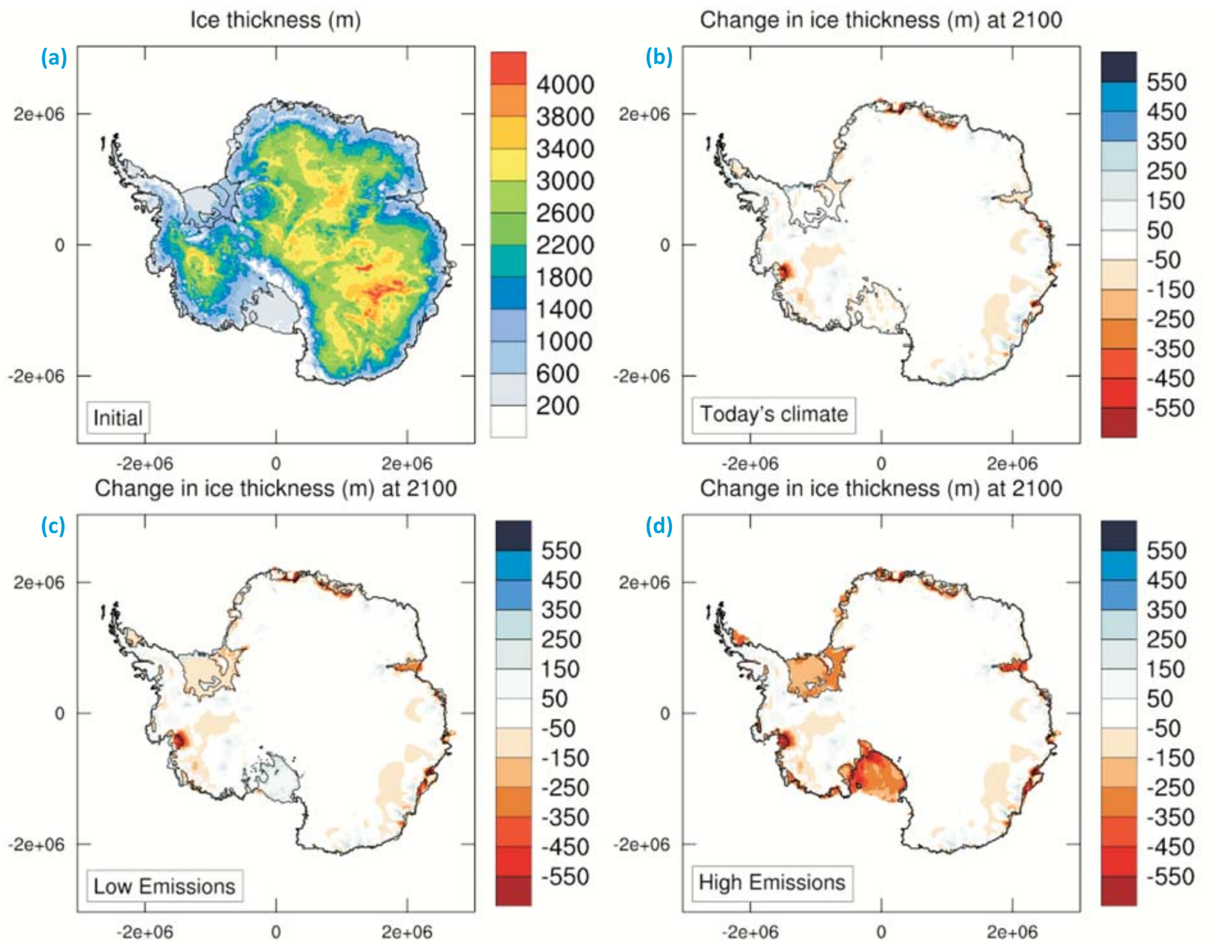

Figure 4: Example of model outputs from the Parallel Ice Sheet Model highlighting the influence of basal melt on ice thickness under different future climate scenarios including (b) a continuation of today's climate, (c) a low emissions future, and (d) a high emissions future.

to melt and contribute to sea level throughout this century. Glaciers store approximately 1% of global ice volume, enough to raise sea level by 32 ± 8 cm if they were to completely melt. Overall, glaciers will likely lose around 18 ± 7% of their ice mass in a low emission scenario (Representative Concentration Pathway, RCP 2.6), or around 36 ± 11% in a high emissions scenario (RCP 8.5), contributing between 9.4 ± 2.5 and 20 ± 4.4 cm to SLR by 2100 (Hock et al., 2019; Marzeion et al., 2020).

New Zealand glacier ice volume was approximately 73 km^3 in 1978, or enough to raise sea level by 0.2 mm if completely melted (Farinotti et al., 2019). Monitoring of New Zealand glaciers since the late 1970s shows that ice has been melting

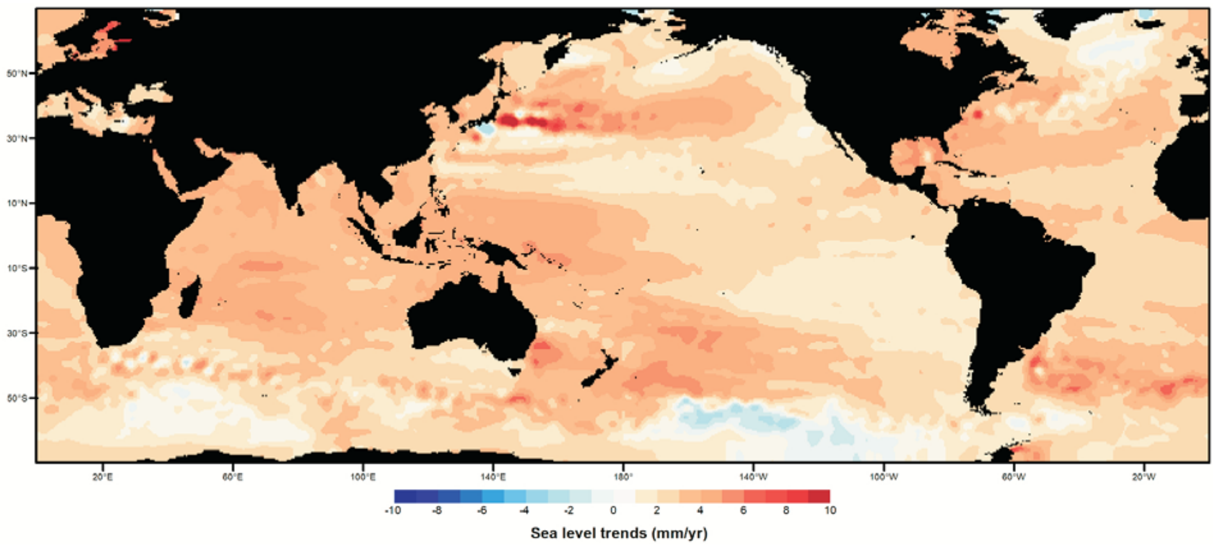

Figure 5: Estimates of local sea level trends for the period from 1993 to 2020 based on measurements from satellite radar altimeters (TOPEX/Poseidon, Jason-1, Jason-2, and Jason-3). Altimetry data are provided by the NOAA Laboratory for Satellite Altimetry.

and retreating, contributing to SLR and influencing water resources and tourism access. Digital elevation models generated from aerial images of New Zealand glaciers (Vargo et al., 2017) show that Brewster Glacier lost approximately 14.4 million m^3 of ice over three years from March 2016 through to March 2019. From 2009 to 2018, Franz Josef Glacier/Kā Roimata o Hine Hukatere retreated 1.4 km, and Fox Glacier/Te Moeka o Tuawe retreated 0.9 km (Purdie et al., 2014; World Glacier Monitoring Service, 2020). A subset of fourteen New Zealand glaciers decreased in area by 21% from 1978 through to 2016 (Baumann et al., 2020). Modelling future changes in New Zealand glaciers shows that these trends in glacier mass loss will continue over this next century (Marzeion et al., 2020).

Terrestrial water storage

Human activity has had a dramatic effect on Earth's surface with significant impact on water exchange between land, atmosphere, and ocean (Wada et al., 2017). For example, natural patterns of river flow have been altered as part of irrigation and flood protection schemes. Construction of reservoirs and artificial lakes to store water for power generation, drinking water supply, and irrigation has reduced the outflow of water to the sea (see Figure 2). In contrast, river runoff has increased due to groundwater extraction, wetland destruction and subsequent storage losses, deforestation, and hardening of surfaces in urban catchments. These activities affect the amount of water flowing from the land to the sea and have had a negative contribution to global mean sea level over the past 120 years (Frederikse et al., 2020). This negative contribution is primarily caused by the construction of reservoirs and dams that began in the 1950s and peaked in the 1970s. These activities produced a cumulative decrease in global sea level of 2.5 to 3 cm.

Future change in terrestrial water storage is closely tied to estimated changes in global population. However current projections suggest changes in terrestrial water storage will contribute a likely range between -1 and 9 cm to sea level between 2081 and 2100 (Oppenheimer et al., 2019).

Gravitational pull and Earth's rotation

The massive ice sheets in Antarctica and Greenland exert a gravitational pull on the ocean around them, causing sea level to be higher next to the ice sheets (see Figures 2 and 6). So, when ice in Greenland melts, sea level drops next to the ice sheet and rises at locations far away from Greenland – including in Aotearoa. The opposite occurs when Antarctica's ice sheets melt because the decreasing ice mass exerts less pull on the nearby ocean and sea level near the ice sheet margin falls. Each ice sheet produces a distinct sea level fingerprint of change (Mitrovica et al., 2009).

Redistribution of mass around the planet due to changes in ice sheet volume and the location of ocean water also affects Earth's rotation, which has a 'feedback' influence on Local Sea Level. For example, a full collapse of the West Antarctic Ice Sheet displaces the south rotation pole towards West Antarctica driving a sea level increase in North America and the Indian Ocean that is greater than the global mean (Mitrovica et al., 2009).

Vertical land movement

Vertical land movement (VLM) has a direct impact on local sea level along the world's coastlines. The shape of Earth's land surface is slowly changing in response to the retreat and final disappearance of massive ice sheets that covered large areas of our planet during the last ice age, 20,000 years ago. In the parts of the world that carried the weight of huge ice sheets – much of the Northern Hemisphere, Antarctica's continental shelves, and New Zealand's South Island – the land is now slowly rising. This process is called glacial isostatic adjustment (GIA). Other areas of land are subsiding as the Earth's mantle flows away from these regions and toward the areas of glacial rebound. These

Figure 6: Schematic illustrating the effect of gravitational pull on sea level. Under scenario 1, if the entire Greenland ice sheet were to melt, global mean sea level would increase by approximately 7 m. In Oslo, close to the ice sheet, sea level would not change. In London and New York, it would rise by 1 to 2 m. In Southern Hemisphere cities like Punta Arenas, sea level will rise by 9 m. In scenario 2, if Antarctica's ice sheets melt, the opposite pattern in sea level rise would occur.

changes in the shape of Earth's crust cause local sea level to fall in some regions and rise in others.

The vertical position of our coastlines is also changing due to the movement of tectonic plates. New Zealanders understand the impact of plate movement better than most people in the world. We live on a plate boundary and our coastline is always changing. Scientists can measure the amount of vertical land movement using global positioning satellite technology and radar systems mounted on Earth observing satellites such as Envisat and Sentinel. These instruments show us that parts of our coast are going up at a rate of 1 cm every year and others are sinking by as much as 5 mm per year.

Areas of land that are going up reduce the effect of global SLR and can even cause a local fall in sea level – at least in the short term. But local SLR will be higher in areas that continue to subside. Subsidence often happens in low lying areas, or deep-seated sedimentary basins or deltas, that are usually filled with soft sediment. These sediments compact over time causing the land to sink. This sinking can be accelerated when we pump water out of the basin to use the land for farming and industry or to build houses and airports. These low-lying subsiding regions are the most susceptible to SLR. The Waikato Coast, Hauraki Plains, mid to lower eastern North Island, Marlborough, Nelson, Wellington, and Dunedin are regions where SLR will be faster than the global and regional means due to land subsidence.

Measuring vertical movement along New Zealand's entire approximately 15,000 km-long coastline through traditional approaches, such as with tide gauges, is near impossible. To help overcome this problem we have combined spaceborne geodetic observations from interferometric Synthetic Aperture Radar (InSAR) and Global Navigation Satellite Systems (GNSS) to increase both the spatial extent and density of VLM estimates around the entire New Zealand coastline (see Figure 7).

New Zealand's permanent GNSS network (https://www.geonet.org.nz/data/types/geodetic) provides precise surface location data that can be used to accurately determine both vertical and lateral movement at sites along our coast, including our tide gauges (Denys et al., 2020). However, the network is generally too sparse to provide continuous estimates of the VLM across many regions of interest including coastal deltas and sedimentary basins, where our urban areas are often located. However, by integrating GNSS with InSAR observations, which provides data at approximately 100 m spatial resolution, we can generate an almost continuous coastal estimate of the VLM (see Figure 7). InSAR utilises radar satellites which illuminate the ground's surface as they orbit the Earth. When received by the satellite, the reflected radar signals give a measurement of the distance between the ground and the satellite. By collecting data acquired on successive passes of the satellite instrument, we can examine the interference patterns produced by the electromagnetic waves (interferograms) to identify millimetre scale surface displacements over thousands of square kilometres. Unlike optical satellites, which rely on the sun to illuminate the Earth's surface and whose view can be obscured by clouds, radar systems are able to see through clouds, and with their own radiation source, acquire images at any time of day or night.

To generate a first VLM map of New Zealand's coast (see Figure 7), we have used historical InSAR images acquired by the European Space Agency's Envisat satellite between 2003 and 2011. One advantage of using this time interval is that we can minimise the influence of some of the larger earthquakes which have struck New Zealand in recent years, starting in Dusky Sound in 2009. Using all the available images, we have generated more than 1000 individual

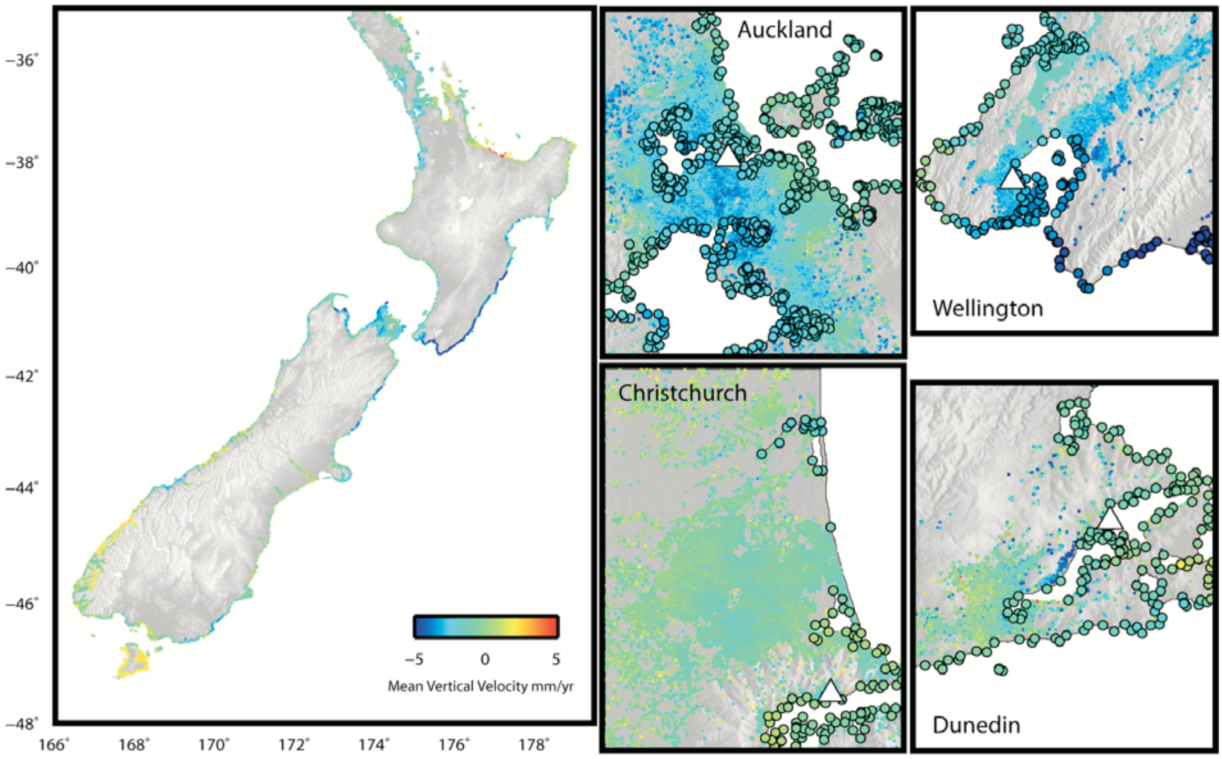

Figure 7: Vertical land motion map for New Zealand with insets for our four major coastal cities (-ve values = subsidence, +ve values = uplift). Circles indicate location and mean vertical velocity of coastal data areas used for sea level projections. White triangles indicate tide gauge locations.

interferograms which are used to estimate the best fitting vertical displacement rate over the approximately eight-year observation period. GNSS data are used to help correct the InSAR observations and put them in a consistent reference frame. In a final step, for any given point along the coast we average all the VLM estimates, from both InSAR and GNSS, within a 5 km radius.

Our preliminary results provide the first almost continuous estimate of the VLM around the entire New Zealand coastline (see Figure 7). The estimated rates show some interesting variations in VLM in different areas of the country. Along the east coast of the North Island, there is evidence of extensive subsidence of up to approximately 5 mm yr^{-1} with a general increase in magnitude from north to south. This variation can be largely attributed to the ongoing subduction of the Pacific Plate beneath the North Island. Across the Bay of Plenty, there is an approximately 30 km-long region of uplift which, over the observation period, reached approximately 10 mm yr^{-1}. This has been attributed to a deep magmatic intrusion associated with the 2005-2009 Matata earthquake swarm (Hamling et al., 2016). Since the end of the swarm in 2009, GNSS data show a drop in the uplift rates highlighting the transient nature of some of the VLM observations. The top of the South Island north of Kaikōura shows subsidence of a 2-3 mm yr^{-1}, but this area was dramatically uplifted during the 2016 earthquake. With the additional complexity of events such as the Matata earthquake swarm and Kaikōura earthquake, estimating the evolution of the coastal VLM will pose an ongoing challenge.

Probabilistic projections for Aotearoa New Zealand

We have generated Local Sea Level (LSL) projections for New Zealand, which are an aggregate sum of individual sources that contribute to sea level change (outlined in previous text). The workflow for these projections is primarily based on a probabilistic methodology for a given RCP and extreme sea level tail distribution, that has been used in local to national scale sea level change assessment in the United States (Kopp et al., 2014). This workflow has been modified to include high-resolution VLM data for New Zealand. The methodology for each contributor is briefly summarised in Box 1.

In this chapter we show new LSL change projections that were produced using the described methods (Box 1) for the tide gauge at Port Chalmers (DunedinTG: -45.814313938, 170.629403272) and an area of reclaimed land along the harbourside boundary of Dunedin City (DunedinHS: -45.89101, 170.508) (see Figure 8). Separate probabilistic

Box 1: How we generate sea level projections

Projections of ice-sheet contributions to global mean sea level change are generated from calibrated time-dependent log-normal distributions fit to the projected rates of equivalent sea level change from the IPCC Special Report on the Ocean and Cryosphere Change (SROCC) (Oppenheimer et al., 2019) and published expert elicitation rates. The SROCC projections inform the median and 'likely' range (16.7th-83.3rd percentiles) of the distribution while the expert elicitation informs the shape of the tails. A rate is sampled at each time step from the fitted distribution and used to project linearly to the next time step where the process is repeated. Samples from these fitted distributions are correlated in time to ensure a single projected time series is self-consistent. The resulting projections of ice sheet melt contributions to the global mean sea level is then localised using a sea level fingerprint that accounts for the uneven distribution of mass across the world's oceans.

Projections of glacier and ice cap contributions to global mean sea level change are generated by fitting a multi-variate t-distribution to ice mass change with a mean and covariance derived from an ensemble of output from process-based models for 17 different source regions. Global contributions are then localised using the sea level fingerprint method like the ice sheets.

Global sea level change due to thermal expansion of ocean water and the local sea level change due to regional steric and dynamic effects are projected using a t-distribution calibrated to the mean and covariance of a multi-model ensemble of Climate Model Intercomparison 5 (CMIP5) models. Each model is represented in this ensemble with a single model realisation (i.e. one model, one vote). A linear correction is applied to the output from each model in the CMIP5 ensemble due to model drift. Furthermore, the standard deviation of the fitted t-distributions is scaled by a factor of 1.7 to be consistent with the AR5 judgement that the 5th-95th percentiles of the CMIP5 model ensemble represent the likely range for global mean thermal expansion.

Global mean sea level change due to terrestrial water storage is estimated by the relationship between changes in reservoir impoundment, ground water depletion, and global population. Reservoir impoundment is estimated with a sigmoidal function response to global population as a function of time. A conservative 2-sigma error in the resulting impoundment of ± 50% is applied. Ground water depletion is represented by a linear response to global population as a function of time. The slope of the linear relationship is sampled from a normal distribution with a mean and standard deviation estimated from model-based studies. An additional 2-sigma error of ± 50% can account for the reported errors in the model-based studies. Global population projections from the Shared Socioeconomic Pathways (SSPs) are used to drive these terrestrial water storage models to year 2100 at which point population rates provided by the United Nations for low, middle, and high scenarios are used to extend the SSP population projections to year 2150.

Rates of vertical land movement were derived from InSAR and Global Positioning System (GPS) measurements with high-spatial resolution obtained from a campaign spanning years 2003-2011. These observed rates and the reported associated errors are used as the moments of a normal distribution from which a rate is sampled and used to project forward in time.

projections for three greenhouse-gas emissions scenarios (Representative Concentration Pathway (RCP) 2.6, RCP 4.5, and RCP 8.5) were generated for the years 2020-2150 in ten-year increments. Projections were generated both with and without vertical land movement to highlight the effect that our dynamic coastline can have on SLR. Rates of vertical land movement at the tide gauge location were determined from the GNSS station (DunedinTG-GPS: -1.25 ± 0.10 mm yr^{-1}) and InSAR data averaged across a 5 km area (DunedinTG-InSAR: -0.75 ± 0.14 mm yr^{-1}) and from InSAR at the harbourside location (DunedinHS: -2.40 ± 1.40 mm yr^{-1}). All projections here report changes in sea level above a zero-baseline set at 2005.

Impacts, risk, and adaptation

Vulnerability of our coastal environment to SLR is already apparent. Exposure assessments show that, after one metre of SLR, around 125,600 buildings, at a replacement value of NZ$38 billion, along with 178,000 residents, could be exposed to future extreme storm-tide events (Paulik et al., 2020). A national-scale assessment of local government assets determined that over NZ$5 billion of public council assets (reserves, buildings, utility networks, roads) are also exposed to a one metre rise in sea level, without considering the impact of extreme storm-tide events (Local Government New Zealand, 2019). These risk exposure assessments point to the challenge ahead for infrastructure in the low-lying coastal areas of Aotearoa New Zealand. Our natural coastal and estuarine environments will also be affected as sea level rises. They will change and migrate inland, but only if they have space to do so – otherwise rising sea levels will diminish these intertidal areas (see 'Estuaries and lowland brackish habitats', p55).

New Zealand's national coastal policy (Department of Conservation, 2010) requires that coastal hazard risk assessments consider the impact of SLR for at least 100 years into the future. Global mean sea level will likely rise between 12 and 26 cm relative to a baseline from 1986 to 2005 by 2050 (Oppenheimer et al., 2019), but sea level projections beyond this time become subject to wider and deeper uncertainty. This is due largely to ambiguity surrounding the rate at which global greenhouse gas emissions can be reduced and whether runaway polar ice-sheet instabilities occur once a tipping point is reached. Despite this uncertainty, practitioners are required to consider best available information on the cumulative and likely effects of climate change when planning for coastal activities, uses, and development. Furthermore, the effect of SLR on communities and our natural environmental systems will differ depending on location. To ensure just and equitable adaptation to SLR, up-to-date and credible information and evidence should be made available to tangata whenua, communities, central and local government, the judiciary and elected representatives. This evidence can then be used to develop adaptation plans. Our national coastal guidance (Ministry for the Environment, 2017) recommends a dynamic adaptive pathways approach to accommodate the range of uncertainty.

Clearly there is a need to present SLR information so it can be used by communities as they work to establish adaptation plans. To this end, researchers within the NZ SeaRise

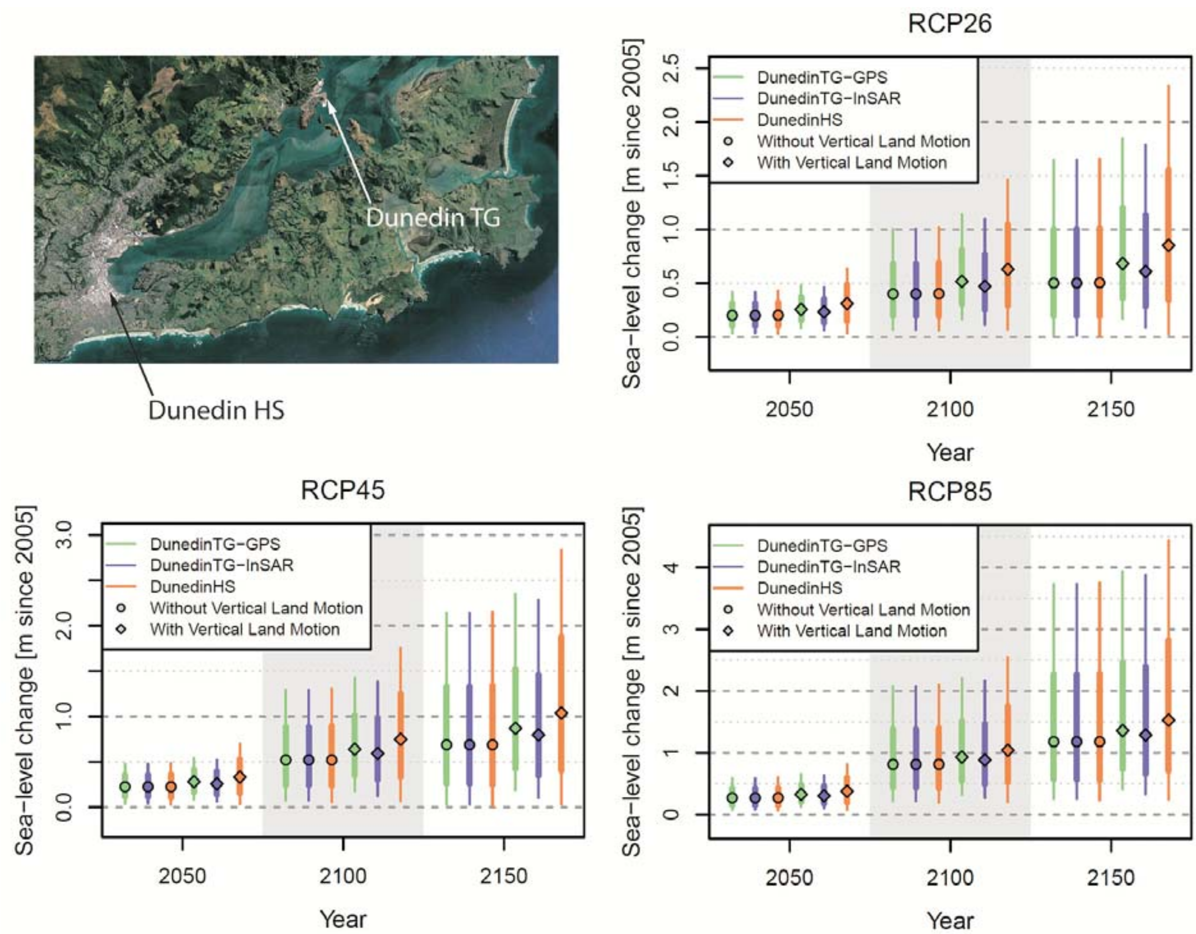

Figure 8: Preliminary Local Sea Level projections for two locations in the Dunedin region under RCP 2.6, 4.5, and 8.5 with and without vertical land movement. Plot bars/symbols – Thin = 5-95th, Thick = 16.7-83.3rd, Circle/Triangle = 50th (percentiles).

Programme and the Resilience to Nature's Challenges (RNC) National Science Challenge (https://resiliencechallenge.nz) are developing a sea level rise toolkit designed for a range of users. This toolkit will likely include an online portal with local SLR projections, vertical land movement data, links to relevant peer reviewed climate change information, and guidance for policy and planning. The toolkit will provide access to scientific evidence that will help agencies, business, and communities to understand the SLR hazard and will inform risk and vulnerability assessments. Access to this underpinning information will assist the discussion and development of planning, funding, design and engineering responses for application at national and local levels. The NZ SeaRise team will begin more active engagement in 2021, alongside the Science Challenges, to design this toolkit which is expected to be available at the end of the NZ SeaRise Programme in late 2022.

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Modelling coastal evolution for rising sea levels

Giovanni Coco, Karin Bryan, Jennifer Montaño and Laura Cagigal

Ngarunui Beach (Photo: Steve Hunt)

Aotearoa New Zealand enjoys an incredible variety of beautiful coastlines. Such variety in coastal types is related to sedimentary characteristics (e.g. sediment type can range from mud to gravel), geological setting (e.g. open coasts versus embayed beaches), and hydrodynamic climate (e.g. wave exposure). Since most of the New Zealand population lives in proximity to the coast, anthropogenic effects can prevent natural coastline evolution. The range of human interventions is broad and involves localised engineering structures to protect properties and infrastructure, and large-scale catchment operations that affect the overall sediment budget. Understanding and possibly predicting coastline evolution under sea level rise (SLR) is increasingly a priority and, in this context, modelling is our most useful tool to address the changes to come.

Over the past few years, the nearshore research community has proposed a number of models to simulate coastal change. The models can be broadly categorised as *process-based*, when the model attempts to simulate as many processes as deemed important, and *data-driven*, when the model entirely relies on local observations. Some of the models are widely available, but their applicability and predictive skills are often questioned. This contribution addresses modelling describing coastal morphodynamic evolution over time scales associated with SLR. While the emphasis of this chapter is on modelling morphodynamics, a quick introduction to modelling hydrodynamics is given, since they constitute the drivers of morphological change.

Coastal hydrodynamics

Predicting SLR is obviously critical to all modelling efforts and is a task that requires specific studies (see 'Future sea level rise around NZ's dynamic coastline', p11). Working on top of SLR are a range of additional effects, needing a detailed understanding of other hydrodynamic drivers.

Astronomical tides are easy to predict, but there are still large uncertainties when it comes to predicting waves and non-tidal contributions (e.g. storm surge). Currently, we can derive timeseries of storm surge and wave characteristics from the projections of Global Climate Models. Using statistical techniques or direct simulations, the projections can be downscaled to the New Zealand coastline. Data of this type is critical and is luckily freely available for the New Zealand coastline (see www.coastalhub.science), empowering researchers and managers to make their own assessment of future change.

Our present understanding of the future New Zealand wave climate generally indicates a variety of effects ranging from moderate increase in wave height along the west coast and slight decrease along the east coast, and significant changes in dominant wave directions. On average, storm surge is also projected to slightly decrease around New Zealand although extreme events, larger than previously measured, are likely to occur (Cagigal et al., 2019). It is evident that more studies of this type are necessary, so that we can better address variability between projections, and update them as new data from increasingly more refined Global Climate Models become available. Aside from projecting future changes, modelling of SLR requires further advances in how flooding will affect urban centers. This type of modelling is conceptually trivial, but is also numerically demanding and requires specific expertise, for example, to set up the grids and the boundary conditions. It is easy to envisage advances in this area of numerical modelling and implementations within the New Zealand urbanscape.

Coastal morphodynamics

Most models of sandy beaches under SLR are somehow related to the (in)famous theoretical approach provided by the 'Bruun rule'. In a nutshell, the Bruun rule assumes that the shoreface retreats while maintaining an equilibrium profile (see Bruun, 1988, for a general discussion). Since external sediment sources or sinks are neglected, the Bruun rule reduces to a sediment balance where a transgression due to SLR increases accommodation space, which is balanced by erosion of the upper beach (see Figure 1).

Depending on the equilibrium beach slope, the Bruun rule predicts a shoreline retreat of the order of up to fifty times of the predicted vertical rise in sea level. The model relies on a number of assumptions that are rarely accounted for or even discussed. Several improvements have been suggested, but the research community is far from accepting this model as a universal tool for prediction.

Aside from the previous assumptions, the Bruun rule fails to address the observed variability in beach response to SLR. It is worth reminding that, depending on a variety of factors, beaches could simply 'rollover' in the onshore direction with no real loss of beach width. At the same time, if a seawall or a cliff backs the beach, it is likely that SLR will cause erosion endangering communities, properties and infrastructure. There are also more extreme cases, usually associated with faster rates of SLR than the ones we are currently experiencing, where beaches struggle to keep up with the change in sea level and become totally submerged. Moreover, despite the rise in sea level, sediment supply could ultimately decide whether accretion or erosion occurs.

Even though the above limitations are widely known, the Bruun rule is still commonly used, often without local measurements providing the possibility of some sort of calibration. Because of the importance of local factors and because of the major simplifications in the approach, the blind use of the Bruun rule as a predictive tool should be discouraged. In this context, it is worth pointing out that studies based on the Bruun rule have been successfully challenged by local communities. Research has been developed to improve the Bruun rule to account for local effects or to address the simplifying assumptions. The generality of these evolved versions of the Bruun rule remains to be tested, but it is certainly a promising area of research.

Recently, data of beach change has become more easily available (e.g. satellite measurements) and many ongoing monitoring programmes now provide time series that are long enough to identify climatic effects. As a result, other models to predict beach change that heavily rely on data to learn the behaviour of a beach have been proposed. One class of these models, usually termed 'equilibrium models', are very simplified and, in their simplest form, focus only on the shoreline dynamics rather than the evolution of the whole beachface profile as in the case of the Bruun rule. The strength of the equilibrium models is their ability to predict shoreline erosion/accretion also on the basis of their current state (e.g. for a given wave field, an accreted beach is likely to erode more than an already eroded shoreline). However, the approach does not specifically deal with the effects of SLR. Results from a variety of beaches worldwide have shown that this modelling approach has predictive capability over an intermediate timescale (order of a few years).

A study involving 19 institutions and 15 models (a mix of established models and novel machine learning algorithms) from around the world (Montaño et al., 2020) attempted to predict the evolution of a Tairua beach over the short term and, for a subset of the models, also over the long term including the effect of SLR (see Figure 2). Results show a large variability but, more importantly, they were useful to assess the difficulty in developing these types of predictions. Specifically, the study highlighted: (a) the need for reliable wave and SLR projections; (b) the potential improvement of predictions based on model ensembles rather than one specific model; and (c) the need for predictions capable of

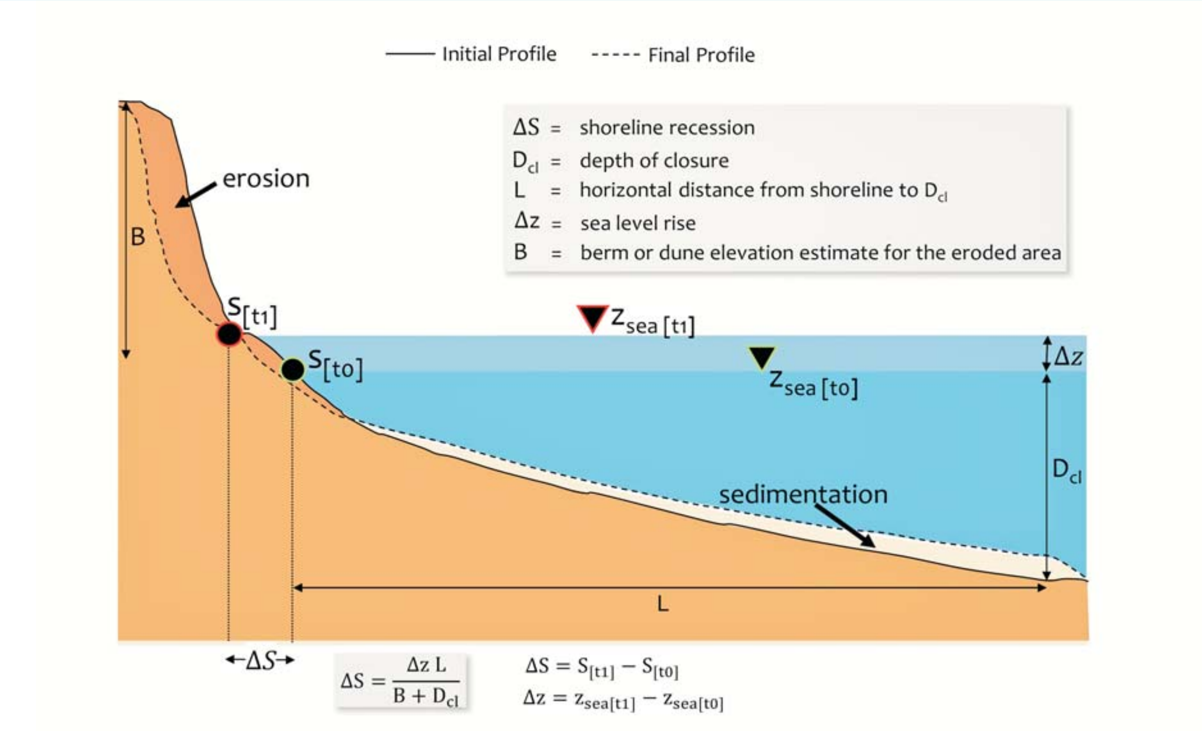

Figure 1: Schematic of the Bruun Rule. Red and green symbols refer to the initial and final conditions, respectively.

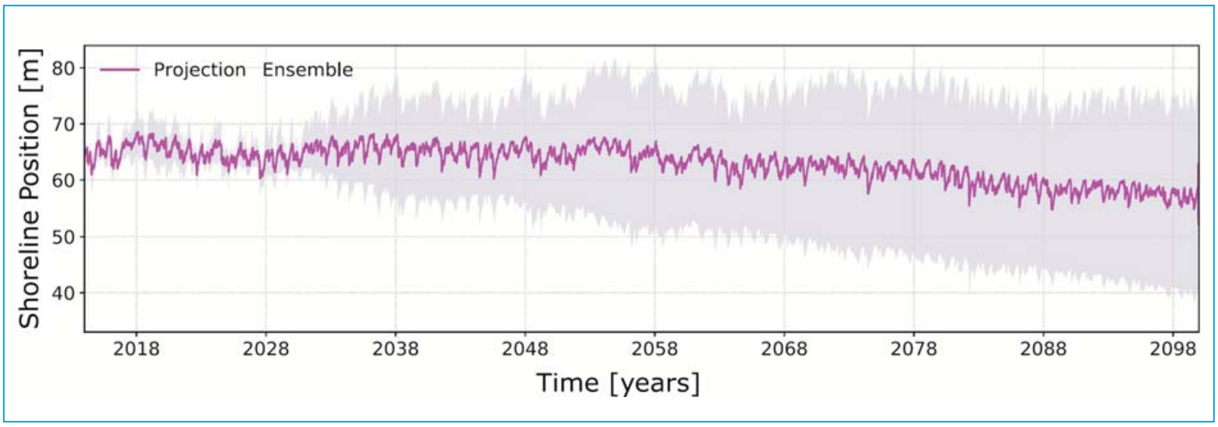

Figure 2: Prediction of shoreline position at Tairua beach under sea level rise. Lower values of shoreline position indicate erosion (initial shoreline position is at about 65 m). The thick line shows the ensemble of different shoreline evolution models while the shaded area shows the standard deviation around the ensemble.

addressing the stochastic nature of waves (this aspect will be further discussed in the following section).

Other models widely and freely available (e.g. Delft3D, XBeach) describe waves, currents and sediment transport in great detail. They are usually based on physical principles and require a significant amount of data (including a detailed surf zone bathymetry) to be properly applied and calibrated. Even when such data are available, the predictive skill of a calibrated model is usually shorter than the time scale associated with SLR. Finally, these models are computationally intensive and their application to long time scales while also assessing the role of stochastic wave variability remains problematic.

Meaningful predictions under climate change

The role of models is to provide useful information to managers, planners, and our communities. The task of modelling and predicting the coastline response to SLR is a formidable challenge and the sources of uncertainty are large in every step of the modelling process. The data to initialise and test most numerical models is not readily available. Information is usually limited to sparse surveys covering limited areas, while information on nearshore shallow bathymetry is almost never available. Predicting the effect of SLR implicitly involves accounting for possible changes in the future wave climate. Although projections of future wave climate are becoming available, their validity is entirely dependent on the Global Climate Models generating them.

The choice of the model to predict coastal change and how to interpret the results is also challenging as outlined in the previous section. Predictions are doomed and dimmed by uncertainty even before choosing the actual model to predict coastal change! The positive aspect is that over the past few years we have been capable of developing a way forward, to address some of these sources of uncertainties.

New methodologies to extract data (from shoreline position to underwater bathymetry) from remote sensing are being developed and continuously refined, promising to increase our ability to learn beach behavior for any beach. We are also rapidly moving towards predictions of shoreline change where the future wave climate is emulated to allow for statistical analysis of shoreline change. For example, we are now capable of developing synthetic time series of wave characteristics that are statistically similar to the original one and use them to predict shoreline change with an established shoreline model (see Figure 3; see Cagigal et al., 2020).

Furthermore, projections of wave and storm surge data until 2100 for the New Zealand coast are already available and we can expect future studies will continue to refine such data. Finally, the hypothesis that model ensembles

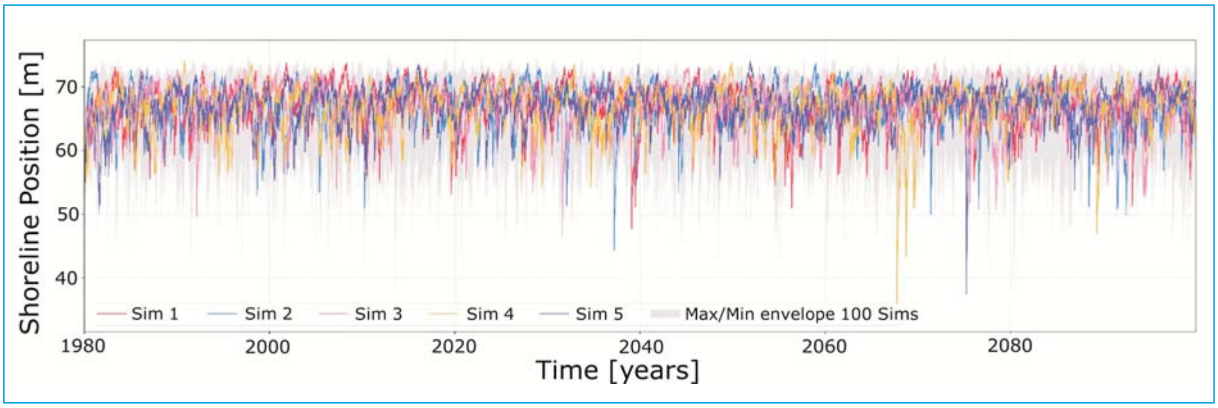

Figure 3: Shoreline evolution at Tairua beach for different realisations of 120 years of synthetic wave climate obtained from a multivariate, stochastic, climate-based wave emulator. Lower values of shoreline position indicate erosion. Shaded areas correspond to the envelope of maximum and minimum erosion and accretion over time for 100 simulations, while the different coloured lines highlight the evolution for five simulations.

and statistical approaches provide more robust and reliable predictions of shoreline change could entirely alter the way to approach the study of SLR effects.

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The response of sandy coastal systems to changes associated with sea level rise

Karin Bryan and Giovanni Coco

St Kilda beach, Dunedin (Photo: Otago University Geography Department).

Sand is stored around New Zealand in beachface and dune systems, in the active nearshore region (the zone of breaking waves), in estuaries and embayments, and on the continental shelf. Continental shelf environments can range from large stores such as in sand banks and ebb-tidal deltas, to smaller, thinner deposits, often associated with 'paleo' features left over from the ice age when the sea level was low. Sand storage within systems is continuously affected by the balance between sources such as rivers and cliff erosion, and sinks, which can range from loss to the deep sea, permanent removal through incorporation into the sedimentary record, and removal by resource extraction. All of these pathways will be affected to different degrees by sea level rise, the ongoing and predicted climatic changes, either through a gradual change in processes driven by sealevel rise, or through changes to the occurrence and duration of events such as storms. This chapter aims to explore these effects in more detail, differentiating between the effects for which we have greater versus diminished uncertainty.

Our beautiful beaches are probably the main way in which people interact with our coastal sand reserves. The way in which these beaches change can be roughly predicted by traditional classifications based on grain size, wave energy, and geological setting (e.g. the Wright and Short classifications (Short, 1999)). Grain size and energy largely control the slope of the beach and the types of geomorphic features that are common on those beaches (e.g. rip channels and cusps), assuming that the supply of sand is sufficient for the beach to evolve naturally. A beach that is closer to source (e.g. an inlet) might have finer sediments and a lower slope, compared to a beach that is partially blocked from its source. For example, Pauanui Beach is close to Tairua Harbour and is low-sloped and finer-grained compared to nearby Tairua Beach, which is separated from the estuary by Paku Hill and so is more reliant on supply from other sources (such as biogenic, cliff erosion, and reworking of paleo-deposits). The degree to which our landscape blocks the transfer of sand is one of the most pronounced features that distinguishes our beaches (Hart and Bryan, 2008). The beaches of the northwest coast have smaller headlands relative to the size of their surf zones, and so sand can move relatively freely between regions (a littoral drift coastline). In contrast, much of the north east coast has large headlands relative to the width of active wave zones (the surfzone), and sand transfer is impeded (an embayed beach coastline).

Bostock et al. (2018) provides the most recent summary of sediment distributions on the continental shelf. Most of our coast is covered with modern terrigenous sediment, with the exception of the Otago, Fiordland and the southern South Island coasts. Of the areas that are dominated by modern sediment, the Westland and East Cape regions have the most extreme inputs, followed by the Auckland, Hawkes Bay, Coromandel, Canterbury and Kahurangi regions. Areas with very high sedimentation rates tend to have high percentages of mud, whereas the moderate sedimentation regions have high percentages of sand. Areas dominated with relict sediments toward the south have high percentages of gravel.

Our beach stores are constantly evolving. Sand moves onshore when the wave energy is lower than average, and offshore during storms, and so the profile is constantly dynamically varying around its 'equilibrium shape' (dynamic equilibrium). Recovery back toward equilibrium is slower than changes to the wave energy, so that an equilibrium form is rarely reached. Clusters or sequences of storms can be particularly damaging because recovery from the first storm of the sequence is incomplete (Senechal et al., 2017).

Temperate storms often form in clusters because they are driven by wave-like perturbations to the westerly belt of dominant winds. Superimposed on profile changes are changes to the movement of sand up and down the beach (beach rotation). If transfer along the coast is impeded by headlands, one end of the beach can be significantly eroded while the other end accretes. On open coasts with few offshore islands (like on the California coastline), rotation is predictably associated with seasonal and climatic changes to the wave direction. On many parts of our coastline, the coastline is shadowed by islands, and the underlying geology causes rapid changes to the exposure. Figure 1 illustrates the results of a SWAN wave model applied to the Coromandel coastline, showing the influence of offshore islands and exposure on the wave height and direction experienced along different parts of the coastline. Subtle shifts in the approach angle of waves can cause large changes to the beach conditions.

On top of beach profile changes and beach rotation are a complex series of local changes to sand stored in the beach caused by the action of rip currents. Rip currents move sand from the shoreface into seaward deposits, but are also modified and redirected by those same deposits ('self-organised'). These feedbacks make it nearly impossible to provide exact predictions of the impact of storms at a specific location, and instead we need to build in a buffer of uncertainty. Figure 2 shows 21 years of January averaged video imagery from the Waikato Regional Council and National Institute of Water and Atmospheric Research (NIWA) video camera overlooking Tairua Beach, in the Coromandel. These images reveals that the natural configuration of rip currents on this beach has not repeated itself in 21 years, meaning that on coasts commonly featuring rip currents it is it very difficult to determine the baseline state of a beach against which to compare climatic and anthropogenic changes.

Nevertheless, we can make some broad scale predictions to the general impact of our changing climate on our

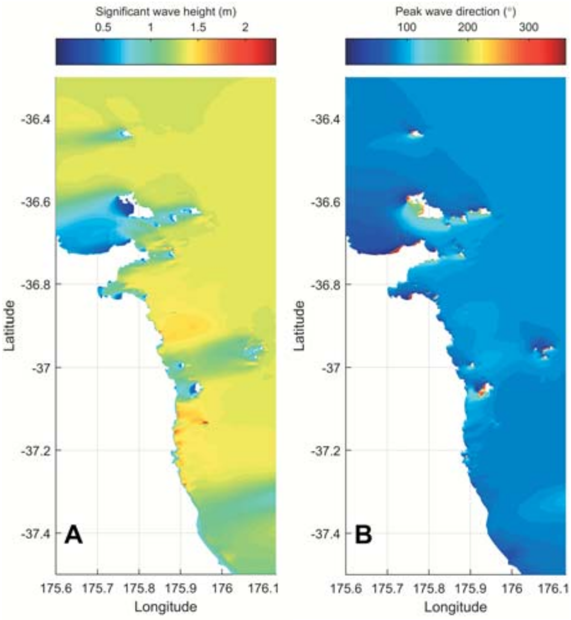

Figure 1: Output from a regional Swan wave model, forced with data from NOAA for the most common wave conditions on the Coromandel. Panel A: wave height, Panel B: wave direction.

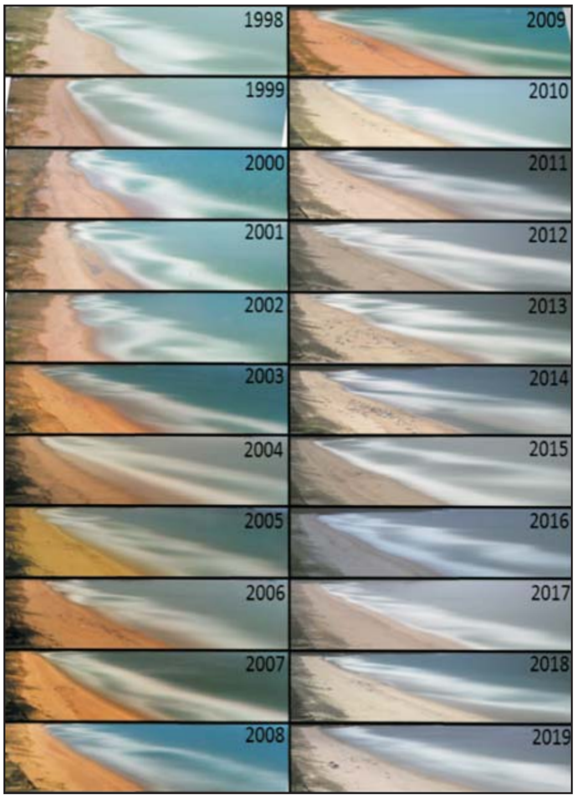

Figure 2: Time-averaged video images of Tairua Beach, Coromandel. Imagery is averaged over 15 minutes, and an example is shown for January each year. Note the camera location changed substantially between 2002 and 2003. The images come from the Cam-Era network hosted by the National Institute of Water and Atmospheric Research. The Tairua station is funded by Waikato Regional Council.

beaches. We do have clear evidence that our beach volume decreases when the wave height increases. Figure 3 shows the average amount the beach volume changes with wave energy increases across 17 Coromandel beaches. Beaches that are oriented more toward the east (e.g. Tairua, Whiritoa, Hot Water) change much more than those exposed toward the north (e.g. Matarangi, Whangapoua, Kuaotunu). The differences are likely to be due to the change in exposure to wave events, and the differences in the likelihood of extreme events and storm clusters. We also have some evidence that our coast is becoming more energetic (see Figure 4a), with the number of extreme storm events increasing (see Figure 4b). In addition, the number of storm clusters are increasing (see Figure 4d), and the duration of those clusters is also increasing (see Figure 4c). These estimates are based on the NIWA 45-year wave hindcast (Godoi et al., 2016; 2017; 2018). Although long hindcasts are needed to detect trends, the change in the way we measure the wind over 45 years (e.g. the recent shift from ground-based towards satellite observations), can create profound uncertainties in these estimates. For example, before satellites observations were used to estimate wind fields, observations were biased toward the northern hemisphere, so there is often an offset in wave hindcasts associated with this switch. A few people have worked to quantify future wave conditions associated with climate change. Hemer et al.'s (2013) paper showed that Southern Ocean wave heights are projected to increase, but wave heights on New Zealand's north east coast are projected to decrease over the next 100 years. Increases in wave height are expected to mainly affect our winter months. They also

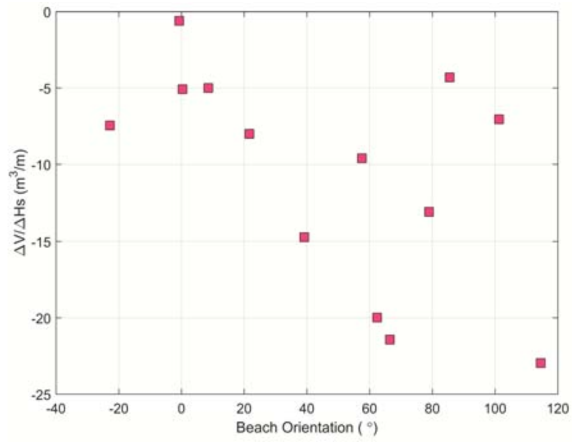

Figure 3: The average amount the intertidal beach volume changes for a meter increase in significant wave height. Each point represents a beach in the Coromandel between Whiritoa to the south and Whangapoua to the north. Data provided by Keith Smith, and waves produced by a Swan model forced with NOAA data.

projected shifts in the orientation of waves over the same time period. A recent paper (Meucci et al., 2020) suggests that the Southern Ocean wave climate will increase by 5% to 15% by the end of the 21st Century. New projections for New Zealand should be available soon from the Auckland University PhD project by Joao de Albuquerque. Again, New Zealand spans the transition from the Southern Ocean conditions to equatorial waters, over which the projections change dramatically, from increasing to decreasing. Minor shifts to the location of the transition zone (which is around East Cape on the east coast, and at the top of the North Island on the west coast) will have major implications to how we should plan.

There is obviously no way to validate future projected changes to our beaches that might be associated with climate change. One of the few ways that we can understand what might happen is by investigating how our coast has responded to past changes to climate, such as to climate oscillations like the Southern Oscillation and the Pacific Decadal Oscillation. Recent work on assessing vulnerability of beaches around the Pacific used the state of these drivers

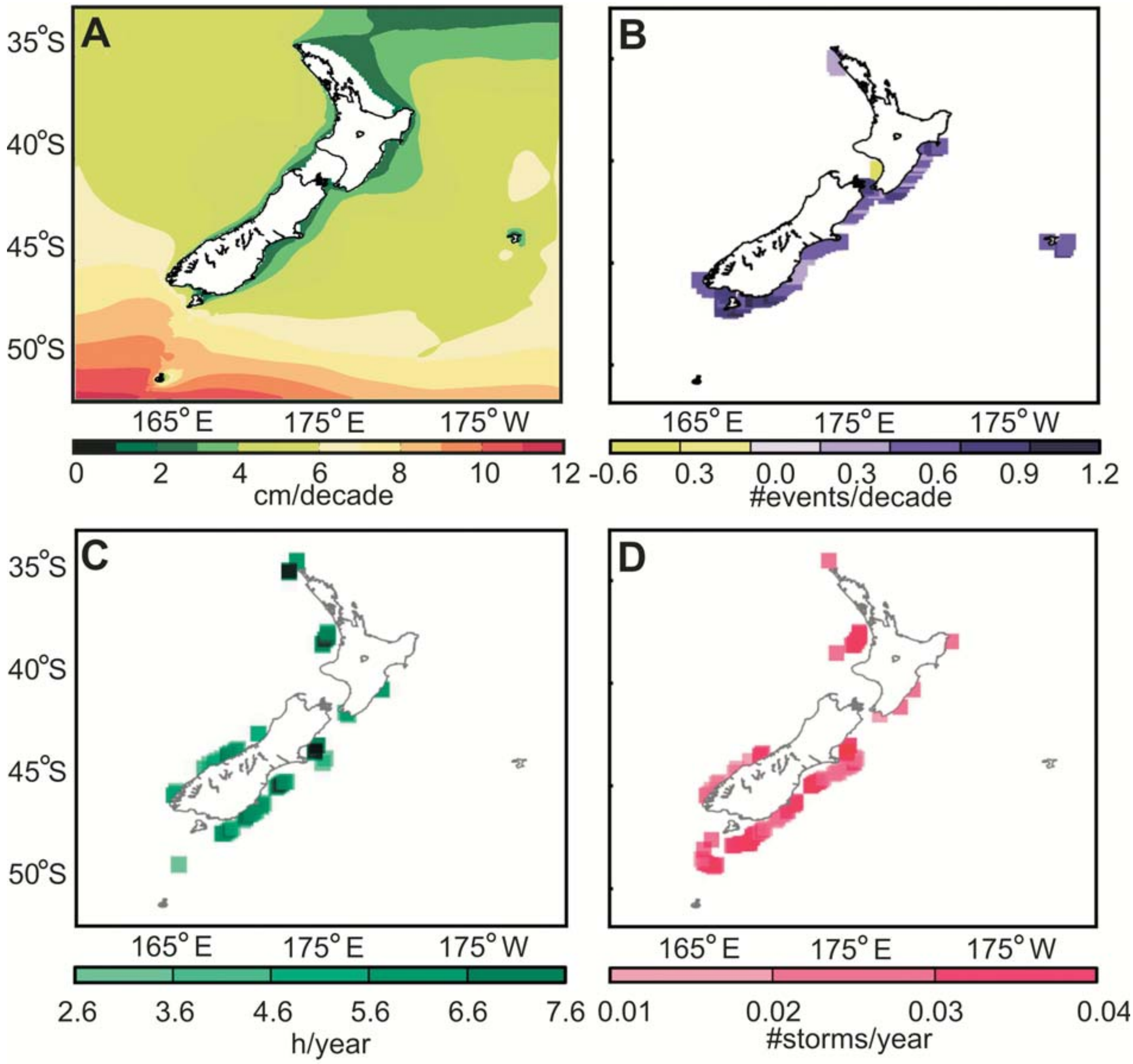

Figure 4: Estimates of historical changes of wave conditions from work by Godoi. Panel A: The trend in wave height. Panel B: The trend in the number of extreme wave events. Panel C: The change in the duration of storm clusters (sequences where the beach has no time to recover between storms). Panel D: The change in the number of cluster events in a year.

as a basis for assessment (Barnard et al., 2015). However, applying this in a local context is confounded by the considerable local variability with respect to how our New Zealand beaches might respond, again due to the effect of islands and the complex orientation of our coastline. Figure 5 shows how our Coromandel beaches respond to a change in a SOI and the PDO. The left panels show how the orientation changes, and the right panel shows how the beach volume changes. In general, the east coast beach volume decreases with a move toward La Niña, and a move toward the negative phase of the PDO, but orientation changes very much depend on the local conditions of the beach. There is evidence that the west coast behaves in the reverse fashion. Global predictions suggest that El Niño events will become more extreme, and that La Niña events will become more frequent, which would cause a general increase in beach erosion, and would likely increase the size of rotation events (Cai et al., 2014; 2015). Although the wave climate is probably the greatest driver of beach erosion, the water level has also been shown to correlate with beach volume changes (Segura et al., 2018).

There are many uncertainties to future erosion trends. Simple Bruun-type models alarmingly predict that our beaches will disappear globally (Vousdoukas et al., 2020), but such modelling fails to account for complexity (Cooper et al., in press). For example, changes to sediment supply could either exacerbate or reduce erosion hazards (Bell et al., 2017). Increased storminess would presumably be accompanied by cliff erosion and increased sediment run-off from land, particularly in those regions such as East Cape that are strongly influenced by terrigenous run-off. We also have increasing population pressure on our coast, and coastal land values growing exponentially. The pressure to protect these valuable assets will increase. Although we are predicting that climate change will cause some of the most dramatic changes at the coast (e.g. Vousdoukas et al., 2020), we must not forget that the direct anthropogenic signature (seawalls, dredging, groins) might overwhelm any of the indirect climate-related changes that might occur to our environment, recognising that the latter is also anthropogenic.

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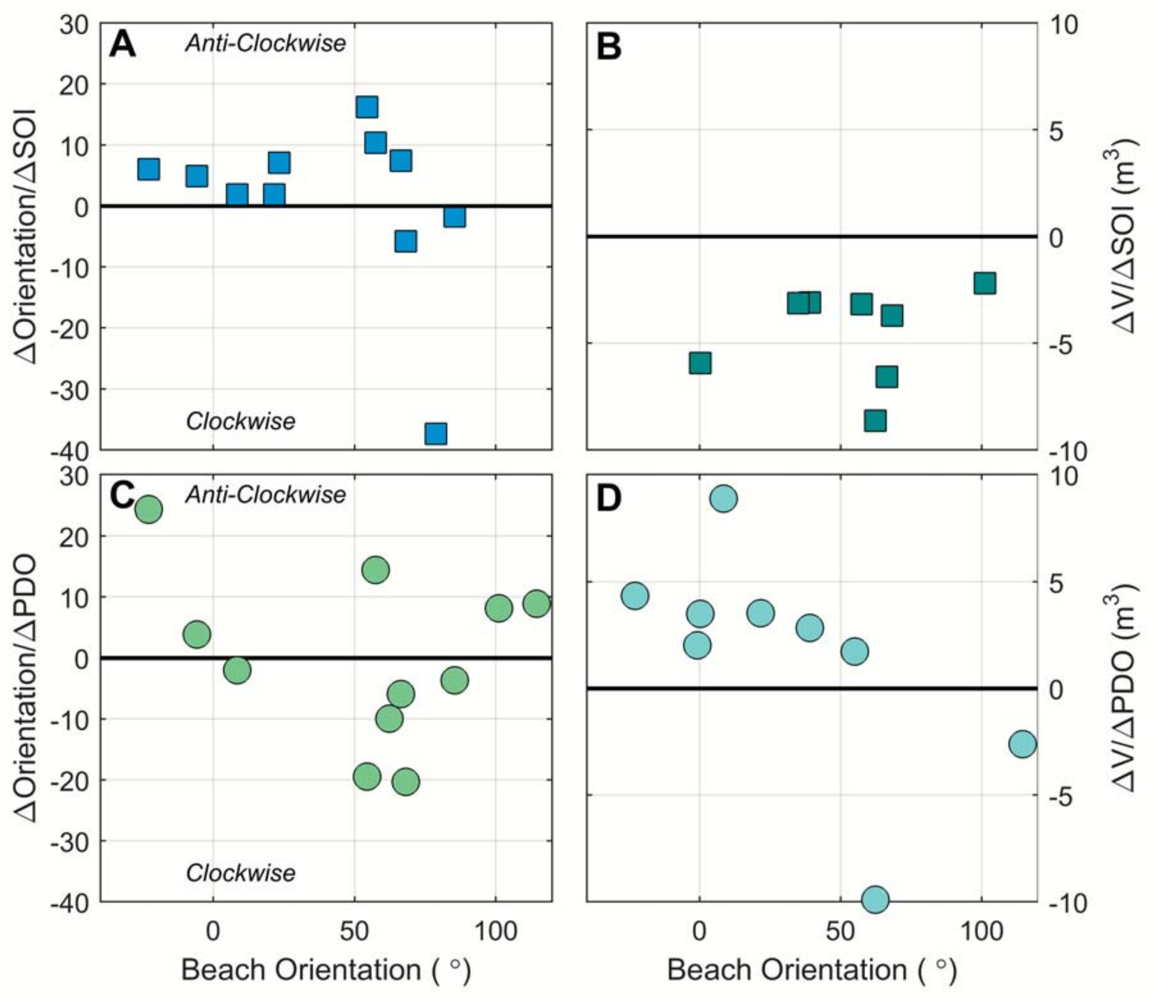

Figure 5: The average amount that the orientation (A and C) and volume (B and D) of beach changes with changes to the Southern Oscillation Index (A, B) and Pacific Decadal Oscillation (C,D). Each point represents a different beach on the Coromandel, distinguished by the average orientation, where a 0˚ orientation faces northward. Only beaches with three or more profiling stations are included, and rotation is assessed by fitting a linear regression line to each time period. Volume changes are averaged across all profiles on a beach. Data provided by Keith Smith, and waves produced by a SWAN model forced with NOAA data.

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Estimating the erosional effects of sea level rise on gravel beaches: Case study of the Canterbury coast

Derek Todd and Kate MacDonald

Amberley Beach (Photo: Sebastian Pitman)

Introduction

Gravel beaches are considered to be globally rare, but they are relatively common in New Zealand, particularly on the east coast of both the North and South Islands (Healy and Kirk, 1992), and the West Coast of the South Island. Contemporary coastal erosion is a common hazard along many of these gravel beaches, posing existing threats to adjacent communities and infrastructure (e.g. roads, wastewater plants and outfalls). As a result of their global rarity, the literature on gravel beach dynamics is limited and their responses to sea level rise (SLR) has been assessed only in general terms. Notably, there is no commonly accepted method or approach available to quantify the predicted effects of SLR on gravel beaches as there is with sand beaches. This leads to significant difficulties in trying to quantify the risk of accentuated erosion due to SLR for the coastal communities and infrastructure located along these gravel beach coastlines.

Two-dimensional geometric shoreline retreat models have been used over recent decades to provide order of magnitude estimates of predicted shoreline retreat with SLR in unconsolidated beach environments. A number of these models are based on the 'Bruun rule' (Bruun, 1962; 1988), which predicts a linear retreat of an equilibrium profile shape across the beach shoreface. The Bruun rule proposes that the eroded beach volume equals that required to raise the seabed profile out to a 'closure depth' (an assumed offshore limit of beach sediment movement) by the same magnitude as SLR. Other models based on Komar et al. (1999) predict the retreat distance by assuming that a constant inter-tidal beach face slope is maintained and that the dune position is related to sea level and wave run-up. Although these models have well documented limitations (e.g. Cooper and Pilkey, 2004), they are well-used and accepted methods to estimate sand beach retreat due to SLR. However, they have limited applicability to gravel beaches, which have different profile shapes and process responses.

There is a general acceptance in the coastal hazards literature (e.g. MfE, 2017) that beaches containing gravel components will erode less than sand beaches under SLR as the coarser sediment is moved landward and upwards by 'beach rollover' caused by waves overtopping the beach, rather than being subjected to large volume losses to the offshore as is predicted with sand beaches. Therefore, applying a sand beach geometric shoreline retreat model to a gravel beach environment without consideration for the processes operating on these beach types is likely to result in grossly over-predicting the amount of erosion that could occur as a direct result of SLR. While models have been developed to provide estimates of future erosion from rollover of these gravel beaches as sea levels rise (Orford et al., 1995; Measures et al., 2014), they are limited by an assumption that all erosion is due to these processes. This is not consistent with observed and recorded beach profile responses involving the offshore movement of sediments, including gravels, in storm events on mixed sand and gravel (MSG) beaches along the Canterbury coast. These observations suggest that the response to SLR will involve more frequent offshore losses from the upper sections of the beach profile, along with more frequent sediment rollover to the backshore, neither of which are well represented in the existing models.

In this chapter we evaluate some existing geometric models that have been developed for, or could be used on, gravel beaches, and assess how well they replicate the processes we know are acting on gravel beaches along the Canterbury coast of Aotearoa New Zealand. From this analysis we have suggested two alternative methods that better incorporate some of these process responses, and with further development and refinement, could provide better quantitative estimates of the effect of SLR on gravel beach erosion.

Gravel beach characteristics

Gravel beaches are typically found in mid-latitude, high-energy environments, so while comparatively rare on a world scale, they are an important element of the New Zealand coastline (Kirk, 1980). They dominate the Canterbury and Hawkes Bay coastlines, and are locally significant in Southland, South Westland, Marlborough, Tasman, and Wairarapa (Goff et al., 2003). Jennings and Shulmeister (2002) identified three types of gravel beaches in New Zealand: pure gravel, mixed sand and gravel (MSG), and composite beaches.

Pure gravel beaches, generally found close to large gravel-bearing rivers or alluvial cliffs, are dominated by gravel throughout their profile and have steep beach faces that may be broken into a series of berms at different elevations relating to run-up processes. These steep slopes are maintained due to the high permeability of the gravels, with the coarsest material (and hence steepest slopes) found on the storm berm at the top of the beach. Surging and collapsing waves dominate in the most severe storms (Jennings and Shulmeister, 2002), with swash lengths being short and run-up dominated due to the high permeability of the gravels. Sherman (1991) observed cycles of storm erosion (by down-combing and flattening of the beach face) and post-storm recovery (by the development and up-slope migration of berms) on gravel beaches.

Mixed sand and gravel beaches have many similar characteristics, but are mixed in sediment size and composition between gravel and sand both horizontally and vertically across the entire profile (Kirk, 1980), as shown in Figure 1. They dominate shorelines that front glacial outwash plains, becoming more common away from gravel-bearing river mouths as gravels are broken down by abrasion. As a result of the presence of sand, beach face slopes are less steep than pure gravel beaches, and swash lengths are longer with a larger component of back wash. As shown in Figure 2, all MSG beaches and some pure gravel beaches have a steep nearshore step on which waves at all phases of the tide break as a single line of plunging breakers. Profiles of this step obtained in 1987 from the Washdyke-Seadown coast near Timaru show there is often also a nearshore ramp marking a transition zone between the step and flat nearshore bed. Beyond the step, MSG beaches change

Figure 1: Mixed sand and gravel (MSG) beach, Timaru.

abruptly to sand on the nearshore bed, suggesting two distinct sediment transport regimes for the different sediment sizes (Kirk, 1980). Observations on the Canterbury coast over the last 30 years show there is an offshore movement of all sediment sizes in storm events, followed by onshore recovery in post-storm conditions. This has also been observed in MSG beaches in other global locations, with Roberts et al. (2013) describing a modified beach cycle model of storm erosion and recovery featuring changes in slope of the nearshore step, based on observed storm responses in MSG beaches in Delaware, USA. The distinct breaks in sediment size distribution and slope at the nearshore step have important implications for the consideration of closure depth for sediment transport if using modified Bruun rule approaches to SLR impacts for MSG beaches.

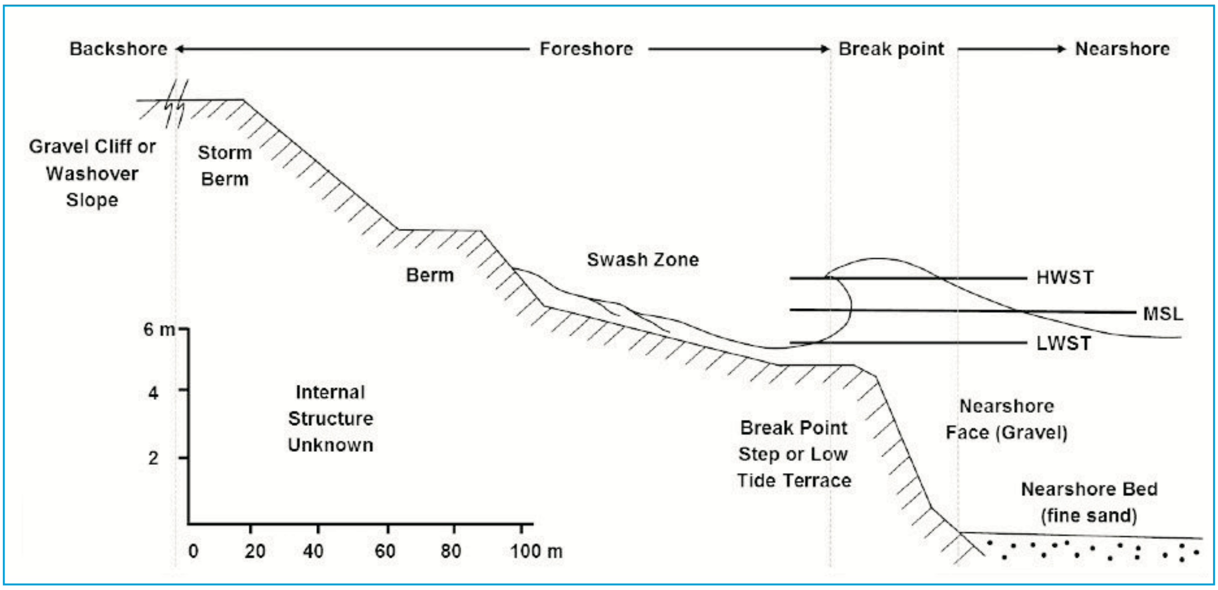
Composite beaches contain sand and gravel, but are hydraulically sorted into two parts, with a gravelly upper foreshore and storm berm, and a sandy lower foreshore and nearshore, as shown in Figures 2 and 3. As a result, composite beaches have a less steep lower foreshore than MSG beaches, with a longer swash zone and greater backwash due to the higher sand content. In the South Island, these beach types are predominantly found in meso-tidal environments on the West Coast. As with sand beaches, composite beaches often have several lines of spilling or collapsing breakers that dissipate across the gently-sloped inner nearshore and offshore bars have been observed to form after large storm events. Although the lower foreshore and nearshore act like sand beaches, the presence of gravel-sized sediment on the upper beach profile suggests that the erosion responses to SLR (including linear shoreline retreat and foreshore volume loss) would still be less at these sites relative to sand beach environments.

The Canterbury coast of the eastern South Island provides useful case studies to look at the effects of SLR on gravel beaches. The region is dominated by MSG beaches, both fronting high glacial outwash plains and as gravel beach ridges at the edge of low fluvial plains in the Waimate, Timaru, Selwyn and Hurunui Districts. Also included within these districts are gravel barriers across Washdyke Lagoon (Timaru), Te Waihora/Lake Ellesmere (Kaitorete Spit-Selwyn) and numerous large, braided gravel river mouths.

In attempting to quantify future erosion due to SLR for the Timaru and Hurunui Districts, we undertook an evaluation of different geometric models at five locations along the Hurunui District coast as shown in Figure 4.

Inputs into the models were obtained from the following sources:

- Beach profiles above the low water position from Environment Canterbury (ECan) annual surveys over the last 30 years. Comparisons of the profiles allowed calculation of annual rollover volumes.
- Nearshore profiles were not available, but were assumed from wave breaking patterns on aerial images to be either sloping (e.g. composite beaches), where there were multiple sets of breaking waves, or stepped (e.g. MSG beaches), where there were single lines of breakers. For MSG beaches the elevation and position of the nearshore step was taken from 1987 diver surveys along the Washdyke-Seadown coast north of Timaru, with the toe of the step and associated ramp being in the range



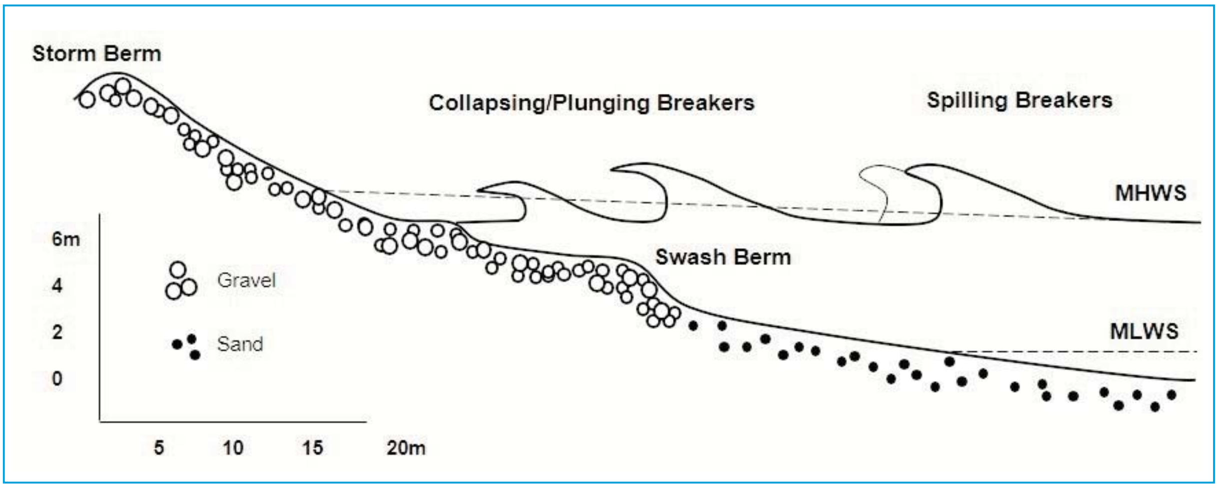


Figure 2: (Top) Mixed sand and gravel (MSG) beach profile, adapted from Kirk (1980); (Bottom) composite beach profile. Adapted from Jennings and Schulmeister (2002).

-4 to -6 m RL, and located 40-90 m offshore from the MSL contour as shown in Figure 5. Measures et al. (2014) gives a similar nearshore step elevation of -5.5 m RL at Taumutu on the Kaitorete Spit. For sloping composite beaches, the nearshore slope was estimated from bathymetric charts.

- Wave data for the calculation of 'Hallermeier limits' for closure depth were taken from the NIWA Coastal Calculator for Canterbury (Stephens et al., 2015).
- Sediment composition of the beach from averaging ECan samples taken at various locations across the beach profile. Percentages of gravel in the profile ranged from less than 20% at Leithfield and Gore Bay, to 70% at north Amberley, and an assumed 75% at Conway Flat and Claverley. However, it is noted that the amounts of gravel at Amberley and Gore Bay are highly variable with wave conditions and/or supply rates, but are considered to better fit into a composite beach classification on the basis of a sloping nearshore profile.

Evaluation of current geometric shoreline retreat models

Three relevant geometric models of shoreline retreat due to SLR were evaluated for several composite and MSG beaches of the Hurunui District. These models were developed by Rosati et al. (2013), Measures et al. (2014), and Orford et al. (1995), and relevant beach parameters and equations are presented in Figure 6.

The Rosati et al. (2013) method is a modification of the Bruun rule to account for landward sediment losses due to dune or beach ridge overtopping (see Figure 6). This modification actually increases the predicted retreat due to additional landward losses as well as seaward losses. However, this method is less applicable to some gravel beach settings where (a) the beach crests are sufficiently high that wave overtopping does not occur (e.g. Leithfield,

Figure 3: Composite beach, Sandy Bay, Motunau (Photo: Kate MacDonald).

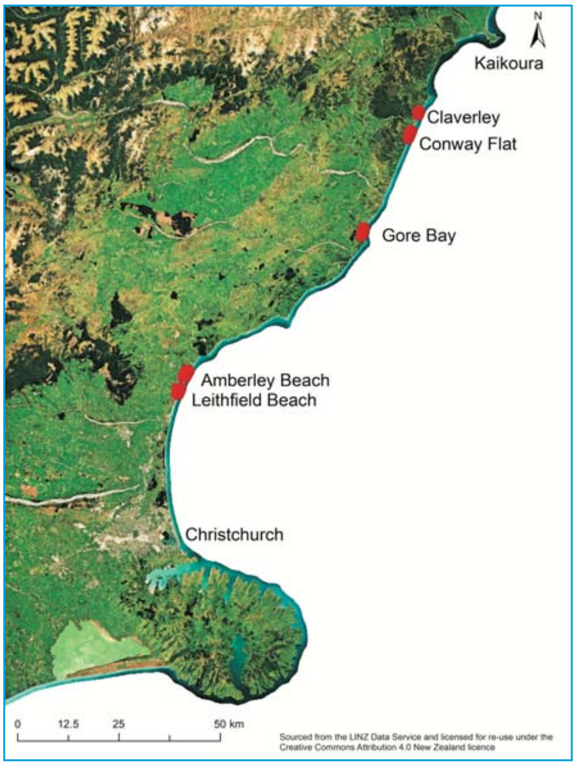


Figure 4: Location map of the five beaches used in this study (marked in red).

Calverley), or (b) nil rollover volume is recorded on profiles where overtopping was known to have occurred (e.g. Amberley, Conway Flat). When rollover does not occur or is not detected by measurements, the erosion formula collapses to the original Bruun rule formula, which is still considered to most likely overestimate the predicted offshore loss of gravel and the consequent erosion of gravel beaches due to SLR.

The Measures et al. (2014) method was developed for the MSG beach ridges in Selwyn District and the gravel barrier on the southern end of Kaitorete Spit (Te Waihora/Lake Ellesmere) where rollover from wave overtopping was considered the dominant erosion process. The model assumes that crest building from waves overtopping the

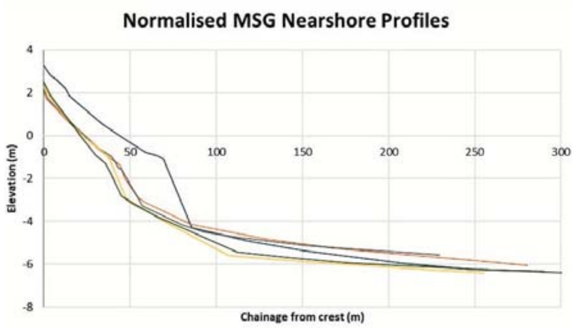


Figure 5: Nearshore step profiles at Washdyke-Seadown from diver surveys in 1987.

barrier crest will keep pace with SLR, and that the sediment volume required to lift the barrier crest will be supplied from a slice of equal volume eroded from the beach face down to the toe of the nearshore step (see Figure 6). The method used in this study was applicable only to the northern MSG beach sites at Conway Flat and Claverley, because the composite beaches at Leithfield Beach, Amberley Beach, and Gore Bay did not have nearshore steps. Applicability was also limited because overtopping did not occur at some beaches over the 30-year period of profile data, and so the principal process of retreat assumed in the method did not apply. Compared to other geometric models tested for sensitivity, the results show that the predicted retreat rates due to SLR are very small and are largely insensitive to crest and hinterland elevation.

The Orford et al. (1995) method was based on the movements of three swash aligned gravel barriers in Canada and Northwest Europe, to develop a correlation between mesoscale (e.g. 1-10-year timeframe) rates of barrier retreat and the 5-yearly average rate of sea level change. The study concluded that movement of the barrier was the result of a relationship between two counteracting factors – barrier retreat driven by onshore wave forces, and 'barrier inertia' whereby the product of cross-sectional beach volume and height acts to resist against barrier retreat. The model does not take wave climate changes into account and assumes that the only source of material to the barrier is that exhumed from barrier retreat.

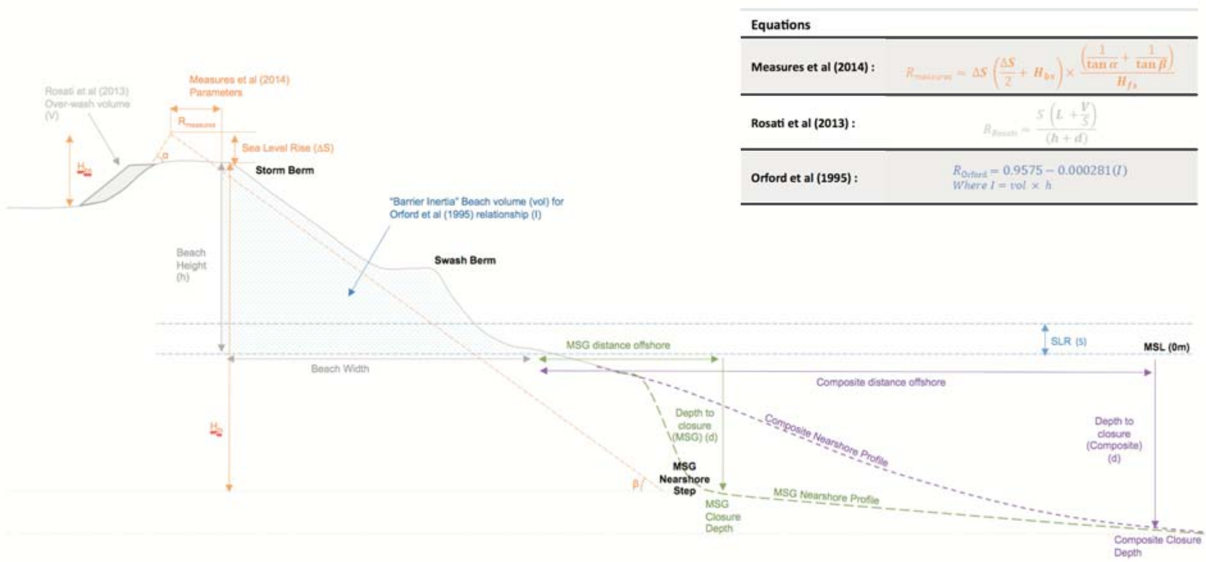


Figure 6: Conceptual diagram of a MSG/composite beach profile that identifies the key beach parameters used for assessing retreat with SLR from 'Rosati', 'Measures', and 'Orford' methods.

A major limitation of the Orford et al. study is that the method was applied to only three sites, which gives a limited dataset for assessing the validity and representativeness of the relationship for Canterbury gravel beaches. The relationship only holds for barrier volumes of less than 3400 m^3/m, and there is also uncertainty about how the barrier volume is measured for the calculation of 'barrier inertia'. This uncertainty was addressed in the present evaluation by applying two assumed substrata profiles – (a) volume above a flat substrate profile located at the MSL contour, and (b) volume above a sloping substrate profile from the MSL contour to the toe of the nearshore step based on actual substrate profiles surveyed at Washdyke.

The three models applied to the five Hurunui District beaches are evaluated in Table 1. The predicted magnitudes of shoreline retreat are calculated for each model and each site using contemporary SLR projections (taken to be 2 mm/yr) and are compared to the measured rates of shoreline movement over the last 60-70 years from aerial photographs by GIS Digital Shoreline Analysis System (DSAS). While it is recognised that the historical movements include components of sediment supply and transport, the analysis focused on how reasonable the modelled results were in relation to the knowledge of the coastal processes operating at the sites.

Although the Measures et al. (2014) and Orford et al. (1995) methods are for gravel beaches, they do not appear to return acceptable results for the contribution of contemporary SLR to trends of shoreline movements of composite or MSG beaches over the past 50 years in the Hurunui District. The Orford et al. (1995) method gives unacceptably large erosion rates, being larger than the Bruun rule results, or are outside of the given acceptable range, hence this method cannot be applied.

The Measures et al. (2014) method appeared to be insensitive to increases in the rate of SLR, with rates of rise of 13 mm/yr (the RCP8.5+ rate of rise averaged over the next 100 years) predicting retreat rates of only 0.05-0.07 m/yr. These insensitivities suggest that the method under-predicts SLR-induced erosion and is less applicable where a raised hinterland or stopbank inhibits the development of the barrier beach backshore formation (e.g. reduces the height of H_{bs} from Figure 6). It is therefore suggested that this method is only appropriate for use on MSG barrier beaches fronting water bodies (e.g. lagoons, river mouths) where the H_{bs} elevation is relatively large.

Because these three current models appear inadequate to predict SLR effects on gravel beaches in Canterbury, a fourth option is proposed that is based on modifications to the Bruun rule.

Possible modification of the Bruun rule for composite and MSG beaches

Although the Bruun rule overestimates the likely amount of erosion from SLR at these gravel beaches, it gives the basis for a model that could be modified to account for some of the processes acting on a gravel beach environment. Two modifications to the Bruun rule were tested to account for (a) the presence of gravel in the sediment composition of composite beaches and (b) the shallow closure depth at the nearshore step in mixed sand and gravel profiles.

(a) Sediment composition modification for composite beaches

For composite beach types where there is a sloping sandy nearshore (e.g. Leithfield Beach, Amberley Beach and Gore Bay) that will suffer offshore losses of beach sand with SLR, the modification to the Bruun formula involved adding a

	Settlements and ECan Profile Sites				
	Leithfield (PC4200)	North Amberley (PC4782)	North Gore Bay (HCH5782)	Conway Flats (HCK8510)	Claverley (HCK9150)
Contemporary rates of shoreline change since 1950s (m/yr)	+0.1 m/yr	-0.91 m/yr	+0.13 m/yr	-0.16 m/yr (Cliff retreat behind beach)	+0.13 m/yr
Predicted Rates of Shoreline Erosion (m/yr) due to Contemporary Rate of SLR (2 mm/yr)					
Rosati et al. (2013) Modified Bruun for landward sediment movement	-0.35 m/yr Not overtop, so no rollover volume	-0.27 m/yr Not overtop, so no rollover volume	-0.36 m/yr	-0.36 m/yr No rollover volume against cliff	-0.31 m/yr Not overtop, so no rollover volume
Measures et al. (2014) Rollover Method	-0.01 m/yr Not overtop	-0.01 m/yr Not overtop	-0.01 m/yr	-0.01 m/yr	-0.01 m/yr Not overtop
Orford et al. (1995) Method for barrier vol above MSL	-0.46	-1.00 m/yr	-1.57 m/yr	-1.36 m/yr	Barrier Inertia out of calculation range
Orford et al. (1995) Method for barrier volume include assumed wedge below MSL	Barrier Inertia out of calculation range	-0.51 m/yr	-0.99 m/yr	-0.76 m/yr	Barrier Inertia out of calculation range

Table 1: Evaluation of geometric models on MSG and composite beach types for the Hurunui District.

component for the average percentage of sand in the beach profile. Hence, the predicted rate of retreat declines as the proportion of sand in the onshore profile decreases.

The resulting modified retreat formula for composite beaches, including landward loses from overtopping is:

$$Retreat\,(Bruun_{Composite}) = \frac{s(L+\frac{V}{s})}{(h+d)}\ x\ \%\ of\ Sand$$

Where L is the Horizontal distance to closure depth from dune crest; s is the sea level rise over the planning timeframe; V is rollover volume; h is the height of beach crest above MSL; and d is the average closure depth calculated by Hallermeier limits.

It is considered that this modification better accounts for the cross-shore sediment transport losses of sand from the beach profile with SLR, as well as the retention of gravels on the upper beach/berms. However, it is recognised that applying this method to gravel beaches raises a contradiction: the Bruun rule requires that a constant nearshore depth is sustained by erosion from the upper foreshore, but it is widely accepted that upper foreshore gravels are less vulnerable to offshore transport. In the long term, this differential rate of loss of sand and gravel components could result in composite beaches converting to a more MSG form unless abrasion of the gravel component keeps pace with the offshore sand losses due to SLR.

(b) Closure depth modification for mixed sand and gravel (MSG) beaches

A second modification was applied for MSG beaches (e.g. Conway Flat and Claverley) to reduce the closure depth from the Hallermeier limit used in the original Bruun rule to the toe of the nearshore step. For these beaches the sediment transport processes indicate that the closure depth for the transport of gravel-sized material will be in the vicinity of this position rather than a deeper position related to sand-sized material. Therefore, the modification involved applying a standard closure depth of 5 m below MSL, and a nearshore slope of 1:10 based on the results of the 1987 nearshore surveys at Washdyke, Timaru, as shown in Figure 6.

The assumption from the modification is that sediment losses will be to both beach rollover and offshore movement, which is more realistic than just rollover losses as in Measures et al. (2014). However, as a result of applying a shallower closure depth and hence steeper closure slope, there is a reduction in the estimated erosion distances with SLR from these predicted by the original Bruun rule using a sand transport closure depth.

The modified retreat formula for MSG Beaches is:

$$Retreat\,(Bruun_{MSG}) = \frac{s(L+\frac{V}{s})}{(h+dt)}$$

Where dt is the closure depth below MSL defined as the toe of the steep nearshore face.

It is noted that sand will be still be lost from the beach profile to the nearshore bed, but this will not keep pace with SLR, hence breaker heights will increase with time due to gradually increasing water depths at the nearshore face. It is also noted that abrasion processes will continue to produce sand in the beach profile.

Evaluation of modified Bruun rule for MSG and composite beaches

Evaluations were undertaken of the modifications made to the original Bruun rule. The comparison presented in Table 2 shows that the modifications produce a lower rate of erosion due to SLR compared to those produced by applying only the original Bruun rule. This is constant with the principles expressed in the literature for gravel beach environments, and hence a more acceptable result than that obtained by applying the relationship from Orford et al. (1995). In comparison with the results from Measures et al. (2014), the erosion rates are only marginally higher for contemporary SLR, but are considered more realistic from a process point of view, and will increase with higher rates of SLR, which does not occur with the Measures method. The differences in the magnitude of retreat between composite and MSG beaches is also considered to be realistic based on the different profile shapes, sand volumes, and offshore transport processes found at the two beach types.

	Settlements and Profile Sites				
	Leithfield (PC4200)	North Amberley (PC4782)	North Gore Bay (HCH5782)	Conway Flats (HCK8510)	Claverley (HCK9150)
Contemporary rates of shoreline change (m/yr)	+0.1	-0.91	+0.13	-0.16 (Cliff retreat)	+0.13
Predicted Rates of Shoreline Erosion (m/yr) due to Contemporary Rate of SLR (2 mm/yr)					
With original Bruun Method	-0.28	-0.22	-0.36	-0.36	-0.31
With sediment modified Bruun for composite beaches	-0.24 (sand = 84.5%)	-0.06 (sand = 29.2%)	-0.21 (sand = 59.2%)	-0.09 (sand = 25%)[1]	-0.08 (sand = 25%)[1]
With closure depth modified Bruun for MSG beaches	Not applicable	Not applicable	Not applicable	-0.02	-0.02
	(1) No sediment sampling available at Conway Flats and Claverley, 25% Sand in profile is assumed.				

Table 2: Sensitivity testing of modified Bruun rule for MSG and Composite beaches.

As a result of this evaluation, these modified methods were adopted for use in coastal erosion hazard assessments for the composite and MSG beaches within the Hurunui and Timaru Districts (Jacobs 2020a, b).

The results from this evaluation also demonstrate that the contemporary rates of shoreline change cannot be totally explained by the contemporary rate of SLR at 2mm/yr over the last 50 years. As expected, there are other factors influencing shoreline movements such as sediment supply and wave climate. This is particularly the case at the Leithfield Beach, North Gore Bay, and Claverely sites, where surpluses of sediment arriving at these beaches have limited the erosional effects of SLR. This demonstrates that while SLR will play a big part in shaping our future shorelines, it accounts for only part of the changes that have been observed over the past 50 years.

Conclusions

This study has shown that existing models of gravel beach response to SLR accounting for only beach rollover most probably underestimate retreat distances, while those developed from limited relationships of barrier inertia to retreat considerably overestimate SLR effects. This study therefore trialled modifications to well-known sand beach models (based on the Bruun rule) to account for some of the profile differences, sediment compositions, and transport processes that occur on gravel beach types. The trials suggest that the modifications can produce more realistic predictions of retreat due to the effect of SLR on these beach types.

While these modified methods also have some inconsistencies in the way they deal with the processes and responses of gravel beaches, it is considered that they better incorporate some of these process responses, and therefore the results are likely to be more representative of future responses to SLR in these environments. Further refinement and testing is required to advance and develop these geometric shoreline retreat models in these environments to provide more accurate and informed shoreline projections and to assist our coastal councils and communities in making decisions about their future with SLR.

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Coastal cliff erosion in Aotearoa New Zealand and the potential impacts of sea level rise

Mark Dickson and Catriona Thompson

Onaero Bay, Taranaki (Photo: Catriona Thompson)

Introduction

Coastal sea cliffs comprise about 25% of Aotearoa New Zealand's coast (Gibb, 1984; Kennedy and Dickson, 2007). These landforms are inherently erosive, so whenever there are properties or infrastructure at the cliff top there is an erosion hazard that requires planning and management (Lee and Clark, 2002). This hazard has been exacerbated in recent decades by urbanisation of cliff-top land in many parts of the world, including Aotearoa New Zealand.

Cliff erosion hazard planning is challenging because rates of erosion can span orders of magnitude, from metres per year to rates that are imperceptibly slow over human time spans. In addition, cliff erosion rates can be highly variable both spatially and temporally. Factors controlling this variability include local differences in lithology and rock structure as well as variability in the process environment, including the local wave climate as well as factors that influence rock weathering efficacy, such as rainfall and temperature (Trenhaile, 1987).

Those responsible for making decisions about cliff erosion hazards are also confronted with uncertainty associated with the implications of future sea level rise (SLR) and changing storminess induced by global climate change (Dickson et al., 2007). Moreover, there are lessons to be learned from many decades of cliff hazard management globally, including unanticipated adverse effects that can arise from erosion mitigation measures (e.g. Uda, 2010).

Hence, decision makers need to consider cliffs as a part of a broader coastal system in which erosion mitigation can potentially impact coastal sediment budgets and beach volumes, with implications for other hazards such as coastal flooding (Dawson et al., 2009). In addition to these factors, a range of complex societal issues require consideration, including who benefits from coastal defence, and who should pay (e.g. Healy and Soomere, 2008).

This chapter discusses coastal cliff erosion in Aotearoa New Zealand. A broad range of cliff lithologies and geometries occur around the country: hard-rock volcanic cliffs plunge into deep water and many have eroded imperceptibly slowly over human time spans; sandstone cliffs of intermediate rock resistance are often fronted by intertidal shore platforms, and typically have long-term average retreat rates of millimeters to centimeters per year; soft mudstone cliffs and unconsolidated gravel cliffs are fronted by beaches that often overlie subtidal rock platforms, and here cliff erosion rates can be tens of centimeters to metres per year. Our focus in the chapter is to provide coastal practitioners with a broad overview of the possible effects of SLR on cliff erosion. We do not discuss coastal landsliding processes in any detail. Instead our focus is to describe processes related to SLR that influence cliff-toe erosion, which can subsequently promote slope failure.

The topic of SLR and cliff erosion is associated with a high level of scientific uncertainty owing to the inherent variability of the physical environment, including localised lithological erosion controls and limitations in our understanding of the physical drivers of cliff erosion. We begin the chapter (section 2) with a general overview of the processes controlling cliff erosion, including the difficult scientific problem of directly linking process measurements to erosion observations. We do not yet have a high resolution understanding of the role of marine processes in cliff retreat, and so there are inherent limitations in our ability to anticipate the implications of SLR on future cliff retreat rates. Section 3 specifically examines the widespread view that SLR will accelerate erosion rates and describes a theoretical framework that recognises a wide-range of possible cliff responses to SLR.

This is followed by an example (section 4) of cliff erosion hazard planning in Aotearoa centred around a recent case study in the Bay of Plenty. The chapter concludes (section 5) with a brief discussion of future scientific and planning challenges.

Processes controlling cliff retreat

Coastal cliffs are subject to erosive action from marine and terrestrial sources. There has been considerable debate regarding the relative importance of these processes (see Kennedy et al., 2011), which depends on the local site context (e.g. local lithological, meteorological, and oceanic conditions). It is important to recognise that different erosion processes operate in unison and that feedbacks exist that may accentuate erosion. For instance, cracks in rock may be enlarged by salt weathering, creating a habitat for organisms that further enlarge cavities, potentially leading to enhanced abrasion when sediments are entrained in water flow. Ultimately, wave erosion is a more effective process when rock resistance is degraded by a number of biological, chemical, and physical weathering processes, which are each modulated by local lithological, climatic, and tidal conditions. Marine and terrestrial erosion processes, alongside anthropogenic and meteorological, interact with each other in complex feedback loops that can enhance or inhibit the influence of these processes. For example, a crack in the cliff face created by salt weathering (a chemical process) may then provide a habitat for an organism to begin bioerosion within. A failure event of the cliff face could also lead to an increase in sediment volume at the cliff toe, thus building up the beach and protecting the cliff from wave attack. At any time, a multitude of these processes are occurring, with varying degrees of importance, which can adjust as the environmental conditions change.

Biological, chemical, and physical weathering processes can be particularly active within the intertidal zone, leading to reduction in rock resistance that can be exploited by wave attack. Bioerosion occurs from biological organisms on the rock (Trudgill, 1987). Chemical weathering is the result of corrosion or solution from acids in salt water interacting with the cliff material, especially important for calcareous cliffs, such as limestone (Duperret et al., 2005). Physical weathering, such as wetting-drying and warming-cooling, vary spatially and temporally, and according to the nature of the rock (Coombes et al., 2011). Freeze-thaw, wherein ice on a frozen rock surface thaws due to the rising tide and forms or widens cracks in the surface, occurs mainly in highly saturated fine-grained rock in cold coastal areas (Trenhaile and Mercan, 1987). Salt weathering needs high temperatures and low rainfall to evaporate seawater and produce salt crystal growth leading to widening of cracks in the rock surface, and this is more common in drier climates such as the Mediterranean coast (Trenhaile, 1987).

Waves erode the base of cliffs through direct wave action (impacts) and abrasion from sediment entrained within the water column (e.g. Trenhaile, 1987; Sunamura 1992). Waves and tide-generated flows are also important processes for removing the material that results from cliff rock falls, thereby enabling renewed undercutting and steepening of the cliff face. Wave-induced changes of the cliff geometry have been shown to produce the necessary conditions for failure (Wolters and Muller, 2002). Breaking wave impacts on the cliff face can cause pressure loading that results in a process known as water hammer as well as compression of air in rock joints followed by its sudden release after the wave recedes; these processes are thought to be capable of dislodging rock fragments and joint blocks and widening cavities within the cliff rock mass (Robinson, 1977; Trenhaile, 1987; Lim et al., 2011).

The amount of wave energy that reaches cliffs is tidally modulated. Studies using seismometers have shown that cliffs generally shake more strongly at higher tidal stages when waves break closer to cliffs (e.g. Norman et al., 2013; Vann Jones et al., 2015; Young et al., 2016). However, this relationship depends strongly on local water depth. For instance, at Okakari Point, north of Auckland, 100 m wide shore platforms are elevated close to high tide level, and here seismometers detect the most significant cliff shaking at low tide when waves break violently against the edge of the shore platform, and dissipate much of their energy before interacting with the cliff (Dickson and Pentney, 2012). It is evident that wave energy dissipation prior to impact is important, as is the nature of the wave impact type. Beach morphology is another important control on wave energy delivery to cliffs. For instance, it has been shown that during extreme storms, steep reflective beaches (including those with coarser grain sizes) amplify wave runup resulting in greater cliff shaking and erosion (Earlie et al., 2015; 2018).

Wave-driven steepening of cliffs can produce the necessary conditions for slope failure (Wolters and Müller, 2008). Cliff landsliding occurs when the weakening of tensile stress or increase in saturation leads to a reduction in gravitational stability, especially in weakly lithified or loosely consolidated material (Hampton, 2002). Landsliding events are often triggered by storms or heavy rainfall, which can reduce material cohesion and increase groundwater level; landsliding occurs when gravitational instability criteria are met (Hampton, 2002; Lee et al., 2001). Landsliding is highly episodic, with periods of inactivity in cliff recession following a landslide event. Hence, trigger events of the same magnitude may not always result in failure (Lee et al., 2001). Failure events are the result of multiple processes acting over different spatial and temporal scales making it difficult to attribute the influence of each process to the resultant cliff retreat.

Will SLR accelerate cliff erosion rates?

It is generally expected that coastal cliff erosion rates will accelerate with SLR (Bray and Hooke, 1997; Limber et al., 2018). Some cliffs will almost certainly erode more quickly under SLR, but others are likely to continue to erode at a similar rate to the past, and others may even erode more slowly! This dizzying array of possibilities has been usefully conceptualised by Ashton et al. (2011) who considered four theoretical types of cliff response to SLR based on the feedbacks that are likely between the cliff profile shape and changes in water level (see Figure 1):

A. 'No Response' cliff systems refer to situations where the cliff erosion rate is unrelated to the level of the sea; future erosion rates will be the same as past rates. This may occur in environments where cliff erosion rates are dominated by biological, chemical, and physical weathering processes, and where wave and tidal energy is important only for removing the detrital products of cliff erosion.

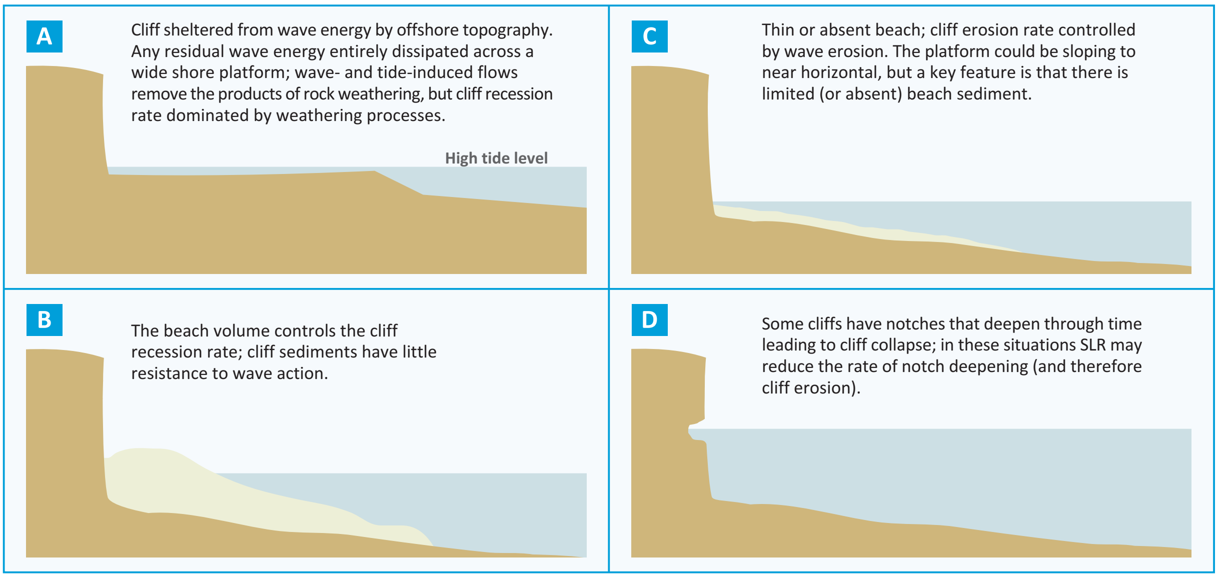


Figure 1: Cliff geometries associated with four possible SLR feedback systems.

B. 'Instant response' cliff systems immediately respond to SLR by eroding to maintain the same cliff geometry: future erosion rates increase linearly with the rate of SLR. This concept is similar to the well-known Bruun-rule for sandy beaches, which assumes the erosion rate is linearly dependent upon the rate of SLR (i.e. there is no feedback between the profile geometry and the wave environment). This scenario seems appropriate only for cliffs with no resistance (perhaps sand or gravel cliffs), but is not relevant for the majority of cliffs in which erosion requires removal of coherent rock and adjustment of the cliff profile shape.

C. 'Negative feedback' cliff systems are dominated by wave-driven cliff erosion and are likely to encompass many of the soft-rock mudstone to sandstone cliffs around Aotearoa New Zealand where there are subtidal to intertidal shore platforms with limited sediment cover. An underlying assumption here is that, if sea level remains constant, erosion rates decline through time as shore platforms widen and dissipate wave energy. In contrast, future SLR increases cliff erosion rates in these systems because deeper water allows greater wave energy to access the cliff toe, changing the cliff-toe wave erosion regime (see Box 1 for further insight into how this occurs).

D. 'Inverse feedback' cliff systems conceptualise the possibility of declining cliff erosion rates with SLR. This situation may seem unlikely, but is theoretically plausible. For instance, some cliffs have notches at water level that are enlarged by biological erosion, eventually leading to cliff collapse. If the rate of SLR increases it is possible that notches may not deepen to the extent that they promote cliff failure. Similarly, cliffs can be undermined by abrasion when sediments are entrained within the water column, and increasing water depths may reduce the efficacy of this process. Another example is provided by cliffs that plunge into relatively deep water, because SLR will increase cliff-toe water depths and increase the proportion of reflected wave energy.

Planning for cliff erosion under rising sea level

At present we cannot directly link observed erosion to the wave processes that over-steepen cliffs eventually leading to slope failure. Hence, it is impossible to develop the sort of physics-based morphodynamic models that are available for sand beaches (e.g. XBeach). However, a number of abstracted numerical models have been developed in which wave forces are linked to historically observed erosion at particular sites through model calibration (e.g. Trenhaile, 2000; Walkden and Hall, 2005; Castedo et al., 2012; Hackney et al., 2013; Limber et al., 2018). These models can be usefully applied in site-specific studies that anticipate the effects of future SLR (e.g. Dickson et al., 2007). Unfortunately, not all coastal management applications will have capacity to commission numerical modelling at the scales required.

In this context, the four types of cliff response to SLR described above can be represented in simple mathematical terms with Equation 1 (Ashton et al., 2011), in which the future cliff recession rate (R_2) is calculated based on the known historical recession rate (R_1), the future rate of SLR (S_2) relative to the past rate of SLR (S_1) and the historical rate of SLR over which R_1 was observed.

$$R_2 = R_1\left(\frac{S_2}{S_1}\right)^m \qquad \text{Equation 1}$$

The critical unknown term in Equation 1 is the exponent 'm'. Values of $m = 0$ are appropriate for no feedback systems (and $R_2 = R_1$), $m = 1$ for instantaneous response (R_2 increases with SLR), $m < 0$ for inverse feedback (R_2 decreases with SLR). However, for most of the cliff systems that managers need to plan for (wave-driven negative feedback systems in which $R_2 > R_1$), m will have a value between 0 and 1. It is possible to further constrain the likely value using published numerical modelling data. For instance, Walkden and Dickson (2008) modelled the likely effects of SLR on cliffs in Norfolk, UK, and concluded that for open-coast cliffs composed of weak rocks (i.e. glacial tills), where wave-driven historical erosion rates have been 0.5 to 1.0 m/yr, typical m values are around 0.5. This is a useful reference value for Aotearoa New Zealand applications, because Gibb (1986) observed that historical cliff erosion rates around many weak mudstone/siltstone lithologies around the country are within 0.25 to 1.0 m/yr.

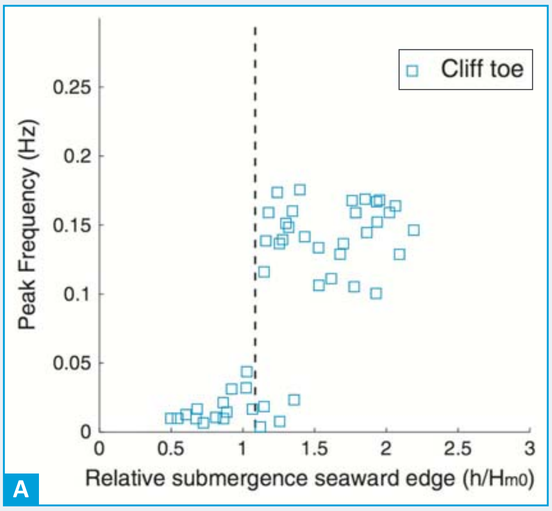
Box 1: Water depth controls the cliff wave erosion regime

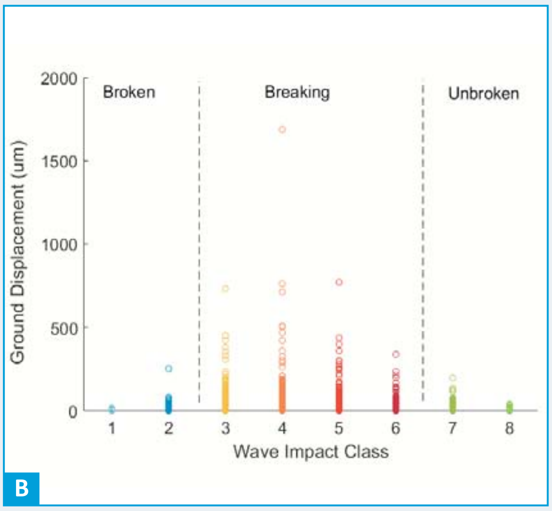
The figures below provide further insight into negative feedback cliff systems, where wave processes are a dominant driver of cliff retreat. Rocky cliffed coasts, unlike sand beaches, do not dynamically respond to changes in marine forcing. This makes it very difficult to link observations of wave impacts to cliff erosion. However, we can study the hydrodynamics of wave processes to reveal how even relatively modest changes in sea level and wave conditions can deliver very different cliff-toe wave regimes.

Panel A shows measurements from Ogawa et al. (2015) of wave-energy transmission across an intertidal sandstone shore platform to a cliff in Auckland during a storm. A critical threshold exists between water depth (h) and significant wave height (Hmo): when the water is relatively shallow and waves are relatively large, the cliff toe is dominated by low frequency infragravity wave energy, but when water depth increases relative to wave height there is a sudden shift toward dominance of waves at incident gravity wave frequencies (see also Sunamura, 1977; and Oumeraci et al., 1993).

Panel B shows measurements from PhD research in Taranaki, New Zealand (Thompson, 2020). Seismometers were buried at a cliff top in Taranaki to detect ground motion from direct wave impacts on the cliff face. Impacts were divided into classes from 1-8 based on the stage of transformation at impact, that is the form of broken, breaking, or unbroken wave, and variations therein.

What is notable, comparing panels A and B, is that SLR will shift cliff-toe water depth for cliffs nation-wide, thereby altering the wave-impact regime at each site in different ways. Some cliffs may receive more violent breaking wave impacts, and erosion rates may increase significantly, whereas other sites may transition to more reflective regimes and erosion rates could decrease. Localised analyses will be required to estimate the likely change in erosion rate from location to location.





Tonkin & Taylor Ltd have recently utilised Equation 1 to provide specific consideration of the future effects of SLR in coastal cliff erosion hazard planning. In the Tauranga Harbour Coastal Hazards Study (hereby referred to as T&T, 2019), predictions of future cliff erosion rates under SLR were required as a part of the risk evaluation process. Historical erosion rates (R_1) were found by mapping cliff erosion from historical aerial photographs. Future cliff erosion rates (R_2) at selected timeframes (e.g. 2080, 2130) could then be derived for different SLR scenarios (S_2) by estimating appropriate m values by analysing published data on the geotechnical properties of cliff-rock within the study area, and considering variation in wave exposure (values between 0.1 and 0.5 were assigned). A second important component of prediction involved allowance for the area of cliff-top land prone to landsliding failure, which was accounted for on the basis of the cliff height (H_c) and the stable angle that cliffs reach upon failure (α). Hence, Equation 2 provides a total Cliff Erosion Hazard Distance (m) for a given planning timeframe (T):

$$CEHD = T(R_2) + \left(\frac{H_c}{\tan\alpha}\right) \quad \text{Equation 2}$$

T&T (2019) applied Equation 2 in a stochastic framework to help account for uncertainty (see Cowell et al., 2006). Probability distributions were assigned to each parameter and a large number of model simulations conducted. Figure 2 provides an example of outputs for Omokoroa Peninsula, located within the central part of the Tauranga Harbour. Historical cliff erosion rates in this area are relatively high (~0.25 m/yr) owing to the presence of silts that make the cliffs susceptible to landsliding after periods of extreme rainfall (Moon et al., 2013), as well as high relative wave exposure and sensitivity to storm surge. A range of m values between 0.3 and 0.5 were adopted for this area. Figure 2b shows erosion probability distributions (histograms) for different SLR scenarios, together with curved lines that show a probability of exceedance for each scenario. Figure 2c then maps selected exceedance probabilities as an area susceptible to erosion over a selected planning period (for instance, P66% means there is a 66% chance of an erosion distance being exceeded within that time frame).

The current state of research

Over the past two decades there have been significant advances in measurement techniques that will be important

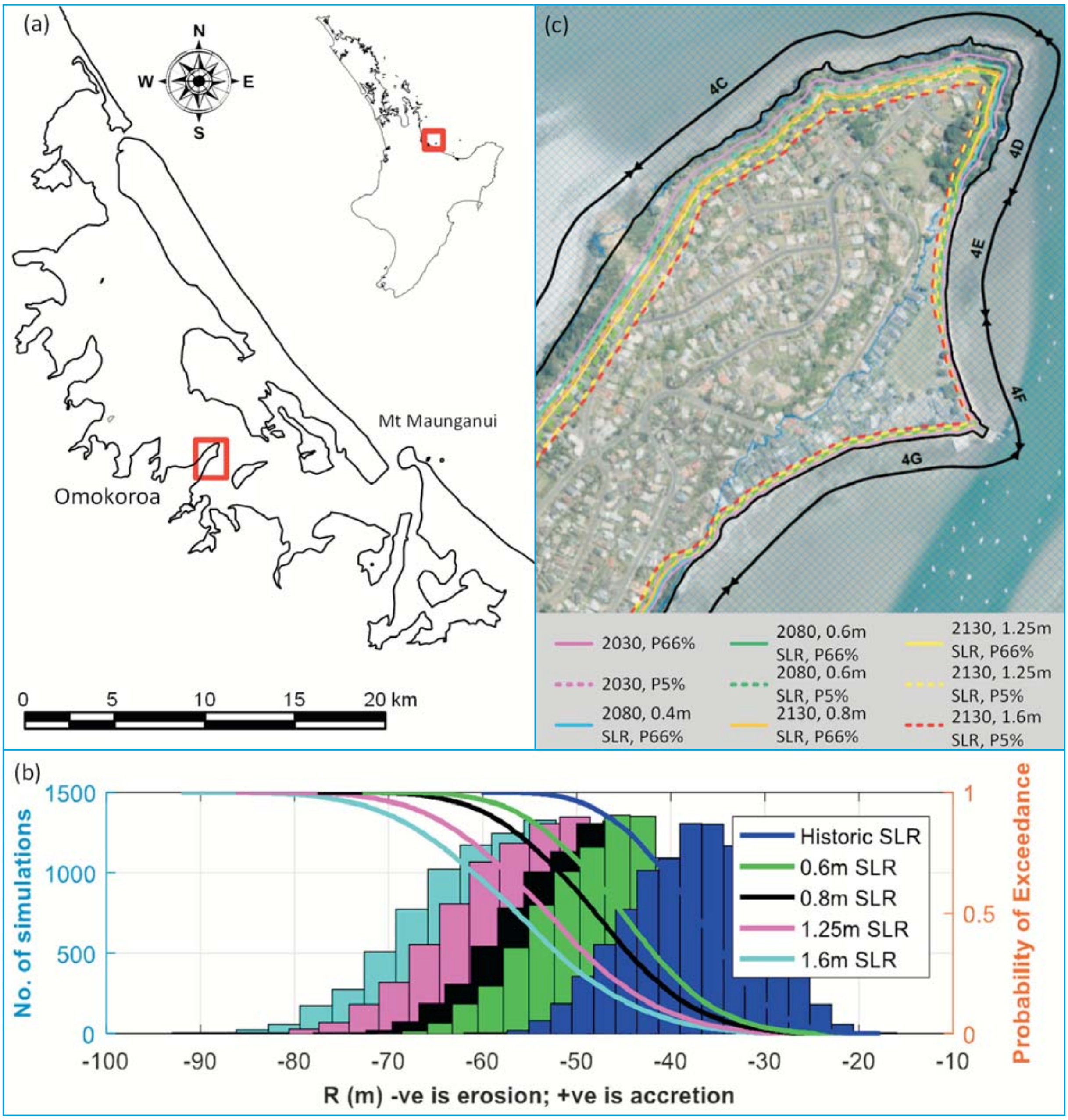


Figure 2: Cliff-erosion hazard planning in Tauranga Harbour. Reproduced with permission: Tonkin & Taylor, Tauranga District Council, Bay of Plenty Regional Council.

for efforts to unravel relationships between SLR and cliff erosion rates. Advances in laser scanning now make it possible to detect very small (i.e. cm-scale) cliff erosion rates over short timescales (days to months and years) (e.g. Gulyaev and Buckeridge, 2004; Rosser et al., 2005; Young, 2018). However, while some datasets now span decades, none have yet drawn an unambiguous link between erosion rates and SLR. It is possible that recent acceleration in global SLR is yet to have had sufficient time to manifest as an increase in cliff erosion rate. A second recent development in rock coast studies involves analyses of in-situ produced cosmogenic nuclides to estimate cliff retreat rates over thousands of years (e.g. Hurst et al., 2016; Swirad et al., 2020). This technique should make it possible to examine relationships between sea level change and cliff retreat over long time periods, but the few published studies to date have not yet drawn clear links between sea level and erosion rates. A third promising area of research concerns the use of cliff-top seismometry as a proxy for wave energy delivery (e.g. Dickson and Pentney, 2012; Norman et al., 2013; Young et al., 2018). The research field awaits compelling evidence to link seismic shaking to measured cliff erosion, but recent measurements show that very different wave-energy delivery regimes can result from subtle changes in water level (Thompson et al., 2019; Thompson, 2020), raising the prospect that future SLR may shift wave-breaking patterns and drive considerable spatial variability in cliff erosion rates from site to site.

One fundamental research challenge to overcome is that there is a temporal disconnect between the processes that contribute to erosion, including SLR and wave energy delivery, and physical observations of erosion. Hence, numerical modelling experiments may provide predictions of future erosion rates at equilibrium (e.g. Walkden and Dickson, 2008), whereas the transitory (disequilibrium or nonequilibrium) response remains very uncertain. The example of cliff erosion planning provided in this chapter provides one example of the way in which coastal managers can respond to efforts to manage cliff erosion under SLR amid these uncertainties.

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Coastal hydrosystem responses to sea level rise

Terry Hume and Deirdre Hart

Dawn at Oneroa Beach
Waiheke Island (Photo: Terry Hume)

Introduction

Coastal hydrosystems comprise a diverse set of environments at the interface of terrestrial and marine systems that span a gradient from near-coast freshwater lakes and wetlands though to fully marine systems. Common terms for these features include: saltmarsh, lagoon, hapua, river mouth, estuary, harbour, sound, fjord, and bay. Hume et al. (2016) classify over 500 individual New Zealand (NZ) coastal hydrosystems, providing data on their bio-physical characteristics, as well as on their services, values and uses. The classification provides a 6-level hierarchy, with each level describing the dominant cause of variation in hydrosystem character at an associated spatial scale (see Table 1). It postulates that climate, geology, ocean, river and catchment factors broadly determine the physical and biological character of coastal hydrosystems. For our climate change and sea level rise (SLR) response analyses we focus on the Geomorphic Class (Level III), which sees hydrosystems defined as single units or complex systems amongst 11 distinct classes (see Table 1 and Images 1 to 11), some with subclasses (denoted by letters A to E). Since these hydrosystems are subject to water, sediment and energy inputs from both land and sea, they are particularly susceptible to both human-induced and natural environment changes. Through a physical process lens, this article discusses the potential responses of different types of coastal hydrosystem to changing climate and SLR, including a range of coastal management implications.

Potential effects of climate change and SLR on coastal hydrosystems

Projections of SLR for the NZ region suggest that by 2120 absolute mean sea levels will be between 0.55 and 1.36 m above mean 1986 to 2005 levels (MFE 2017). The actual rise largely depends on our global greenhouse emissions pathway and the non-linear response of the polar ice sheets to warming above a tipping point. Up to 2060 there is more certainty in projections, with a NZ region absolute mean SLR expected to total between 0.3 and 0.5 m. Locally and regionally relative SLR will be offset or enhanced to some degree by long term and event based vertical land movements (MFE 2017, pp. 82-86; and see 'Future sea level rise around New Zealand's dynamic coastline', p11). In addition to SLR, climate change is predicted to result in an increase in the frequency of occurrence and intensification of storms, affect long term through to inter-annual timescale sea level variations, cause changes in sediment supply, and alter the levels of incident wave energy at the coast. As a result, coastal systems of many kinds are expected to experience more frequent, widespread and intense inundation and erosion relative to the present day (Oppenheimer et al., 2019).

Effects of SLR and climate change will likely vary between hydrosystem classes, through the interaction of key factors that distinguish the form and function of coastal hydrosystems. These factors include: basin morphometry (shape and depth), hydrodynamic forcing from river inputs (flows, and volume of water and sediment), ocean forcings (tidal reach and prism, wave climate), and the longshore transport of sediment (see Table 1). For instance, shallow basins with extensive intertidal areas flanked by low lying plains will be more affected by SLR than deeper largely subtidal systems with steep sided shores. SLR will see intertidal areas deepen and more frequent, widespread and intense inundation of low lying coastal margins. Where this is prevented by rising ground or stopbanks the intertidal area will be reduced by coastal squeeze, disproportionately affecting upper tidal zones. Consequent changes in drainage

Level	Spatial scale (km^2)	Controlling factors	Potential changes in controlling factors with CC & SLR
I Global Temperate Australasian Realm	Macro 10^6 - 10^4	climate, landmass, watermass	• Warmer climate on average, with increased climatic extremes and more intense events. • Landmass: no change at this scale. • Increased ocean wave energy, temperatures and acidity with changes in storminess and ocean temperatures, higher absolute sea levels.
II Hydrosystem Palustrine, lacustrine, riverine, estuarine, marine		landform, water regime	• Landform: changes in basin morphometry (shape and depth) possible. • Water regime: increases in wetter weather in western NZ and southern SI, increase in frequency of heavy precipitation events and flooding throughout NZ, increase in intensity of ex-tropical cyclone events, longer dry spells in the north of the NI and east of both islands. • Shifts in the balance between river, tide and wave processes could trigger potential shifts between hydrosystem level II types for a limited number of systems (e.g. waituna - lacustrine to estuarine to marine).
III Geomorphic Class 11 classes (damp sand plain lake; waituna-type lagoon; hāpua-type lagoon; beach stream; freshwater river mouth; tidal river mouth; tidal lagoon; shallow drowned valley; deep drowned valley; fjord; coastal embayment), with 21 subclasses	10^3 Meso 10^1	geomorphology, hydrodynamics/ hydrology	• Geomorphology: changes in hydrosystem bathymetry and shorelines with (resulting from?) increases in coastal inundation extents & depths, changes in rates and patterns of sedimentation and longshore transport. • Hydrodynamics: altered balance between wave/tide /river influences, varying between hydrosystem class and around the country due to changes in the balance between hydrodynamic forcing (with changing river flows, volume and sediment transport) and ocean forcing (tide range and prism, wave climate) and longshore transport of sediment, with consequent changes in mixing, flushing, tidal exchange, saline intrusion. • Potential switching between classes for a limited number of hydrosystems, changes between some subclasses more common.
IV Tidal Regime Subtidal, intertidal, supratidal		inundation by the tide	• Inundation by the tide: zones elevated and translated landward via movement of groundwater and surface water with rising sea levels, where topography and development allow.
V Structural Class Vegetation, substrate, water structure	1 Micro 0.1	bio-, geo- and hydro-components	• Bio-, geo- and hydro-components: ecological succession and/or 'ecosystem squeeze' processes depending on supratidal topography, sediment supply and type, and anthropogenic modification of shore and invasive species.
VI Composition Dominant biota, substrate and water types		a mixture of the above	• A mixture of the above: gradual to extreme shifts in dominant biota with ecological successions, ecosystem squeeze and, for some systems and locations, hydrosystem class and subclass switches.

Table 1. NZ coastal hydrosystems classification hierarchy of levels, and sensitivity of hierarchical controlling factors to the effects of climate changes and sea level rise.

patterns and water table elevations will displace freshwater aquifers, rendering some current freshwater sources unusable, and rivers may experience greater saline intrusion, increased backwater effects and increased hinterland inundation. Climate changes will cause changes to freshwater inputs as rainfall and runoff patterns change, altering balances between river and tide forcing. More frequent floods or droughts could deliver greater or lesser catchment sediment volumes to coasts, though basin shallowing from this may be offset by SLR.

NZ coastal hydrosystem classes and response to SLR and climate change

This section describes the distinguishing characteristics of each NZ coastal hydrosystem geomorphic class (see Images 1 to 11) and the potential SLR and climate changes responses (attributions for the images used are presented at the end of this section). We refer readers to 'Estuaries and lowland brackish habitats' (p55) and to 'The response of sandy coastal systems to changes associated with sea level rise' (p25) for more information regarding estuarine and coastal embayment 'pocket beach' systems, respectively.

1. Damp sand plain lakes

Damp sand plain lakes are palustrine hydrosystems occurring as small, shallow (1 to 2 m deep), fresh/brackish water bodies, that are never connected to the sea. They are located in depressions between sand dune ridges and often associated with vegetated wetland areas. They form where the wind has removed sand to create shallow depressions down to about the level of the water table. They receive freshwater inputs from rain and groundwater, with salt spray and evaporation making them mainly brackish. They are variable in planform, ephemeral in space and time, and can dry out in drought conditions. Examples occur at: Parengarenga Spit (Northland) and Farewell Spit (Golden Bay), and on low lying coastal plains at the Kaipara Heads and Manukau Heads (Auckland).

For damp sand plain lakes, the overall responses to climate changes and SLR are likely to result in a range of outcomes between complete losses of some systems to minor water balance effects in others.

Rising sea level and storm tides will inundate these features in situations where the sand plains are low lying, unless inundation is offset by plain accretion through aeolian processes. As a result, damp sand plain habitat will be lost as inundation advances inland while a warming climate may see the lakes drying out more frequently, with consequent shifts in their biota. In some places, rising groundwater levels could lead to lake formation in previously dry depressions or to the deepening of lakes.

2. Waituna-type lagoons

Waituna-type lagoons are lacustrine hydrosystems occurring as large, shallow (mean depth 1 to 2 m) coastal lagoons, enclosed by a coarse clastic barrier or barrier beach and situated on wave-dominated high-energy coasts. Their waterbodies are typically fresh, fed by small streams, with brackish pockets. Drainage to the sea is generally via barrier percolation since their most frequent state is closed to the sea. Short-lived openings occur when water levels build a sufficient lagoon hydraulic head to induce a barrier breach. Sustained openings to the sea are rare unless mechanically opened. Two subclasses are recognised: 2A coastal plain depressions (e.g. Te Waihora Lake Ellesmere) and 2B valley basins (e.g. Te Roto o Wairewa Lake Forsyth) (both in central Canterbury).

For waituna-type lagoons, the overall responses to climate changes and SLR are likely to be pronounced, including shifts in the balance between river, tide and wave processes, affecting water quality and potentially triggering shifts for vulnerable lagoons into other system types.

Climate and wave climate changes, and SLR have the potential to decrease barrier percolation and restrict outlet drainage, leading to greater inundation of hinterland supratidal areas, barrier roll back, and erosion. If not balanced by increased sediment from longshore transport, these processes can lead to barrier breaching and breakup, transitioning waituna (2A) into estuarine (class 7) and/or embayment (class 11) systems. Barrier erosion and breaching processes have seen waituna lost in the past (e.g. Waimataitai, south Canterbury, Kirk and Lauder, 2000). Over Holocene timescales, waituna also have transitioned between non-estuarine, estuarine and embayment classes, with river avulsions and tsunamis (e.g. Norman, 2016).

Where waituna (2A) are fed by local streams and small rivers that experience reduced freshwater inflows in areas with drier climates, such as in eastern NZ plains and foothill catchments, this will lead to increased water residence times and longer-lived brackish conditions, water quality degradation and algal blooms. Water quality degradation is already common in many NZ waituna, due to the combination of catchment use intensification over recent decades with the long water residence times of these systems (Tables 5.2 and 5.3 in Hume et al., 2016). Alternatively, where waituna are fed by catchments projected to experience increased rainfalls, such as in Southland, increased inundation around the landward margins could allow natural barrier breach regimes to be maintained but may be undesirable to surrounding land users, leading to pressure on councils to increase mechanical openings. Intolerance of inundation around the landward margins could lead to shoreline protection works and ecosystem squeeze, while increased frequency of openings may prove difficult to maintain in the face of changing wave climates, and/or may accelerate hydrosystem flips into estuarine (7) or embayment (11) systems. Waituna 2B will be less prone to coastal inundation, given their valley basin morphometry. These systems may become either more or less connected to the ocean depending on the unfolding balance between SLR and coastal erosion/accretion with changes in longshore sediment transport.

3. Hāpua-type lagoons

Hāpua-type lagoons are riverine hydrosystems occurring as narrow, elongate and shallow (mean depth ~2 m) river mouth lagoons, enclosed by mixed sand gravel barrier beaches formed by strong longshore sediment transport. They occur on wave-dominated coasts, with micro- to meso-tidal ranges, typically with cliff backshores. River flow is seaward except just after large floods breach or widen outlets. They experience tidal backwater effects. Their outlets can migrate kilometres along the shoreline over days to weeks. Four subclasses are recognised: 3A occurring at the mouths of large braided rivers with alpine source areas (e.g. Rakaia rivermouth); 3B at the mouths of hill rivers (e.g. Ashburton rivermouth); 3C at the mouths of streams or small rivers (e.g. Opihi rivermouth); 3D on coasts where wave and tide dominance switches over time (e.g. Ashley rivermouth) (all in Canterbury).

For hāpua-type lagoons, the overall direct effects of SLR will likely be minor compared to current freshwater related pressures, though climate changes affecting catchment water balances could significantly compound current pressures. We will likely see changes in lagoon and barrier beach dimensions, water quality and ecosystem degradation, and increased pressure for management interventions.

In general, hāpua are not thought to be particularly vulnerable to SLR and coastal erosion processes alone under natural conditions, since these lagoons have persisted through Holocene SLRs and shoreline transgressions via parallel lagoon backshore retreat (i.e. via natural chronic erosion (Kirk and Lauder, 2000)). However, over the last few decades pronounced changes in many Canterbury hāpua indicate that these hydrosystems will be very sensitive to river flow changes from altered climates and any associated changes in freshwater use, as well as to effects from mechanical openings and structures (Hart, 2007; 2009; Creed, 2014; McHaffie, 2010).

Altered wave climates and stronger longshore transport, combined with lower river base flows due to drier climates and/or increased water abstractions, can lead to barrier strengthening (increased width and stability) in hāpua 3A to 3C. This can lead to more extensive and frequent inundation of low-lying margins during floods, since larger flows will be required to induce barrier breaches. More intense storms could induce more frequent barrier beach wave overtopping, flooding of lagoon margins and larger storm breaches (Hart, 2007). With projected reductions in plains rainfall in eastern NZ, lagoon closure could also become frequent and prolonged in hāpua 3B and 3C, with consequent reductions in lagoon flushing, water quality degradation and increases in algal blooms (Creed, 2014). Drier climates and increased freshwater use could see lower river flows at levels below peak floods, leading to lagoon shrinkage where subaerial and fluvial processes are less effective in eroding lagoon backshores, or where artificial openings are maintained to reduce hinterland inundation.

4. Beach stream

Beach streams are small shallow riverine hydrosystems that flow over a sand or mixed sand and gravel beach face. Drainage to the sea occurs for most of the time, except during drought conditions and/or when waves build a beach berm to close the outlet, so that water percolates through the beach face to the sea. There is no tidal inflow, except during storm events coupled with high tides. Five subclasses are recognised on the basis of the nature of the path the stream takes to the sea namely: 4A hillside stream (e.g. Heaphy Stream, West Coast SI); 4B damp sand plain stream (e.g. Granity Stream, West Coast SI); 4C stream with pond (e.g. Piha Stream, Auckland west coast); 4D stream with ribbon lagoon (e.g. Patten Stream, West Coast SI); 4E intermittent stream with ribbon lagoon (e.g. Shearer Swamp, West Coast, SI).

For beach streams, the overall responses to climate changes and SLR will vary greatly between subclasses, from very minor loss and landward migration of coastal fringes (4A) to complete losses with inundation, erosion and transgression (4D). River flood event increases could see breaching of lagoon barriers and streams taking a more direct path to the sea.

The effects of climate changes and SLR will be quite different for each beach stream subclass, with topography being a key determinant of responses in these systems. Minor effects will occur in subtypes situated on steep terrain while major effects will occur in those situated on flat, narrow, low-lying plains. The least affected will be 4A hillside streams, which discharge to the sea via a short, direct path over the beach. By contrast, systems that discharge to the sea over low-lying coastal plains (4B to 4E) could have their lower reaches inundated by SLR or be forced into landward retreat and squeezed against high ground, unless the plain is able to build higher via sediment supplied by stream and wave processes. SLR could also see a reduction in the drainage and flow capacity of systems and, in areas where river flows are reduced, the outlets to the sea might close more frequently, perhaps necessitating more mechanical openings to address flooding and water quality issues. Under SLR seawater will enter the mouths of beach streams more frequently during storm events. Beach streams 4B to 4D are likely to be sensitive to river flow changes from altered climates and, in particular, to any associated increase in freshwater inflow events and to effects from artificial openings to mitigate flooding. In extreme cases, 4D streams with ribbon lagoons fed by river flow may breach more regularly compared to 4E systems, which are buffered from floods by their connection to wetland drainage.

5. Freshwater river mouth

Freshwater river mouths are riverine hydrosystems that occur where river flow is large enough to cut a permanent subtidal channel through the shoreline and beach to the sea. The river channel gradient is steep enough to prevent tidal ingress, except at times of storm tides. While river flow dominates the hydrodynamics, there can be a tidal backwater effect. River mouths can discharge large amounts of sand and gravel to the sea and build a coastal plain over geological time. Three subclasses are recognised on the basis of the nature of the mouth namely: 5A unrestricted mouth (e.g. Waiau Toa Clarence River, Canterbury); 5B deltaic mouth (e.g. Tapu, Coromandel); 5C barrier beach enclosed mouth (e.g. Paringa River, West Coast SI).

For freshwater river mouths, the expected responses to climate changes and SLR will be minor overall, and dominated by changes in response to climate shifts, in particular those that alter the flow regime.

It is anticipated that there will be little overall effect from SLR on these systems. While SLR may enhance erosion of the shoreline where Holocene transgression is already occurring (e.g. Waiau Toa Clarence River mouth), this effect could be offset by any increase in river flows and sediment input. An increase in sea level could result in greater backwater effects in the rivers overall as well as for short periods during storms, resulting in flooding of adjacent low-lying land.

6. Tidal river mouth

Tidal river mouths are estuarine hydrosystems occurring as elongate, narrow and shallow (a few metres deep) basins. They occur where river and tidal flow are large and persistent enough to maintain a permanent subtidal channel through the shoreline/beach to the sea. River inputs to the system during a tidal cycle represent a significant proportion of the basin's total volume and exceeds tidal input to the system. Hydrosystem-scale hydrodynamic processes are dominated by river flows and the systems are well flushed. River floods can expel all the seawater from the system for days at a time. A salt wedge develops in deeper systems. Seawater can intrude kilometres upstream in systems occurring on low-gradient coastal plains. Wind-generated mixing and wave-driven resuspension are minor as wind fetch and waves are small and depths are largely too great for significant bed stress to be produced. Thus, sediments inside the waterbody tend to be muddy except in areas of high tidal flows. Five subclasses are recognised: 6A unrestricted mouth (e.g. Waihou River River, Waikato); 6B spit enclosed (e.g. Whanganui River, Taranaki); 6C barrier beach enclosed (e.g. Hokitika River, West Coast SI); 6D intermittent with ribbon lagoon (e.g. New River, Greymouth); 6E deltaic (e.g. Motueka River, Tasman Bay).

For tidal river mouths, the expected responses to climate changes and SLR will vary with subclass and could be significant.

The larger deeper systems that can extend kilometres inland (6A, 6B and 6C) are likely to see tidal intrusion and backwater effects extending further inland as sea levels rise, potentially threatening freshwater water supply intakes that are located further upstream, increasing flooding of low-lying coastal plain areas adjacent to the river, and a redistribution of ecological facies upstream accompanying the change in water level and salinity regime. Tidal river mouths enclosed by narrow sandy spits and gravelly barriers (6B and 6C) may experience an increased frequency of wave overwash events during storms. Small shallow systems such as 6D intermittent types, which today are particularly sensitive to changes in river flow and mechanical openings, are likely to experience an increase in barrier breaching events.

7. Tidal lagoon

Tidal lagoons are estuarine hydrosystems of shallow mean depth (1 to 3 m), with circular to elongate basins and simple (not dendritic) shorelines, and having extensive intertidal area. The narrow inlet is constricted by a wide spit or sand barrier. Strong tidal currents flow at the mouth where ebb and flood tidal deltas occur. Tidal inflow makes up a large proportion of total volume of water in the system and river inputs are correspondingly small. Lagoon salinities are close to that of the sea. River flows can dominate the hydrodynamics for short periods during floods. Storm tides can back up outflows causing low-lying land around the lagoon margins to be flooded. Two subclasses are recognised: 7A permanently open (e.g. Blueskin Bay, Otago) and 7B intermittently closed that become eutrophic when closed to the sea (e.g. Hoopers Inlet, Otago).

For tidal lagoons, the expected responses will mostly result from SLR. We may see progressive flooding of the low-lying margins by the sea, unless inhibited by structures or other processes, and potentially coastal squeeze in some systems while others will close more frequently due to reduced drainage, with consequent increases in eutrophication.

Effects from climate changes and SLR in these systems will mostly result from SLR, as freshwater flow to these systems is small compared to tidal exchanges. Lagoon intertidal areas will deepen unless offset by sedimentation and there will be progressive flooding of their low-lying margins unless this is inhibited by stopbanks or other structures, in which case there will be a decrease in intertidal area and coastal squeeze. The effect will be most pronounced in locations where the tidal range is small compared to the relative SLR. There is likely to be increased flooding of lagoon margins during storms, as incoming tides and elevated coastal water levels back-up outflows.

In larger, wider, and more open examples of this hydrosystem type, higher water levels will allow waves to attack soft shorelines for longer periods at high tidal stages, increasing the shoreline erosion rates. In contrast, 7B intermittently closed systems will close more frequently as SLR inhibits drainage, resulting in more eutrophic events. There is likely to be some landward migration of ecological facies (e.g. mangrove and saltmarsh) as SLR submerges present-day intertidal areas. An increased frequency of rainfall and runoff events in some regions could lead to more frequent smothering of sandy substrate benthic communities with muddy sediment inputs (see 'Estuaries and lowland brackish habitats', p55). At the entrances to barrier enclosed systems on sandy coasts, larger tidal prisms may increase the capture of longshore transport, resulting in a build-up of sand in the tidal delta sand bodies and consequent erosion of adjacent open coast beaches (Hicks and Hume, 1996). Low elevation sandy spits and barriers may experience an increased frequency of wave overwash and breach events during storms.

8. Shallow drowned valley

Shallow drowned valleys are estuarine/marine hydrosystems of shallow mean depth (<5 m) having complex dendritic shorelines with narrow arms leading off a main central basin or channel. They range in size from small tidal creeks to large harbours and have extensive intertidal flats. Hydrodynamics are dominated by tidal processes. Their mouths are permanently open, being constricted by hard headlands or substantial barriers. Flood and ebb tidal sandy deltas are present at the mouths on high wave energy, littoral drift shores (e.g. Raglan Harbour) but absent on zero-drift shores (e.g. Waitemata Harbour). These hydrosystems are significantly infilled with sediment, being sandy at the mouth and muddy in the headwaters where narrow intertidal tidal creeks occur (e.g. Paremoremo Creek, Waitemata Harbour).

For shallow drowned valleys, the expected responses to climate changes and SLR are likely to be significant overall, particularly in relation to changing climates. Adjustments will occur both around the edges and in central basin areas.

Shallow drowned valleys will see increased flooding of low lying coastal margins accompanying SLR, unless held back by engineering structures, and potentially increased depth, which may partially but not completely offset current and future sedimentation. Today the tidal creeks are scoured by increased flood flows from catchment urbanisation, and this will likely be exacerbated by climate change induced increases in rainfall intensities. In most systems the resultant increases in mud delivered to their wider basin areas will only partially offset SLR, meaning most systems will deepen overall. Channel dredging may need to increase though, to offset channel infilling and maintain vessel drafts. In larger, wider and more open systems, higher water levels will see greater wave attack on soft shorelines at high tidal stages, increasing shoreline erosion. This may, in turn, raise coastal erosion concerns for development on low-lying coastal terraces as well as some loss of soft shoreline amenity. SLR induced intertidal area losses will cause some redistribution of ecological facies (e.g. salt marsh and mangrove distribution may move landwards). Extensive landward transgressions will be prevented where margins include naturally steep valley sides or the artificial shoreline hardening of stopbanks and reclamations, resulting in coastal squeeze.

9. Deep drowned valley

Deep drowned valleys are estuarine/marine hydrosystems, typically large and deep (mean depth 10 to 30 m). Formed by the partial submergence of unglaciated river valleys they have a planform inherited from the flooded valley. Typically, they have a straight planform without significant branches, but they can be dendritic. In the Marlborough Sounds and Wellington Harbour there are islands which are the summits of partly submerged hills. The size of the valleys seems large for the size of the rivers currently entering the system. They are permanently open to sea and mostly subtidal. Both tidal and river inputs are small relative to their basin volumes. Circulation is forced by density currents and stratification is common. Wind and tide modify the circulation at times but are not responsible for the mean circulation over extended periods of time. These systems differ from shallow drowned valleys in that they are deeper, lack sand deltas at the mouth, have steeper margins and far less intertidal area, and their hydrodynamics are less tidally dominated. Examples include: Firth of Thames; Wellington Harbour; and Akaroa Harbour.

For deep drowned valleys, the expected responses to climate changes and SLR are expected to be minor overall, and edge focussed.

Changes in rainfall and tidal processes associated with climate changes and SLR are unlikely to affect the hydrodynamics of these hydrosystems, which are largely controlled by their deep basins and large total water volumes. However rising sea levels will allow waves to attack any soft margins for longer periods of time at high tidal stages, increasing shoreline erosion. This may, in turn, increase coastal erosion hazards for poorly sited developments in coastal areas, with potential losses of shoreline amenity and increases in pressure for management interventions. Rising sea levels will also see gradual reductions in habitat in smaller headwater intertidal areas from coastal squeeze, unless offset by river derived sedimentation. Deep drowned valleys with extensive low-lying coastal plains (e.g. Miranda coast in the Firth of Thames) are likely to experience more frequent coastal inundation of the plains, initially during storms with eventually total inundation. Overall, the effects in these hydrosystems will be minor and focussed around the edges.

10. Fjord

Fjords are estuarine/marine hydrosystems comprising long, narrow and very deep (70 to 140 m average) U-shaped basins with steep sides or cliffs, formed in glacial valleys flooded by Holocene SLR. Fjord basins are largely subtidal, with only very small headwater intertidal areas. Former terminal moraines form sills at the mouth and along the length of these systems. Both river and tidal inputs are very small compared to total basin water volumes. Water movement near the surface is controlled primarily by thermohaline forcing, due to large density differences between outflowing river-derived freshwater on the surface and inflowing seawater below. Wind-driven circulation dominates at times but is not responsible for the mean circulation over extended periods. Consequently, these systems are characterised by poor flushing, particularly in more complex-shaped (multiple arm) systems. The very deep basin and partitioning by sills means that flushing takes place in a relatively thin layer of freshwater, which moves over the top of a ‘quiescent zone’ of seawater. The substrate is generally fine sand or mud as the catchments are forested and resuspension by wind waves is minimal in these very deep basins. Fjords are restricted to Fiordland, with examples including: Charles Sound, Te Awa o Tū/Thompson/Doubtful Sound, Bligh Sound and Milford Sound.

For fjords, the expected responses to climate changes and SLR will be minor overall and focussed on erosion and habitat changes around the edges. Increases in ocean acidification and temperatures have the potential to strongly affect fjord ecology.

Changes in rainfall and tidal reach associated with climate changes and SLR are unlikely to affect the hydrodynamics of these hydrosystems, since circulation is largely a function of their very deep, steep-sided basins and large total water volumes. However, SLR may allow greater wave attack and localised erosion of soft shores and pocket beaches in their upper reaches. SLR will also see gradual intertidal habitat reductions in fjord headwaters from coastal squeeze, with river derived sedimentation unlikely to offset this process in these steep-terrain systems. More significantly, ocean acidification and temperature shifts could affect fjord ecology, alone and in combination with invasive species, with flow-on effects for tourism, the major economic activity in NZ’s fjords. Overall fjord responses to climate changes and sea level rise will be minor in terms of geomorphology but potentially significant with regard to ecology and management challenges.

11. Coastal embayment

Coastal embayments are marine hydrosystems, occurring on low littoral drift shores as an indentation in the shoreline with a wide entrance, and bounded by rocky headlands. Their waterbodies are circular to elongate in planform, shallow to medium depth (4 to 8 m), and mostly sub-tidal. These pocket beaches contain small sandy dunes or shelly ridge systems above high tide, and small intertidal areas in the headwaters. Hydrodynamic processes are dominated mostly by tides as the enclosing headlands provide for only a narrow sector of wave entry. Coastal embayments differ from shallow drowned valleys in that they are largely subtidal, with their wider mouths allowing a greater degree of wave forcing. Examples include: Taemaro Bay and Matai Bay (Northland); and Te Matuku Bay (Waiheke Island).

For coastal embayments, the expected responses to climate changes and SLR are likely to be minor and to include intertidal habitat losses in their upper reaches, and increased shoreline rotation and/or erosion.

SLR in these hydrosystems is likely to see gradual reductions in intertidal habitat via coastal squeeze and potential increases in shoreline erosion rates, though net sediment losses are likely to be small as deposits are contained between headlands. These systems will be partially protected from changes in mean or storm wave directions, since wave energy can only enter these bays from a narrow sector, although planform shoreline rotation may occur as sand shifts from one end to another. Freshwater inflows into coastal embayments may alter with climate changes that affect rainfall or catchment aridity, but given their small inflows from streams, such changes are unlikely to have any substantial effects on the hydrodynamics and sedimentation in these hydrosystems. Overall, the effects will be minor both in relation to climate changes and SLR.

Images 1 to 11: Examples of the 11 different types of NZ coastal hydrosystem identified in Hume et al. (2016).

(1) Damp sand plain lake, Manukau North Head (Doug Ramsay, n.d.);

(2) Waituna-type lagoon, Te Waihora/Lake Ellesmere, Canterbury (Google/Landsat/Copernicus, 2016);

(3) hāpua-type lagoon, Hakatere/Ashburton River, Canterbury (Google/Maxar Technologies/CNES/Airbus, 2016);

(4) Beach stream, Piha Stream, Auckland (Google/Maxar Technologies, 2015);

(5) Freshwater river mouth, Waiau Toa/Clarence River, Canterbury (Google/ Maxar Technologies, 2020);

(6) Tidal river mouth, Whakatne, Bay of Plenty (Google/Maxar Technologies, 2020);

(7) Tidal lagoon, Waiputai, Blueskin Bay, Otago (Google/Maxar Technologies, 2020);

(8) Shallow drowned valley, Mahurangi Harbour, Auckland (Google/Landsat/Copernicus/Maxar Technologies, 2020);

(9) Deep drowned valley, Akaroa, Canterbury (Google/ Copernicus/Maxar Technologies/CNES Airbus, 2020);

(10) Fjord, Te Awa o Tū/Thompson Sound, Southland (Google/ Landsat/Copernicus/Planet.com/Maxar Technologies, 2020);

(11) Coastal embayment, Taemaro Bay, Northland (Google/Maxar Technologies, 2020).

Conclusions

Climate changes and SLR have the potential to alter the primary drivers of coastal hydrosystem processes, namely fluvial inputs, tidal and wave processes, and to a lesser extent rainfall and longshore sediment transport (see Table 1). Resultant responses in these interface systems will be small or large depending on the degree to which their driver balance is altered, as well as on the nature of direct and indirect human responses.

In terms of SLR, effects will be most significant in hydrosystem classes where marine forcings are a significant portion of their total water volumes and flows. These effects will vary and may include the deepening of the channels and basins, and intertidal habitat migration and/or losses (with some offsetting via sedimentation, and some increased losses due to natural or human induced coastal squeeze). Comparatively minor adjustments to SLR are expected around the edges of systems where their total water volume is large compared to fluvial and tidal inputs, including deep drowned valleys, fjords and coastal embayments (classes 9, 10 and 11).

Responses to SLR will vary not only between coastal hydrosystem classes, but also as a result of regional differences in tidal range (Byun and Hart, 2020), wave energy ('The response of sandy coastal systems to changes associated with sea level rise', p25) and climate (MfE, 2017). For tidal river mouths (6) and tidal lagoons (7) effects will differ between regions, as will the importance of edge effects in deep drowned valleys (10) and coastal embayments (11). In contrast, damp sand plain lakes (1), freshwater river mouths (5) and fjords (10) are clustered according to similar tidal, wave and/or climate conditions, such that lessons from one system may be extrapolated across other systems of the same type.

Some hydrosystems are considered relatively robust in the face of SLR alone, but hypersensitive to the combined effects of climate changes and human influences. Hāpua (3), for example, have persisted through Holocene SLR but are experiencing significant and growing negative effects from river flow and freshwater use changes, mechanical openings and structures, pressures that will likely increase with climate changes unless managed via altered catchment and coastal use practices.

While some coastal hydrosystems will exhibit gradual ongoing effects from SRL and climate changes, others may switch geomorphic class subtype (e.g. hāpua 3, tidal river mouths 6, and tidal lagoons 7); flip into completely different types (e.g. waituna 2A); or disappear completely (e.g. damp sand plain lakes 1) once thresholds for change are reached.

Overall this review of the potential and likely responses of New Zealand coastal hydrosystems to climate changes and SLR underlines, not only the range of response types and rates but also, that catchment and coastal management practices can strongly influence responses across all system types. Numerous examples exist today where anthropogenic developments or interventions have produced physical process changes with undesirable hydrosystem effects. Key interventions include reclamations, stopbanks, shoreline hardening or re-contouring, mechanical openings, dredging, water extractions, spoil dumping, and mangrove removal. In many cases these have greater consequences for coastal hydrosystems than climate changes and SLR effects combined. They are also typically the most immediately modifiable component of hydrosystem influences.

There is a sensitive balance of processes operating in coastal hydrosystems, combined with uncertainties in the trajectories of climate changes and sea level rises, and in how systems are responding. This means that robust monitoring of systems is needed to feed into adaptive management policies and practices (e.g. Tait and Pierce, 2019) and to minimise adverse effects from SLR and climate changes. Few New Zealand coastal hydrosystems are currently subject to robust monitoring and adaptive management regimes and further research is needed to improve management outcomes. Thus, a significant shift in regional and national management approaches to coasts and catchments is urgently needed to safeguard New Zealand's diverse coastal hydrosystems.

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Estuaries and lowland brackish habitats

Andrew Swales, Rob Bell and Drew Lohrer

Wenderholm Regional Park (Photo: Alastair Jamieson/WildEarthMedia.com)

Introduction

New Zealand's estuaries formed between 12,000 and 7,000 years ago in the early Holocene, as rising sea level flooded lowland river valleys at the end of the last ice age. Epochs of change punctuated by periods of relative stability in mean sea level (MSL) have been the backdrop to the evolution of these dynamic coastal environments ever since that time. More recently, over the last 170 years, our estuaries have been unmistakably transformed by human activities. Increases in catchment sediment loads due to deforestation, subsequent development of pastoral agriculture, urbanisation and land-use intensification in recent decades have been the major drivers of environmental change. Receiving estuaries have infilled with eroded sediment and have been adversely impacted by nutrients and stormwater pollutants. Sediment accumulation rates (SAR) are now typically ten-fold higher than the prior several thousand years (which were 0.1 to 1 mm yr^{-1}). This rapid increase in SAR during the historical era has seen most estuaries transform from sand- to mud-dominated systems, accompanied with loss or degradation of ecosystems sensitive to increased water turbidity, reduced light levels and sedimentation (e.g. seagrass meadows, filter-feeding shellfish) (e.g. Thrush et al., 2004).

This pattern of environmental change in New Zealand estuaries mirrors that described by Roy et al. (2001) for southeastern Australian estuaries, and echoes the changes seen around the globe over a longer time frame. Estuaries will continue to be under increasing pressure in the foreseeable future as human activities in catchments intensify (PCE, 2020).

Historical reclamation and drainage of tidal flats has measurably altered tidal volumes, hydrodynamics, sediment dynamics and habitats, while extensive shoreline protection (e.g. seawalls, rock revetments) and infrastructure (e.g. roads, stopbanks) prevent any future landward adjustments in fringing habitats, as estuaries progressively infill and sea level rises (Kettles and Bell, 2016). The action of tides, waves, historical changes in the supply of sediment from rivers, vertical land movement (VLM), episodic 'disruptors' (i.e. storms, tsunami, earthquakes) and emergence of distinctive ecosystems have also shaped the estuaries and brackish habitats that we see today (see Figure 1). Future projected climate change impacts on estuaries include changes in freshwater flows and sediment and nutrient loads, changes to extreme storm-tide and rainfall event frequency and intensity, and a rise in the underlying groundwater level – all taking place on the back of ongoing sea level rise (SLR). These multiple pressures, from both the catchment and the sea, will magnify the issues and pressures already facing New Zealand's estuaries and lowland brackish habitats over the coming decades (Kettles and Bell, 2016).

Figure 1: Tairua estuary, Coromandel Peninsula. This former river valley, flooded by rising sea levels 12,000-7,000 years ago, has infilled with marine and catchment sediment (Source: Alastair Jamieson/WildEarthMedia.com).

In this chapter we review the potential impacts of SLR on the biophysical environments of New Zealand's estuaries and lowland brackish habitats. We also describe an adaptive pathways approach to planning for the challenges posed by SLR over the coming decades.

Classification

Estuaries form part of the spectrum of coastal hydrosystems. These hydrosystems comprise a diverse set of environments at the interface of terrestrial and marine systems where water is a dominant feature. Coastal hydrosystems span a spectrum from near-coast freshwater lakes and wetlands though to complex coastal-ocean systems such as inlets, fjords and coastal embayments (Hume et al., 2016; and 'Coastal hydrosystem responses to sea level rise', p45). In this spectrum, estuaries are represented on the basis of their basin morphometry and fluvial and marine dominance by tidal river mouths, tidal lagoons, shallow and deep drowned valleys, and fjords (Hume et al., 2016). Fjords and tidal river mouths are not considered in this chapter. Estuarine systems, being the transitional places where freshwater and saltwater mix, have their own distinct values, pressures and management needs. Just as changes in catchments and their waterways impact estuarine systems, changes in the marine environment also can impact lowland freshwater systems upstream, primarily through a rise in the base MSL (Kettles and Bell, 2016).

Context

New Zealand's estuaries are geologically recent coastal features that formed as rising sea level flooded lowland river valleys at the end of the last ice age. Sea levels were some 120 m lower than today at the peak of the last (Otira) ice age, 16,000-18,000 years ago. At that time, most of New Zealand's inner continental shelf was dry land occupied by lowland forests. Sea level fluctuated during the Holocene, with a temporary high-stand sea level 1–2 m higher than today occurring 6,000-7,000 years ago followed by a long period of relative stability until recently (Clement et al., 2016; King et al., 2020).

Estuaries progressively infill with river and marine sediment since their formation. Stages of development range along a continuum from youthful systems that have retained a substantial proportion of their original tidal volume, to mature estuaries that have largely infilled with sediment and have little accommodation volume for sediment. In these mature estuaries, new sediment accommodation volume is created by SLR and 'excess' sediment is exported to the adjoining coastal marine environment. In semi-mature estuaries, expansion of accreting intertidal flats progressively displaces subtidal basins. This biogeomorphic evolution of estuaries from youth to old age is summarised in Figure 2.

Intertidal habitats are most vulnerable to inundation from rising seas as they attempt to maintain their bed elevation in adapting to the relative SLR (RSLR)* of the area, by trapping additional sediment, primarily delivered by rivers (Leuven et al., 2019). In turn, the rate at which estuaries infill reflects the original volume of the ancestral river valley, sediment supply and changes in sea level. Evidence from global sedimentary records indicate that low rates of sea level

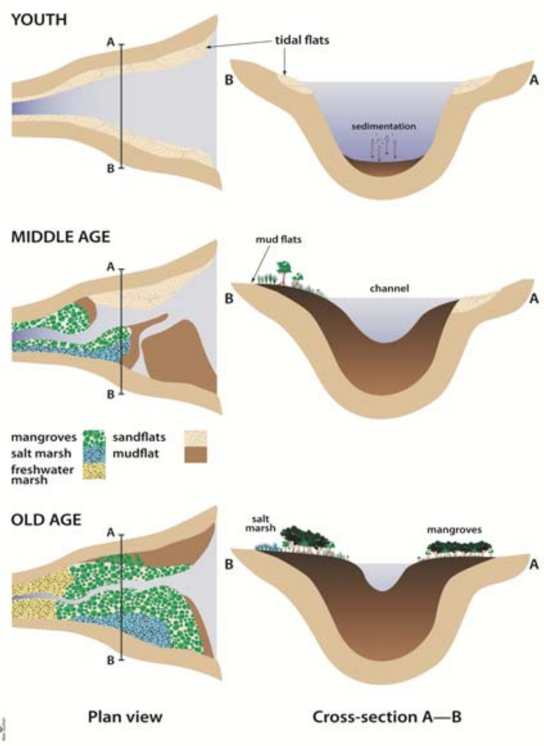

Figure 2: Biogeomorphic evolution of estuaries. Estuaries follow a cycle of development, the rate of which is determined by the size (volume) of the ancestral basin/flooded river valley and the sediment supply trapping efficiency of the system. Sediment trapping efficiency typically reduces as estuaries infill due to reduction in accommodation volume and increased efficiency of sediment remobilisation and transport by fetch-limited waves, tidal currents and export to the coastal marine environment. Reproduced with permission (Swales et al., 2020).

change (i.e. tenths of mm yr^{-1}) persisted until as recently as the start of the 20th century (King et al., 2020). Both sedimentary and tide-gauge records in New Zealand show that average rates of RSLR have increased to the order of a few mm yr^{-1} in the modern era (King et al., 2020; MfE/StatsNZ, 2019).

The relationship between the rate of sediment supply and an estuary's sediment accommodation volume has been demonstrated for large drowned-valley systems in New South Wales (Australia) that have high-tide surface areas of tens of km^2 (Fig. 7, Roy et al., 2001). This relationship between sediment supply and estuary maturity is also demonstrated for Auckland estuaries of various geomorphic/hydrosystem types using the ratio of intertidal to high-tide area as a metric of estuary infilling. The relationship is described as the relative area of intertidal flat above MSL compared to the predicted annual catchment sediment load normalised by tidal prism volume based on average spring-tide range (see Figure 3) (Hume et al., 2007; Swales et al., 2020).

The analysis shows that intertidal area above MSL in these estuaries can be predicted from catchment annual sediment loads (r^2 = 0.69, P = < 0.001). Sediment yields from these largely rural lowland catchment-estuary systems vary from ~80 t km^2 yr^{-1} (funnel-type estuaries) to ~160 t km^2 yr^{-1} (barrier-enclosed estuaries) and are relatively modest compared to yields from New Zealand's upland/steepland catchments that deliver several thousand tonnes km^2 yr^{-1}

* RSLR includes vertical land-mass movement by tectonic and/or sedimentary basin compaction processes.

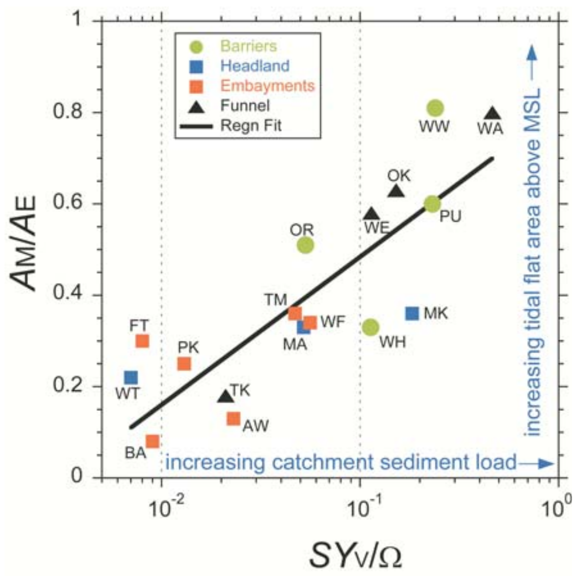

*Figure 3: Auckland east-coast estuaries – relationship between annual catchment sediment load to estuary tidal prism volume (SY_V/Ω) ratio and intertidal-flat above MSL to estuary area (A_M/A_E) ratio. **Model fit**: $A_M/A_E = 0.139*LN(SY_V/\Omega) + 0.808$ ($r^2 = 0.69$, P = < 0.001). **Geomorphic class** (after Hume and Herdendorf, 1988): (1) Barrier-enclosed estuaries with inlets formed by Holocene spits. Estuaries: Waiwera (WW), Puhoi (PU), Orewa (OR) and Whangateau (WH); (2) Headland-enclosed estuaries with inlets restricted by rocky headlands. Estuaries: Matakana (MK), Mahurangi (MA) and Waitemata (WT); (3) Coastal embayments typically with small catchments. Estuaries: Te Matuku (TM), Whitford (WF), Awaawaroa (AW), Putiki (PK), Firth of Thames (FT) and Bon Accord (BA); and (4) Funnel-shaped estuaries that have no inlet barrier, are simple or branched and form on low-energy coasts. Estuaries: Wairoa (WA), Weiti (WE) and Okura (OK). **Definitions**: (vertical axis) A_M/A_E – ratio of the tidal flat above MSL to the estuary mean high-tide surface area (km^2), (horizontal axis) SY_V/Ω– ratio of the estimated annual average catchment sediment load (m^3) to the spring-tidal prism volume (m^3). Annual load is converted from tonnes to m^3 using a typical wet-bulk sediment density of 1.2 t m^3. Reproduced with permission (Swales et al., 2020).*

to the coast (Hicks et al., 2011). Coastal embayment-type estuaries are less infilled due to their relatively modest catchment sediment supply. By contrast, barrier-enclosed estuaries formed in drowned river valleys are substantially more infilled than coastal embayments due to their larger sediment supply (see Figure 3).

Relative sea level trends

Ultimately, the local RSLR trend in an estuary is largely determined by the interaction of VLM with the regional increase in sea level. Depending on the direction of VLM (i.e. subsidence or uplift) the rate of RSLR will be increased or decreased. For example, in the Wellington/Hutt area, if the secular trend in subsidence of 2.5-3 mm/year (excluding co- and post-seismic influences from earthquakes) continues (Denys et al., 2020), it would bring forward the effective RSLR for lower- and upper-range projections by five decades and one to two decades respectively within a 100-year planning timeframe. Key drivers of VLM include ongoing glacial isostatic adjustment from the last ice age, tectonic processes at active plate margins (e.g. co-seismic, post-seismic, inter-seismic crustal slip) and, particularly relevant for estuaries, the subsidence due to compaction of deep unconsolidated sediment at river deltas and in coastal sedimentary basins (Swales et al., 2016). The rates of compaction can be further exacerbated by fluid extraction (e.g. groundwater and surface drainage).

In New Zealand, near instantaneous changes in RSLR in some estuaries due to co-seismic rupturing and liquefaction during strong earthquakes have been documented for the Porirua (1855, magnitude [MW] ~8.1, uplift of 0.6 m) and Avon-Heathcote (2010–2011, MW ~7.1, spatially-varying uplift and subsidence of ±0.5 m) systems (Grapes and Downes, 1997; Orchard et al., 2020). In the Avon-Heathcote Estuary, the upper intertidal area, between the Highest Astronomical Tide (HAT) and Mean High Water Spring (MHWS) marks, reduced in area by 21.4 ha (2011-2015) due to compression (Orchard et al., 2020). In the southern Firth of Thames, RSLR of ~10 mm yr^{-1} is largely driven by gradual compaction of a sedimentary basin, whereas the long-term sea level trend at the Port of Auckland (74 km to NW) is only 1.5 mm yr^{-1} over the same period (Swales et al., 2016). Overall, across New Zealand, based on the four long-term main port gauge records back to ~1900, the average RSLR has doubled to 2.44±0.10 mm yr^{-1} since 1960, compared with a similar timeframe before 1960 of 1.22±0.12 mm yr^{-1} (StatsNZ/MfE, 2019).

Coastal squeeze and the flood sandwich

Two colloquial terms – 'coastal squeeze' and 'flood sandwich'– are now in vogue to describe emergent changes in estuaries and coastal lowlands caused by climate change, RSLR and physical interventions to adapt to climate change and protect the built environment.

In the absence of physical barriers, estuarine habitats will naturally migrate landwards to occupy fringing brackish/freshwater habitats as sea level rises (see Figure 4a). Where artificial barriers prevent this natural response, estuarine habitats maybe lost where the supply of sediment is not sufficient for vertical accretion to keep pace with RSLR (Mangan et al., 2020) and if the barrier inhibits sediment accumulation. This so called **coastal squeeze** has varying definitions, but a narrower focus is the definition by Pontee (2013): *Coastal squeeze is one form of coastal habitat loss, where intertidal habitat is lost due to the high water mark being fixed by a defense or structure (i.e. the high water mark residing against a hard structure such as a seawall) and the low water mark migrating landwards in response to SLR* (see Figure 4b). Where the landward margin of these intertidal habitats, including wetlands and marshes, are constrained naturally by rising topographic features (see Figure 4c), which may be the case in many of our estuaries situated in New Zealand's seismically-active setting, a less emotive term for this similar, but natural, process, is '**coastal narrowing**' as a general description for natural shrinking of intertidal area (Pontee, 2013).

Consequently, running in parallel with the projected impacts of climate change and RSLR on estuarine systems will be the ongoing direct and indirect pressures of society's responses to climate change adaptation. If cascading climate change effects are not thoroughly explored and evaluated in a holistic manner, attempts to counteract the impacts on the built environment and existing land-use rights (e.g. shoreline protection works, reclamations to reinstate shoreline buffers,

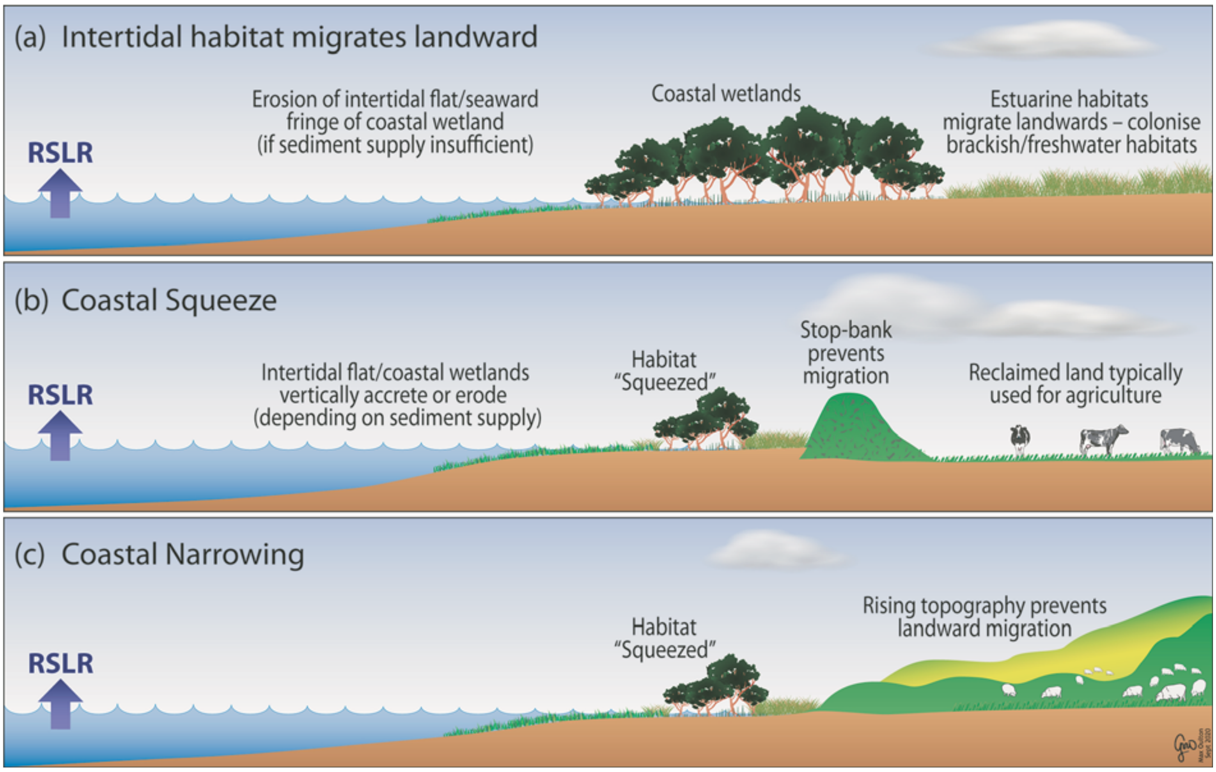

Figure 4: Potential estuarine habitat responses to relative sea level rise (RSLR): (a) habitats naturally migrate landward to displace brackish/freshwater habitats where there are no physical barriers; (b) coastal squeeze occurs where natural landward migration of estuarine habitats is prevented by hard protection structures and/or reclamation; and (c) migration is prevented by rising land topography (i.e. coastal narrowing). Adapted from Pontee (2013).

stopbanks and alteration to drainage schemes), will invariably lead to coastal squeeze (Kettles and Bell, 2016). This would result in reduced intertidal habitat and eventual submergence, if the rate of tidal-flat elevation gain (i.e. related to but not necessarily equivalent to SAR) does not keep pace with RSLR. However, emergent research is focusing on creating living edges to enable inland habitat migration through a range of financial, policy, planning, and on-the-ground management tools (Leo et al., 2019).

Estimating future change in estuaries and coastal lowland hydrosystems is challenging due to compounding complexities (Passeri et al., 2015). These complexities arise from the interplay between marine and freshwater systems and how these are likely to shift under climate change. One of the main compounding effects, is the so-called 'flood sandwich' that arises from the progressive increase in MSL and compound freshwater/coastal flooding processes. These processes include: changes in freshwater flows and sediment loads; sequencing of dry periods interspersed with more intense rainfall and river flood events; spatial changes in wave characteristics and sediment transport arising from estuary deepening or shallowing; rising groundwater; and increased occurrence of coastal storm-tide impacts up estuaries and lowland rivers (e.g. Ganguli and Merz, 2019; Passeri et al., 2019). The balance between sea level and catchment drivers of the flood sandwich will also change over time and spatially, as these lowland coastal systems strive to migrate landward, where they are not constrained by engineered barriers or natural topographic features.

Hydrodynamics and sediment transport

Sea level rise induces nonlinear changes in hydrodynamics of estuarine systems, which in turn influences sediment transport, ecological and nutrient processes (Passeri et al., 2015). Changes in water depth and bathymetry will alter tidal characteristics due to the net effect of RSLR and SAR. Accommodating the gradual changes from increased tidal volume through the mouth over each tide phase as the ocean level rises, and changes upstream in river slope (i.e. water surface), will also influence tides. A balance between bed friction and channel-width, convergence and expanding length determines whether the tidal range amplifies, remains constant or dampens in the landward direction (Leuven et al., 2019; Du et al., 2018). A future increase in MSL generally reduces bed friction so that tides are amplified. However, landward expansion of intertidal areas (if not constrained – see Figure 4a), provide storage volume and additional friction for the tidal wave propagating through an estuary. This process naturally reduces the tidal range and flood risk that would have otherwise been the case if shoreline protection was implemented. In contrast, infilling through sedimentation can reduce tidal range, but at the cost of a higher mean tide level (Palmer et al., 2019). Although estuarine systems are known to be dynamic and likely to exhibit non-linear behavior under rising sea level, many studies have employed a simplistic static ('bathtub') modelling approach. Recent work has considered the dynamic and compounding inundation effects associated with SLR, such as tidal and storm-surge hydrodynamics under SLR and the balance between hydrodynamics, estuary basin infilling and fluvial flow regimes (Leuven et al., 2019; Palmer et al., 2019; Moftakhari et al., 2018).

Future impacts of SLR

Looking to the future, SLR during the 21st century and beyond will fundamentally drive major environmental changes in New Zealand's estuaries, with secondary compounding effects arising from other climate change drivers (see Figure 5). Running in parallel with the impacts of climate change, are the ongoing direct and indirect anthropogenic pressures that already significantly affect many estuarine systems. These pressures include urbanisation along estuarine margins associated with population growth, catchment-related stressors (e.g. water abstraction, soil erosion), drainage schemes, and in-situ changes to habitats (e.g. dredging or reclamation, shoreline armouring, shellfish harvesting and introduced marine pests) (Kettles and Bell, 2016). Recent work by Mangan et al., (2020) in a hypsometric analysis (hypsometry: distribution of surface area versus depth) of 11 New Zealand estuaries suggests 27% to 94% loss of intertidal area with a 1.4 m increase in sea level that could occur by the end of this century or beyond. Estuaries with more gently sloping intertidal areas were projected to have the earliest and largest losses of intertidal area, in the absence of compensating sedimentation. The relationship between SLR and predicted intertidal habitat loss was also highly non-linear in some estuaries, however, with sharp declines in intertidal habitat occurring only after RSLR reached a certain threshold (e.g. after 0.6 m RSLR for Mahurangi Estuary), in relation to the shape of the intertidal seabed profile.

Retaining intertidal habitats, including coastal wetlands, and the ecosystem services they provide in the future will also depend on vertical sediment accretion keeping up with RSLR. Cahoon and Guntenspergen (2010) have defined the term 'elevation capital' for coastal wetlands, but this concept is broadly applicable to intertidal habitats. The elevation capital of an intertidal habitat is the vertical difference between the upper and lower elevation limits of its range relative to sea level. Elevation capital will therefore also increase or decrease with the local tidal range. A salt marsh, for example, located in the upper-intertidal zone with a lower growth limit at MSL will have more elevation capital than a salt marsh growing close to MSL. Consequently, the upper salt marsh has greater capacity to maintain itself for decades even without sedimentation.

Numerical models are used to explore interactions and biophysical feedbacks that drive the maintenance of elevation capital as well as simulate the long-term biogeomorphic evolution of estuaries over decadal to centennial time scales. One such modelling approach, the zero-dimensional (0-D) or point model, has a relatively simple numerical scheme that can encapsulate the biophysical feedbacks controlling the long-term biogeomorphic development of estuaries (e.g. Marani et al., 2010). Such a model has been used to investigate how SLR is likely to affect intertidal habitats in Auckland estuaries of varying sizes over the next century (see box below).

The results for a 20th Century hindcast indicate that an average sediment supply rate (i.e. SSC) of about 40 mg l^{-1} was sufficient to develop intertidal flats matching present day average elevations (~0.3 m above MSL) across all three estuary scales by the early-2000s (see Figure 6). These conditions correspond with a sediment supply rate averaging ~120 t km^2 yr^{-1} for these largely rural lowland catchments (Swales et al., 2020).

Simulations for the 21st Century IPCC scenarios of low- and high-SLR rates (i.e. 4.8 and 9.2 mm yr^{-1}) suggest that intertidal flat habitats in tidal creeks (0.1 km fetch) and small estuaries (1 km fetch) will be able to keep pace with SLR even at relatively low sediment-supply rates (see Figure 6). By contrast, intertidal flats in the largest estuaries (10 km fetch) will be more susceptible to erosion and inundation even at the lower rate of SLR anticipated under the IPCC RCP2.6 scenario.

Zero-D model

The 0-D m model was calibrated using measurements from the study estuaries to estimate an initial platform height (IPH) (i.e. circa 1900) and tune model parameters to achieve realistic IPH values by the early-2000s. Data included present-day average intertidal flat elevation and sediment accumulation rates from dated cores. An IPH (1900 AD) of -0.3 m MSL (1900 AD) was based on average elevation of +0.3 m MSL (2008 AD) and average SAR of 5 mm yr^{-1} in the study estuaries. Estuary-average intertidal platform elevations ranged from -0.14 to 0.59 m MSL.

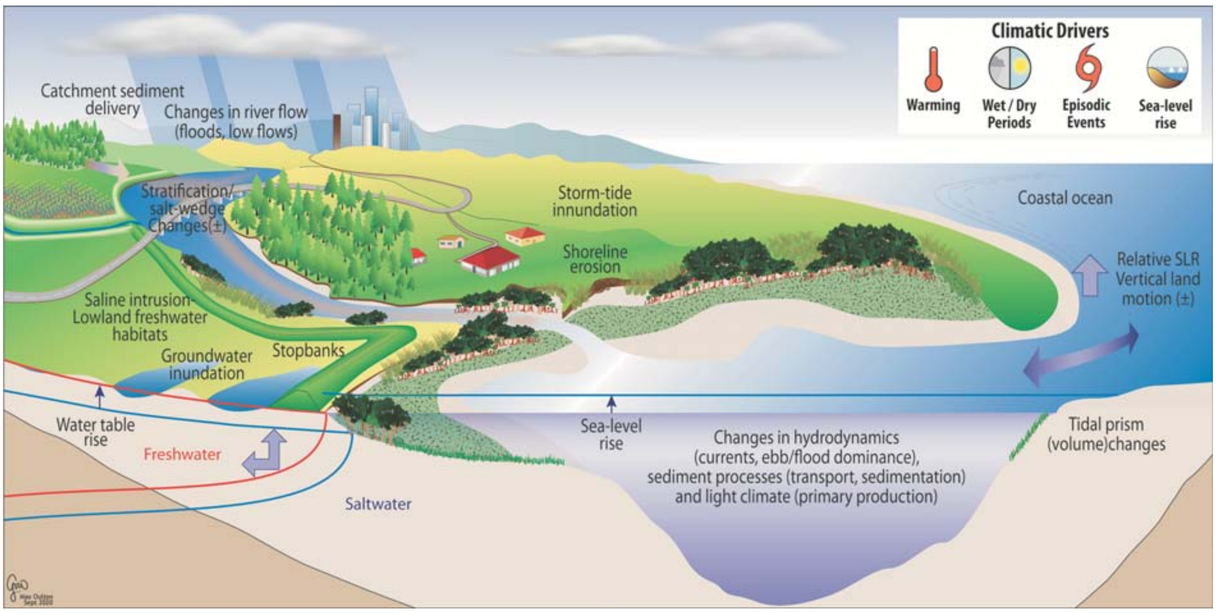

Figure 5: Potential effects of climate change and sea level rise in estuaries.

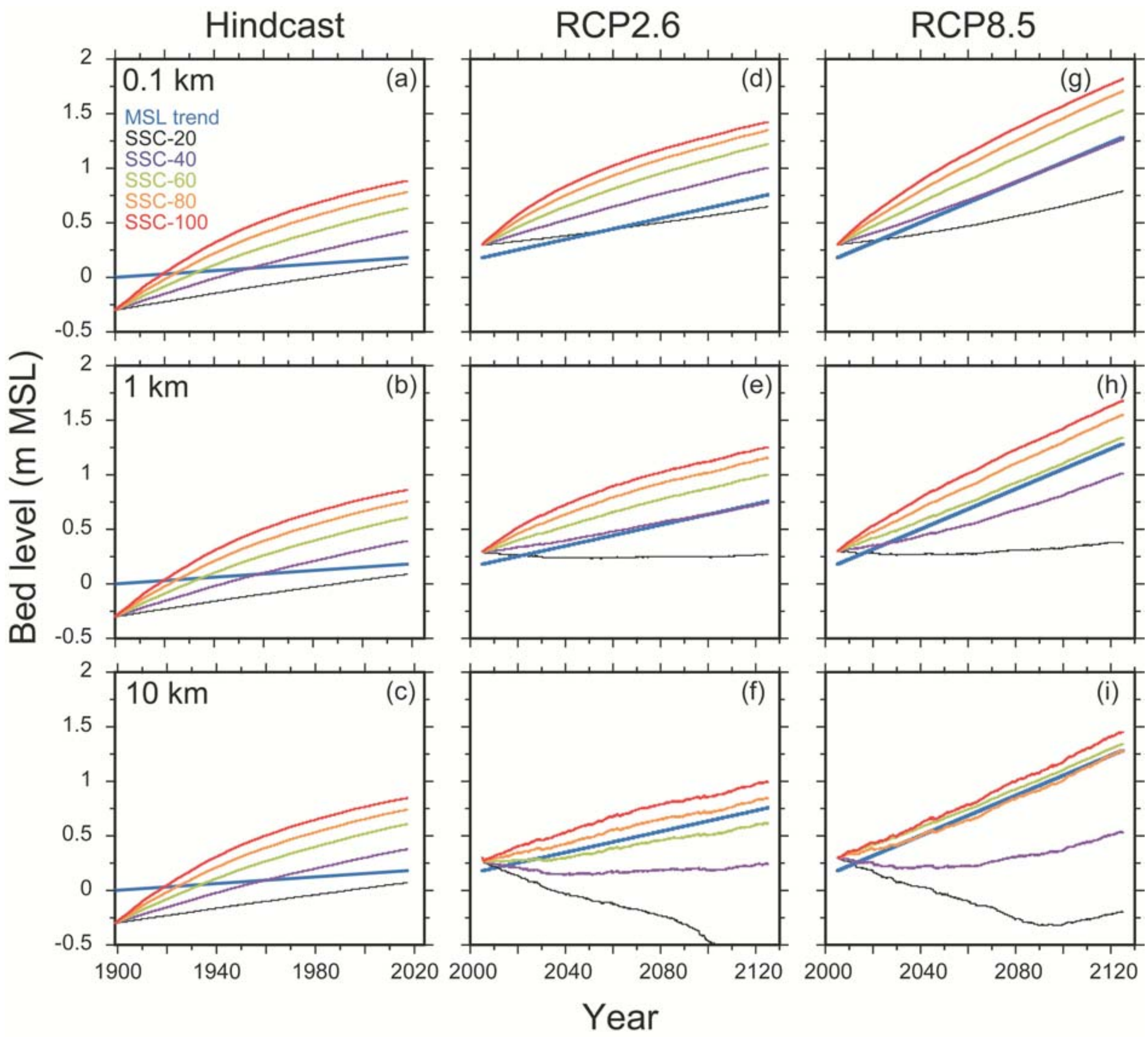

Figure 6: Zero-dimensional (0-D) model simulations of intertidal flat evolution for Auckland's east-coast estuaries for a range of time-average suspended sediment concentrations (SSC, mg l^{-1}) and fetch (0.1-10 km, successive rows) for the historical period 1900-2018 (a-c) and future climate-change scenarios (2005-2125, d-i). Bed-level is relative to Auckland Vertical Datum-1946. Future scenarios are based on IPCC (2013) climate and SLR for the Representative Concentration Pathways RCP2.6 (d-f, SLR = 4.8 mm yr^{-1}) and RCP8.5 (g-I, SLR = 9.2 mm yr^{-1}). The MSL trend for the historical period is for the Port of Auckland (1.6 mm yr^{-1}, 1899-2015, Swales et al., 2016). Note: minimum bed level for scenario RCP2.6 with 10 km fetch is -0.57 m MSL. Reproduced with permission (Swales et al., 2020).

Loss of intertidal flats could begin as early as the 2020s if rates of RSLR exceed ~5 mm yr^{-1} and where sediment supply is limited. Catchment sediment supply to these largest estuaries would need to be two-fold higher than historical rates (~40 mg l^{-1}) that sustained the vertical accretion of intertidal flats during the 20th century (see Figure 6f). Sediment-poor estuarine systems, such as coastal embayments with small land catchments (see Figure 3), are likely to be most susceptible to loss of intertidal flat habitats.

These results are generally consistent with previous modelling studies, with intertidal flats replaced by subtidal habitats at higher rates of SLR. Sediment supply rates are critical to maintenance of intertidal flats and coastal wetlands, with a transition from stable to unstable systems likely to occur at higher rates of SLR (5-10 mm yr^{-1} for systems with limited sediment inputs (e.g. Kirwan and Murray, 2007; Kakeh et al., 2016)). Large estuaries are more susceptible to loss of intertidal flats due to insufficient sediment supply (Leuven et al., 2019).

Legacy sediment

Legacy sediments* have played a formative role in the biogeomorphic evolution of New Zealand's estuaries over the last ~150 years. The development of intertidal habitats, including rapid expansion of mangrove forests in our northern estuaries, has followed historical pulses of legacy sediment delivery associated with catchment deforestation, agriculture, and land use intensification (Morrisey et al., 2010). Catchment sediment delivery to many New Zealand estuaries following the historical peak approximately a century ago have been sufficient to maintain intertidal habitats (e.g. Figure 6). It is also likely that flood-defence stop banks in the lower reaches of rivers has enhanced sediment delivery to estuaries by reducing the frequency of over-bank flood flows and associated sediment deposition on floodplains.

* Accelerated deposition of sediments in estuaries from human activities over the historic period (usually post-European development).

The potential role of legacy sediment stored in estuaries, as well as contemporary river inputs, in maintaining intertidal habitats as SLR accelerates is not well understood. Legacy sediment in the Firth of Thames has sustained rapid accretion of intertidal flats and triggered mangrove colonisation in the early 1960s (Swales et al., 2015) despite a rapid rate of RSLR (~10 mm yr^{-1}, Swales et al., 2016). This RSLR is similar to what is anticipated to occur in many New Zealand estuaries by the late 21st century under business-as-usual global emissions scenarios. Coastal wetlands are major sinks for legacy fine sediment and associated stormwater contaminants, however where sediment supply is insufficient to maintain these habitats, there is a risk that this legacy sediment and contaminants will be released, resulting in adverse outcomes for estuarine ecosystems. Paradoxically, improvements in catchment soil conservation associated with limits setting for estuaries could lead to unanticipated negative outcomes – this emphasises the need for holistic/integrated management of catchment-estuary systems.

Estuarine ecosystems

Estuaries are among Earth's most dynamic and productive environments and they play critical roles in ecosystem service provision and represent global hotspots for organic matter processing, nutrient cycling, and primary production. Marshes, mangroves, and seagrass meadows are the most visibly obvious sources of productivity in estuaries. These estuarine plant communities provide essential habitat for birds and fisheries species and can alter current and wave energy, stabilise sediment with root mats and affect drainage patterns, thereby influencing estuary morphology.

In most New Zealand estuaries, emergent salt marsh and mangroves (in the upper North island) are restricted to the upper intertidal zone, with the area of vegetated habitat generally being many times less than that of unvegetated tidal flats. Microphytobenthos, composed of microscopic photosynthetic algae (e.g. diatoms) and bacteria (e.g. cyanophytes), occur in surficial sediment from the upper intertidal to the subtidal zone.

Although emergent vegetation can be highly productive (i.e. per m^2) microphytobenthos likely dominates benthic primary productivity in most of our estuaries due to its vastly greater spatial coverage. This productivity supports a wealth of secondary and tertiary consumers (e.g. molluscs, crustaceans and polychaetes) that feed on fresh sedimentary organic material, and demersal fish and wading birds that feed on the invertebrates. This productivity and the biodiversity it supports contributes to the many ecosystem services recognised and valued by New Zealanders (Thrush et al., 2013; Rullens et al., 2019; PCE 2020).

Although microphytobenthos can thrive at a range of depths, they are likely to be more productive in shallow estuaries. This is because there is more sunlight available for photosynthesis in shallow water, due to the reduction in light with increasing depth in the water column. The rate of light attenuation is largely influenced by suspended sediment concentrations. As a result, the quantity and quality of light reaching the seabed may be insufficient to support benthic primary production, thereby excluding sea grasses and microphytobenthos from subtidal habitats.

Intertidal habitats uncover and receive direct unattenuated sunlight at low tide (even if turbidity limits productivity while submerged). The importance of low tide primary production in turbid estuaries (Drylie et al., 2018) and the potential for SLR-related losses of intertidal habitat to impact ecosystem function (Mangan et al., 2020) is now recognised. Thus, gradual increases in sea level and resulting increase in mean water depth and/or reduction in intertidal habitat have the potential to exacerbate reductions in estuarine productivity. This is one of the lesser recognised threats of SLR, including to ecosystem services.

The role of microphytobenthic productivity is not limited to underpinning estuarine foodwebs (Hope et al., 2019; Thrush et al., 2012). For example, microphytobenthos oxygenate surface sediment, which accelerates the organic matter degradation and affects subsequent transformations of the remineralised products (e.g. conversion of ammonium to nitrate). Pratt et al. (2014) showed how reductions in benthic primary production resulted in less efficient trapping of ammonium (NH_4^+) and thus greater effluxes of ammonium from the sediment to the overlying water. This suggests that the problem of nutrient overloading into estuaries may be exacerbated if coupled with inputs of suspended sediment. Reduced microphytobenthic primary productivity with SLR could have similar indirect effects and alter the outcomes of multiple stressor interactions.

Overall, SLR has the potential to affect multiple estuarine ecosystem components directly and indirectly, which makes predicting the future ecological status of New Zealand estuaries difficult (O'Meara et al., 2017). Research at large spatial scales and that incorporates the potential for multiple interacting stressors, including SLR, is urgently needed.

Management strategies

There is certainty that by the 2050s, SLR in New Zealand will lie in a narrow range of 0.2-0.3 m. Towards the end of this century and beyond, SLR projections are subject to widening or deep uncertainty (MfE, 2017). This uncertainty arises mostly from the uncertain rate at which global emissions can be reduced and the spectre of runaway polar ice-sheet instabilities once a tipping point is reached (see 'Future sea level rise around NZ's dynamic coastline', p11). Further, MSL will continue rising for centuries, albeit at a rate tied intricately to global mitigation efforts to reduce emissions. This presents a challenge now to planners and decision-makers, as the New Zealand Coastal Policy Statement (NZCPS, 2010), requires a planning timeframe for considering climate change effects out to 'at least 100 years' (i.e. to at least 2120 and beyond) for our coastal environments that includes estuaries, marshes, brackish wetlands, and their margins.

Estuaries also exhibit uncertainties from compounding impacts of VLM (i.e. RSLR), groundwater rise, increasing rainfall intensities and changes in river flow regimes (baseflow and flood intensity/frequency). Consequently, planning and management of existing and new land use (including settlements, cultural sites and the built environment) around estuaries must explicitly tackle deep uncertainty. This must be purposely framed for an ongoing changing risk environment, rather than persist with conventional 'predict-and-act' or 'hold-the-line' management paradigms. Adaptive decision-making approaches specifically address the deep uncertainty, through methods such as Dynamic Adaptive Pathways Planning (DAPP) and Robust Decision Making (Marchau et al., 2019). Second guessing the future (e.g. selecting a best- or most-likely estimate, or 'worst case' through a single- or once-only investment perspective) invariably results in inflexible options or actions that are difficult to unravel if there are surprises either way (e.g. if RSLR is faster or slower than the selected case). Rather, adaptive approaches such as DAPP, which is a framework on which New Zealand's national coastal guidance is based (MfE, 2017), encourage stakeholders, communities and iwi/hapū to map out a range of alternative pathways for adapting to climate change and RSLR. These alternative pathways, which keep options open until the next local adaptation threshold is nearing, comprise a mix of short-term actions and/or longer-term options that meet specific objectives or levels of service for flooding, road access or other utility services.

However, a timely response (i.e. not too early/late) to the compound effects on estuaries and adjoining lowland environments of climate drivers and anthropogenic pressures, will require more detailed monitoring on the changing state of these hydrosystems (PCE, 2020). Furthermore, improved monitor and review cycles need to be integrated into an adaptive planning framework like DAPP. This can be achieved with the development of indicators that provide both an early signal of declining performance and triggers, which act as decision points to implement the next option in the suite of pathways set out in the DAPP, allowing for sufficient lead time to implement the next option (Lawrence et al., 2020b). Further research is needed to develop approaches and mechanisms to evaluate the benefits (including blue carbon, that is, carbon dioxide sequestered in coastal and marine habitats by marine plants, such as salt marsh, mangroves, seagrass), ecosystem services and the cost of delaying decisions or interventions. This must be considered in the context of a continually changing environment for implementing adaptation options and pathways that address the four well-beings (i.e. environment, social, cultural, economic). Ongoing decision making on estuaries and their land margins, where compound flooding from both ends and coastal squeeze or narrowing of intertidal habitats, presents an increasingly contested space around safeguarding natural resources and/or adaptation of the built environment and communities. Leo et al. (2019) identified mechanisms and enabling conditions to accommodate migration of intertidal/wetland habitats through a range of financial, policy, planning and on-the-ground management tools. These tools can be implemented or modified to enable inland habitat migration to reduce coastal squeeze.

Given that RSLR will continue for centuries and estuarine areas are by definition low-lying, it will be inevitable that communities and infrastructure in many parts of Aotearoa-New Zealand will need to consider and sequentially plan for managed retreat (Lawrence et al., 2020a). Part of that long-term adaptive planning will also need to consider re-purposing the land-use around the margins of estuaries after retreat of the built environment. This includes implementation of managed realignment of the shoreline if coastal defences or stopbanks are present, taking in the lessons and the need for scale from projects undertaken in the UK (Esteves, 2013; Kiesel et al., 2020).

Conclusions

New Zealand's sediment-infilled estuaries are now increasingly facing the compounding impacts of SLR, storm surge, catchment flooding, groundwater rise, drainage issues, and coastal squeeze/narrowing. Intertidal flats and coastal wetlands will evolve with local conditions (e.g. RSLR, sediment supply) as estuary morphology strives to achieve a new equilibrium. However, this will be in the context of ongoing changing climate drivers and a MSL that continues rising for several centuries at an uncertain rate that is substantially higher than during the recent geological timescale when these estuaries were formed (Holocene). As the PCE (2020) rightly identifies, climate change impacts, including the unavoidable prospect of accelerating SLR, will magnify the issues and pressures already facing New Zealand's estuaries. Adaptive decision-making approaches, which specifically address deep uncertainty in future RSLR (e.g. DAPP), are now embedded in the national coastal guidance (MfE, 2017) and provide opportunities to make robust and informed management decisions. Given that RSLR will continue for centuries and estuarine areas are invariably low-lying, it will be inevitable that communities and infrastructure in many parts of Aotearoa-New Zealand will need to consider and sequentially plan for managed retreat, and re-purpose to alternative land uses. New Zealand has much of the know-how and adaptive frameworks needed to transform the way we manage estuaries. But the pressing needs are the improved coupling of research capacity with local government, matauranga Māori and communities to achieve sustainable and durable inter-generational outcomes.

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Conclusions

Lucy Brake

Rākauroa/Torrent Bay (Photo: Eric Verstappen).

Managing Aotearoa New Zealand's coastal environment in regards to sea level rise (SLR) is a complex undertaking. Through the eight chapters of this Special Publication we have taken a look at the science behind how these different coastal environments and systems operate, how they will likely respond to SLR, and what needs to be considered as we progress our thinking in terms of research, planning, engineering and management.

The overarching chapter on *Mātauranga Māori and its role in coastal management* highlights the origins, nature, breadth and depth of mātauranga Māori and the value it brings to everyone involved in managing the coastal environment. Dan Hikuroa discusses its value as a repository of takutai information and considers the importance of both the broad understandings, as well as the specificity in maramataka and taniwha. He concludes by highlighting how, 'similar to an Earth Systems view, kaitiakitanga seeks to work with the environment, not command and control it, by managing our relationships with the environment and what we do in the takutai' and outlines the importance of weaving mātauranga Māori with science to ultimately yield 'significant mutual benefits to Aotearoa New Zealand'.

By exploring the role of the NZ SeaRise Programme through the chapter Te tai pari o Aotearoa – Future sea level rise around New Zealand's dynamic coastline, a team of experts discuss how different regional scenarios for SLR can help support planning and monitoring of responses to help with local adaptation. They point out that to empower communities and decision makers to identify pathways to adapt to SLR, 'there is a need to present SLR information so it can be used by communities as they work to establish adaptation plans'. They conclude their review by observing that researchers within the NZ SeaRise Programme are developing a toolkit which will 'provide access to scientific evidence that will help agencies, business, and communities to understand the SLR hazard and will inform risk and vulnerability assessments.' The NZ SeaRise Programme is an important part of progress towards this for local communities.

Models of SLR responses provide important information for managers, planners and communities to make informed decisions. Through their review a team of scientists note that the task of modelling and predicting the coastline response to SLR is 'a formidable challenge and the sources of uncertainty are large in every step of the modelling process'. They outline in the *Modelling coastal evolution for rising sea levels* chapter the many significant obstacles facing the development of models, including limited information, validity of data, choosing the right model, and interpreting results. However, there are glimmers of hope, including being able to address some of the uncertainties, developing new methodologies to extract data using remote sensing, being in a position to incorporate future wave climate to allow for statistical analysis, and by increasing the availability of projections of wave and storm surge data. They conclude by observing that these new methodologies provide 'more robust and reliable predictions of shoreline change' which could 'entirely alter the way' to approach the study of SLR effects.

In the chapter on *The response of sandy coastal systems to changes associated with sea level rise*, Karin Bryan and Giovanni Coco explore the anticipated impacts of SLR on sandy beaches in more detail, differentiating between the effects for which we have both greater and diminished certainty. They point out that there are many uncertainties to future erosion trends and that different models show different impacts based on changes in sediment supply and increased storminess. They also note the rise in human pressures and the demand to protect the sandy beaches around New Zealand. In conclusion they discuss how, whilst climate change is predicted to cause some of the most dramatic changes at the coast, it is important to remember that 'the direct anthropogenic signature (seawalls, dredging, groins) might overwhelm any of the indirect climate-related changes that might occur to our environment'.

There is limited information about the impacts of SLR on gravel beach processes, so various existing geometric models that have been developed, or could be used, for gravel beaches are evaluated by Derek Todd and Kate MacDonald in their chapter on *Estimating the erosional effects of sea level rise on gravel beaches: Case study of the Canterbury coast*. They show that existing models of gravel beach response to SLR accounting for only beach rollover 'most probably underestimate retreat distances, while those developed from limited relationships of barrier inertia to retreat considerably overestimate SLR effects'. Through this study they trial modified methods, which they consider 'better incorporate some of these process responses, and therefore the results are likely to be more representative of future responses to SLR in these environments'. They emphasise that in order to provide more accurate and informed shoreline projections, further refinement and testing is needed to ultimately support future decision making about SLR impacts on gravel beaches.

In the chapter on *Coastal cliff erosion in Aotearoa New Zealand and the potential impacts of sea level rise*, Mark Dickson and Catriona Thompson explain that there have been important advances in measurement techniques that will significantly assist efforts to unravel relationships between SLR and cliff erosion rates. This chapter focuses on describing processes 'related to SLR that influence cliff-toe erosion, which can subsequently promote slope failure', and to provide coastal practitioners with a broad overview of the possible effects of SLR on cliff erosion. They reveal it is likely that 'recent acceleration in global SLR is yet to have had sufficient time to manifest as an increase in cliff erosion rate'. They share some of the recent developments in analysis and techniques to understand more about the relationships between sea level change and cliff retreat. One of the fundamental research challenges to overcome is the 'temporal disconnect between the processes that contribute to erosion, including SLR and wave energy delivery, and physical observations of erosion'. Finally, the chapter offers an example of cliff erosion planning to help show a way that coastal managers can 'respond to efforts to manage cliff erosion under SLR amid these uncertainties'.

The authors of the *Coastal hydrosystem responses to sea level rise* use a 'physical process lens' to discuss the potential responses of different coastal hydrosystem types to our changing climate and rising sea levels, including a range of coastal management implications. Terry Hume and Deirdre Hart explore how 'climate changes and SLR have the potential to alter the primary drivers of coastal hydrosystem processes, namely fluvial inputs, tidal and wave processes, and to a lesser extent rainfall and longshore sediment transport'. They also emphasise that resultant responses in these interface systems will be 'small or large depending on the degree to which their driver balance is altered, as well as in relation to the nature of direct and indirect human responses'. In conclusion, they note that catchment and coastal management practices can strongly influence responses across all coastal hydrosystem types, and how in many cases 'these have greater consequences for coastal hydrosystems than climate changes and SLR effects combined'. They also point out that 'few New Zealand coastal hydrosystems are currently subject to robust monitoring and adaptive management regimes and further research is needed to improve management outcomes'. From their perspective, a significant shift is needed in regional and national approaches to managing coasts and catchments that connect to coastal hydrosystems.

The final chapter on *Estuaries and lowland brackish habitats* describes how New Zealand's sediment-infilled estuaries are now increasingly facing the compounding impacts of SLR, storm surge, catchment flooding, groundwater rise, drainage issues and coastal squeeze/narrowing. Andrew Swales and Rob Bell draw attention to how the Parliamentary Commissioner for the Environment 'rightly identifies, climate-change impacts, including the unavoidable prospect of accelerating SLR, will magnify the issues and pressures already facing New Zealand's estuaries'. They note that it will be inevitable that communities and infrastructure in many parts of New Zealand will 'need to consider and sequentially plan for managed retreat, and re-purpose to alternative land uses'.

Central government, councils and communities need clear and informed science and data on a broader scale to support decision making about the future with sea level rise. There will always be uncertainty, but improved knowledge and a wider understanding of coastal systems response to sea level rise is needed to foster the linkages between scientists, local government, Māori and communities, and to collectively map out a pathway towards the sustainable inter-generational outcomes.

This Special Publication provides a key part of this jigsaw about coastal systems and sea level rise, and what to look for in the future.

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This publication is the fourth in the NZCS Special Publication series. The previous titles are listed below and all are available from the NZCS website (www.coastalsociety.org.nz).

- *Rena: Lessons learnt* (2014)
- *Adapting to the consequences of climate change* (2016)
- *Shaky shores: Coastal impacts & responses to the 2016 Kaikōura earthquakes* (2018).

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