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A Sea Change is Needed

For Adapting to Sea-Level Rise in Aotearoa New Zealand

Abstract

Sea-level rise is accelerating globally and will continue for centuries under all shared socio-economic pathways. Although sea-level rise is a global issue, its impacts manifest heterogeneously at the local scale, with some coastal communities and infrastructure considerably more vulnerable than others. Aotearoa New Zealand is poorly prepared to deal with sea-level rise impacts, and some places are already approaching the limits of adaptation, short of relocation. Maladaptive choices threaten Aotearoa's ongoing ability to adapt going forward. Development of climate-resilient pathways requires an immediate adoption of non-partisan, long-term, system-scale approaches to governance and decision making (from local to national), that integrate effective adaptation and emissions mitigation. This also requires proactive and collective action underpinned by indigenous and actionable knowledge (e.g., NZ SeaRise projections) designed for our unique circumstances. There is still time to put in place sustainable, equitable and effective solutions, but funding and governance models need urgent attention.

Keywords sea-level rise, impacts, risks, just and effective adaptation, te ao Māori, indigenous knowledge, community values, actionable knowledge, uncertainty, decision making, governance, adaptive pathways, climate-resilient pathways

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The increased occurrence of deadly, damaging and costly climate-related natural disasters around the motu has our public and decision makers on notice (see NIWA, n.d.). For our coastal communities, concerns were further heightened when the NZ SeaRise programme projected the impacts of sea-level rise arriving earlier than previously thought (Levy et al., 2024; Naish et al., 2024). While lowering greenhouse gas emissions will help reduce the warming driving these events, it will not eliminate the impacts. A recent assessment of progress towards the National Adaptation Plan (Ministry for the Environment, 2022) by the Climate Change Commission shows that effective adaptation to current and future impacts is not happening on the scale, or at the pace, that is needed (Climate Change Commission, 2024). Following a parliamentary inquiry into adaptation in 2024, the government's Finance and Expenditure Committee has made a range of recommendations to strengthen climate adaptation in Aotearoa (Finance and Expenditure Committee, 2024). These focus on objectives, principles and system change for climate change adaptation and will inform the development of an adaptation framework and supporting legislation.

Here, we review some of the challenges of adapting to climate change in Aotearoa that are relevant to the impacts and risks from sea-level rise and the design and implementation of a national adaptation

BOX 1 Key policy relevant messages

Latest adaptation science and implications

- Sea-level rise is accelerating globally including around Aotearoa New Zealand and will continue for centuries under all emission scenarios. However, decisions made today can impact the timing and the scale of impacts arising from SLR, with significant consequences for centuries to come.
- SLR increases the frequency of flooding on existing communities and infrastructure manifesting in multiple hazards, including storm surges, coastal flooding and erosion which compound with rising groundwater, and saltwater intrusion into soils, aquifers and lowland rivers.
- Deep reduction in greenhouse gas emissions, in line with the Paris Agreement target of 1.5°C, is critical to avoid crossing tipping points that would yield rapid and irreversible SLR with multi-generational consequences.
- While it now seems inevitable warming will exceed 1.5°C, effective adaptation still requires sustained commitment to stabilisation of warming as close to the Paris target as possible.
- Even meeting the Paris Agreement target, 0.4-0.5m of average global SLR by the end of the century is unavoidable due to the heat already baked into the land ice and oceans. It is estimated that this amount of SLR will impact 1 billion people globally by the end of the 21st century.
- Impacts of SLR will further entrench environmental and climate injustice at all levels of global society. In Aotearoa, Māori experiences of SLR intersect with the ongoing settler colonial imposition and understanding the breadth of these impacts requires analysis through conceptual frameworks like environmental and climate justice.
- Compounding and cascading climate change impacts are increasingly being felt globally and in Aotearoa, and these are destined to intensify.

Local context matters for assessing coastal risk

- Although SLR is a global issue, it impacts differently on different communities, with some considerably more vulnerable than others. Responses to SLR need to be integrative and context-specific; there are no one-size fits-all solutions or panaceas.
- Anticipating the impacts of SLR for tectonically active regions such as Aotearoa requires knowledge of vertical land movement (VLM). Forty percent of our coastline is subsiding (sinking) at rates greater than 2 mm/year, which makes a significant contribution to localised SLR projections, bringing forward adaptation decision thresholds by decades.
- With just 0.3-0.4m of relative SLR above the 2005 baseline, the historic 1 in 100-year extreme coastal flood will occur annually, on average, around Aotearoa's coastline. Nuisance flooding will fast become chronic flooding. This important decision-making threshold (eg., with respect to planned relocation) may be reached as early as 2040 in some parts of Aotearoa where the coast is subsiding rapidly (eg., Wellington/Lower Hutt).
- The national *Coastal Hazards and Climate Change Guidance* (MfE, 2024) presents updated sea-level projections that incorporate the latest Intergovernmental Panel on Climate Change sea-level scenarios (IPCC, 2021), together with localised rates of VLM around the coast to provide local relative SLR estimates every 2 km (https://www.searise.nz/maps-2). This information is critical for planning and implementing hazard and risk assessments, as well as adaptation approaches locally along our complex and dynamic coastal environments.

Dealing with uncertainty in coastal risk assessment

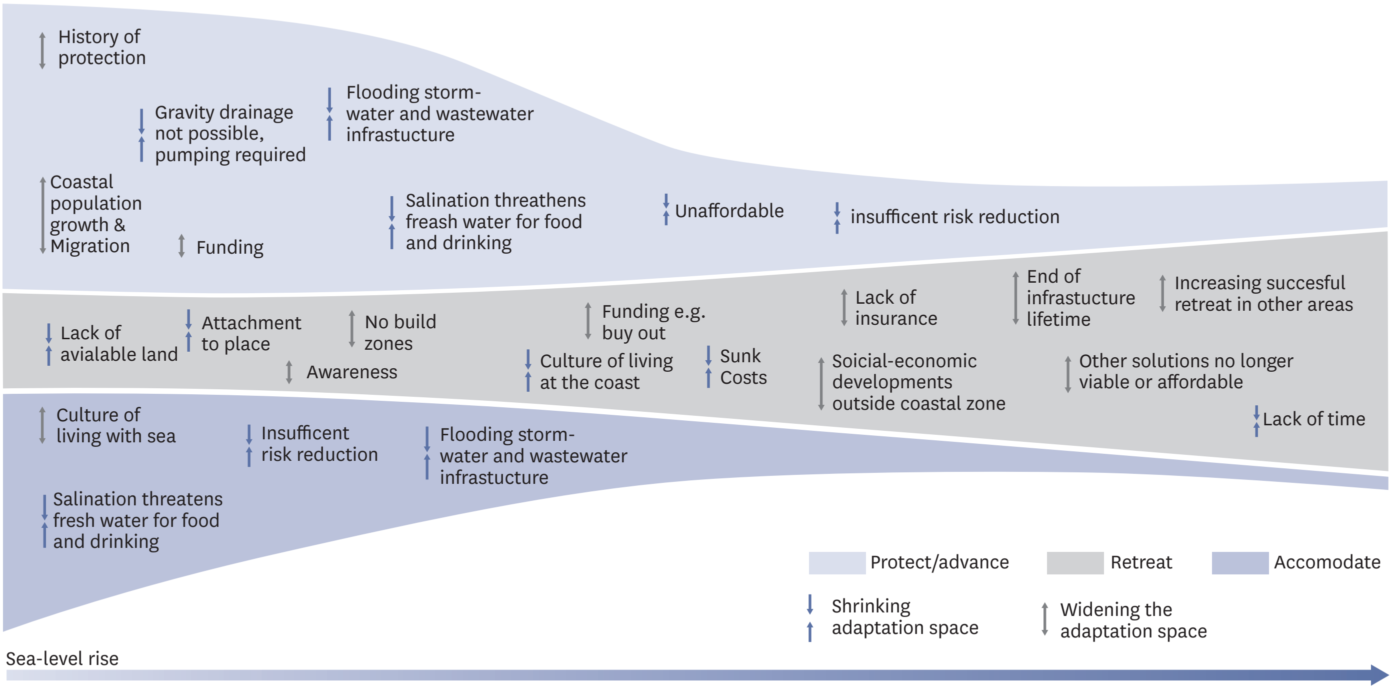
- Due to the potential of non-linear (rapid ice melting) processes, tipping point behaviour and irreversible loss of ice sheets and glaciers, coastal risk assessments and management plans should include a high-end sea-level projection (2m by 2150) that allows for stress-testing the impacts and implications from High Impact Low Likelihood (HILL) events.
- Further, due to uncertain future emissions pathways beyond 2060, and the inherent uncertainties, a dynamic adaptive pathways planning (DAPP) approach should be used. This combined with enhanced local monitoring of signals and triggers will enable adjustments to adaptation strategies as new information emerges, and in time for decisions to be made that avoid maladaptation.

Actionable knowledge for a climate resilient future

- Achieving climate resilient pathways for coastal infrastructure and communities in Aotearoa requires long-term, system-scale approaches to governance and decision making (from local to national), that integrate effective adaptation and GHG emissions mitigation to advance sustainable development. Inclusive approaches to decision-making should be prioritised. This will require additional support for most vulnerable regions, sectors and communities.
- Some parts of the coast around Aotearoa are approaching the limits of adaptation, short of relocation. Actionable knowledge, such as the NZ Sea Rise projections, along with cultural knowledge, and community values in assessments of risk, can inform proactive, collective systems-scale action. There is still time to put in place sustainable, equitable and effective solutions, if there is the political will and foresight to do so.
- Aotearoa New Zealand's, interdisciplinary and transdisciplinary research communities stand ready to provide actionable knowledge that is aligned with te ao Māori and te Tiriti o Waitangi and is crucial to successful decision- and policy-making on mitigation, adaptation, finance, and resilience related to relative SLR.
- There is a critical need for a National Climate Adaptation Research Platform to be funded. A well-supported platform would facilitate system-wide dialogue between policymakers, social scientists and physical scientists, and Indigenous and local communities, on evidence-based policy options, and community aspirations in ways that can anticipate and manage future risks.
- A well-designed Climate Adaptation Act or equivalent legislation is urgently needed, one that mandates the required governance arrangements, policy tools, planning mechanisms, public institutions, and funding instruments.

Figure 1: An illustrative example of adaptation options in an evolving and shrinking adaptation space

Different drivers and hard and soft limits shape this space. The figure highlights: 1) a narrowing of the adaptation space as a whole, and 2) a change in the ratio between the three adaptation strategies, with retreat becoming dominant. This will apply differently for different coastal types due to local contexts.



Source: adapted from Haasnoot et al., 2021 and Lawrence and Bell, 2022

framework. We assess the current state of relevant science, summarise the challenges and barriers to effective adaptation, and outline how to formulate and implement equitable, climate-resilient pathways based on inclusive and context-specific actionable knowledge.[1] We make a series of key policy-relevant statements and recommendations that are summarised in Box 1.

The coastal adaptation challenge

Coasts pose a special case for adaptation due to the progressive and changing risks from sea-level rise, which impact on our communities and ecosystems both through permanent inundation of the lowest-lying areas and by increasing the frequency of flooding affecting the wider coastal environment. Risks will emerge earlier where local rates of relative sea-level rise are higher (due to land subsidence) and will be larger if 'high impact low likelihood' (HILL) processes associated with collapsing polar ice sheets occur (Sherwood et al., 2024). There is already committed sea-level rise that will eventuate due to the heat stored in the oceans, polar ice sheets and glaciers from past anthropogenic greenhouse gas emissions. Coastal hazards and their impacts are occurring in Aotearoa, and their near-term risks are projected to escalate well before 2050 (Stephens, Bell and Lawrence, 2018; Naish et al., 2024). Our ability to anticipate and adapt to sea-level rise and curtail its acceleration beyond 2050 will determine how we cope with increasing coastal risks. But this ability depends on access to context-specific risk information and strategies tailored to Aotearoa's unique environmental, cultural and social setting, together with near-term and ongoing commitment to emissions mitigation so as to avoid maladaptive decisions that lock Aotearoa into unsustainable pathways.

A survey about understanding of sea-level rise showed that publics in Aotearoa 'are aware of, and concerned about, 21st century sea-level rise' and recommended that public engagement efforts are 'more focused and nuanced than raising awareness of the issue' (Priestley, Heine and Milfont, 2021). The publication of relative sea-level rise projections for every 2km of the Aotearoa coastline (Levy et al., 2024; Naish et al., 2024) allows for location-specific communication about necessary adaptation and the available adaptation options. Choice of messages and communication channels, though, needs to take into account the rise of mis- and disinformation about climate change (Clark and Stoakes, 2023) and recent research that shows high levels of consistent news avoidance in Aotearoa (Beattie, Kerr and Arnold, 2024). Ensuring that local communities are aware of local impacts, and engaging them in decision making, is vital to the success of effective and equitable adaptation and needs to be appropriately resourced and prioritised.

There are hard limits to adaptation in the face of progressive sea-level rise, because sea-level rise may become irreversible this century and will become an existential threat for many communities and ecosystems. Inundation threatens habitability and sovereignty for some small island developing states, and some communities, such as Tuvalu and Fiji, are already implementing relocation or managed retreat from the coast or exploring new visions of a digital community (Rothe et al., 2024). Many parts of the low-lying coastal margins around Aotearoa will require the staging of managed retreat in the coming decades. Planning for this will need to occur before the limits to adaptation are surpassed even for low to moderate levels of relative sea-level rise. Adaptations such as nature-based solutions, those that accommodate the risk (e.g., raising floor levels or filling land), and engineering protection against higher levels will become ineffective or unaffordable. Forearmed with actionable risk information, planned relocation/managed retreat can mitigate the inevitable and rising risk of flooding in low-lying areas (Lawrence and Bell, 2022). Figure 1 illustrates this as an expanding, shrinking and evolving adaptation space for different types of options or actions as sea level continues to rise (Haasnoot, Lawrence and Magnan, 2021).

Investment in adaptations that have limited life, and 'lock-in' of permanent buildings and infrastructure, increases the future risk by making the transition harder and more costly as sea-level rise continues. That said, temporary adaptation options, such as nature-based solutions restoring mangrove and coastal wetland buffer zones and accommodating limited sea-level rise, can buy time to implement longer-term sustainable options such as the phased transition to managed retreat. On the other hand, expensive options such as seawalls, reclaiming land and raising floor levels entrench unsustainable development, and can provide a false sense of security, that when breached or overwhelmed ultimately makes the transition to managed retreat more costly for current and future generations.

Without considering a phased long-term adaptation approach, including for at least the next 100 years (as required by the New Zealand Coastal Policy Statement), communities are increasingly confronted with a shrinking adaptation space (see Figure 1), and adverse consequences will be disproportionately borne by indigenous and marginalised communities.

Implications for Māori

Māori experiences of climate change intersect with ongoing experiences arising from settler colonialism (Johnson et al., 2022). Two centuries of dispossession from lands and waters, oppression of cultural norms and traditions, marginalisation within hegemonic political and economic systems, and forced participation in ill-suited retributive processes have left Māori particularly vulnerable. Estimates suggest that 30–50% of marae across the motu are likely to be significantly affected by climate change and 41 marae across Aotearoa are currently at potential risk of a 100-year flooding event based on estimated sea-level rise by 2200 (Bailey-Winiata et al., 2024). Te Puni Kōkiri (2023) estimates that 14% of Māori households are in areas

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highly susceptible to coastal inundation due to projected sea-level rise. Climate change also affects Māori in unique ways, including loss of taonga species and the practice of mahinga kai, and the disproportionate area of their whenua (land) that is in vulnerable locations.

Environmental Justice is an instructive conceptual framework through which we can more fully appreciate the intersectionality of climate change and settler colonialism for Māori. Grear and Dehm (2020), for example, frame environmental justice to include: distributive patterns and structural unevenness; procedural justice and relational recognition; identifiable wrongs and corrective and retributive reparations; interrogating the sociopolitical; and ontological justice and the politics of meaning. Such frameworks can help to make explicit the injustice that remains unaddressed when hapū and iwi are simply 'consulted' or 'engaged' in climate initiatives and adaptation planning. Just (as in justice) and effective climate adaptation planning approaches must engage with historical injustices experienced by Māori. Local and culturally appropriate environmental justice applications exist (e.g., Parsons et al., 2021; Bargh and Tapsell, 2021) to support progress towards just (or tika) climate adaptation approaches.

Mātauranga Māori (the Māori knowledge tradition) has a rich history of adaptation in close association with the lands and waters of Aotearoa throughout many geological, ecological, cultural and climatic shifts. That means that Māori whānau, hapū and iwi hold deep repositories of information within their oral and visual traditions that may illustrate those changes through time, and also illuminate effective adaptation strategies for such shifts. These repositories of information are complemented by knowledge processes (such as waiata, whakairo and much more) inherent to mātauranga Māori that mobilise knowledge. Such knowledge processes provide an alternative that may overcome the personal and political inertia that appears common in response to climate change research and knowledge mobilisation approaches. Supporting Māori hapū- and iwi-led climate adaptation initiatives makes good practical sense for effective adaptation for all of Aotearoa.

Despite being disproportionately affected by and vulnerable to climate change, Māori resilience is built upon whakapapa and Māori already demonstrate leadership in climate adaptation and response. The severe weather events of 2023 along the east coast of the North Island saw marae become coordinated response centres after national response efforts were hampered by damaged infrastructure. Whakapapa networks were activated all across the motu to support hapū and iwi communities to rebuild. The Covid-19 pandemic elicited similar leadership from Māori across the country as checkpoints were established to manage movement and ensure our most vulnerable were cared for during the lockdowns (Bargh M. & L. Fitzmaurice, 2021). This resilience is also reflected in the development of climate strategies and plans and on-the-ground action by Māori communities at hapū and iwi scales (Stephenson et al., 2024).

The New Zealand government is being held to account for their inaction in a claim before the Waitangi Tribunal, on behalf of all Māori, that the government is in breach of the Treaty of Waitangi by failing to implement adequate policies to address the threats posed by global climate change (Wai 3325) (Ministry for the Environment, n.d.). Again, partnership with and leadership of Māori hapū and iwi at place, all across Aotearoa, is critical for effective climate adaptation, as emphasised by the National Adaptation Plan (Ministry for the Environment, 2022) and by the Expert Working Group on Managed Retreat (2023).

The current policy challenges

A political environment driven by short-term thinking, vested interests, unclear mandates, conventional static approaches such as blunt insurance levers, fixed land-use zones and funding limitations continues to delay effective adaptation to sea-level rise in Aotearoa. Compounding such influences are very strong incentives to house people affordably, often on flood-prone land and low-lying coastal land (where population has historically been and continues to be located), and maintain traditional infrastructure to service them, and a human desire for living by the coast (Lawrence, Allan and Clarke, 2021; Boston, 2024).

Governance structures and institutional arrangements are required that can operate at large scales, for the long term, are non-partisan, and can work as integrated systems. This involves central and local government agencies in partnership with iwi/Māori and with communities, infrastructure providers, and finance and risk management sectors to take into account social and cultural inequities for climate-resilient development of coastal communities in Aotearoa. Effective decision making under uncertain conditions involves judgements based on the aspirations of communities, informed by actionable knowledge, and appraisal of a range of futures and opportunity costs.

The role of actionable knowledge

Enabling a just transition, and effective climate-resilient development, requires inclusive decision-making processes informed by accessible, actionable climate risk data and information. Such knowledge should include mātauranga, and downscaled global and regional drivers, and take into account local factors that may exacerbate the risks. Moreover, there are ongoing deep

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uncertainties in some of the processes driving sea-level rise (e.g., polar ice sheet melting), and uncertain divergent future emissions pathways beyond 2050. A dynamic adaptive pathways planning approach can provide a means of testing adaptation options against a range of plausible futures for their sensitivity to different failure conditions (thresholds), so as to reduce lock-in of unsustainable adaptation (Haasnoot et al., 2024; Craddock-Henry et al., 2023). This approach may also be driven by community values and indigenous knowledge so that decision makers can make judgements on robust adaptation strategies that reduce the worst of the risks while retaining flexibility to adjust as the conditions change (Lawrence et al., 2021; Haasnoot, Lawrence and Magnan, 2021).

Future global mean sea-level rise will be controlled primarily by the thermal expansion of ocean water and mass wasting of land ice from glaciers, ice caps and ice sheets. The latter is now dominating global sea-level rise at an accelerating rate (Fox-Kemper et al., 2021; Hamlington et al., 2020). Aotearoa is one of many countries with extensive coastlines that sit astride an active tectonic plate boundary (others include Japan, Italy, Indonesia, and the western United States). Here, ongoing changes in land surface elevation at the coast can dramatically reduce or increase the rate of sea-level rise. These local changes matter. The magnitude and direction of vertical land movement can change across short distances, resulting in highly variable rates of relative sea-level rise, with different impacts across short sections of coastline. Accurately determining the ongoing rate and pattern of VLM along coastlines significantly improves location-specific (relative sea-level rise) estimates needed for adaptation planning and risk management.

As an example of actionable knowledge, the NZ SeaRise programme has produced relative sea-level rise projections every 2km for the more than 15,000 km of Aotearoa's coastline (Levy et al., 2024; Naish et al., 2024). These projections incorporate the latest regional sea level information from the IPCC (Fox-Kemper et al., 2021; Kopp et al., 2023), but also include highly variable rates of VLM identified from satellite-based observation systems (Hamling et al., 2022). As the public face of NZ SeaRise, a web-based GIS tool with enough versatility to engage public and stakeholder users (www.searise.nz/maps-2) was developed by Auckland-based data management and analytics platform Takiwā. These new projections improve upon the one-size-fits-all approach to sea level projections previously available and have been recommended to local and regional authorities through the national *Coastal Hazards and Climate Change Guidance* (Ministry for the Environment, 2024). The guidance outlines how practitioners should use the relative sea-level rise projections and recommends their use in planning and decision making where coastal subsidence or uplift is greater than 0.5mm/year, as timing of threshold exceedance for coastal flooding can be brought forward (or delayed with uplift) by decades. With just 0.3–0.4m of sea-level rise above the 2005 baseline, the sea levels historically associated with the one-in-100-year extreme coastal flood will occur annually around the coastline of Aotearoa (Paulik et al., 2023). This important decision-making threshold may be reached as early as 2040 in some parts of Aotearoa where

Figure 2a: An example of how vertical land movement (VLM) is illustrated on the NZ SeaRise website tool via data points every 2km around Aotearoa's coast-line, from dark red, representing 9mm/year uplift, with a gradient through pink, white and light blue to dark blue, representing 9mm/year subsidence

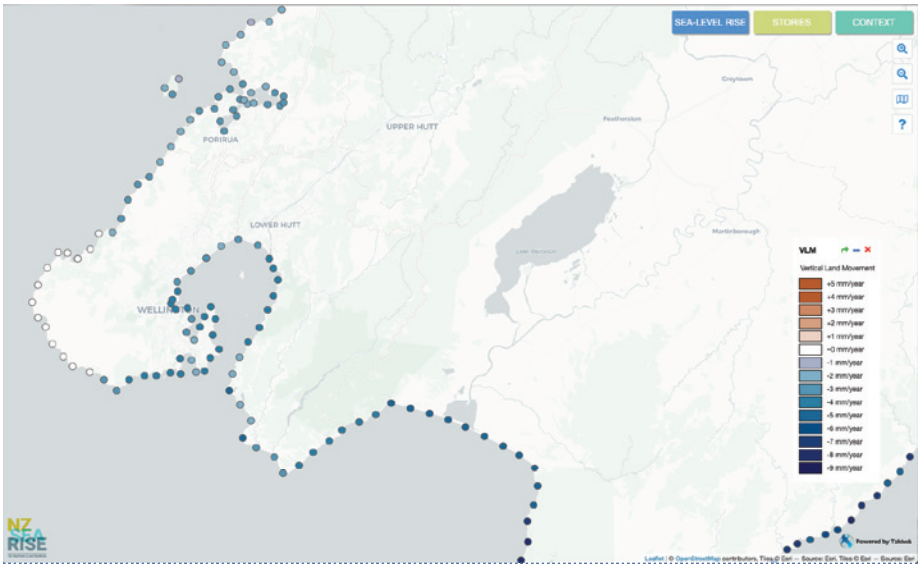


Figure 2b: Sea-level rise projections for a location on the Petone foreshore, Wellington Harbour (site 22494), where the VLM rate is –3.7 ± 0.3mm/year

Occurrences of extreme coastal flooding levels will increase from what used to be a rare 1% AEP (historical one-in-100-year) event of the recent past to become more regularly exceeded. Flooding thresholds (when local flooding occurs annually and monthly) are shown in relation to sea-level rise projections for SSP2-4.5, both with VLM included and without. Inclusion of local subsidence rates brings flood frequency thresholds forward by 20 years.

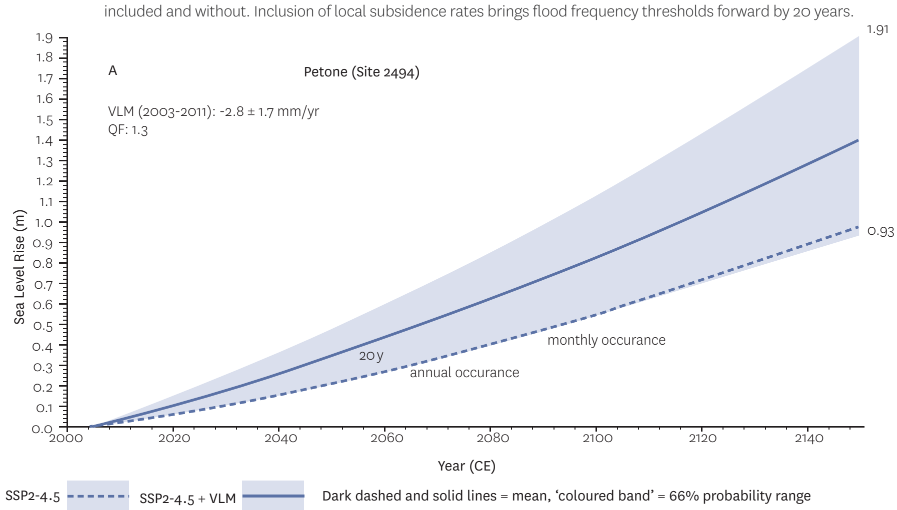
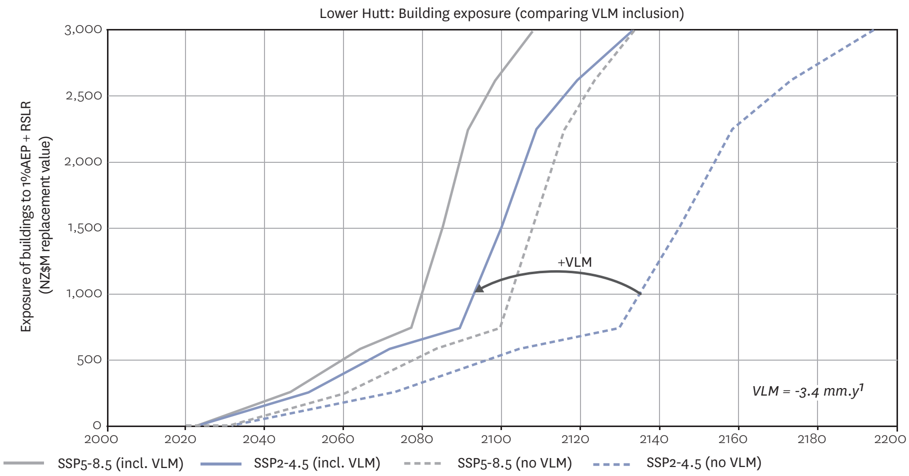


Figure 2c: Building replacement value (2021 NZ$m) exposed to 1% AEP coastal flooding and median sea-level rise projections for SSP2-4.5 and SSP5-8.5, with the solid lines incorporating average VLM rates of –3.4mm/year for Lower Hutt city (north of Petone foreshore)



Source: Paulik et al., 2023; Naish et al., 2024

the coast is subsiding rapidly (e.g., Wellington/Lower Hutt: see Figure 2). Land subsidence also increases the flood-risk exposure of built environments. As shown in Figure 2c, Lower Hutt's high subsidence rate means the SSP2-4.5 projection with VLM overtakes building exposure for the higher-emissions SSP5-8.5 projection without VLM. Here, just 30cm of sea-level rise in low-lying areas is enough to trigger a systems change in storm water services (Kool et al., 2021). This highlights the critical role relative sea-level rise plays in informing adaptation planning locally, compared with only using regional or national downscaled global projections.

Living with uncertainty

Like Aotearoa's dynamic coastline, knowledge is never static, and uncertainties regarding future sea-level rise and its impact will always remain. Not acting in the face of deepening uncertainty involves considerable risk. Instead, uncertainty needs to be accounted for by considering a wide range of plausible future conditions in developing an adaptive planning strategy (Ministry for the Environment, 2024).

Notwithstanding this, there are some certainties in coastal risk assessment. While the pace of change in sea-level rise is uncertain, sea level will continue rising for at least several centuries (Fox-Kemper et al., 2021). This will lock in ongoing sea-level rise on top of an increasing frequency of extreme events that manifests in a variety of hazards, including storm surges, coastal floods and coastal erosion, at the same time as rising groundwater and salt water intrusion into soils, aquifers and lowland rivers and streams. We do know 0.4–0.5m of average global sea-level rise by the end of the century is unavoidable due to the heat already baked into the Earth system combined with the long lag in the response of the ocean and ice sheets to increased heating. It is estimated that this level of sea-level rise will affect 1 billion people globally by the end of the 21st century (IPCC, 2023). We do know that on subsiding coasts sea-level rise will be faster and decision-relevant thresholds will be reached sooner.

Key uncertainties

Climatic surprises

This is especially an issue for the marine margins of the Antarctic ice sheet, where non-linear (rapid melting) processes may drive disintegration of ice shelves and the abrupt, widespread onset of irreversible ice sheet collapse, with a tipping point near +1.5°C of global warming (Armstrong-McKay et al., 2022). The latest IPCC report assessed that these processes were understood with low confidence but included them in a high impact low likelihood (HILL) storyline (projection) in sea-level rise estimates,[2] stating 'that 2 m of SLR by 2100 could not be ruled out', manifesting as 10m by 2300 (Fox-Kemper et al., 2021). The IPCC synthesis report reinforces that ambitious mitigation in line with the Paris Agreement target of 1.5°C is critical to avoid crossing thresholds that would yield rapid and irreversible sea-level rise with multigenerational consequences, and to enable more successful and considered coastal adaptation (IPCC, 2023).

Economists have long noted, for example, that risk is dominated by the upper tail on the probability distribution of climate sensitivity, rather than the central value, due to the highly non-linear increase of damages with warming (Ackerman and Stanton, 2012; Nordhaus, 2011). Consequently, 'stress-testing' to anticipate the potential impact of surprises and unknowns (HILLs) is central to a risk-based adaptation strategy – which the dynamic adaptive pathways planning approach is designed to help deliver. This is especially the case for coastal risk assessments and management plans: as explained above, the response to the climate drivers may be non-linear and deeply uncertain. For this reason, the national *Coastal Hazards and Climate Change Guidance* (Ministry for the Environment, 2024) includes a high-end sea-level rise projection that allows HILL events to be stress-tested using the 83rd percentile of the uncertainty range known as SSP5-8.5 H+.

Unclear future emissions pathways

The IPCC's global sea-level rise projections (Fox-Kemper et al., 2021) are based on new scenarios called shared socio-economic pathways (SSPs: Meinshausen et al., 2020), which include socio-economic assumptions and changes that influence future emissions trajectories. The scenarios span a wide range of plausible societal and climatic futures, from a 1.5°C 'best case' low-emissions scenario (SSP1-1.9) to a more than 4°C warming scenario (SSP5-8.5) by 2100. The lack of action to date on global emissions reductions, and decisions made in the next decade, will largely determine our long-term future emissions pathway, a trajectory that will begin to emerge in the second half of this century. All projections for sea-level rise begin to diverge after 2050, by which time 0.2–0.3m global mean sea-level rise (and similarly for Aotearoa) will have mostly occurred due to heat from past emissions. Beyond this the future is uncertain, with global median sea-level rise projections ranging from 0.44m (SSP1-2.6) to 0.77m (SSP5-8.5) by the end of century, with equivalent median projections of 0.44m and 0.80m for Aotearoa.[3] Adding in deep uncertainty due to Antarctic ice sheet processes (described above) for the high-emissions scenario leads to even higher levels of future sea-level rise and uncertainty. It is not possible to assign likelihoods (probabilities) to a particular sea-level rise projection, which precludes picking a best estimate at this stage (Horton et al., 2018; van de Wal et al., 2022). Therefore, using projections across a range of scenarios to stress-test options using a dynamic adaptive pathways approach avoids a pre-selected estimate of sea level change (and associated impacts) being locked in, and possibly later invalidated.

Vertical land movements may not be linear

We have outlined above that on decision-relevant timeframes (<100 years), and for coastal locations that are subsiding at >0.5mm/y, the government's coastal hazard guidance recommends using relative projections of sea-level rise that include estimates of vertical land movement. However, just like the climatic drivers of sea-level rise, projections of VLM also include uncertainties and require caveats with their use. The NZ SeaRise projections assume linear rates of VLM estimated from relatively short observational time series (global navigation satellite systems (GNSS) and satellite-based synthetic aperture radar interferometry (InSAR)), and do not specifically account for processes that cause non-linear or episodic motion that may occur due to: (a) earthquakes; (b) landslide events; (c) differential subsidence, erosion or sediment deposition and accretion in low-elevation coastal zones such as deltas, wetlands and estuaries; (d) changing rates of sediment compaction where coastal reclamation has occurred; or (e) variations in subsidence rate due to changes in groundwater extraction. The chance of a large-magnitude earthquake causing significant vertical displacement at any given point along the coastline over the next 50–100 years is relatively low due to long recurrence intervals of most of the faults (Gerstenberger et al., 2023; Litchfield et al., 2014; Stirling et al., 2012). Therefore, the measured inter-seismic (between earthquake) rate that drives local VLM on decadal time scales will be the significant contributor to future relative sea level change around Aotearoa, and should be accounted for in sea level projections and

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risk assessments.

For 40% of the coastline (southern Hawke's Bay, Wairarapa, Wellington, Nelson, Marlborough and parts of Auckland), VLM makes a significant contribution to the sea-level rise projection (generally those sites where tectonic VLM is >2mm/y), and the mean trend is significant compared to the uncertainty. Here it is assumed that extrapolation of the VLM rate out to 100 years is valid (in the absence of an earthquake) and the VLM uncertainty is incorporated as part of the full range of uncertainty in the relative sea level projections. These projected uncertainties in local VLM add to those associated with 'climatic' drivers of sea-level rise (in the reported uncertainty ranges) and provide another reason for coastal planners and practitioners to adopt a flexible approach to adaptation (Haasnoot et al., 2013; Hamlington et al., 2020). This approach allows the option to monitor VLM alongside other factors that may trigger the need for a shift in adaptation response. If a significant earthquake eventuates, a pre-existing dynamic adaptive pathways planning strategy for a coastal locality can always be updated, the implementation either delayed if uplift occurs or rapidly actioned for significant co-seismic subsidence.

Compounding and cascading hazards

Sea-level rise compounds with other hazards (e.g., river flooding, landsliding, rising groundwater) and the impacts cascade across communities, local and nationally, and intensify the effects on those groups most vulnerable already. These effects are in part uncertain and may be exacerbated by external climate change effects and other impacts occurring globally, including in the Pacific islands. Further research is needed to unpick which coastal areas and communities are most at risk across Aotearoa from compounding and cascading hazards from sea-level rise, and the measures that can best avoid the worst impacts and manage the movement of people out of harm's way.

Outlook and future prospects

The research community is up to the challenge of assessing this uncertain future, and with adaptation science and dynamic assessment tools can help prepare communities and decision makers in the changing environment at all levels. These challenges include addressing:

- What potential high-impact climate hazards, surprises or irreversible changes should society be genuinely worried about and how can the associated risks be assessed robustly and communicated well?
- How can the priorities, values and aspirations of communities be reconciled with 'safe' pathways to a future climate that are consistent with the global Sustainable Development Goals?
- How can the science community, alongside all communities of interest and iwi Māori, assess risk and inform the calibration of responses in a way that is geographically, socially and culturally aware, and that can be incorporated into a flexible management strategy, and address the risk of compounding and cascading threats?

These questions are interrelated. Answering them will require the climate research community to be funded to work across disciplines to identify risks arising within the entire earth/human system, and to connect with all aspects of society. Engagement with relevant expertise, especially early in project design, can increase the long-term effectiveness of adaptation action. Scenarios will remain the cornerstone of sea-level rise projections. Nevertheless, the climate risk information community is already moving away from traditional approaches that only consider the means and likely ranges of uncertainty (e.g., IPCC reports). This trend is in favour of transdisciplinary risk-oriented frameworks that focus on HILLs, extreme events, progressive and ongoing changes like sea-level rise, and exceedance of planetary boundaries and absolute adaptation thresholds (Rockström et al., 2023; Sherwood et al., 2024).

> Sea-level rise offers one clear opportunity to apply an approach that identifies precursors in the physical environment.

Various stakeholders, academics and iwi Māori have turned to a variety of methods that embody futures thinking. Examples include serious 'games' to simulate hypothetical yet plausible future scenarios (Bontoux et al., 2020; Blackett et al., 2021; Lawrence and Haasnoot, 2017). Gaming exercises alongside scenario planning in simple stakeholder workshops can illuminate the feedbacks and conditions that lead to unexpected outcomes, and help identify trigger points that lead to decisions that can avoid adverse impacts. Other approaches, such as digital futuring in indigenous cultures (Rothe et al., 2024) and community engagement approaches such as used for the South Dunedin Future programme (Climate Change Commission, 2024) and the Thames Coromandel Shoreline Management Pathways project (Thames Coromandel District Council, 2022), have been used in low-lying coastal areas. Such approaches involving community and sectoral experts throw light on the issues and timing for different adaptation actions in the decision-making process. A successful approach must include scientific experts, stakeholders, industry partners, indigenous and community groups and policymakers to include input on geopolitical, societal, cultural, technological, economic and sustainable advances in knowledge. The results of these exercises can inform new and nimble scenarios for climate modelling efforts, for assessments using dynamic adaptive pathways planning, development of international and local policies, and communication of climate risks.

Sherwood et al. (2024) propose that such an approach requires the identification of signposts, or sentinels of change (Hermans et al., 2017; Haasnoot, van 't Klooster and van Alphen, 2018), that would foreshadow the need to alter a regional planning pathway, particularly when exceedance of a relevant threshold in some global process essentially rules out lower projections. By anchoring adaptation plans to such signposts of change, we can simultaneously guide adaptations to better manage the greatest risks, while also making adaptation more predictable so that it can be incorporated into projected future global pathways.

Signposts, triggers and tipping points are not restricted to physical processes and can manifest in a range of transitional risk factors associated with communities and their values, cultural and social thresholds, financial markets, insurance frameworks, ecosystems and conflict levels. Sea-level rise offers one clear opportunity to apply an approach that identifies precursors in the physical environment. Sea-level rise is highly heterogeneous globally: increased rates of ice sheet melting contribute unequally to sea level acceleration across the globe (Kopp et al., 2015), and, as discussed, VLM will change the local expression of sea-level rise. The HILL risk of rapid sea-level rise in a region, over a multi-decadal planning horizon, is, however, strongly influenced by tipping point indicators associated with Antarctic ice sheets. These will not be noticeable in time for adaptive action by only monitoring local sea level itself (Houston, 2021; Wenzel and Schroter, 2010). A regionally targeted 'signposts' approach could escalate local responses based on specific changes in remote climate impact drivers. Moreover, a signpost-like approach can mitigate modelling limitations by identifying observable indicators of risk. One example is that Antarctic sea ice losses (Purich and Doddridge, 2023), Antarctic surface warming (Casado et al., 2023), ice shelf hydrofracture (Lai et al., 2020), and/or warm water incursions into ice shelf cavities (Lauber et al., 2023) would be precursors to accelerated ice sheet loss and global sea-level rise.

Conclusion

In summary, for various reasons policy decisions on mitigation and adaptation are never likely to address the full risks posed by climate change. There will always be a level of residual risk depending on HILL events, ongoing and progressive sea-level rise, and the need to account for compounding and cascading events due to uncertainties about how they will propagate. Furthermore, the capacity of decision makers to address the changes, their projected acceleration, and community acceptance of appropriate measures and their cost and loss of place will lead to additional residual risk.

Here, we propose a strategy that pivots climate science towards addressing two pressing needs, both of which require sustained funding and effort – for example, by way of a dedicated adaptation research platform. The first concerns identifying the key decision-relevant global and regional climate-related risks and working in partnership with community aspirations to understand how best to communicate and manage them. The second concerns identifying the range of possible pathways (good or bad) that lie before Aotearoa, and how to communicate them and implement climate-resilient adaptation solutions. Combined with the use of dynamic adaptive pathways planning, this strategy will involve a stronger focus on worst-case outcomes and the various limits to adaptation that must be avoided. It will also aim to identify and hence avoid maladaptive policy outcomes. To achieve this, climate science must become more integrative and explore transdisciplinary approaches. This requires considering a richer and more flexible family of future pathways using exploratory techniques like gaming, community futures thinking or expert elicitation, with diverse interests and values. Next, adaptive frameworks need to be employed that include signposts and triggers to mark socially significant thresholds of change and help continually update assessments of where affected communities stand and what can still be achieved.

However, none of this will matter unless there is timely, fit-for-purpose, nationally accessible, actionable climate risk information, and well-integrated governance structures and institutions empowered and funded to take a long-term strategic approach to climate adaptation. Accordingly, a well-designed Climate Adaptation Act (or equivalent legislation) is urgently needed, one that mandates the required governance arrangements, policy tools, planning mechanisms, public institutions and funding instruments.

The finance and expenditure committee inquiry on adaptation addresses some but not all of the essential enablers for effective adaptation in coastal settings affected by sea-level rise. In particular, the funding of adaptation measures, including managed retreat, and the funding of sustained decision-relevant science and practice are yet to be addressed. Without these, sea-level rise poses existential risks for many communities.

Finally, there is a critical need for a national climate adaptation research platform to be funded. A well-supported platform would facilitate system-wide dialogue between policymakers, social and physical scientists, and indigenous and local communities on evidence-based policy options and community aspirations in ways that can anticipate and manage future risks.

1 Actionable knowledge focuses on providing usable information that addresses policy and socially relevant problems and advances knowledge.
2 Note that this HILL scenario becomes increasingly more likely as temperatures rise, and will be close to a certainty should global warming reach 2°C (an important point from Sherwood et al., 2024).
3 These projections do not take into account local vertical land motion.

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