Coastal Environment Programme of RNC2
Title: Adapting to New Zealand's Dynamic Coastal Hazards

Impact Statement

The Coastal theme will resolve fundamental science and policy questions faced by coastal communities around Aotearoa-New Zealand (NZ) regarding uncertain coastal hazard futures. Future sea-level rise (SLR) is inevitable, and while the rate of change is uncertain, there will undoubtedly be progressive increases in the intensity of extreme erosion and flooding events, and a succession of more frequent nuisance events. The 'slow onset' risk that results from the changing and cumulative impacts of long-term coastal exposure represents a profound challenge for coastal communities and managers. In directly addressing this challenge the Coastal theme is distinct from other themes within RNC that largely focus on major events or shocks. In 2018 we held an extensive series of stakeholder workshops around NZ. We identified knowledge gaps and found that despite new guidance on coastal hazards and climate change [1], councils are limited by fragmented, inconsistent shoreline change data and remain embedded in practices that focus on disaster events. This means they cannot adequately implement coastal adaptation decision making in the face of irreversible SLR.

Working closely with end-users, this theme will develop and implement new state-of-the-art, nationally consistent approaches to tackle NZ's current and future coastal hazards and their rising risk. We will resolve past and present physical changes in NZ's coastline, identify hotspots of coastal risk exposure and determine current and future changes in coastal flooding risk in low-lying areas. These outcomes will be delivered through novel applications of cutting-edge science, including: using high cadence satellite imagery and cloud-based computing to fundamentally transform NZ's shoreline change detection to national-scale, semi-automated analyses in near real time; and developing a universal model based on machine learning algorithms for predicting flooding around data-poor estuaries. Integrated erosion, flooding and risk datasets will address global research questions around the impacts of compound hazards under a changing climate and SLR. Consistent, proactive national approaches will be developed for assessing coastal hazard exposure and vulnerability (including quantifying adaptive capacity); importantly, these new approaches will befit changing risk associated with SLR. We will develop a new suite of coastal hazard adaptation methodologies and adaptive planning options that are locally suited, cost-effective, and can be practicably implemented. These will be delivered through improved national guidance and codes of practice that management agencies and practitioner groups can use to address the daunting coastal adaptation challenge. Collectively, these outputs will provide the scientific data, insight and enablers necessary to inform a resilient coastal hazard management strategy for NZ for the next 50-100 years and beyond.

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Overarching Research Objectives

Ongoing and changing SLR, storms and wave patterns will fundamentally re-shape our coastlines and re-define NZ's future coastal hazards (the impact of erosion and flooding on land, assets and people) and their risks (exposure and vulnerability to increasing erosion and flooding). The overarching aim of the Coastal theme is **to better inform decision making and enable implementation of adaptation in coastal and estuarine settings** in the context of uncertain and increasingly dynamic coastal hazard exposure over the next 100 years and beyond. The Coastal theme comprises three complementary 'Pillars', each of which generates new science outcomes to support hazard identification, risk assessment and effective adaptation essential to underpin the strengthening of NZ's resilience to coastal hazards (Figure 1). The three pillars (NZ's Changing Coastline, Coastal Flooding and Coastal Adaptation) are complementary, with knowledge or data transfers, but not critically dependent on each other to advance.

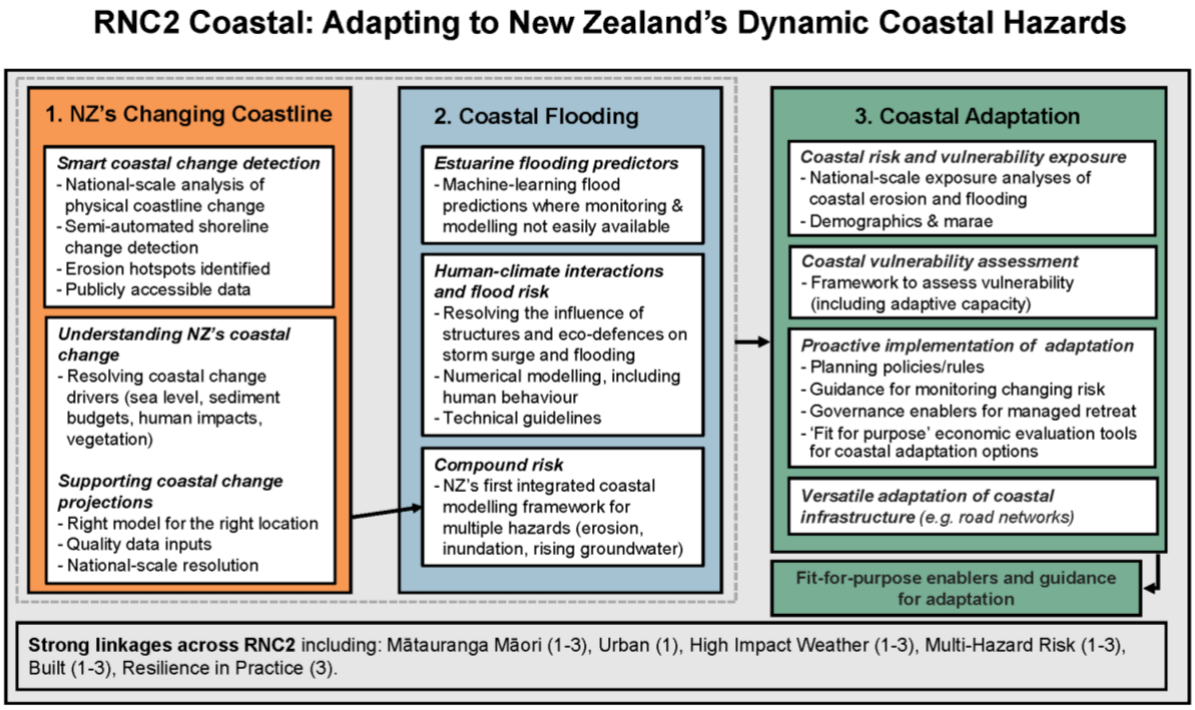

Figure 1. Three complementary research Pillars underlie the Coastal theme.

Pillar One: NZ's Changing Coastline: "Increasing rates of shoreline change as a consequence of slow onset climatic change"

Coastal erosion is a major hazard facing coastal communities throughout NZ. Risk exposure of assets and natural coastal environments is rapidly increasing as SLR accelerates and a legacy of poor coastal planning decisions takes effect. However, we have an incomplete picture of shoreline change around NZ, including coastal erosion trends. Current work on coastal change is fragmented, undertaken by local government without a consistent approach to data collection and analysis, and spans timescales that are often misaligned with hazard planning and management goals. Pillar 1 will fundamentally change the way that past, present and future coastal change is detected and modelled. It will provide the data necessary to explain how coastal change interacts with the natural and built environment through increasing risk (Pillar 3), and how it amplifies and modifies other hazards, particularly coastal flooding (Pillar 2). Pillar 1 will develop and apply cutting-edge remote sensing and geospatial tools to transform our understanding of past and present coastal change and provide the scientific datasets necessary for future-casting physical coastal change.

Pillar One Research Objectives and Sub-projects

The aim of Pillar 1 is to develop **a national framework for assessing NZ's changing coastline** that will deliver an understanding of slow onset coastal change and data to underpin modelling efforts to future-cast ongoing impacts. A national-scale approach is proposed, comprising two sub-projects:

1. Smart coastal change detection
2. Understanding NZ's coastal change and supporting projections of future shoreline change

1. Smart Coastal Change Detection

Reliable projections of future coastal change require robust analyses of past coastal behaviour that address the attribution problem of multiple drivers (targeted in sub-project 2). Solving this problem requires reliable, consistent nation-wide records of historical coastal change. This dependency on historical data is shown in national-scale coastal change programmes in the USA (National Assessment of Coastal Change Hazards) and UK (Shoreline Management Planning), and illustrated in the widespread use of predictive coastal-change models that are calibrated using historic shoreline-change rates [2,3]. Historical aerial photographs are available for much of NZ extending back >70 years and were used in a nation-wide survey of coastal change in the 1970's [4] that established a benchmark for many subsequent coastal management projects in NZ. Since this time regional-scale coastal monitoring

in NZ has advanced minimally and is now characterised by *ad hoc* collection and analyses of imagery. This sporadic approach provides little basis for scientists and coastal managers to understand and manage coastal change. Recent advances in remote sensing provides exciting new opportunities to transform the way coastal change is assessed. Over the past decade the number of high-resolution Earth Observation satellites has increased dramatically; we now have unprecedented ability to map earth-surface changes. The aim of sub-project 1 is to **transform NZ's coastal change detection from small-scale, sporadic, manual and unselective monitoring, to multi-scale, near real-time, semi-automated shoreline detection and change analysis** [5].

Sub-project 1 – Objectives:

a) Develop a publically available national coastal-change database that quantifies historical (~70 years) coastal-change patterns and identifies current erosion hotspots;
b) Develop and apply geospatial methods for consistent nationwide shoreline identification and change detection using high cadence satellite imagery (~2000 to present);
c) Develop a hierarchical coastal-change detection methodology in which high-resolution studies are initiated by a combination of national-scale coastal change data (i.e. objective 2) and stakeholder triggers (economic, social and cultural);
d) Determine the mapping potential of high-frequency satellite images using low-frequency, high-resolution multispectral airborne survey.

Sub-project 1 – Methods:

The objectives of *Smart Coastal Change Detection* will be achieved through a programme of data compilation, historic shoreline mapping, and development of new geospatial methods applied within a cloud computing framework for detecting and analysing change. We will compile existing fragmented historical shoreline vector data into a common database and conduct additional shoreline mapping using historical aerial photographs to provide national-scale coverage of shoreline positions over decades. We have extensive experience in this field and will develop protocols to ensure a high level of mapping consistency. High-frequency shoreline changes over the past decade will be mapped using Landsat and Sentinel 2 satellite imagery. Machine-learning and edge detection algorithms will be used to statistically determine the shoreline and map national-scale coastal change. A hierarchical coastal-change detection tool will be developed to enable managers to identify the level of monitoring required for different coastal areas. Criteria will be developed that consider coastal-change rates and stakeholder interests. When triggered, higher-frequency shoreline detection could utilise existing beach profile data, commercial daily satellite imagery (<1 m resolution), and beach monitoring programmes that yield planform and volumetric coastal-change estimates (cm resolution). We will undertake fieldwork on selected sites with UAV-based multispectral image capture (~5 cm resolution) synchronised with satellite image capture (~1 m resolution). Image comparison will ground-truth the algorithms to automatically classify satellite images (e.g. shoreline, beach slope, surf-zone width, vegetation).

2. Understanding NZ's Coastal Change and Supporting Projections of Future Shoreline Change

Coastal systems are highly complex, involving multiple interactions. Some sections of NZ's coast have on-going systemic patterns of coastal change that are relatively predictable, but other sections exhibit behaviour that is difficult to unravel. A first step in the future management of NZ's coastline is to clearly distinguish areas where different types of behaviour have occurred in the past; a section of chronically eroding coast should be managed differently to a section of coast subject to only occasional acute erosion. Understanding the relative contributions of different drivers to observed shoreline change is arguably the biggest question in physical coastal science, because this understanding underpins our ability to predict future changes and make informed management decisions. At present there is limited scientific basis for projecting future coastal change to support decision makers. This is a global problem [6] that has prevented other national-scale coastal change projects (e.g. in the UK and USA) from providing quantitative predictions of future shoreline positions. Three basic difficulties exist: (i) shoreline data are insufficiently resolved temporally to capture dynamics; (ii) relative sea level is only known in sufficient detail where tide gauges are available [7]; and (iii) technical limitations at present fundamentally prevent the development of detailed predictive coastal impact models that would be driven by downscaled regional climate models [8]. The aim of sub-project 2 (Pillar 1), therefore, is to **provide the shoreline data inputs necessary to obtain full value from the existing state-of-the-art models that future-cast shoreline change**, including: simplified process-based behavioural

models [3,9] data-driven models [10,11], and the models that are currently used in NZ for probabilistic coastal erosion hazard assessments [12].

Sub-project 2 – Objectives:

a) Develop a nationally applicable coastal-change typology to characterise observed coastal change across NZ;
b) Undertake a case-study exploration of Māori oral histories of coastal change, comparing mapped and oral histories, and informing forward modelling;
c) Explore the underlying causes of NZ's observed coastal change over the past several decades;
d) Deliver coastal-change information in a format that supports future projections of shoreline change using different types of existing models.

Sub-project 2 – Methods:

In sub-project 2 we will develop a coastal-change typology that clearly discriminates the range of coastal behaviours that have occurred in the past and where they occur around NZ. Once a dataset has been compiled we will run a workshop with local experts to build an empirically consistent and nationally applicable typology and approach to classification. We will examine linkages between measured historical coastal-change patterns and a range of drivers (e.g. regional variability in rates of relative SLR and wave climate, tectonics and sediment transport, changes to coastal vegetation, catchment-coastal sediment flux, and a range of human impacts). We will develop a database containing historical shorelines and associated metadata that support future projections of shoreline change. Existing database resources (e.g. CKAN Landcare Datastore, NIWA Coastal Explorer, NIWA Coastal Vulnerability Index) and technical expertise (e.g. Centre for eResearch) will be utilised to deliver publically available national coastal-change data.

Pillar One Outputs

- A publically accessible national coastal-change database that identifies erosion hotspots and coastal change trajectories
- PhD thesis: Satellite-based coastal-change detection
- PhD thesis: Quantifying coastal-change patterns
- PhD thesis: Coastal-change drivers on vegetated dune coasts
- Honours dissertation: Comparing synchronous ground-based multispectral and satellite imagery
- MSc thesis: Māori oral histories of coastal change

In addition, we aim to publish 4 or more papers in international journals. Key manuscripts could include:

- Application of high-frequency satellite observation to detect shoreline change
- Spatial and temporal scale resolution effects on shoreline change detection
- Historical shoreline change trends around NZ
- Multiple drivers of shoreline change: distinguishing the effects of humans, sediment supply, vegetation and sea-level change

Pillar Two: Coastal Flooding: "Flood response to climate change"

Accelerating SLR is exposing vulnerable communities to increasingly deeper and more frequent coastal flooding in NZ [13,14] and globally [15–17]. To successfully manage flooding risk and inform coastal adaptation decision making, we must understand how human actions will impact flooding risk and plan for flooding from multiple sources (e.g. [18]). Many NZ cities and rural communities are developed around estuaries and harbours, which are vulnerable to a "flood sandwich" between rainfall delivered by rivers and stormwater systems, and high sea levels driven by tide, storm surge, and rising mean sea level. However, few sea-level or bathymetry datasets exist for most NZ estuaries, and wind-driven surge inside estuaries is poorly understood. Thus, estimating extreme sea levels to assist planning is difficult, both currently, and under conditions of climate change and SLR. In addition, human modifications such as causeways and stop-banks, and subtle morphological changes, will have unknown consequences on future flooding hazard. Current coastal flood modelling to support climate change adaptation in NZ has used present-day bathymetry and management practices combined with changing climate drivers such as SLR. Our key challenge is to embed future morphological change into flood models and to integrate future adaptation approaches with flood hazard and risk assessment.

Pillar Two Research Objectives and Sub-projects

Our overarching aim is to **improve understanding of current and future coastal flooding hazard and risk, and its implications for decision making**, in the complex environments that characterise NZ's coast (including estuaries and riverine-influenced environments) through three sub-projects:

1. Estuarine flooding predictors
2. Influence of human–climate interactions on coastal flood hazard and risk
3. Compound risk from multiple coastal hazards

1. Estuarine Flooding Predictors

Sub-project 1 will **develop and apply new methods to estimate the flooding hazard in data-poor NZ estuaries nationwide**. We will link with Pillar 1 using satellite data and LINZ information to derive bathymetric data for estuaries within NZ, which is a critical missing component needed to better model estuarine hydrodynamics and extreme sea levels. We aim to develop rapid-simulation machine-learning algorithms to provide total water level predictors within estuaries using the entrance tide and surge forecasts, river discharge and wind as inputs. We will test their ability to provide storm-tide predictions for data-poor estuaries, thereby filling a knowledge gap for many NZ estuaries that lack sea-level records or hydrodynamic models, enabling extreme sea-level modelling and future-casting. The role of internal versus external storm surge generation will be examined to better understand the potential storm surge hazard now and under future conditions of climate change and SLR.

Sub-project 1 – Objectives:

a) Develop algorithms for automated estuarine bathymetry extraction from satellite data;
b) Develop machine-learning algorithms to predict tide, surge and extreme sea level in NZ estuaries;
c) Generalise predictors into an enclosed area exposure tool.

Sub-project 1 – Methods:

We will use Sentinel II satellite data to map tidal variation in the water's edge [19] and combined with LiDAR (Light Detection and Ranging) and hydrographic information, create bathymetric data for estuaries within NZ. The derived bathymetry will be used to predict sea level in data-poor estuaries. We will develop and train rapid-simulation machine-learning algorithms to provide total water level predictors (machine-learning algorithms are statistical models where the form of the model is not chosen *a priori*, but is adaptively developed to suit a training dataset). Existing field measurements from water level recorders will be used to validate predictions for different estuary types. Standard statistical analysis on new and existing measurements will be undertaken to determine the percentage of variability that can be predicted from open coast water level predictions alone, and how this changes between estuaries. Then, in cases where the response is more locally controlled, machine-learning algorithms will be developed to predict water levels. These algorithms will be extended to predict water level response in a wider range of estuaries, with the end goal of creating a universal model for predicting spatial variations in NZ estuaries. The research will leverage databases used in the NZ estuary classification [20] and existing hindcasts and climate change futurecasts for storm surge and waves on the open coast (outside of estuaries).

2. Influence of Human–Climate Interactions on Coastal Flood Hazard and Risk

Coastal flood-hazard modelling in NZ currently uses present-day bathymetry when modelling SLR impacts into the future (e.g. [21]). However, coasts and estuaries will change with SLR both from natural and anthropogenic causes (including sedimentation, vegetation change, and engineering defences). Morphological change, natural or anthropogenic, is a little-studied but important source of uncertainty within climate change adaptation studies [22]. Storm surge and tidal propagation within estuaries are sensitive to subtle variations in the estuarine morphology [23] and this will be compounded by SLR. As estuaries become increasingly urbanised into the future, modifications such as causeways, stopbanks and dredging become more common, which can increase flooding risk by removing areas that store and dissipate flood waters. In many parts of the world, stopbanks and flood protection are being removed to activate the power of coastal wetlands to process catchment derived nutrients [24] and the maintenance or removal of stopbanks is a critical land-management issue for NZ councils. Societies and economies will interact with climate change and SLR (and flood hazard) to influence land use choices and associated risk. For flood-risk projections to be useful, they must include assessments of how adaptation options reduce risk. Current flood risk assessment models are ill-equipped to address this as they assume a static adaptation path, implying that vulnerability will remain constant. Sub-project

2 thus aims to **explore the effects of natural and anthropogenic morphological change in estuarine environments on flood hazard and risk.**

Sub-project 2 – Objectives:

a) Understand the trade-offs between engineering defences versus natural solutions to mitigate coastal flooding hazard;
b) Better understand how natural morphological change will alter flood hazard in a changing climate;
c) Model the interplay between human action and climate change on coastal risk and explore a range of adaptation pathways.

Sub-project 2 – Methods:

Sub-project 2 will focus on a case study: the river dominated and highly stop-banked Waihou/Piako River Estuary in the Hauraki Plains that is economically important for agriculture but vulnerable to flooding, with varying degrees of human and natural modifications. The Delft3D morphodynamic modelling package will be used to study the effects of storm-tide flooding on this system, now, in the past, and with future SLR. Detailed present-day morphological data are already available, and past morphologies and fringing vegetation types will be reconstructed using charts and aerial photographs. Past sedimentation rates [25] will be used to project forward responses to changing conditions caused by SLR and associated effects. The effect of human-induced modifications e.g. stopbanks, will be modelled, and the influence of tidal ranges, surge and rate of sediment accumulation and 'land-building' will be examined. We will quantify the uncertainty in flood hazard caused by human and natural morphological change, and apply a multi-disciplinary approach to integrate different types of adaptive behaviour with flood hazard and risk models. The research will show how flood risk and adaptation might develop and reveal the decisions that can optimise flood risk reduction and economic benefit under conditions of changing climate and SLR. We aim to determine whether adaptation decision making can outweigh the differences between various climate change scenarios on future flood risk.

3. Compound Risk from Multiple Coastal Hazards

NZs coasts are vulnerable to multiple hazards that will be exacerbated by SLR and climate change. Coastal flooding, erosion and rising groundwater risk are usually managed independently, yet frequently these risks are interconnected by processes such as hydraulic connectivity, longshore sediment transport and resulting broad-scale morphological behaviour [26,27]. With Pillars 1 and 3, sub-project 3 of Pillar 2 aims to **integrate a coupled system of hydrodynamic, morphological and socio-economic models to consider multi-hazard risk interactions, for the first time in NZ**. This new science will contribute to global research questions around integration of erosion and flooding risk under conditions of SLR and climate change. Two case studies will be analysed, utilising our work in sub-project 2 in the Hauraki Plains, and adding a case study in Hawkes Bay, where we have extensive data and strong end-user relationships following the RNC1 Living at the Edge project.

Sub-project 3 – Objective:

a) Develop and apply a multi-hazard modelling framework for the combined hazard associated with multiple origins such as coastal erosion, overtopping, storm surge and groundwater.

Sub-project 3 – Methods:

We will build on research conducted in Pillar 1 (coastal change) and sub-projects 1 and 2 (Pillar 2) to develop an integrated GIS-based modelling system to predict the evolution of flooding risk, and its joint dependency on other coastal hazards, under conditions of climate change and SLR. A modelling framework will be developed that can simulate the physical interactions between flooding and other coastal hazards under changing SLR scenarios, enabling evaluation of the combined hazard and risk over time.

Pillar Two Outputs

- PhD thesis: Estuarine flooding predictors
- PhD thesis: The influence of human–climate interactions on coastal flood hazard and risk
- A NZ-first integrated modelling study of compound coastal hazards and risk from climate change and SLR

In addition, we aim to publish 4 or more papers in international journals. Key manuscripts could include:

- Simple predictors of flood hazard in enclosed estuaries
- Reconstructing the effect of morphological change on flooding
- Appropriate flood risk adaptation decision making under future climate change and SLR
- Modelling of combined coastal hazards

Pillar Three: Coastal Adaptation: "Enabling proactive coastal adaptation in a changing risk environment"

The coastal edge is experiencing major impacts from coastal/river/pluvial hazards and semi-permanent inundation at higher tides on the back of a rising sea, which will be ongoing throughout this century and beyond. A recent national-scale screening assessment of coastal flooding exposure has highlighted that while only 0.6% of NZ's land area has an elevation within 3 m of spring high tides, these coastal areas account for 6–7% of NZ's building replacement costs and resident population [21] and $14B of local government assets [28]. This poses a significant adaptation challenge [29]. Traditionally-used adaptation strategies that "protect" and "accommodate" are increasingly becoming ineffective, short-lived and expensive to maintain. **Decision makers in NZ urgently need new adaptive tools, planning approaches and policy-relevant enablers that address changing coastal systems**, mesh with enabling institutional frameworks and policies, and consider the intrinsic uncertainties surrounding the magnitude and rate of SLR. Such adaptive tools [30] have begun to be applied in NZ [31]. However, uptake is slow and further research is needed to **develop 'fit for purpose' decision tools, governance arrangements and processes to enable sustainable and cost-effective adaptations to be implemented**. Pillar 3 addresses these necessary aspects.

Pillar Three Research Objectives and Sub-projects

The overarching aim of Pillar 3 is to provide **consistent, proactive and implementable knowledge to address the coastal adaptation challenge**. A new suite of technical material, approaches and enablers will be developed for national guidance, risk and vulnerability assessments, land-use planning and codes of practice for decision making in different coastal environments around NZ. They will be 'fit for purpose', aligned to the changing risk regimes for implementation at different levels of governance, and have resilience outcomes (e.g. community cohesion, health and safety, and infrastructure needs) that achieve more effective and sustainable decision making. Pillar three consists of four sub-projects:

1. Improved understanding of coastal risk and vulnerability exposure
2. A vulnerability assessment (VA) framework that 'fits' the changing coastal risk
3. Enabling proactive implementation of coastal adaptation
4. Versatile adaptation of coastal infrastructure

1. Improved Understanding of Coastal Risk and Vulnerability Exposure

Several national-scale risk exposure assessments for SLR inundation have been undertaken for NZ's coastal margin [21,28,32], highlighting the high exposure. However, our national risk exposure of assets, infrastructure and communities to coastal erosion (potentially permanent losses) is unknown, and we have not assessed the characteristics of coastal communities (e.g. demographic and well-being characteristics) or marae throughout NZ in this context. This sub-project will address these unknowns. For infrastructure, a key emphasis will be the exposure of roading networks (e.g. squeezed against steep topography or low-lying areas) and this will be an input to sub-project 4. National exposure to inundation will be updated towards the end of the funding period to include new regional LiDAR (funded by the Provincial Growth Fund).

Sub-project 1 – Objectives:

a) Improve understanding and awareness of national/regional-scale coastal risk exposure to coastal erosion and inundation, focussing on roading networks and marae.
b) Improve understanding and awareness of national/regional-scale coastal vulnerability through well-being indices and demographic characteristics.

Sub-project 1 – Methods:

We will build on the national-scale methodology and mapping used for previous coastal risk exposure assessments using RiskScape, incorporating asset inventories and mapped hazard and SLR exposure (with inputs on national-scale erosion from Pillar 1). The sub-project will explore present and future projections of demographic, social and economic well-being indices on coastal demographics to tie in

with the new Living Standards Framework (Treasury). The national coastal-risk exposure assessment for coastal inundation will be updated with new or improved datasets for assets, demographics, other indices of change (e.g. local SLR and socio-economic pathway projections) and new LiDAR topography. LINZ, StatsNZ and Treasury will be key information providers at the national scale.

2. A Vulnerability Assessment (VA) Framework That 'Fits' the Changing Coastal Risk

The MfE coastal guidance [33] outlines the need for a combination of risk assessments and VAs but provides limited guidance on their undertaking. Vulnerability [34] is "*the predisposition to be adversely affected*", encompassing sensitivity or susceptibility to harm or damage, and capacity of systems and communities to cope and adapt (adaptive capacity). Adaptive capacity relates to well-being across communities, tangata whenua, institutional/governance systems, insurance/banking access, business sustainability, infrastructure levels of service, environmental services and social and economic well-being. In the face of uncertainty, adaptive capacity is a critical system property for mobilising resources to anticipate ongoing stresses [35]. At the coast these comprise an amalgam of frequent shocks and slow onset impacts. **Practitioners need a future-focused framework with enablers for VA that 'fits' the changing risk profiles for coastal areas, which are approaching critical coping thresholds**.

Sub-project 2 – Objectives:

a) Develop a framework for undertaking VAs that sits alongside conventional risk assessments, which is 'fit' for the NZ coastal context under changing climate risk profiles with SLR;
b) Analyse different paradigms for enhancing resilience related to sudden shocks/events versus slow onset rising risk situations.

Sub-project 2 – Methods:

We will critically review different types of VA approaches and develop an improved NZ-relevant VA framework, tested through workshops, incorporating advice from national and international experts in the field of social vulnerability from climate change stressors. The framework will inform future revisions of the MfE coastal guidance and have wider applicability in national- to local-scale assessments that assimilate well-being, demographic and other socio-economic characteristics (sub-project 1), including the ongoing series of National Climate Change Risk Assessments (a proposed component of the Climate Change Bill). We will compare framings for enhancing resilience that prioritise responses to sudden shocks with those that address pervasive, slow onset hazards in coastal areas.

3. Enabling Proactive Implementation of Coastal Adaptation

There is urgency to further develop Decision-making under Deep Uncertainty (DMDU) tools that 'fit' the NZ governance context for coastal hazard, risk, VAs, and adaptation planning and implementation. Such tools are at the global forefront of challenges that encompass deep uncertainty and rising risk, and these tools include: scenario analysis; exploratory modelling; expert elicitation; multi-modal ensembles; sensitivity analysis; and a number of Robust Decision-making (RDM) tools such as Dynamic Adaptive Policy Pathways (DAPP) planning and Real Options Analysis (ROA) for economic evaluation of the cost of delaying implementation of adaptation options. The application of RDM in NZ has been limited to only one river flooding setting and two coastal settings, one of which was developed in partnership with the Living at the Edge project (RNC1). RDM lessons are growing in NZ [36], but the efficacy and relevance of these tools and approaches require further testing in a wider range of coastal settings, and a focus on understanding implications of their use at the adaptation implementation stage. **Sub-project 3 aims to develop flexible and adaptive approaches for implementing coastal adaptation options over at least the next 100 years.**

Sub-project 3 – Objectives:

a) Develop planning objectives, policies and rules for NZ's coast that address changing rates, frequency, and magnitude of hazard impacts;
b) Develop guidance on efficient, focused coastal adaptation monitoring programmes that can discern changing risk and vulnerability and can support DAPP;
c) Develop an enhanced understanding of effective governance enablers for implementing managed retreat;
d) Test and provide guidance on 'fit for purpose' economic costing tools for evaluating adaptation options (particularly managed retreat) and pathways;

Sub-project 3 – Methods:
A mix of methodologies will be deployed, underpinned by a collaborative co-production approach with other research groups in NZ and internationally, and NZ end-users including consultants, local and central government, infrastructure agencies and communities. The approach will ensure practical usability, credibility and relevance of the research outputs. The range of appropriate tools for the dynamic problem in NZ settings will be identified using desk-top research as well as workshops and interviews with end-users and experts to identify and test assessment methods and tools (e.g. DAPP and ROA) as they are developed and applied. Assessment methods and tools will be applied and tested in different coastal settings and at different scales and to elicit lessons about their efficacy, relevance and credibility, to enable proactive implementation of staged coastal adaptation. Ongoing implementation of coastal adaptation in Hawke's Bay (building on Living at the Edge research in RNC1) will also be monitored to explore wider applicability of lessons learnt.

4. Versatile Adaptation of Coastal Infrastructure

Recent advances by the Infrastructure programme in RNC1 in the cascading impacts and interdependencies of shocks (e.g. earthquakes, floods) to distributed networks/infrastructure will be extended in sub-project 4 to **appraise the effects of slow onset coastal hazard exposure from SLR on coastal roading infrastructure** and how effective, but flexible adaptation can be applied. Furthermore, we will explore how DAPP can be applied to interdependent networks and coastal infrastructure, which tends to hug steep coastlines, confounding adaptation possibilities. The project will **explore versatile ways of adapting road networks and infrastructure** in a "middle-ground" between hard coastal protection and managed retreat (e.g. versatile staged designs, shorter design life, longer-term sequencing towards managed retreat).

Sub-project 4 – Objective:

a) Develop and test versatile approaches to proactively adapt coastal roading networks and link to the DAPP framework informed by a detailed case study and laboratory testing of options.

Sub-project 4 – Methods:
Case studies will be drawn from the Hauraki/Coromandel SH25, or elsewhere where overtopping or flooding is an issue. Potential engineered solutions and how these can fit within the DAPP framework will be explored. Physical laboratory investigations will investigate progressive failure and repair/adaptation of coastal revetments, or progressively increased overtopping and risk-reduction options. The project is novel in its requirement to interface with the DAPP framework for developing sequenced or alternative pathways for adaptation, in association with monitoring the emergence of critical service-level thresholds, factoring in lead time to switch pathways. Further discussion will occur in the first three months of RNC2 with the Built theme to firm up the key elements of this sub-project.

Pillar Three Outputs

- National-scale coastal risk exposure assessments and spatial distribution of demographic characteristics and well-being indices
- MSc/ME Thesis: National-scale coastal risk exposure assessments
- MSc Thesis: Planning and policy enablers for supporting the DAPP approach
- PhD Thesis: Economic evaluation methodologies that fit the slow onset and ongoing rise in risk for coastal areas
- PhD Thesis: Versatile adaptation of coastal roading infrastructure (joint with Built theme)
- Guidance reports and policy advice (e.g. new VA framework, 'fit for purpose' planning objectives, policies and rules, monitoring programmes for signals and triggers to support DAPP, and new guidance on economic costing tools for evaluating coastal adaptation options)

In addition, we aim to publish 4 or more papers in peer-reviewed journals and a range of popular articles targeted at local practitioners. Key manuscripts could include:

- National-scale coastal risk exposure assessments, demographic characteristics and updated coastal flooding assessment
- The application of a new VA framework appropriate for NZ to support decision making
- Governance enablers for managed retreat
- Implementation of coastal adaptation in Hawke's Bay – lessons learned for future guidance.

- Versatile adaptation options for coastal road infrastructure
- Compare the paradigms relating to enhancing resilience for sudden shocks/events versus slow-onset rising risk situations in coastal areas

Contributing to a more resilient NZ

The three Pillars of the Coastal theme will contribute to enhancing NZ's resilience as outlined below.

1. Pre-emptive assessment of NZ's coastal erosion and inundation risk exposure will support **improved and targeted adaptation planning** and National Climate Change Risk Assessments, **reducing the ongoing financial costs of hazard exposure**.
2. **Supporting sustainable governance of rising coastal risk** through the development of a national set of new guidance and practice notes and evaluation methodologies for flexible adaptation planning and contributing to revised versions of the MfE coastal guidance.
3. Consistent NZ-relevant frameworks for assessing coastal risk exposure and vulnerability to slow onset impacts will support governance at national to local scales by providing a platform of **nation-wide publically accessible data, assessments and approaches that are tailored to better inform coastal adaptation planning and funding models**.
4. Provision of **nationally consistent approaches for coastal hazards and climate change decision making,** which at present varies regionally, is inefficiently undertaken or not undertaken at all and seldom considers the slow onset nature of the problem. **This work is imperative for efficient and informed decision making on coastal hazard risk in NZ.**
5. Increasing consistency and accessibility of new knowledge, applying it at the most appropriate levels of governance, and supporting decision makers and their communities in addressing coastal erosion and flooding risks, delivers a better chance that **sustainable decisions can be made, reducing tensions at the coast that undermine effective adaptation decisions.**
6. Improving shared access to resources among decision makers at the relevant management scales **will support organisational capacity building, reducing costs and duplication of effort between regions**.
7. Involvement of post-graduate students, research assistants and post-doctoral researchers will **build capability and skillsets across disciplines that are urgently needed in the adaptation sphere in NZ**.

Science/innovation benchmarked to state of field(s)

The Coastal theme will make substantive contributions to several global science questions.

1. **Resolving the attribution problem.** Understanding the role of ongoing SLR in driving coastal change and exacerbating coastal hazards is one of the biggest unresolved questions in coastal science. Myriad confounding factors exist (e.g. variability in sediment supply, human factors, vegetation change). Pillar 1 has a unique opportunity to resolve this problem for NZ because the analyses will be at national-scale, using high resolution imagery covering decades to years.
2. **New methodologies of coastal change detection.** Pillar 1 will deliver new semi-automated methodologies to capture large-scale coastal landform changes, and a hierarchical coastal-change detection tool to identify appropriate levels of coastal monitoring for different areas.
3. **Flooding predictors for estuaries.** Using state-of-the-art machine-learning algorithms with bathymetric variations, local winds and pressure fields, Pillar 2 will develop a new approach (a global first) for predicting flooding in data-poor estuaries.
4. **Anthropogenic impacts on hazards and risk.** Pillar 2 will develop an understanding of the effect of anthropogenic modification in estuarine systems on hazards and risk. Previous work has been case-by-case and not considered the populated estuarine types at risk in NZ.
5. **Integrated coastal change and flood modelling.** It is increasingly recognised that changes in the coastal landscape will alter the frequency and magnitude of coastal flooding. Working across Pillars 1-3 we will consider the integrated effects of coastal change and coastal flooding and the consequences in respect to coastal adaptation.
6. **Coastal adaptation.** Adaptation of coastal settlements and infrastructure to SLR is globally emerging as a major societal challenge with widespread implications. We will introduce new frameworks, methodologies and fresh guidance that address the deep uncertainties, which are needed to allow for appropriate adaptive planning and decision making under ever-changing risk conditions. Consequently, the project promises to lead global thinking on new approaches to the coastal adaptation challenge.

Vision Mātauranga

The Coastal theme has vision, aims and outcomes for Vision Mātauranga across all three pillars of our programme. We recognise that coastal iwi and hapū are particularly vulnerable to coastal hazard risk, and that many do not have the resources to protect their land or alternate locations to retreat as they may have done traditionally. We also recognise the need to privilege Māori ways of knowing, particularly in the context of knowledge of coastal hazards around Aotearoa that have been sustained through intergenerational transmission. Our aim is to conduct Māori-led and Māori-relevant research, and to conduct our research with an openness to learn. We will foster existing iwi connections in Hawke's Bay (Ngāti Kahungunu) and Mahia (Ngāti Rongomaiwahine) and develop new connections in Hauraki (Ngāti Maru) with Māori researcher Shari Gallop. In consultation with the Mātauranga Māori theme we have identified three priority areas for Vision Mātauranga in the Coastal theme:

1. Coastal will co-join with the Built and Mātauranga Māori themes in identifying risk exposure of marae to SLR, including the emergence of high-risk sites requiring priority attention (Pillar 3).
2. We will fund a Māori Masters student to explore Māori oral histories of coastal change in a selected case study (e.g. Mahia) and provide co-supervision through Māori researcher Darren King (Pillar 1).
3. Inputs from Mātauranga Māori theme to sub-project 3 (Pillar 3) on the use of iwi management plans in developing land-use policies/rules to support coastal adaptation in district and regional plans.

End-user Engagement plan

The research team was heavily engaged in consultation meetings across NZ in March-April 2018 to discuss the proposed research in the form of three pillars, identify knowledge gaps for stakeholders, and begin to broker different opportunities for ongoing engagement as active research participants and end-users who will utilise new tools emerging from the project. The resulting feedback has been incorporated into further design of the three Pillars. Further engagement discussions are on-going to determine how stakeholders will be integrated into the research. To date the level of interest in the project goals has been very high.

Table 2. Stakeholders/end-users engaged in the Coastal theme.

Northland Regional Council	Hazards SIG Group	Ministry for the Environment
Auckland Council	Environment Canterbury	Department of Conservation
Waikato Regional Council	Hastings District Council	New Zealand Transport Authority
Bay of Plenty Regional Council	Otago Regional Council	Insurance Council of NZ
Gisborne District Council	Dunedin City Council	Met Service
Hawke's Bay Regional Council	Environment Southland	Property Council of NZ
Taranaki Regional Council	Tonkin and Taylor	Infrastructure Council of NZ
Wellington City Council	Stantec	LINZ
Greater Wellington Regional Council	Wsp-OPUS	NZ Coastal Society
West Coast Regional Council	Beca	Centre for Space Science & Technology
Tasman District Council	Mitchell Daysh	Engineers NZ
Marlborough District Council	NZ Planning Institute	The Coastal Restoration Trust
Napier City	Market Economics	First Gas

Team composition and track record

The research team includes national leading researchers with expertise in coastal hazard processes, landscape change, coastal management and adaptation to climate change. **A/Prof Mark Dickson (UoA)** will lead the Coastal theme, building on his leadership in the Living at the Edge project (RNC1) and 17 years (post-PhD) experience in interdisciplinary research on coastal hazards and management. **Dr Rob Bell (NIWA)** will co-lead the Coastal theme and has 38 years research experience in coastal engineering, coastal adaptation and was lead author of the MfE coastal guidance. **A/Prof Mark Dickson and Dr Murray Ford (UoA)** are leaders in the analysis of coastal change and analysing shoreline adjustment to increased sea level and will oversee Pillar 1. **A/Prof Giovanni Coco (UoA)**, **Dr Darren King (NIWA) and A/Prof Mike Hilton (Otago)** bring further expertise and supervisory experience to particular aspects of Pillar 1 (coastal change modelling, Māori research and vegetated soft coasts). **Prof Karin Bryan (UoW) and Dr Scott Stephens (NIWA)** will lead Pillar 2, based on their extensive experience in coastal flood analysis, coastal processes and numerical modelling techniques.

Dr Shari Gallop (UoW) brings expertise to Pillar 2 in numerical hydrodynamic and morphodynamic modelling. Pillar 3 will be led by **Dr Judy Lawrence (VUW) and Dr Rob Bell,** who are at the forefront of climate change adaptation research on SLR and adaptation, and decision making under deep uncertainty. Pillar 3 will also be supported by **Dr Paula Blackett (NIWA)**, a leading NZ social researcher on adaptation, along with practitioners (in-kind co-funding), and experts in economics, law and planning. **Dr Emma Ryan (UoA)** is an emerging coastal researcher with extensive expertise in the successful Living at the Edge project and will focus her efforts on Pillar 1.

Appendix 1. Reference list for Coastal theme proposal

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