# Modelling the economic implications of coastal managed retreat


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# Abstract

Climate change is an issue for all of humanity and with it comes many challenges. At the coast, climate change drives sea-level rise and increases the magnitude and frequency of storms, which erode shorelines and flood properties. Managing these coastal hazards requires assessing the risk and economic impact of medium-term planning options. One such planning option available to governments in New Zealand is large-scale managed retreat. However, it requires research to examine how to implement it and what are the impacts.

This thesis presents a new method to support robust approaches to implementing managed retreat of coastal communities exposed to climate change through rising sea levels and increasing storminess. It uses Evolutionary Economic analysis, System Dynamics, Scenario Planning and Robust Decision Making to identify Dynamic Adaptative Policy Pathways for implementation. The approach models nine scenarios of climate risk, coastal mitigation and adaptation to assess the economic implications of a large-scale managed retreat for a study area in Hawke's Bay, New Zealand, well known for exposure to a range of coastal hazards. The thesis first develops a baseline scenario, or status-quo, where managed retreat is unavailable to society, and exposed communities either endure coastal flooding, inundation or erosion or adapt through *ad-hoc* (forced or voluntary) relocation. The baseline scenario covers three climate futures: no sea-level rise, a mid-range scenario based on the Representative Concentration Pathway (RCP) of 4.5, and a worst-case scenario based on RCP8.5. The thesis then develops and examines two scenarios (mid-range and worst-case) where planned mitigation measures are implemented through coastal defence, two scenarios where central government fund managed retreat through climate bonds, and two scenarios where local government fund managed retreat through a property rating taxes.

The thesis develops a new integrated assessment model called C-ADAPT in System Dynamics to assess possible pathways for vulnerable communities to adapt to coastal hazards until 2050. The economic impact modelling within the thesis utilises the quasi-computational general equilibrium model 'MERIT' developed by Market Economics and the Institute of Geological and Nuclear Sciences (Smith, McDonald, et al., 2016). This thesis creates an integrated assessment model, C-ADAPT, by adapting and extending MERIT with exogenous inputs that fall outside its regular operation. C-ADAPT includes exogenous input modules on how coastal managed retreat can be planned and financed to examine direct and indirect impacts of floods, risk, local-scale insurability and coastal property market behaviour, business inoperability, infrastructure outages and interdependencies, land use planning, coastal defence costs, local government rating taxes and central government climate bonds. The approach enables the evaluation of management futures by not only assessing the medium-term local economic impacts of coastal hazards but also assessing the flow-on regional-scale economic impacts through Evolutionary Economics. Scenarios are then assessed using key performance indicators to examine adaptation pathways that minimise regret through Robust Decision Making.

Model results indicate that managed retreat is beneficial for society when viewed from an aggregated regional economy perspective to manage coastal hazards as households and industries benefit more than continuing with the status quo baseline. However, the economic impacts of managed retreat are not evenly distributed across sectors, industries or time. Results indicate that managed retreat is likely to leave exposed households and industries as 'winners' at the expense of households and industries in the greater region that bear a proportion of the costs. Furthermore, construction and manufacturing industries benefit at the expense of primary production industries. Local government will require prudent financial management to implement a large-scale managed retreat, given the significant expenditure required as a proportion of revenue, to not only relocate its own assets but to also purchase land and built capital for managed retreat.

In contrast to expert input engaged through scenario planning, the use of property rates as a financial mechanism to support managed retreat performed better than the other scenarios when exploring the key performance indicators selected, as property prices adjust to the risk and a longer-term implementation of managed retreat. In contrast, while the bonds scenarios had the greatest benefit to households, they tended to remove capital investment away from the regional economy, restricting growth. Model results indicate that coastal defence is a suitable short-term option to minimise damage and disruption and provide time for capital accumulation to finance managed retreat. However, over the economic medium-term (to 2050) or under extreme climate conditions, managed retreat outperformed coastal defence.

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# Glossary and Abbreviations

ADM: Agile Development Methodology.
AEL: Annual Expected Loss.
AEP: Annual Exceedance Probability.
Baseline Scenario: The societal reality of business as usual, or when society continues with the status quo.
C-ADAPT: The Integrated Assessment Model built for this thesis.
CDEM: Civil Defence and Emergency Management.
CGE: Computational General Equilibrium.
CLD: Causal Loop Diagram.
CHZ: Coastal Hazard Zone.
DAPP: Dynamic Adaptive Policy Pathways; a methodology for evaluating future options with uncertainty.
DCGEM: Dynamic Computational General Equilibrium Model.
Dynamic Equilibrium: An economic state whereby a system/variable oscillates around an observable trend.
EQC: The Earthquake Commission.
Evolutionary Economics: A diversion from mainstream economics where economies are constantly changing (dynamic) due to the holistic and evolving behaviour of society.
GIS: Geographic Information Systems.
GOVT: Government.
HDC: Hastings District Council.
HBRC: Hawke’s Bay Regional Council.
HHLD: Household.
HPUDS: The Heretaunga Plains Development Strategy.
IAM: Integrated Assessment Model.
IND: Industry.
IVA: Industry Value Added; industry revenue less intermediate consumption.
IPCC: Intergovernmental Panel on Climate Change.
Kondratieff cycle: The long-term economic oscillation of 40-60 years of growth and recession.
KPI: Key Performance Indicators.
Managed Retreat: The planned relocation of communities away from hazards.
Matariki Plan: The regional economic development plan for Hawke’s Bay.
MERIT: Measuring the Economic Resilience of Infrastructure Tool.
MHWS: Mean High Water Springs.
MSL: Mean Sea Level.
NCC: Napier City Council.
NZVD2016: New Zealand Vertical Datum 2016.
Overshoot and collapse: a period of asymptotic or exponential growth followed by an exponential decline after an apex is reached, then asymptotic decline.
PYRDM: Python 3 matrix for Robust Decision Making.
RCP: Representative Concentration Pathway.
RDM: Robust Decision Making; a quantitative and iterative mathematical approach to decision-making.

ROI: Return On Investment.
Scenario Planning: A methodology to create plausible futures through collaborative development.
SLR: Sea Level Rise.
System Dynamics: A computational modelling approach for interacting and complex systems.
TVA: Total Value Added; similar to Gross Domestic Product, but excluding taxes and subsidies.
TWL: Total Water Level.

# 1. Introduction

## 1.1 The rationale and problem setting for the thesis

Climate change and associated increases in sea level and storm frequency and intensity are exacerbating coastal hazards (IPCC, 2014b). In particular, these changes are generating more extreme waves and higher storm surge elevations at the coast (Komar, 2013). It can increase precipitation, all of which exacerbate coastal flooding and can contribute to accelerated coastal erosion (NIWA, 2019). These phenomena become hazards when integrated with the human-use system: "a hazard is a function of risk, exposure and response, and if there is no human interaction, there is no hazard" (Williams & Micallef, 2009, p. 121).

Coinciding with these physical environmental impacts are a series of economic impacts, including built capital damage and loss, infrastructure disruption, business inoperability, and population displacement. Aggregated global annual economic losses from climate change for a temperature increase of ~2°C are estimated to be between 0.2 and 2.0% of income (IPCC, 2014c). Or, if we do nothing, the loss associated with climate change is projected to be 5% of global GDP annually (Stern, 2007). Still, there is much uncertainty in assumptions, and these estimates do not account for catastrophic climate changes (IPCC, 2014c). When considering coastal impacts alone, substantial differences between and within countries will exist, and losses are expected to accelerate with increased warming (IPCC, 2014c). In New Zealand, the National Institute of Water and Atmospheric Research (NIWA) (2019) estimated that 132,650 people, 2,273 km of roads, 5,572 km of water pipes, 2,457 $km^2$ of land and $NZ_{2016}$\$26.18B of buildings are vulnerable to a SLR of 0.6 m above present (2019) mean sea level (MSL).

Understanding coastal hazards associated with climate change is critical for effective policy decision-making (McBean, 2017). SLR is an issue that has and continues to emerge gradually over time, and governments have been slow to respond to the issue owing to a lack of clear or defined environmental thresholds (Boston, 2017), recognition of the full extent of the hazard, or often there may be a paucity of useful data. In contrast, disasters are swiftly responded to as affected communities have an immediate need (Jones, 19 February 2018), and insurance payments are required to replace damaged assets (Fleming et al., 2018). The current approach of reinstating assets and infrastructure behind coastal defences provides communities with a short-term solution to coastal hazards, but such an approach does not reduce the risk. In order to mitigate and adapt to an evolving coastal hazardscape, society needs to understand acute and chronic risks in isolation and combination, noting that there are cascading hazards that may compound (Moftakhari et al., 2017) over the economic long-term of 30 to 50 years. These multiple hazards can combine during extreme events augmenting dynamic natural processes, triggering cascading effects, enhancing the uncertainty of outcomes, and reducing the human response as outcomes are less predictable (Forzieri et al., 2016; McBean, 2017).

Often, poor planning and uninformed investment practices in these environments can result in community maladaptation, increasing vulnerability or exposure to future people, places, or sectors (IPCC, 2014c). However, planning resilient future coastal communities is complex. Low-probability, high-impact events, slowly changing coastal processes, cross-scale effects and path-dependent policy interventions all present challenges to decision-making (Kwakkel et al., 2015). Path-dependent policy processes can lead to society being locked-in to specific mitigation or adaptation trajectories associated with historical decision-making (van den Bergh, 2004). Similarly, funding shortfalls, poor implementation strategies or a lack of stakeholder consensus can also inhibit adaptation strategies (Robichaux et al., 2019). Conversely, societal preferences, values and interests between nature and development can also change unpredictably over time (Kwakkel et al., 2015), creating further uncertainty.

Adapting to coastal hazards in New Zealand has traditionally been undertaken by local government through structural protection or modifications to building standards (Lawrence et al., 2013). At this local scale, planning and managing at-risk coastal communities is decentralised, *ad hoc* and focused on mitigation through physical structures that protect vulnerable assets (Boston & Lawrence, 2017). Relocating assets away from hazards has generally been viewed as a last resort only after repeated failure of technical fixes (Waikato Regional Council, 2006).

## 1.2 Contribution of the proposed research

The contribution of this thesis is to understand the economic impacts of scenarios for the large-scale managed retreat of exposed communities on stakeholders through System Dynamic modelling. Dynamic adaptation through managed retreat (Figure 1.1) has emerged as a proactive, strategic, long-term management approach to relocate people and exposed assets away from harm when sea levels rise and coastal erosion shifts the shoreline landward (Cutler et al., 2020; Hino et al., 2017; Owen et al., 2018; Reisinger et al., 2015). Ideally, it allows for the evolution of coastal systems in response to future changes, both expected and unknown, thereby emphasising sustainable land-use management and development (Boston, 2017). In principle, managed retreat minimises coastal risk for communities and provides for resilient futures, but while it has been discussed and proposed by researchers, government agencies and communities (Lawrence et al., 2020), aside from isolated examples, the implementation of large-scale managed retreat has gathered little momentum (Noy & Townsend, 2020). In reality, there are many gaps in our knowledge on how to envisage managed retreat. Seldom are an array of material and immaterial costs and benefits explored to facilitate managed retreat. For example, how financing adaptation can be assessed equitably, inter-generationally and intra-generationally, what barriers need to be overcome in local planning policy, and how society maintains coastal amenities in perpetuity. This thesis proposes a new modelling framework to address these knowledge gaps by integrating the economy and the environment with scenarios of managed retreat to provide multi-scale (across space, through time, for multiple stakeholders) analyses that are seldom considered.

The thesis develops a new integrated assessment model (IAM) to define possible pathways for vulnerable communities to adapt to sea level rise (SLR) and increasing storminess through managed retreat. It draws on Evolutionary Economics, Ecological Economics, System Dynamics, Scenario Planning, and Robust Decision Making (RDM) to define Dynamic Adaptive Policy Pathways (DAPP) and improve system understanding to provide evidence that supports informed decision-making; evidence not previously available. First, it explores how historically sustainable management and development have shaped the coastal environment. From this, it develops plausible future baseline scenarios in which society maintains the status quo and communities remain exposed to coastal hazards. The baseline scenario increases damages to built capital, land losses, business and infrastructure disruption and eventually, insurance retreat. Second, the thesis investigates possible scenarios for government interventions that would enable managed retreat. It utilises economic impact modelling in the MERIT (Measuring the Economic Resilience of Infrastructure Tool) model and RDM to explore DAPP that could provide plausible sustainable futures for exposed coastal communities. A third case is also developed, which sees implementing mitigation measures by local government through coastal defence structures. Such a scenario was incorporated as its likelihood as a pathway is high and provides completeness to the analyses.

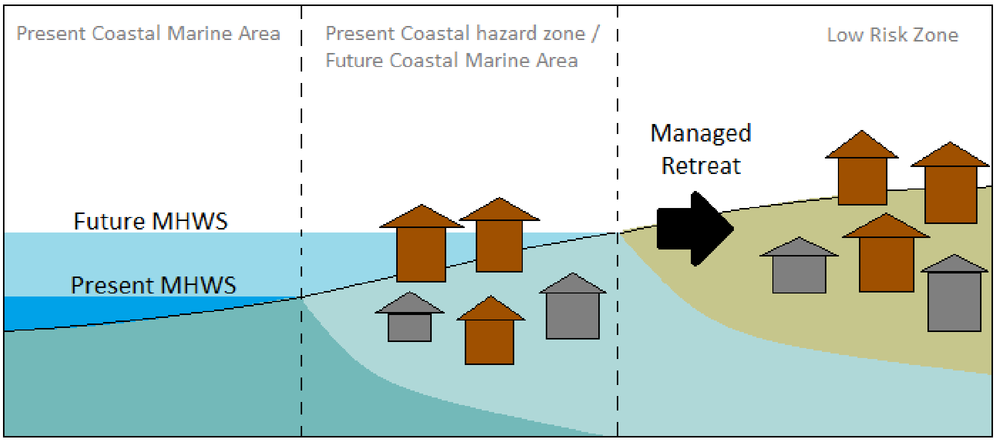



**Figure 1.1** Coastal managed retreat is the strategic relocation of assets away from a coastal hazard zone (CHZ) as the Mean High Water Springs (MHWS) increase due to sea-level rise.

## 1.3 Research Aim

Develop a new systems modelling approach to investigate the implications of coastal managed retreat scenarios through economic impact analysis.

## 1.4 Research Questions

The research poses two main research questions and two secondary questions:

1. What are the socio-economic implications of managed retreat for impacted communities and economic actors through time?
2. What managed retreat scenarios generate a beneficial regional economic impact across sectors and over time?

a) How can System Dynamics, Scenario Planning, RDM and DAPP contribute to a coordinated approach to managed retreat for coastal adaptation?

b) What strengths and weaknesses can an integrated systems simulation modelling approach provide when analysing future scenarios for managed retreat when faced with imperfect knowledge and uncertainty?

## 1.5 Thesis Structure

The thesis structure is as follows. Chapter 2 presents the theoretical framework for adapting to coastal hazards through managed retreat with a brief background on coastal hazard management in New Zealand. It also covers the evolutionary economic theory of this complex system by bridging environmental-social-economic system interactions with a view to a resilient managed retreat.

Chapter 3 introduces the conceptual framework of the thesis. It bridges the theoretical framework and methods by defining concepts to tackle living with coastal hazards or enable managed retreat. Here the connectivity of system components is introduced.

Chapters 2 and 3 include material rewritten for this thesis from the published book chapter: Eaves, A., Kench, P., McDonald, G., & Dickson, M. (2019), Balancing Sustainable Coastal Management with Development in New Zealand. In Sustainability Perspectives: Science, Policy and Practice (pp. 97-118), Springer Nature.

Chapter 4 highlights the study area for the research, showing the Coastal Hazard Zone (CHZ) spatial layout and municipal and planning boundaries. It highlights the setting of the physical environment and the exposure of coastal communities. It also describes Hawke's Bay's economy, its sectors, industries, population, household income and employment.

Chapter 5 explains the development of a new IAM called C-ADAPT. C-ADAPT uses System Dynamics, MERIT and RDM to define DAPP through economic impact analysis.

Chapter 6 presents the results of the economic impacts of the baseline scenario at a local scale using System Dynamics. It evaluates the direct risks and estimated losses from future coastal hazards and the behavioural response of communities. The chapter discusses the future of insurance in 'risky' communities and why many households choose to stay at the coast for amenity values in the face of escalating coastal hazards.

Chapter 7 examines the impacts of coastal hazards at a regional scale. Here the results of the coastal defence mitigation and managed retreat adaptation scenarios are compared. The scenarios are examined to discover the risk, direct losses and disruption and their impacts on households, industries and governments through time. Discussion of each of these sectors and the impacts follow the results.

Chapter 8 evaluates C-ADAPT outputs from Chapter 7. In particular, scenarios are evaluated using a least-regret approach which minimises the maximum amount of regret an option (pathway) might have given varying climate futures. Scenarios are compared by measuring regret to see how they stack up against each other over time. Thus, the pathway of least-regret can be determined by the scenario that performs better than the others across sectors (based on Key Performance Indicators) and time. Thus, Chapter 8 provides a timeframe for implementing a preferred scenario by utilising RDM and evolutionary economic principles to define DAPP.

Finally, Chapter 9 synthesises the research to highlight its contribution to coastal management and complex systems modelling. Here, the research questions and objectives are appraised and applied to coastal managed retreat, and the Integrated Assessment Modelling through C-ADAPT is evaluated. Lastly, the chapter outlines any research limitations and suggests future research initiatives.

# 2. A theoretical framework for coastal adaptation

Chapter two develops a theoretical framework that builds on an extensive literature review traversing a broad range of disciplines relevant to coastal managed retreat. First, it considers the physical risk to coastal communities as the environmental and economic systems evolve. Second, it examines historical decision-making through planning and policymaking within New Zealand and how this has increased exposure to the economic system. Third, it investigates the role Evolutionary Economics can play in coastal management and how to view transformational systems against a backdrop of institutional rigidity. Finally, it discusses possible mechanisms to enable coastal managed retreat by examining governance, socio-economic influences and finance.

## 2.1 The evolving risk from coastal hazards in a changing climate

This section examines the intricate relationship between hazards, risks, exposure and vulnerability of coastal communities. Simply put, risk can be expressed as the product of hazard, vulnerability and exposure (Lempert et al., 2013). Or more concisely, the IPCC (2012) defines managing the *risk* of extreme storms through *hazards*, as the potential for a natural event to cause injury, damage, or loss; the *exposure*, as the presence of people and assets that could be adversely affected; and the *vulnerability*, as the predisposition of people to be adversely affected. At the outset, it is essential to understand the scale and magnitude of the problem before solutions can be proposed. Each of these elements will now be addressed in turn to develop a consistent ontology for the thesis and illustrate any gaps in our current thinking.

### 2.1.1 Coastal hazards

Climate change reflects the climate system in a perpetual flux due to multiple interacting sub-systems exhibiting new collective behaviours that create emergent properties (Wimmer & Kössler, 2006). These changes include increasing sea-levels and more extreme and frequent storm events (IPCC, 2014b), which in turn generate more extreme waves and storm surge elevations at the coast (Komar, 2013). Climate change has also altered event probabilities, return periods, and the environmental characteristics of shorelines (Eaves & Doscher, 2015) as systems adapt to dynamic, reinforcing feedbacks such as thermal expansion and ice melt. It is viewed as a hazard where there is a risk to a human population (Williams & Micallef, 2009) which can result in death, property damage, environmental damage, damage to resources, social disruption, or disruption to the flow of essential goods and services (Fitzharris, 2007).

Coastal hazards should be understood in isolation first and then in combination with each other when analysing the complexity of intersecting environmental and economic systems. For example, SLR is a slow onset hazard that emerges gradually over time. Short-term and sectorial-isolated thinking do not efficiently address such slow-onset hazards due to their chronic nature and often lack critical environmental thresholds to act (Boston, 2017). Yet combining the slow-onset hazard with high impact extreme events can augment dynamic natural processes (e.g. ex-tropical cyclone Fehi and spring tides on the West Coast of New Zealand, February 2018 (Lee, 4 February 2018) and king tides with storm surge in Auckland (Martin & Fonseka, 01 February 2018)), trigger cascading effects (e.g. levee collapse and forced migration in New Orleans during Hurricane Katrina, August 2005 (Oliver-Smith, 2006) and flooding and power outages in South Dunedin (McNeilly & Daly, 4 June 2015)), to enhance the uncertainty of outcomes (Forzieri et al., 2016) and/or reduce the human response (McBean, 2017).

Once these historical trends in climate change and coastal hazards are recognised, it becomes possible to project future scenarios. To project future SLR to support planning and adaptation, the IPCC couples predictions from greenhouse gas concentration trajectories, or Representative Concentration Pathways (RCPs), for future emissions scenarios with past sea-level trends (Eaves & Doscher, 2015). The IPCC (2014b) high-emissions scenario (RCP 8.5 W $m^{-2}$) illustrates a future with no policy to reduce emissions; the intermediate emissions scenario (RCP 6 W $m^{-2}$) shows a world where emissions peak by 2060 at 75% above current levels; and the low emissions scenario (RCP 2.6 W $m^{-2}$), where $CO_2$ emissions peak by 2050 and global temperature warming is kept below $2°C$ (Bjornes, 2017; IPCC, 2014b). Global SLR of 0.45 to 0.82 m (mean = 0.63 m) is probable by 2081-2100 under RCP8.5 (IPCC, 2014b). When analysing the medium term (to 2050), tightly clustered RCPs allow for a prediction of between 0.2 and 0.4 m SLR (Ministry for the Environment, 2017).

### 2.1.2 Defining coastal risk

Risk results from associating each potential adverse event's negative consequences with its probability of occurrence (Foudi & Nuria, 2014) or damage caused by the frequency and magnitude of adverse events. An acceptable measure is the return period, which measures the frequency of the inundation or flooding event, or the inverse probability of occurrence in any one year, otherwise known as the Annual Exceedance Probability (AEP) (Foudi & Nuria, 2014; Lang et al., 1999). In New Zealand, the Ministry for the Environment (2017) has prescribed the 1% AEP as one approach for measuring the statistical uncertainty of hazards used in this thesis. Here the Ministry for the Environment adopts this approach as experts can calculate with reasonable accuracy the likelihood and magnitude of a 1% AEP event (Ministry for the Environment, 2017). Bosello (2014) claims that its use can lead to a precise detection of the total hazard exposure and identify vulnerable areas to multiple hazards. However, its functionality to provide an accurate assessment of exposure becomes increasingly compromised due to its limited capacity to incorporate the non-linearity of climate change (Eaves & Doscher, 2015).

Foudi and Nuria (2014) describe the risk elements as inundation extents, return periods, AEPs and estimated damages, which define hazards, risks, vulnerabilities, and exposure, as adapted in Figure 2.1 for this research. The figure illustrates how one can step through from hazards to exposure to vulnerability and finally define risk using a damage probability curve. Any risk reduction through luck or intervention is quantified using the Annual Expected Damage (Groves & Sharon, 2013) or the area under the damage probability curve (Foudi & Nuria, 2014). Projects can then be compared and ranked based in part on their Annual Expected Damage (Groves & Sharon, 2013).

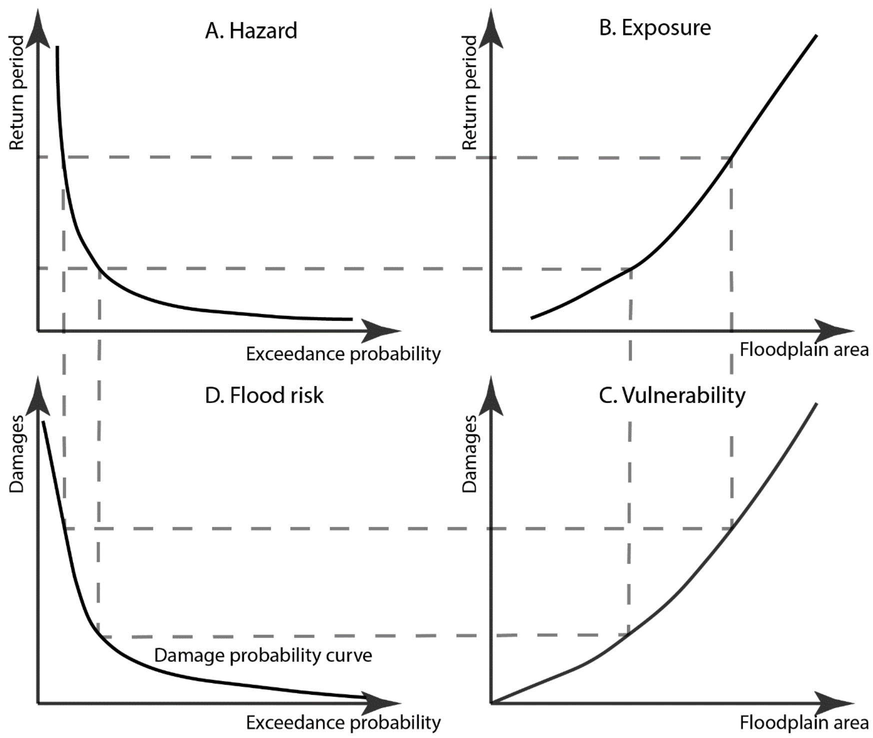



**Figure 2.1** A traditional flood risk assessment criteria illustrating the interaction between hazard, exposure, vulnerability and risk. Figure adapted from Foudi and Nuria (2014) and applied to this thesis. A shows the flood hazard as an exponential inverse relationship between the return period and the AEP. B simplifies exposure, displaying a positive relationship between the return period and the flooded area. C shows vulnerability as a positive relationship between flooded areas and damage. Finally, D depicts a damage probability curve or the exponential inverse relationship between exceedance probability and damage.

Coastal risks are intertwined with the human pressures of population growth, asset exposure through economic development and demand for ecosystem services, which will significantly increase in the decades to come (IPCC, 2014b). There is a need for risk-informed investment to reduce capital from flowing into hazard-prone areas, as there is currently a mispricing of risk-generating behaviour (Longworth, 19 June 2017). Local Government New Zealand, for example, has estimated that $1 spent on risk reduction circumvents disruption and losses worth at least $3 (Boston & Lawrence, 2017). However, such measurements only illustrate part of the problem, and risk also needs to be assessed across stakeholders, time and space to provide a more holistic view of investment implications.

Here is where a more granular approach offered by this research can be of benefit. First, the spatio-temporal distribution of impacts on stakeholders is incredibly beneficial in mitigating high-risk investment in exposed areas now and in the future. Second, stakeholders represent many sectors or industries, each with different issues and needs, which creates 'winners' and 'losers' from catastrophic events. For example, the replacement of ageing infrastructure to a more resilient location as storms destroy the network vs the farmer losing productive soil through coastal erosion. Modelling the risk and impacts on the whole economy allows for a direct comparison of the impact on stakeholders. Therefore, presenting and understanding the coastal risk associated with climate change is critical for effective policy decisions (McBean, 2017) by modelling the whole economy and advising the public.

Successful coastal hazard management aims to avoid increased risk exposure to communities. However, poor planning practices, exaggerating short-term outcomes, or a lack of consequence anticipation may result in community maladaptation, increasing vulnerability or exposure to future people, places, or sectors (IPCC, 2014b). Some decisions to mitigate increasing risks related to climate change can also limit future choices by locking in dependence on a particular mitigation measure (IPCC, 2014b). Similarly, where risk information is uncertain, government decision-makers are averse to providing information that could negatively affect property values or limit property owners' expectations (Manning et al., 2015). Exposed households and businesses are complicit in this practice in order to develop their properties or maintain a positive resale value (Cairns, 29 September 2015). Uncertainty can inhibit or stall proactive planning practices to reduce risk until more comprehensive assessments are undertaken. Underestimating risk can lead to consequences occurring earlier and with more ferocity than expected, whereas overestimating risk can incur interim penalties or lead to inappropriate adaptation (Ministry for the Environment, 2017).

Historically the local government manages coastal risk based on prescription in policies set out by the central government in New Zealand. Although, the local government struggles to develop long-term strategies to accommodate climate change impacts due to the nature of risk profiles being dynamic and uncertain and therefore require flexible and evolving strategies (Boston, 2017). Here central government could provide more pragmatic scientific guidance to local government, rather than purely providing high-level policy that is open to interpretation. A better understanding of risk can be achieved through a) risk assessments that integrate into a national risk database, b) applying a standardised methodology that enables data comparison, and c) risk modelling of future losses as per

Priority 1 of the Sendai Framework (Boston, 2017; Longworth, 19 June 2017). Therefore, addressing the drivers of risk is a three-pronged approach: 1) corrective; reduce the existing levels of risk; 2) prospective; avoid risk creation; 3) and compensatory; manage the residual risk (Longworth, 19 June 2017). This thesis aims to address points 1 and 2 by considering the implications of managed retreat.

### 2.1.3 Exposure to coastal hazards

Exposure to coastal hazards is arguably the most straightforward of the elements to comprehend, given its reliance on tangible assets located within a derived hazard zone. Exposure manifests as threats to a community when the extent of a hazardous event interferes with human occupation (Foudi & Nuria, 2014). Extreme weather events are often the catalyst for damage and loss. They are projected to increase losses and enhance loss variability worldwide, with a similar trend expected in New Zealand (IPCC, 2014b). More than 90% of all natural disasters are from storms and flooding, which account for the highest cumulative economic losses over a typical year of any hazard (World Meteorological Organisation, 2019). Unfortunately, weather-related disasters are becoming more common; the reinsurer Munich Re claimed that there were only 200 disasters in 1980, which increased to over 600 in 2016 (The Economist, 2017).

These events are becoming more costly due to the increasing frequency, construction costs and populations moving to the coast (Fitzharris, 2007; The Economist, 2017). At the national scale in New Zealand, a recent assessment of estimated exposure identified 94,000 buildings with an estimated replacement cost of $NZ\$_{2019}$6B for a SLR of 0.6 m and a 1% AEP of extreme water level (NIWA, 2019). In reality, the escalating insured losses for extreme weather events were $NZ\$_{2017}$240M from 25,000 claims of homes and businesses (Insurance Council of New Zealand, 2018). There has also been an escalating annual cost of repairing purely weather-related damages to land transport networks from $NZ\$_{2017}$20M to $NZ\$_{2017}$90M over the last ten years (Boston & Lawrence, 2017). Local Government New Zealand claims that Canterbury has the greatest infrastructure exposure to storms and SLR, followed by Hawke's Bay (2019). However, the Hawke's Bay region has the greatest water infrastructure exposure, with approximately $NZ\$_{2019}$430M exposed to 1 m (approximately 11 mRL) of SLR, including a treatment plant (Local Government New Zealand, 2019).

However, quantifying direct exposure of capital stock approach does not consider price changes due to supply changes, how disruptions to markets influence socio-economic systems or account for spillover trade effects (Sugiyama et al., 2008). These represent losses in economic activity, or flows of economic transactions, which are not typically covered by insurance. Most investigations into the economics of coastal hazards and SLR in New Zealand have focussed on asset loss (see NIWA, 2019; Reese & Ramsay, 2010). However, more focus is needed on the losses of economic activity (income, industry value-added, infrastructure disruption etc.) in New Zealand, such as an approach similar to that of Bosello et al. (2012) and Darwin and Tol (2001).

### 2.1.4 The vulnerability

The IPCC (2001, p. 6) defines vulnerability as "the degree to which a system is susceptible, or unable to cope with, adverse effects of climate change. It is a function of the character, magnitude and rate to which a system is exposed, its sensitivity and adaptive capacity". Thus, climate change creates a societal vulnerability across regions, communities, timeframes, and unique socio-economic conditions (IPCC, 2014b). The vulnerability can also relate to buildings' structural integrity described by flood fragility curves (Reese & Ramsay, 2010). Vulnerability is exacerbated in more impoverished communities, enhancing the likelihood of sickness or loss of life, while wealthier neighbourhoods are usually more at risk due to exposed capital investment (IPCC, 2014b).

Vulnerability extends beyond the direct impacts of hazards, such as flooding and inundation, to manifest after an event through higher-order impacts such as property access, commerce/economic impacts or infrastructure disruptions, which are more spatially extensive (Stephenson, 2010). Higher-order effects fall into two categories: 1) indirect effects where, for example, a reduction in supply from one firm generates reduced demand to another firm; and 2) induced effects, impacts that alter the interactions between consumers and firms (New Zealand Treasury, 2015b). Higher-order impacts are flow measures that better represent the cost of disaster as they capture the timeframe of disruption and return to regular industry operation (Boston, 2017). Non-market intangible losses also exist, such as the loss of ecosystems, biodiversity or life. Assessing these is beyond the scope of this thesis, which is focused on market-based impacts and their distribution. The reader is instead directed to Merril (2015), Thrush et al. (2013) and Franzke and Torello (2020) for a critical review of possible non-market impacts.

Business disruption or inoperability is a higher-order impact defined as any external influence on industries that prevents 'normal' production levels (Smith, McDonald, et al., 2016). It includes the physical impossibility of working at premises and any disruption to critical infrastructure services that enable operation (Smith, McDonald, et al., 2016). The typical business operation may be inhibited by a) property access due to flooding, b) loss of electricity/water/communications supply to plant and machinery, c) contaminated water on-site, d) physical plant and machinery damage, and/or e) flood remediation activity. It features a temporal component defined by the duration of the outage or the period before normal operation resumes (Brown et al., 2015). Business operation is also vulnerable to the level of service provided by utility networks and, therefore, business and infrastructure disruption are interdependent (Market Economics, 2017a). The infrastructure service level is also directly influenced by the interdependency of individual infrastructure (Zorn, 2017b).

Understanding future vulnerability, exposure, and response capacity of integrated human and natural systems is challenging due to interacting social and economic factors such as wealth and its distribution, demographics, migration, access to technology and information, employment patterns, the quality of adaptive responses, societal values, governance structures, and institutional conflict resolution (IPCC, 2014b). More focus is needed on these non-climate components of SLR, as there is generally potential for high impacts (Nicholls & Cazenave, 2010). This thesis explores many of the factors in this space to provide a high-level, generalist approach to collectively understand the intersecting pressures of coastal hazards.

## 2.2 Current knowledge-driven behaviour and traditional decision-making in coastal systems

The following section now moves beyond quantifying risk elements to analyse how society has resulted in communities being exposed to coastal hazards in the first place through historical deficiencies in managing coastal systems.

Planning for resilient coastal communities is a complex but necessary task for society to minimise risk. Low-probability, high-impact events, slowly changing environmental variables, cross-scale effects, and path-dependent policy processes can cause current decision-making to be inadequate (Kwakkel et al., 2015). For example, path-dependent policy processes lead to a society being locked-in to a specific trajectory given historical decision-making (van den Bergh, 2004). Similarly, the assumption that the future is a predictable progression of today will only enhance the current outcomes of policies. These interactions lead to cross-scale effects, whereby changes to one system result in perturbations to a dependent system (Cash & Moser, 2000). As system structures and processes change over time, a tractable and analytical approach to developing principles becomes more difficult (Foster & Hölzl, 2004).

Where decision making is concerned, there are currently issues between central government inaction on policy around slow-creep hazards and local government's lack of financial resources and leadership in New Zealand (Mitchell, 24 July 2017). However, given the decades of climate change research, it would appear a little unfair that the burden falls entirely with governments and that property owners should share in the responsibility for repair, mitigation or adaptation strategies. Yet, most homeowners cannot afford to build coastal defences, let alone purchase property elsewhere while their current property is worthless and therefore look to local government for assistance (Mitchell, 24

July 2017). When local government does take a proactive stance, as in Hawke's Bay, it seeks guidance from the Ministry for the Environment to identify the barriers and issues facing projects such as managed retreat (Sharpe, 31 January 2020). Specific issues such as who pays for what (public goods vs private goods) and the roles and responsibilities of local vs central government (local rates vs central funding vs utility agency responsibilities) have stalled local governance (Sharpe, 31 January 2020). Compounding these issues is the recalcitrance of local communities with a "no worries" or "wait and see" attitude (Schneider et al., 2020)

Nonetheless, according to Boston and Lawrence (2017), current arrangements in New Zealand are: a) *ad hoc* and *post hoc* responses insufficiently addressing pre-event resilience; b) inadequate at the integration of funding arrangements across policy sectors and tiers of government; c) inequitable at the sharing of climate change adaptation costs, both inter-generationally and intra-generationally; and d) insufficiently resourced to meet the increasing costs of adaptation. Thus, New Zealand requires policy reform, funding instruments, spatial planning, and new institutional arrangements that are flexible, future-focussed, cost-effective, fair and resilient (Boston & Lawrence, 2017).

### 2.2.1 A legacy to inherit

Management of flooding and inundation risk and erosion has traditionally relied on technical, structural solutions that have been institutionalised (Kourgialas & Karatzas, 2011) and implemented by local authorities. This approach has led to the over-reliance on engineered structural defences such as revetments and walls based on historic water levels. These structural mitigation measures can increase long-term exposure to climate change-related risks and limit future choices by generating a dependence on a particular mitigation measure (IPCC, 2014b). In their current form, structural defence measures do not conform to the principles set out in the New Zealand Coastal Policy Statement 2010 (NZCPS 2010) as they fail to accommodate coastal processes or allow for natural coastal change (New Zealand Government, 2010). Limiting environmental dynamics in such a way leads to a squeeze on coastal habitats (see Mills et al., 2016) or accelerated erosion of adjacent land at the end of defence structures (Bernatchez & Fraser, 2012). Thus, the "dominant legal, engineering design and planning practices that have been developed for responses to past and current climate conditions based on static assumptions will have to become more flexible and adapt to meet changing climate conditions" (Milly et al., 2008, p. 573). From an Evolutionary Economics perspective, structural defences can be viewed as the technological standardisation of the dominant design (Cowan et al., 2006).

These structural mitigation measures lack diverse environmental knowledge or anticipation of coastal hazards by the government, leading to societal maladaptation when the structure is no longer fit for purpose. Maladaptation can also take the form of increasing maintenance costs of exposed infrastructure assets, an over-reliance on early warning systems and emergency response mechanisms, or the continuation of risky behaviour sponsored by insurance or subsidies (Stern et al., 2014).

### 2.2.2 Legislating the New Zealand coast

Coastal land use planning in New Zealand is currently governed by the Resource Management Act 1991 (RMA 1991) and the NZCPS 2010. Previously, it was under the influence of the Town and Country Planning Act (TACPA). These Acts highlight a dominance of engineered solutions, protection of assets and 'existing use' rights of property owners. The RMA 1991 is to be repealed and replaced by three new Acts (New Zealand Government, 10 February 2021): 1) the Natural and Built Environments Act (NBA) for land use and environmental regulation. 2) The Strategic Planning Act (SPA) for legislation integration relevant to development and the requirement of long-term regional spatial strategies. 3) The Climate Change Adaptation Act (CCA) addresses issues associated with managed retreat and funding and financing adaptation. Although given the split, planning for and implementing managed retreat will require legislative consistency across all three.

Other legislation that influences the coastal zone are the Local Government Act 2002 (LGA 2002), the Public Works Act 1981 (PWA 1981), the Civil Defence and Emergency Management Act 2002 (CDEM 2002) and the Building Act 2004. However, these statutory acts are not well integrated and operate under differing time frames (Boston & Lawrence, 2017). Table 2.1 highlights the Acts and their purpose.

***Table 2.1 Historical and contemporary coastal legislation in New Zealand***

| Act | Timeframe | Purpose | Key characteristics |
|---|---|---|---|
| TACPA (Town and Country Planning Act) | 1953-1977 | • State-centred spatial resource planning. | • The utility of natural resources dominates.<br>• Extensive subdivision and structural development of the coastal environment.<br>• Many devolved councils and boards with minimal interaction. |
| TACPA | 1977-1991 | • Amended original act. | • Introduced much needed regulatory zoning for hazards.<br>• A novel emphasis on scientific investigation. |
| RMA (Resource Management Act) | 1991- | • Effects-based resource planning and management.<br>• Preservation of environments from inappropriate development while maintaining public access and ecosystems.<br>• Implicitly applies the precautionary principle.<br>• Legislatively enables the provision of the NZCPS. | • Assessment of environmental effects dominates.<br>• Mitigation of environmental impacts enables development in almost any location.<br>• Hazard and vulnerability mitigation required for 100 years.<br>• Acceptable policy, poor implementation due to stakeholder contestation |
| NZCPS (New Zealand Coastal Policy Statement) | 1994 & 2010- | • Identify coastal hazards for 100 years.<br>• Assess the risks of climate change on new and existing development.<br>• Allow for the amenity and natural character of the coastal environment. | • Historically ambiguous for local government. |
| LGA (Local Government Act) | 2002- | • Provide infrastructure.<br>• Land use plans at the annual and decadal interval with provision for public consultation.<br>• Building control.<br>• Meet the needs of future generations through the provision of services, roads and access. | |
| PWA (Public Works Act) | 1981- | • Provision of infrastructure.<br>• Allowance for the compulsory acquisition of land for public areas and infrastructure.<br>• Long-term planning, usually through cost-benefit analysis. | • It could be helpful for the provision of ecosystems and amenity values.<br>• Provides for the maintenance and protection of roads in the coastal environment. |
| CDEM (Civil Defence and Emergency Management Act) | 2002- | • Provision for emergency powers during a disaster.<br>• Enables the centralisation of power.<br>• Provides for the allocation of emergency funding and resources. | • A reactive approach to hazard management.<br>• Provides effective short-term responses in emergencies by overriding usual legislative barriers.<br>• Lack of long-term planning. |
| Building Act | 2004- | • Building regulation through the building code. | • The local government as the authority can be liable for known risk. |

Historically, many coastal developments in New Zealand were authorised under the TACPA 1953. They were established for proximity to coastal amenities and leisure, often lacking prior robust environmental assessment of hazards. Part 1 of the TACPA 1953 required the preparation of regional planning schemes with an accompanying survey of natural resources and their potential uses and values for conservation and economic development. The approach employed a static use of planning instruments through structure plans. It focussed on land as an economic 'resource', contributing to expanding residential development into the coastal environment. There was also little regard for hazard identification or scientific investigation in zoning, allowing for the easy incorporation of coastal environments into structure plans.

An example is Omaha Beach in the Rodney District, which illustrates coastal environments as resources. The Omaha Beach development started on the spit in 1971 with mitigation in the form of a 'dune stabilisation wall'. In 1975, severe erosion led to beach nourishment implemented by the council and paid for through a targeted rate. Next, a series of storms between 1976 and 1980 created more erosion. Engineers proposed a three groynes system to mitigate the hazard to protect homes from storms eroding the beach face, which was regarded as providing 'dubious' success by the Cawthron Institute. Finally, an abnormally high tide and a storm event in 1978 led to emergency remedial works and the implementation of the groyne network without the need for any environmental impact assessment. The building permit ban was lifted, and hence the council could raise rates and revenue to cover the cost of beach protection infrastructure (Barrowman, 2011; Omaha Beach Community Inc, 2017; Peart, 2009).

The central government envisaged such poor coastal management as becoming a common issue and amended the TACPA 1977 to introduce regulatory zoning and identify areas vulnerable to natural hazards (de Lange, 2006). These historical planning regimes focused less on coastal hazards and SLR and more on coastal 'resources' through farm subdivision, maintaining amenity values and preserving coastal access (Barrowman, 2011; Peart, 2009). However, in these early days, the science around SLR was still in its infancy, and therefore policy actions were not prescribed.

Post TACPA 1977 saw the introduction of the RMA 1991, which adopts a precautionary approach to decision-making. Councils grant resource or land use consents based on the premise that applicants mitigate any adverse effects and undertake an appropriate assessment of effects (New Zealand Government). This approach can lead to development on hazardous land under the proviso that the applicant remedies any adverse effects, which often leads to a technical or engineered mitigation solution (Barrowman, 2011; Komar, 2009). These 'effects' are often complex in time and space, can be beyond quantification, and are thus not simply remedied. Developers can take advantage of this and provide evidence only on straightforward mitigations (Komar, 2009). Limited knowledge and high uncertainties often mean that presiding commissioners accept the developers more simplistic worldview (Komar, 2009) rather than the complex long-term System Dynamics and coastal evolution.

Next, the NZCPS 2010 was introduced with its purpose as the sustainable management of the coastal environment (New Zealand Government). The legislation aims to limit/manage development in coastal environments by using a risk-based approach to managing hazards (Shand et al., 2015). The

NZCPS 2010 "requires consideration of areas both 'likely' to be affected by hazards (focussing on existing development) and areas 'potentially' affected (focussing on new development)" (Shand et al., 2015, p. 1). Coastal managers currently utilise the Ministry for the Environment's (2017) 'Coastal Hazards And Climate Change: Guidance for Local Government' for climate change effects and impacts. This is a non-statutory best-practice guide for local government to apply the NZCPS 2010 and the RMA 1991 (Ministry for the Environment, 2017).

Conversely to previous legislation listed, the LGA 2002 requires local government to provide communities with effective and efficient infrastructure now and into the future alongside annual and ten-year action plans for its communities (New Zealand Government). There is particular emphasis on the need for local authorities to provide functions, anticipate circumstances and provide services that meet present and future generations (Boston, 2017). This provision has seen councils' protection of many local roads and parks when they succumb to erosion and inundation, an approach at odds with the NZCPS 2010.

Governments' decision-making process around land use planning frequently results from balancing the environmental, social and economic costs of resource allocations within an adversarial legal setting of competing stakeholders until some form of consensus is reached (Gibbs, 2015). Former Hastings District Council Mayor Lawrence Yule notes that when a local government seeks to implement planning rules to manage the creeping problem of SLR, they are challenged by development interests (Campbell, 2017). Denial of the real threats of climate change and incorporating risk and adaptation into the existing management structure has inhibited progress in resilience planning (O'Brien et al., 2007). Thus, the Environment Court has chosen a halfway mediation between competing interests (Campbell, 2017). This approach to land use planning through consensus among multiple competing stakeholders for zoning changes is cumbersome, litigious (Gibbs, 2015) and often yields inadequate outcomes.

A process to this effect ensued in *Foreworld Developments v Napier City Council (1998),* where Napier City Council (NCC) imposed the principle of managed retreat through s106 of the RMA 1991 on new coastal development. NCC required mitigation of adverse effects through vesting vulnerable land to erosion and inundation with the council because of their liability given future coastal hazards ("Foreworld Developments Ltd v Napier City Council," 1998). Donating land was not a palatable situation for Foreworld, and therefore mitigation measures were introduced ("Foreworld Developments Ltd v Napier City Council," 1998). This case illustrates the local government's priority to assess their level of risk within the NZCPS 2010 and the RMA 1991 to inform their responses to coastal hazards over 100 years (NIWA, 2015).

Although not all coastal management decisions are compromised, governments may implement regulations that lead to a timely but eventual removal of 'at risk' assets by permitting occupation for the next decade or two or until shoreline retreat reaches a certain point (Hino et al., 2017). Tasman District Council used this approach through Plan Change 22 in Mapua and Ruby Bay, where it installed a Residential Closed Zone into their structure plans after a full hazard assessment of the areas (Ministry for the Environment, 2017). The Residential Closed Zone is where: subdivision is now prohibited; no new buildings are allowed; no intensification or infilling is permitted; and no building replacement is to exist closer to the shoreline (Ministry for the Environment, 2017).

Conversely, the Environment Court ruled in favour of a shorter-term resource consent to build in the coastal environment at Mahia, Hawke's Bay (Sharpe, 1 November 2020), provided houses were relocated when the sea was within 7 m of the dwelling (Sharpe, 1 November 2020).

To conclude this section, New Zealand requires policy integration, funding instruments, spatial planning and new institutional arrangements that are flexible, future-focussed, cost-effective, fair and resilient (Boston & Lawrence, 2017). Downscaling climate change vulnerabilities to national, sub-national or local scales requires introducing new tools and analytical methods that reduce uncertainties (Losada & Diaz-Simal, 2014). The relationship between coastal management and community vulnerability also needs assessment, so only practical management approaches are carried forward (Barrowman, 2011). Bridging long-term goals with increased inter-generational resiliency can be achieved by integrating longer-term plans into policy (Murray et al., 2015). To ensure these plans continue long into the future, they require general acceptance and ingrained customs through action and behaviour (Murray et al., 2015) in an iterative forum free of political coercion.

## 2.3 Evolutionary economies as adaptive systems of knowledge and information competing against institutional rigidity

This section now moves beyond an inherited legacy to address how coastal communities can develop long-term resilient goals using the alternative economic analysis of Evolutionary Economics. Evolutionary Economics is a sub-discipline of economics that applies different analytical approaches to that of the mainstream (Foster & Hölzl, 2004) which are currently missing from coastal science. Here, Evolutionary Economics allows for the analyses of dynamic systems as influences and relationships modify trajectories with new knowledge and information over time. Evolutionary Economics can then be applied to investigate coastal vulnerability and assess the implementation of adaptation planning within the policy framework. First, one must start by investigating the current state of economic analyses at the coast.

New Zealand currently uses the direct-cost method to assess vulnerability through flood fragility curves available in NIWA's Riskscape (NIWA, 2017c). It estimates asset damage over an area for a given inundation depth. This approach gives a valuable static snapshot of exposure and vulnerability to quantify direct built capital impacts. Still, it neglects price changes due to changes in quantity, and it does not consider how changes in markets influence each other, or any spillover trade effects (Sugiyama et al., 2008). It would benefit from the capacity to manage cascading hazards so that once an asset is damaged, a new fragility curve is available. Similarly, it needs regular updating of land-use, building footprints and projections for future development. Thus it is helpful to take stock today, given up-to-date asset inventories and fragility curves, but it needs to account for the temporal response of markets following a disruptive event and allowances for the distribution of impacts through time highlighted above.

Any direct-cost method also needs to account for price changes in the property market, as they change dramatically from demand, supply or regulation and need to be addressed equitably by society. Property price changes in coastal areas differ from the norm. First, knowledge of hazard assessments negatively affects property equity through declining valuations and reduced insurability (Christchurch City Council, 2015; New Zealand Government; Parker, 19 May 2017). Second, the finite supply of land resources and future population growth leads to increasing land demand, forcing adjacent section prices up (Watson, 2013) in nearby 'safe' zones. The sustainable and socially acceptable equilibrium property market price competes against speculative property investment and market uncertainty due to divergent stakeholder interests in the resource (Watson, 2013). Effective policies will require a pragmatic balance between social welfare and market regulation to achieve sustainable development through accommodating variation in built capital stock rather than the influence of representative agents.

In New Zealand, property price distortions arise due to the collision of rising property demand with supply constraints (Nunns, 2019). Demand is influenced by population growth, availability of mortgage credit, and tax policies that incentivise investment, where supply constraints occur from zoning rules limiting new subdivisions, limited redevelopment of existing sites, or the requirement of large lots and expensive features such as on-site car parking (Nunns, 2019). All of this has led to house price inflation over recent decades. Computational General Equilibrium (CGE) is one approach that is beneficial here as it applies demand-supply curves to derive a more accurate economic impact through market redistribution and define an equilibrium (Sugiyama et al., 2008). Generally, CGE only caters to the status quo regime for production functions and consumption patterns that will dramatically change with the climate and our need to adapt.

Other current approaches to socio-economic decision-making at the coast utilise Cost-Benefit Analysis (New Zealand Government), Multi-Criteria Analysis (Daysh, 2017), Real Options Analysis (Infometrics Consulting Limited, 2017a), Fiscal Impact Analysis (Freudenberg et al., 2016) and neo-classical economic theory (van den Bergh, 2004). As noted above in Section 2.1, economic impact analysis should be supplemented with hazard and risk projections, environmental impact assessments, integrated long-term modelling (Freudenberg et al., 2016), social impact assessments and an evaluation of funding streams. However, not all of these are achievable during the course of this thesis.

Current environmental policy theory applies neo-classical economic welfare theory; it strives to maximise welfare through a competitive equilibrium in the present (van den Bergh, 2004). However, climate change impacts create a problem with this model because the burden falls more heavily on future generations than the present generation (Boston, 2017). Adaptation policies can then lead to society viewing governments negatively for imposing economic restrictions to benefit future generations. Here the cumulative costs of relocation outweigh the perceived benefits, which maintains behavioural entrenchment. Therefore, governments have to balance current expenditure on welfare and capital with saving for future investment. Thus, climate change adaptation may not be logical under a neo-classical framework due to the critical determinant of cost outweighing the present benefits (Sugiyama et al., 2008). However, an economic analysis must go beyond the neo-classical framework by incorporating a behavioural aspect to solve the different and simultaneous problems coastal planners face (Sugiyama et al., 2008). This traditional framework based on rational responses needs to be extended in this context to accommodate stakeholders' behavioural responses (Sugiyama et al., 2008), which is achievable through Evolutionary Economics.

### 2.3.1 Analysing complex systems through Evolutionary Economics

Evolutionary Economics is a switch from an incentive-based perspective to analysing the economic systems' transformations (Pyka & Hanusch, 2006). This thesis utilises the approach to define and analyse interacting environment-economic systems. The traditional view of gradual growth in equilibrium is not a view held by it (van den Bergh, 2004). Instead, selection and mutation processes continually change the economy in an irreversible way (van den Bergh, 2004). These processes extend time horizons, making Evolutionary Economics appropriate for use in sustainable development and climate change research (van den Bergh, 2004).

Evolutionary Economics provides an analytical framework to examine knowledge structures and information flows (Foster & Hölzl, 2004). It allows for a reflective dynamism inherent in complex systems when new information is presented (Foster & Hölzl, 2004). This approach can be used to consider the usefulness of potential coastal management policies by analysing their effects on complex systems. Modern Evolutionary Economics came to be based on the interaction of processes of behavioural variation in a population of heterogeneous economic agents characterised by a certain degree of inertia (heredity), selection and replication characterised by (Foster & Hölzl, 2004):

1. Knowledge and information as stocks and flows, and economic systems are knowledge-based.
2. A population (aggregated) approach instead of a typological approach based on representative agents.
3. The interdependence between selection and development in systems.

Evolutionary economists view the economy as a domain characterised by non-equilibrium processes rather than a system transforming from disequilibrating shocks to a stable equilibrium state (Foster & Hölzl, 2004; Wimmer & Kössler, 2006). They do not view economics as being primarily concerned with the optimisation of resources but seek analytical representations of the economic system as processes of consolidation and change (Foster & Hölzl, 2004). Evolutionary Economics marks a more behavioural and temporal approach to analysing populations and the tendencies they display within and between complex systems (Foster & Hölzl, 2004). It also adopts an aggregated behavioural approach which contrasts with the incentive-based utilitarianism commonly used as a guiding ethical principle in Cost-Benefit Analysis desired in the decision-making process and for analysing transformations in economic systems (Gorddard et al., 2012; Pyka & Hanusch, 2006).

DeAngelis and Waterhouse (1987) define three broad states for communities based on a non-equilibrium dynamic ecology perspective that has many features in common with Evolutionary Economics, which are applied to this thesis:

1) **Stably Interactive Communities:** Populations linger around their fixed values, and any deviations caused by disturbances are counteracted by feedback that returns to the status-quo equilibrium.
2) **Unstably Interactive Communities:** Or biotic feedback instability. Populations experience reduced growth rates, internal conflict, positive feedback, and underdamped negative feedback that drives the system away from stable equilibrium.
3) **Weakly Interactive Communities:** Or stochastically dominated. Stochastic fluctuations knock populations away from typical values. The forces causing the fluctuations are stronger than any homeostatic biotic forces acting to restore the population to the status quo.

Currently, coastal communities predominantly operate in State 1. Lived values associated with place (or amenities) outweigh the minor negative disturbances caused by infrequent storms, maintaining the dynamic equilibrium for stable interactive communities. Forrester (1971) refers to lived values of an area as ‘attractiveness’, the combined effect of all factors that cause population movements to or away from areas. As stochastic storms increase and inundation becomes more severe with SLR, communities move to State 2, where growth in an area is limited due to attractiveness. An unstable dynamic equilibrium unfolds. Finally, in State 3, future coastal communities capitulate to environmental forcing, and the status quo can no longer be maintained. Communities relocate *ad hoc* to the attractiveness of other areas, which re-establishes a new population equilibrium in the new area.

Evolutionary Economics also combines the concepts of entropy, saltation, bifurcation and stochastic fluctuations from biological evolution. Entropy, disorder, or the Second Law of Thermodynamics, is adapted in this regard as an irreversible process where the economy perpetually mutates into new realms that lead to scarcity and limits the growth of economic systems as disorder increases through time (Georgescu-Roegen, 1971). Saltation is where evolution remains structurally consistent to a point at which it then jumps to a new equilibrium, induced by gradual change but leading to a profound perturbation (Rosser, 2011). Saltation can be explained as a cycle of continuous and discontinuous processes of non-linearity leading to stochastic fluctuations, which define the results of the phase transitions that manifest as bifurcation (Rosser, 2011; Wimmer & Kössler, 2006). Bifurcation is where the evolution of a system diverges into two paths based on stochastic fluctuation, eventually creating 'order through fluctuations' (Rosser, 2011). These stochastic processes that form the bifurcation do not conform to optimising behaviour or equilibrium but fluctuate due to an out-of-equilibrium state (Rosser, 2011).

We can use the coastal environment to explain these abstract states. First, entropy is consistent with what coastal communities face with SLR, resulting in scarcity and limited growth in impacted communities and systems. Then stochastic fluctuations are imposed on the system through extreme weather events that lead to coastal flooding and inundation. Fluctuations play out through perturbation, saltation or bifurcation before finally coming to rest at a new dynamic equilibrium. Saltation (abrupt evolutionary change or mutation) creates the catalyst for societal change where community entrenchment is finally overcome due to a trigger or tipping point. Tipping points may include land loss, insurance withdrawal, a significant loss of savings, or risk to physical wellbeing. Bifurcation (path separation into divergent branches) is realised when communities set plausible pathways (scenarios) for managed retreat. Finally, pathway perturbations follow as policy implementations cycle through the system over time to settle at a dynamic equilibrium or an irreversible new normal, similar to a limit cycle with growth as described by Ford (2010).

There are nevertheless criticisms of applying analogies of biological evolution to understanding economics. This is due to cultural, economic and industrial practices evolving based on their perceived success, providing a more self-aware and self-controlled evolution than purely a biological one (Nelson & Winter, 1982; Rosser, 1991). Therefore, economic systems have the control to adjust to a state of more suitability, a state which may have already existed (Nelson & Winter, 1982). In contrast, biological succession through 'survival of the fittest' usually renders its predecessor inferior and unable to compete (Nelson & Winter, 1982). This is a crucial point to note as the modelling in this research relies on this collective knowledge to enhance the likelihood of long-term adaptation success, which is often unavailable in biological evolution.

However, the irreversibility of decisions or options leads to adaptation pathway dependency. Here society is locked into the outcomes of decision-making today with the consequence that adaptation alternatives are not sought in the future (Ministry for the Environment, 2017). Path dependency is a trait of Evolutionary Economics due to many irreversible processes within complex systems (van den Bergh, 2004). According to Magnusson and Ottosson (1997), path dependency occurs for three main reasons: 1) the dependence on the initial event, 2) irreversibility of required investments, and 3) tasks and functions needed to manage the event are interrelated and, in turn, develop a sequential path. Therefore, path dependency can prove problematic for analysing multiple dynamic adaptation responses with reversibility (van den Bergh, 2004). Rosser (2011) summarised that industrial, residential, and transportation processes have very low reversibility due to the long market response duration. Such processes could hinder the uptake of managed retreat for specialised assets and networks, leading to coastal defence as the preferred short-term option. Conversely, Rosser (2011) also noted that labour and residential mobility were highly reversible, which is beneficial where managed retreat alters each industry’s labour requirements for relocation. It is, therefore, essential when analysing future options to discover if there is any potential for significant pathway dependencies such as substantial up-front costs or technological commitments that reduce long-term wellbeing (Boston, 2017). Therefore, the decision for managed retreat may be irreversible and path-dependent if the original site no longer exists due to SLR (Wimmer & Kössler, 2006).

### 2.3.2 Institutional rigidity of current practices

Not only are there systemic issues to be overcome for the successful implementation of managed retreat, but there are also institutional practices in need of improvement. The current political environment supports institutional barriers by impeding information flow within organisations and limiting jurisdictions and legal barriers to recourse (Lawrence et al., 2013). This silo effect and a lack of understanding of scientific information and communication around adaptation options and processes inhibit the local government from developing robust and informed decision-making

(Lawrence et al., 2013). The regulatory environment needs greater cross-scale integration and provision of risk and exposure information across government levels to develop a more responsive framework outside the current arrangements (Manning et al., 2015). There is plenty of scientific information available to governments regarding the risks, vulnerabilities and exposures to hazards (see NIWA, 2015, 2019; NIWA MWH GNS and BRANZ, 2012). Also, policy statements and departmental guidance summarise the actions local government should take to mitigate and adapt, such as the objectives outlined in the NZCPS 2010 (New Zealand Government), or applying a DAPP approach as outlined by the Ministry for the Environment (2017). Therefore, why do local government decision-makers struggle with choosing a precautionary approach and plan for adaptation when the central government explicitly requires it (see Policy 3, NZCPS 2010)?

To answer this question, first, there is a need for greater integration of environmental, economic and government knowledge through impact analyses to examine the direction of the status quo and adaptation strategies. Society needs to better understand extreme climatic events' economic impact and advance damage estimates for low-probability, high-damage events (Burke et al., 2016). Once known, this information needs greater integration into the regulatory environment across all governments to develop a more responsive framework and utilise strategic spatial planning that is reactive to dynamic climate changes and social values (Manning et al., 2015). Better communication of information around the impacts we face not only widens our understanding but also makes decision-makers more accountable to the public (Pearce et al., 2015). Governments can then adopt an acceptable level of risk in their decision-making rather than advocating for the risk-averse approach.

Second, adaptation costs money, and it is perceived that the cost of relocating capital to local government will stifle local economic growth short-term. Logic dictates that stakeholders and institutions wish to maintain the existing economic growth paradigm; often, society views adaptation as reducing growth because replacement and relocation are purely maintaining exposed capital with investment. However, without increasing equality or individuals' relative welfare, economic growth is not useful to society (van den Bergh, 2004). Here any gains in growth should be greater than the increase in the Consumer Price Index and the Housing Price Index in order to circulate benefits back toward households. Thus productive growth over capital growth is more beneficial to households and firms.

Third, the significant capital and labour costs of adaptation to climate change are often beyond most councils' annual budget allocations, and new funding mechanisms are needed (The New Zealand Infrastructure Commission Te Waihanga, 2021). Tony Bonne, the Whakatane District Mayor, states that they do not have enough money to deal with climate change-induced coastal erosion and inundation, and help is required from the central government (Campbell, 2017). Similarly, Former Hastings District Council Mayor Lawrence Yule claims that regional and local governments cannot deal with this matter themselves (Campbell, 2017). Thus, councils are under-resourced, lack the capability to manage dynamic change under a traditional framework and are reluctant to invest in new innovative solutions. For example, local governments can allow for funding adaptation in annual budgets to relocate their infrastructure away from hazards over successive years or redirect funding for protection works and emergency procedures. Such allocations would first have to pass a democratic council process of vested local interests and increase property rates if successful. Thus adaptation can lead to the public viewing governments negatively for imposing taxes that benefit future generations.

Finally, prudent adaptation planning is a long and comprehensive process that involves impact analyses of proposed options, public participation, and alignment of central government policies, regional policies and plans, and district plans and rules (New Zealand Government). To implement longer-term initiatives, adaptation plans to SLR will extend beyond the regular three-year political cycle and therefore need to be removed from this bipartisan process. The Sixth Labour Government has addressed this issue somewhat by creating the Climate Change Adaptation Act previously mentioned. Combining resource allocation and management, the local government's traditional role, with progressive and fluid adaptation policies, is the next step for all governance levels (Ministry for the Environment, 2017). Therefore, authorities will need to incorporate proactive economic planning for hazards instead of the traditional approach of reacting to events to manage communities' long-term futures. This is by no means a new concept, but it has undoubtedly failed to gain traction at the coast.

## 2.4 Mechanisms for change: dynamic adaptation through managed retreat that builds resilient communities

Given the issues and inadequacies previously raised, this section now changes direction to describe how society can move forward from a position of behavioural entrenchment to embrace dynamic adaptation and its subsidiary of managed retreat. Here the discourse of this thesis settles on a series of issues that can enable a successful large-scale managed retreat and sets the scene for further conceptual development in the next chapter. Yet, before delving into the issues, the context of dynamic adaptation and managed retreat is explored.

Dynamic adaptation refers to a process involving the ongoing evaluation of the vulnerability and exposure to hazards in response to future environmental changes, both expected and unknown

(Weissenberger & Chouinard, 2015). It provides flexibility through alternative options and pathways modifiable over time by stakeholders, thereby preventing poor choices from becoming engrained. Dynamic adaptation necessitates governments' mobilisation and the instalment of public policies that help populations transition away from the adverse effects of climate change (Weissenberger & Chouinard, 2015). Adaptation is specific to place and context (IPCC, 2014b); it also has essential organisational, behavioural and institutional constraints that can be as, if not more, important than technological approaches to reducing damages (Callaway, 2014).

Levels of resources, social behaviours, desire for risk reduction, and the integration of new technologies define a region's adaptive capacity (Ministry for the Environment, 2017). According to Fitzharris (2007), New Zealand retains a high adaptive capacity given its developed economy, strong science base, small and educated population, access to technology and institutional support. Establishing knowledge bases that support policy and behavioural change, developing new markets, making changes to operations, and implementing contingency measures that enhance capacity lead to a successful adaptation (Fitzharris, 2007).

More specifically, there are "three main categories of adaptation used in theory and practice: soft policy approaches, hard engineered approaches and ecosystem-based approaches" (Ojea, 2014, p. 195). Soft policy approaches involve policy and behavioural shifts (Ojea, 2014), which are the main focus of this research. This approach includes 1) accommodation through building standards and land use zoning, 2) applying a precautionary approach to planning coastal development, and 3) impact modelling of futures. Hard or engineered methods allow for the installation and maintenance of artificial structures, which are also included in this research to a lesser degree, given the appetite of local authorities and communities for their implementation in Hawke's Bay. Engineered approaches include seawalls, floodgates, dykes, revetments, offshore breakwaters, artificial reefs, and beach nourishment. These forms of protection are generally the first response to inundation issues, as property rights are not compromised. Although, over the long term, they can prove costly, ineffective and often impact amenity values and ecosystems (Weissenberger & Chouinard, 2015). Ecosystem-based adaptation allows for conservation and the enhancement of biodiversity and ecosystem services, thereby increasing resilience and reducing vulnerability (Ojea, 2014). Some options are establishing or improving dune biomass or extending estuarine salt marsh for hydraulic and aeolian sediment entrapment. Ecosystem-based approaches are beyond the scope of this thesis, as limited information is available on the economics of these approaches for the study area.

### 2.4.1 A background to managed retreat

Managed retreat combines soft policy approaches for dynamic adaptation, such as integrated risk reduction plans, land use development restrictions, financial incentives, rezoning land use or accommodating affected parties (Abel et al., 2011). It is the deliberate breach or neglect of built barriers while simultaneously relocating land use away from hazardous areas (Hayward, 2008). It requires vast construction and requires long time frames during which temporary fixes may take place while policy and plans are developed. The implementation of managed retreat is affected by the cost of relocated assets, ongoing costs of maintaining the existing situation, the cost of alternative actions, the effectiveness of current practice, and societal acceptance (Abel et al., 2011; Hino et al., 2017). Managed retreat aims to tailor local adaptation strategies with a long timeline, the needs of exposed residents met, a standardisation of funding, a streamlined participation across municipalities and stakeholders, a use for the acquired land, and installed programmes before hazards become severe (Freudenberg et al., 2016). The feasibility of managed retreat is improved by combining it with broader, sustainable redevelopment goals, such as urban regeneration and intensification (Hino et al., 2017). However, high upfront costs, behavioural entrenchment and a lack of leadership from government are but a few barriers to its implementation (Hayward, 2008; IPCC, 2014a). Many planning professionals and councils strongly advocate for managed retreat as a rational, long-term and cost-effective solution (Hayward, 2008).

Hino, Field and Mach (Hino et al., 2017) quantified that approximately 1.3 million people in 22 countries over the last three decades have been relocated through managed retreat, both voluntary and involuntarily, and pre and post-disaster. Of note, in the USA, Oakwood Beach in New York State initiated a voluntary, community-driven buy-out scheme after Hurricane Sandy (Freudenberg et al., 2016). Nearly 99 % of the community took part, totalling 326 properties (Freudenberg et al., 2016). Its success is attributed to the relay of information regarding the fiscal context, relating SLR projections to damage and dislocation costs, and increased flood insurance premiums (Freudenberg et al., 2016). Freudenberg et al. (2016) claim that incentivising all the participants to partake in the scheme by offering above pre-storm fair market value if most participants voluntarily agree is considered in the USA to be a preferred approach. This research utilised nominal market value for managed retreat.

There have only been a few small-scale attempts at a coastal managed retreat in New Zealand to date. One example is at Mokau Spit in the Waitomo District, where between 1962 and 1965, 11 sections were revested with the Crown and compensation paid (Waikato Regional Council, 2006). Another example was at Ohiwa Spit in the Bay of Plenty, where houses were lost to the sea between 1965 and 1975, and titles revested with the Crown and compensation paid for new sections (Waikato Regional

Council, 2006). More recently, Matata has undertaken a managed retreat of 34 houses for fear of loss of life from future debris flows and SLR (MacDonald, 2020). However, the approach has been met with great contestation by owners primarily because the valuations provided were below that required to buy a new house and relocate (MacDonald, 2020). The process has also exposed vulnerabilities in policy to implement the managed retreat (MacDonald, 2020).

Conversely, the Canterbury earthquake series of 2010-2011 enabled the implementation of a pseudo-managed retreat in some coastal suburbs. Coastal subsidence and liquefaction saw coastal hazard zones redrawn and a residential red zone implemented where homes were at high risk of inundation and flooding. The central government applied legislative powers to supersede the RMA 1991 for land-use zoning protocol (Canterbury Earthquake Recovery Authority, 2016). A new act was passed in Parliament to enable redevelopment: the Canterbury Earthquake Recovery Act 2011 (Canterbury Earthquake Recovery Authority, 2016). The government offered residents compensation, and uptake was voluntary to avoid litigation on the government's part (Canterbury Earthquake Recovery Authority, 2016). The process successfully relocated people away from at-risk areas. Although given the circumstances they had been through with liquefaction, repair costs and insurability, most residents were willing to relocate than risk capital loss. Before the disaster, the proactive funding through taxes of the Earthquake Commission (EQC), the government-operated natural hazards insurance agency, made land compensation possible.

Nonetheless, in an ideal scenario, authorities need to implement some initiatives to enhance the uptake of managed retreat, a theme consistent with the Federal Emergency Management Agency (FEMA) in the USA (Freudenberg et al., 2016). First, municipalities need to educate communities on the long-term benefits of eliminating risks, such as stable house prices, the security of services, and environmental or financial stress reduction. Second, government agencies should develop long-term localised adaptation plans in consultation with stakeholders and allow neighbours to relocate together if desirable through developer partnerships (Freudenberg et al., 2016; Hino et al., 2017). Third, parties need to define the financial mechanisms, compensation, negotiate contracts and define the fiscal responsibilities involved with a legal mandate (Freudenberg et al., 2016). Offering settlements above fair market value can maintain the voluntary nature of managed retreat and enhance its acceptance, given declining property prices caused by municipal hazard assessments (Freudenberg et al., 2016). Fourth, affected communities should be empowered by designing and developing the new open spaces, whether through ecosystem restoration or creating a municipal park (Freudenberg et al., 2016).

Enabling adaptation from coastal hazards requires establishing knowledge bases that support policy and behavioural change (Fitzharris, 2007). Similarly, new approaches to impact assessment, land-use regulation, investment in new locations, impact-based investing and the formation of new governance structures need an avenue for implementation into the hazard management practice to enable sustainable development (All Answers Limited, 2019; IPCC, 2014b). Some of these approaches will now be expanded on for institutional governance, socio-economic influences and finance, finally wrapping up with some issues facing managed retreat.

### 2.4.2 Institutional governance to enable managed retreat

A historical literature review of global climate change by Stern et al. (2014) discovered that adaptation policy requires transparency on risk, values, scale and governance. It also requires reconfiguring the roles and responsibilities across all government levels, thereby removing functional gaps and overlaps to achieve better integration between and within tiers of governance (IPCC, 2014b; Manning et al., 2015). Therefore, the issue here is whether governance frameworks are structured to implement managed retreat.

Kourgialas and Karatzas (2011) assert that local authorities will most likely need to: (a) delineate hazard areas; (b) acquire property in high-risk regions and relocate the residents from such regions; (c) establish or strengthen legislation and the planning of secure land-use to regulate growth in exposed areas; (d) create economic incentives; and (e) publicise flood risk information. However, Hino et al. (2017) note governments that value economic efficiency may fail to support relocation due to vast expenditure on a small community or where sovereign rights compromise its legality. Thus, uptake of large-scale managed retreat in New Zealand has not been forthcoming, as all of these tasks need to be satisfied for success. New Zealand has been particularly adept at (a) and (e), is working constructively through (c) and reacts to disaster with (b) and (d). The current devolution of responsibility should see central governments coordinate local government adaptation efforts by protecting vulnerable groups, supporting economic diversification, providing information and technical support, amending policy and legal frameworks, and providing financial support (Freudenberg et al., 2016; IPCC, 2014b).

Simultaneously, an overarching standardised and transparent central government-driven approach to economic development would provide consistency across New Zealand to manage coastal hazards (Mitchell, 24 July 2017). However, the local government and the private sector are critical actors in down-scaling adaptation for communities and managing risk information (IPCC, 2014b). Therefore, it would be wise for central government to regularly assess actions by local government and society more generally to define best-practice at the national level, thus providing a feedback loop of knowledge from the bottom-up. Concurrently, a top-down feedback loop should also exist for local governments' procedural application of central government policy. Although care is needed here, a one-size-fits-all policy is not always appropriate in New Zealand, given the diversity of environments and communities.

Limitations of spatial scale also exist between regional and city/district planning and therefore integrated local government spatial planning is necessary (Grace et al., 2018), which accounts for not only economic growth but climate change adaptation. Between authorities, integration is necessary as risk reduction is the regional council's role through their Regional Policy Statement, while spatial land-use planning and development is the role of the city/district council (Grace et al., 2018). Thus, knowledge of implementing land-use rules is held by city/district councils, but the ability to apply them to reduce risk resides with the regional council (Grace et al., 2018).

Grace et al. (2018) expand on the previously mentioned Plan Change 22 with some amendments to the RMA 1991 that could enable managed retreat and risk reduction through amending regional rules to:

1. only allow existing uses, such as buildings, to be set back on the section following a disaster;
2. require existing uses such as dwellings to have a resource consent that is consistent with the timing of SLR;
3. or turn existing uses into a prohibitive activity.

However, this last point carries a timing problem. It is challenging to introduce a prohibited activity rule ahead of the risk becoming significant, as outlined under Section 85 of the RMA 1991 (Grace et al., 2018). Thus, legislative change is required to enable managed retreat before the risk is seen as significant (Grace et al., 2018). Such legislative changes are anticipated when the new Climate Change Adaptation Act comes into existence.

Implementing institutional spatial planning instruments such as land zoning and structure plans provides certainty for future resource management by minimising risk. Activities are centred away from hazard zones through statutory documents. Development setbacks and building restrictions that incorporate shifting AEPs can also limit new development and re-development threatened by coastal hazards (Eaves & Doscher, 2015; Scouler, 2010). Governments should provide structure plans responsive to dynamic climate changes, social values (Manning et al., 2015), land supply scarcity, population and trade dynamics with managed retreat in mind. Thus, accounting for the reinforcing feedback associated with property loss from SLR, which leads to higher demand for land and capital alongside economic growth. Within this regime, it is essential to undertake regular economic impact assessments to inform markets of changing risk profiles and provide robust assessments of economic activity expectations to stakeholders. Whatever approach is selected, it is important that it accounts for the behaviour of informed communities, the unpredictability of the environment and the often counter-intuitive behaviour of institutions and markets.

Finally, the length of long-term plans, or temporal scale of governance, needs adjustment to facilitate managed retreat. Currently, a 'long-term' plan has an outlook of 20-30 years (e.g. the Auckland Plan 2012) rather than up to 100 years (Murray et al., 2015), which is the length of an assessment under the NZCPS 2010. Incorporating longer-term plans into the legislative framework facilitates bridging long-term goals and increasing intergenerational resiliency (Murray et al., 2015). Amalgamating these plans with long-term risk analyses, risk management plans, adaptation strategies (including limitations and worst-case scenarios) and reporting on long-term policy targets provide avenues for legislative amendment (Boston, 2017; Jevrejeva et al., 2014). However, when applying an integrated assessment approach, the reliability of economic analyses on which governments can act becomes increasingly unreliable as the time horizon of analysis extends due to increasing uncertainty. Therefore, a pragmatic balance is needed when integrating environmental and economic planning.

### 2.4.3 Socio-economic influences on managed retreat

Socio-economic influences such as income, wealth, business and infrastructure disruption, and amenity values also define future development trajectories for coastal communities. Similarly, values placed on health, safety, belongingness, community cohesion, tradition, attachment to place and self-actualisation determine how communities adapt (Barnett et al., 2014; Graham et al., 2014). Understanding how adaptation policies impact the diversity of lived values within the community can enable distributively fair policies (Graham et al., 2014). Although finding consensus on adaptation decisions is difficult when there are different values (Barnett et al., 2014). Fortunately, the social decision-making process is increasingly quantified through economic analyses by logically applying accounting conventions on values (Gorddard et al., 2012).

In particular, understanding coastal amenity values enables assessing the intangible impact on communities of coastal hazards and any managed retreat. Accounting for amenity values can take the form of contingent valuation or society's Willingness to Pay (WTP) for non-market environmental goods and services. Valuation is by assessing what value an individual may place on specific environmental changes to capture attributes and account for them in an economic manner (Brouwer & Schaafsma, 2013). Thus, future environmental changes are attributed to welfare gains or losses and addressed by their WTP, their willingness to accept loss (WTAL), or be compensated after a disaster (Brouwer & Schaafsma, 2013). The expectation is that people are risk-seeking when their decision contains potential losses with low probability, but high-impact outcomes result in behaviour motivated by a desire for security (Kahneman & Tversky, 1979). This dichotomy in non-market valuation is increasingly leading us to reassess the government's role as solely responsible and, in turn, accountable for flood risk (Brouwer & Schaafsma, 2013).

Non-market valuation of coastal amenity value can be applied to managed retreat through hedonic pricing. Hedonic pricing is where the benefits of a location are observed through changes in the real estate market (Daniel et al., 2009; Ojea, 2014). A housing unit is considered a differentiated market good represented by a basket of qualitative and quantitative characteristics (Daniel et al., 2009). The implicit value of a characteristic, in this case, locational amenity, can be determined through the partial first derivative of the properties' sales price (Daniel et al., 2009). This approach follows that of Filippova (2009) for the influence of sub-markets on water-view house price premiums and Filippova et al. (2020) for the influence of future SLR on property values. However, as stated by Daniel et al. (2009) and Filippova et al. (2020), the hedonic pricing techniques include a potential bias as property owners may have a subjective perception of the level of risk a property may face from high-impact but low-probability events. Therefore, it is often difficult to differentiate the positive influence of coastal environments and the negative influence of coastal hazards.

"People who are socially, economically, politically, institutionally, or otherwise marginalised in society are especially vulnerable to climate change and also to some adaptation responses" (IPCC, 2014b, p. 50). Rarely is this heightened vulnerability due to one cause; it is more likely the product of interconnecting social processes resulting in inequalities in socioeconomic status, income and exposure (IPCC, 2014b). These vulnerabilities are exacerbated by a lack of affordable housing in 'safer' areas or a lack of economic resources to facilitate relocation (Freudenberg et al., 2016; Hayward, 2008). However, given the allure of coastal living and the private amenity value of waterfront property, it is not always poor or marginalised, but 'rich' stakeholders with a high adaptation capacity (Gorddard et al., 2012; Weissenberger, 2015). Understanding these intersecting social drivers can enable individuals, households, and communities to move towards resilience through managed retreat (IPCC, 2014b).

### 2.4.4 Financing adaptation

Governance around climate change adaptation in New Zealand also focuses on the public sector's legal obligations regarding who pays for managed retreat (Tombs & France-Hudson, 2018). Proactive finance and funding are critical to implementing policies. Initiatives to address the high costs of managed retreat need to be discussed at the central government level to enable long-term statutory funding mechanisms (Boston & Lawrence, 2018) with further deliberation at the regional and local levels. However, budgets must balance, and therefore issues may arise where the provision of government funding may lead to a restriction in services provided elsewhere. Also, a balance is required to proportion the financial burden paid by current and future generations. The last two centuries have seen governments increasingly perform a risk management role for society, such as disaster relief, environmental protection, disaster insurance and social services when there is a systemic failure with the private provisioning of goods and services (Moss, 2002). Given this ideology of governments as the risk manager on behalf of communities, there is little reason to assume that this role will not continue for climate change adaptation; the fundamental issue is how they will go about it (Stern et al., 2014).

Therefore, relocation finance through funding mechanisms needs to be analysed through a multi-sectorial approach to implement managed retreat. Finance is incorporated in two ways; first, given the consequence of the disaster, communities need reactive financial relief to survive storm damage, usually covered by insurance companies. Second, adaptation strategies require proactive funding to generate new capital. Where insurance is available to impacted coastal properties, funding for replacement or relocation generally comes from national or global companies with support from the public insurance provider EQC. Conversely, where insurance is not available, capital losses to impacted communities lead to a permanent net loss to the New Zealand economy, which can have further ramifications to leveraged investments on the impacted capital. Thus, funding managed retreat is a prudent option to avoid a significant loss to the national economy.

#### *2.4.4.1 Insuring risk*

When expanding on the first point above of reactive financial relief, it is important to describe insurance as a current mechanism for risk management briefly. Simply put, insurance acts to transfer and redistribute risk rather than lessen it (Boston & Lawrence, 2017). Thus, risk transfer to insurance schemes increases proportionally to the size of the ensuing loss and the likelihood of consequence (Middleton, 2016). "The insurance industry argues that greater use of risk-based premiums, in tandem with a requirement for preventative measures as a precondition for insurance cover, can act as a good incentive for raising awareness, adapting to and preparing for the risk faced" (Murray et al., 2015, p. 452). Therefore, by default, the insurance industry becomes the key driver in reducing potential human exposure and the financial costs of disaster through market withdrawal (Murray et al., 2015). Such was the case in Christchurch after the earthquake series, where the rebuilding of many coastal properties of low elevation was decided by insurance companies.

Similarly, unfavourable insurance premiums and excesses can also discourage development in high-risk areas as policies become unpalatable for households and firms, leading to cancellation. Because insurance policies communicate probabilistic risk (Freudenberg et al., 2016), they enhance vulnerability through annual policy termination when the probability of claims is high (Boston & Lawrence, 2017). Similarly, risk pooling becomes obsolete with more granular assessments through risk-based premiums, extreme excesses or insurance withdrawal for an individual property. These granular assessments can lead to uninsurable 'stranded assets' (Allen et al., 2015).

New Zealand households also rely on the public insurer, EQC, for flood damage or loss. New Zealand is fortunate to have a government agency solely mandated to provide relief from natural disasters, thus providing contingency funding and long-term financial resilience against disaster (Earthquake Commission NZ, 2019). However, where storms are concerned, EQC only covers the remediation of land or the provision of a modest nearby section in the case where the land is uninhabitable (Earthquake Commission NZ, 2019).

Stern, Jotzo and Dobes (2014) note that for an insurance system to be efficient, risk pooling for uncorrelated events requires perfect information available on risks to both the insured and the insurers. Events must also be fortuitous; in other words, they have reasonably foreseeable outcomes, and pre-existing conditions are uninsurable (Stern et al., 2014). Therefore, Stern et al. (2014) argue that SLR is predictable and gradual and should be treated as 'losses in progress' and classified as uninsurable. Insurance can also create a 'moral hazard', whereby the insured neglect any risk mitigation due to the availability of compensation or fail to inform the insurer of any foreseen risk (Stern et al., 2014). These issues are also prevalent where government insurance programmes or compulsory insurance exist (Stern et al., 2014).

#### *2.4.4.2 Funding adaptation*

Current policy in New Zealand is devoid of practical guidelines on financing managed retreat (Boston & Lawrence, 2018). There is also an issue of investment decisions having non-simultaneous exchanges of immediate costs with distant benefits, with future returns depending on outlays today (Boston, 2017). The longer the temporal gap between costs and the realisation of benefits, the greater reluctance of governments (and stakeholders) to invest (Boston, 2017). Albeit society needs to move beyond catering for the current generation. Some possible funding instruments include bonds, taxes, charges and subsidies (general or targeted rates), public-private partnership (PPP) finance, loans, government grants and funding, improved resource pricing, regulations and risk transfer mechanisms such as insurance (Boston & Lawrence, 2017; Cunniff & Meyers, 2017; IPCC, 2014b; Kartez & Merrill, 2016; van den Bergh, 2004). As the thesis focuses on bonds and rates, a brief background on each is to follow.

Bonds are debt instruments widely used to generate private capital to finance new projects (Hall & Lindsay, 2017). There are many different types of bonds; of particular interest are climate and resilience bonds. Climate bonds mobilise investment capital to transition to a low carbon, climate-resilient future by driving down the capital cost of climate solutions (Climate Bonds Initiative, 2019). Similarly, resilience bonds allow for investment that provides for a proactive transition to resilient assets and infrastructure (Kartez & Merrill, 2016). They differ in that resilience bonds produce a rebate to the owner based on resiliency, i.e., reductions in expected loss through risk modelling or more resilient infrastructure projects (Cunniff & Meyers, 2017; Kartez & Merrill, 2016). However, both types of bonds enable prioritising adaptation actions and risk reduction (Climate Bonds Initiative, 2019; Kartez & Merrill, 2016). Climate and resilience bonds effectively mobilise capital from the private sector (Kartez & Merrill, 2016) and provide investors with certainty that their long-term investment focuses on sustainability. However, due to the size of the capital investment required, their use for large-scale managed retreat requires government intervention.

Another means for governments to raise revenue for public use is through taxation. At the central government level, adaptation can be funded through a general tax take without special fiscal instruments. Whereas at the local government level, funding is by way of 1) a property tax or council rates, 2) or fees and service charges for public goods or services (annual general charge) (Kartez & Merrill, 2016). Taxes are effective as they provide better incentives and create standards that modify human behaviour and create more efficient outcomes (van den Bergh, 2004). Governments are already designed to manage these types of financial transactions, and therefore set-up costs are relatively small and procedural uncertainties reduced. However, the acceptability of taxes depends on communities' perception of the personal benefits of any new adaptation scheme (Kartez & Merrill, 2016). Targeted rates are also an appropriate mechanism available to local governments for funding adaptation. The burden of paying the rates falls on those who directly benefit from the process.

### 2.4.5 Barriers to managed retreat

Dynamic adaptation to hazards through managed retreat has its issues primarily due to capital costs, the behavioural entrenchment of communities and priorities of governance. Many stakeholders in hazardous areas vehemently oppose managed retreat (Hayward, 2008). The opposition can be due to high up-front financial costs, the loss of place association, community life disruption and the loss of assets of emotional value (Boston & Lawrence, 2017; IPCC, 2014b). However, understanding the bigger picture is crucial to prevent further social and economic loss by removing vulnerable assets and communities, which increases coastal resiliency (Dyckman et al., 2014).

As expected from a long-term and large-scale option seeking to install community resilience, there are multiple barriers to managed retreat (Table 2.2). Historically, it has been viewed as a high-regret option that is not easily reversed; a finding from Hino et al.'s (2017) evaluation of 27 recent cases globally. Often the cost of land to relocate to is more expensive than the hazardous land, often leaving some residents needing to re-mortgage their homes (Fleming, 24 October 2017). Lack of financial compensation makes relocation near impossible for the poor. Where financial compensation exists, managed retreat can also be stifled by urban boundaries that concentrate development into allowable zones (Freudenberg et al., 2016). This land supply restriction creates scarcity of developable land, which increases property values in restricted zones (Freudenberg et al., 2016). Therefore, as mentioned earlier, the local government must amend structure plans to rezone residential boundaries to mitigate increasing property values brought on by scarcity.

***Table 2.2 Historical barriers and enablers to managed retreat***

| **BARRIERS** | **ENABLERS** |
|---|---|
| The non-refundable economic cost of relocation for populated areas [1] | Application of international research and best practice [2] |
| Economic losses from the inundation of fertile coastal agricultural land (IPCC, 1990) | Consistent methodologies for risk assessment with frequent updating of new information [2 3] |
| Climate science resolves outcomes at a multi-decadal timescale, whereas adaptation needs to respond in the interim [4] | Shared information and experiences across councils [2] |
| A lack of scientific input into the decision-making process [5] | Practitioners linked across scales of government [2] |
| Legislation and regulation alone do not produce a viable result [6] | Centralised funding for risk assessment [2] |
| A negative perception of local government due to hazardous area zoning and development constraints [6] | Contingency funding for capacity development and retreat [2] |
| Disaster relief funding is seldom used to acquire exposed coastal property [6] | Sincere public engagement [2 3] |
| Entrenched property interests [6] | A rational approach advocated by planners [7] |
| Local governments' need for continued growth [6] | Buy-out compensation [8] |
| Shifting priorities and values of governments and weak governance relationships [3] | Supply of new land [8] |
| Long-term political and institutional agreements [9] | Long-term planning on natural hazards which integrates across levels of governance [2 3 7 8] |
| Variability of data quality within and across regions [2] | Community-created open space design for hazardous land [8] |
| Evolving climate change risks [2] | Mechanisms to share information and experience [3] |
| Differences in professional opinions [2] | Fostering and creating social networks based on values [3] |
| Limited assessments, methodologies, reduction and databases on risk [2 3 10] | |
| Denial of climate change [3] | |
| Opposition to the impact of hazard zones on property values [8] | |
| Risk mitigation through structural protection funded by rates [2] | |
| Perception of adequate control of land uses in at-risk areas [2] | |
| Lack of consistency and fleixbility in district plans and decision-making [2] | |
| Significant up-front financial costs [11] | |

| | |
|---|---|
| Loss of amenity values, place association and community disruption [8,12] | |
| Lack of statutory consistency and misalignment [2,3] | |
| Inequality of representation [3] | |
| [1] (IPCC, 1990) [2] (Lawrence et al., 2013) [3] (Manning et al., 2015) [4] (Barnett et al., 2014) [5] (Tribbia & Moser, 2008) [6] (Dyckman et al., 2014) [7] (Hayward, 2008) [8] (Freudenberg et al., 2016) [9] (Cash & Moser, 2000) [10] (Longworth, 19 June 217) [11] (Boston & Lawrence, 2017) [12] (Boston & Lawrence, 2017) | |

## 2.5 Final remarks

Historically, populations worldwide have relocated in response to altered climate conditions (Hsiang et al., 2017). More recently, increasing populations have seen the increased settlement of marginal lands, resulting in enhanced climate change-related economic losses (Hsiang et al., 2017). Peacock and Ragsdale (1997) state that exposure to coastal hazards leading to disaster indicates a failed social system that should be able to prevent such losses from occurring proactively. Alternatively, resilient communities that eliminate future risk by developing comprehensive long-term plans reduce social and economic vulnerability brought on by climate change. Here sustainable development seeks to break the cycle of disaster > damage > repair > disaster when marginalised communities return to the status quo following a hazardous event (Tobin, 1999). These plans require diligent scientific investigation coupled with robust economic analyses of plausible future options openly and transparently to provide fairness, equity and integrity to the decision-making process.

Managed retreat offers a possible path to resilience through the planned relocation of assets and communities away from hazards, or sustainable development, thereby eliminating exposure to the human-use system. Yet, given a lack of uptake at a large scale and few analytical constructs of robust implementations, this research seeks to address these gaps by analysing the local and regional economic impacts of managed retreat over time against the status quo scenario. Ideally, managed retreat eliminates future damages and future climate change costs (Burke et al., 2016; Freudenberg et al., 2016). Although managed retreat may not always be rational, given its cost, it must go beyond this by incorporating long-term economic behaviour to address cascading and inextricably interconnected problems (Sugiyama et al., 2008) presented by SLR and multiple simultaneous hazardous events.

# 3. A new conceptual framework for managed retreat

Chapter three now takes the theoretical knowledge reported in Chapter two and applies it to a set of concepts to develop a modelling framework. Here the thesis defines a conceptual framework to analyse complex coastal systems using Evolutionary Economics, System Dynamics, Scenario Planning and RDM to assess the usefulness of intervention scenarios that enable DAPP for coastal managed retreat. First, it applies systems thinking through System Dynamics and Evolutionary Economics to determine knowledge and behaviour common in coastal communities and environments. Second, it develops an ontology between Scenario Planning, RDM and DAPP to develop, understand and assess futures. Finally, it discusses the value of economic modelling of futures through MERIT and integrated assessment modelling.

## 3.1 Applying systems thinking to determine knowledge and behaviour in dynamic coastal environments

Understanding behaviour and transformation in these dynamic coastal environments are necessary to plan for resilient futures. Systems thinking and Evolutionary Economic analysis provide a valuable approach to understand the dynamic equilibria of economic indicators, systems adjusting to new knowledge and information, a holistic approach to phenomena, and evaluations over time (Foster & Hölzl, 2004; Hodgson, 1998).

### 3.1.1 Introducing systems thinking

Systems thinking views the world as a holistic and complex system where everything is interconnected (Sterman, 2001). Sterman (2013) describes two foundations of systems thinking as 1) the development of mental models to form and change a model structure by accounting for feedback, testing and simulation; and 2) a system structure that generates behaviour, where dynamics result from knowledge, information and decision rules. These two foundations form the basis for modelling dynamic complexity in this research.

Unfortunately, the human mind struggles with interpreting behaviours in social systems, or multi-loop non-linear feedback systems (Forrester, 1971) and therefore, computational resources are helpful. In particular, dynamic complexity is an issue at the coast because non-linear coastal hazards affect exposed communities independently, creating many diverging approaches and tensions on managing the risk (Komar, 2007). Forrester (1971) described how the evolution of the human mind had not kept pace with recent advancements in the complexity of dynamic behaviour in our social systems. This certainly helps to explain the diverging views and behaviour of stakeholders at the coast. Hence well-intentioned efforts to solve complex problems (such as coastal managed retreat) with mental models alone can lead to unanticipated side effects and provoke unforeseen reactions (Sterman, 2001). These side effects or reactions can result in policy resistance or defeated interventions designed in response to the problem itself (Sterman, 2001). Sterman (2001) claims that dynamic complexity can arise in a system due to the non-linearity of cause and effect, evolution and adaptation, time-dependent trade-offs, path-dependency (irreversibility), or policy resistance and embeddedness. Managing dynamic complexity with mental models alone is thus seemingly difficult and adopting a computational System Dynamics approach is beneficial.

### 3.1.2 Developing understanding through System Dynamics

System Dynamics is a computer-aided approach to policy analysis and design that applies to complex and dynamic problems arising in economic, social, managerial or ecological systems (Macharis, 2000). In particular, System Dynamics is appropriate where any system exhibits interdependence, mutual interaction of key variables, information feedback between variables, and circular causality of the system in question (Macharis, 2000). Like Evolutionary Economics, System Dynamics seeks to integrate knowledge from diverse disciplines to understand complex systems and inform decision-making (Macmillan, 2012). It attempts to identify all influential agents, causal relationships, stocks (levels or accumulations) and flows (transactions), information feedback loops, time delay impacts and system perturbations to map the system structure for simulation modelling (Ford, 2010; Sterman, 2001). It also allows for the integration of Evolutionary Economic theory into a computational framework. System Dynamics models can then explore multiple future scenarios when communities face evolving risk and uncertainty and apply this new knowledge to decisions and policies (Lyneis, 2000; Macharis, 2000). System Dynamics enables the integration of semantic theory (meaning) with the syntactic structure of models (logic) for adaptation planning.

Modelling multi-loop non-linear feedback in complex systems is helpful for long-term decision-making and understanding the reinforcing feedback loops associated with climate change and, in turn, managed retreat interventions. System Dynamics modelling requires discovering all influential feedback processes, with all dynamics arising from the interaction of reinforcing (positive) loops and balancing (negative) loops (Sterman, 2001). Insights into system behaviours, such as non-linearity or cycles, are discovered through variable manipulation, simulation iteration and parameter sensitivity analysis (Ford, 2010). The key is to simulate a general pattern of behaviour rather than discover exact values (Bosomworth et al., 2017). Nonetheless, the quantification and comparison of trends are employed here to prove the success or failure of scenarios. Similarly, causal relationships, thresholds and tipping points become apparent by discovering a dynamic equilibrium, a new steady-state or an extreme response resulting from the presence of reinforcing feedback loops.

System Dynamics has been used to unravel many policy problems. It was used to analyse economic and environmental scenarios for policy and planning processes with long time frames by Forrester (1961, 1971), Meadows, Meadows and Behrens (1972) for limits to growth, and Ford (2010) for modelling the environment. System Dynamics has had broad appeal in New Zealand. Bodger and May (1992) adopted this approach to compare the global energy market with the local market; McDonald (2005) applied it to understand future development trajectories in Auckland's urban economy from an ecological economics perspective; Macmillan (2012) illustrated its use in participatory policy analysis for public health. Smith et al. (2016) modelled cascading economic consequences for the tourism industry from extreme events and market failures following the Christchurch earthquakes. Van den Belt et al. (2012) applied System Dynamics to create a mediated model of coastal issues in Tauranga. More recently, McDonald et al. (2020) have used System Dynamics to understand issues in the New Zealand residential construction pipeline.

### 3.1.3 Causal Loop Diagrams for climate change and managed retreat

System Dynamics starts with causal mapping, or Causal Loop Diagrams (CLD). Causal mapping of variable relationships and multi-loop non-linear feedback can provide a conceptual framework of system relationships, influences, external factors, lags and delays on which to build computable System Dynamics stock-flow models (Forrester, 1971; Smith, Orchiston, et al., 2016). CLD are usually built from preliminary information available through previous studies, technical reports, literature reviews or focus groups (Smith, Orchiston, et al., 2016). These diagrams can contain activity models, natural systems models and valuation models (Turner, 2000). Figure 3.1 shows the global CLD for climate change and coastal hazards developed by the author for this thesis. It illustrates a highly simplified representation of the current reinforcing (positive, +) feedback of climate change and its effect on the economic system and any balancing (negative, -) feedback through government intervention. It highlights how climate change reinforces emissions through increased consumption (repair, rebuild, replace) after frequent damage and loss. The increased emissions lead to increased greenhouse gas concentrations in the atmosphere, enhancing radiative forcing to alter the hydrological cycle by increased thermal expansion of the oceans, ice melt, extreme weather events and precipitation (loop 1). However, to balance climate change, society has installed governance arrangements (such as the Paris Agreement in 2015) to mitigate emissions (loop 2).

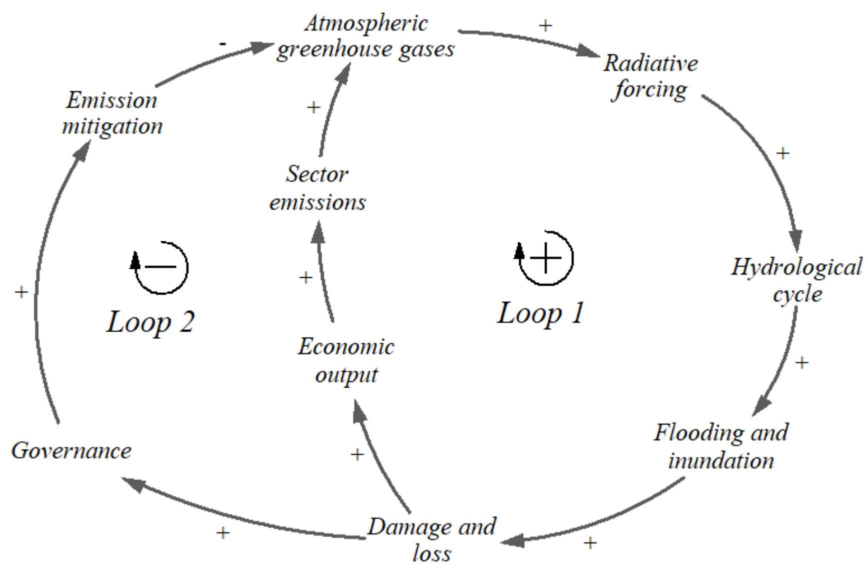



**Figure 3.1** The simplified global-scale Causal Loop Diagram (CLD) applied to this thesis. It illustrates the current positive reinforcing (Loop 1) feedback within the environmental and economic systems at the coast under climate change. Loop 2 illustrates possible balancing feedback through government intervention and emissions reduction.

Modelling climate change in complex systems at the coast is a significant technical challenge. Local-scale interventions to reduce emissions do not resolve global positive reinforcing feedback outlined in Figure 3.1. The timing and magnitude of SLR are driven by the global population's ability to curb emissions sooner rather than later to minimise local effects (Stern, 2007). Thus, the balancing system feedback of loop 2 to reverse the scale and magnitude of climate change requires multilateral intervention over many decades. For a global assessment, Hasselman (2010) has outlined a policy-driven System Dynamics model appropriate for the economics of climate change mitigation. In contrast, the research presented in this thesis aims to model local and regional-scale impacts and interventions but is mindful of reinforcing global feedback, which drives SLR and increasing storminess.

The CLD is expanded to account for greater system complexity (Figure 3.2). Government, household and industry asset stocks are damaged or destroyed, which leads to an increase in demand for construction and resources. Increased construction (and indirectly business activity) increases emissions and thus coastal exposure creating loops 3, 4 and 5. Specifically, Loop 1 illustrates reinforcing feedback present in the oceans to enable SLR. Loop 2 shows how coastal flooding leads to the damage of capital stock, in this case, government stock, which leads to policies that mitigate emissions and reduce the accumulation of greenhouse gases. Loop 3 shows the damaging impact of coastal hazards on the government's asset stock, leading to increased construction and, in turn, increasing atmospheric greenhouse gases. Similarly, Loop 4 accounts for these changes but for the household sector. Finally, loop 5 traces damages to industry capital stock requiring rebuild, which again enhances greenhouse gases.

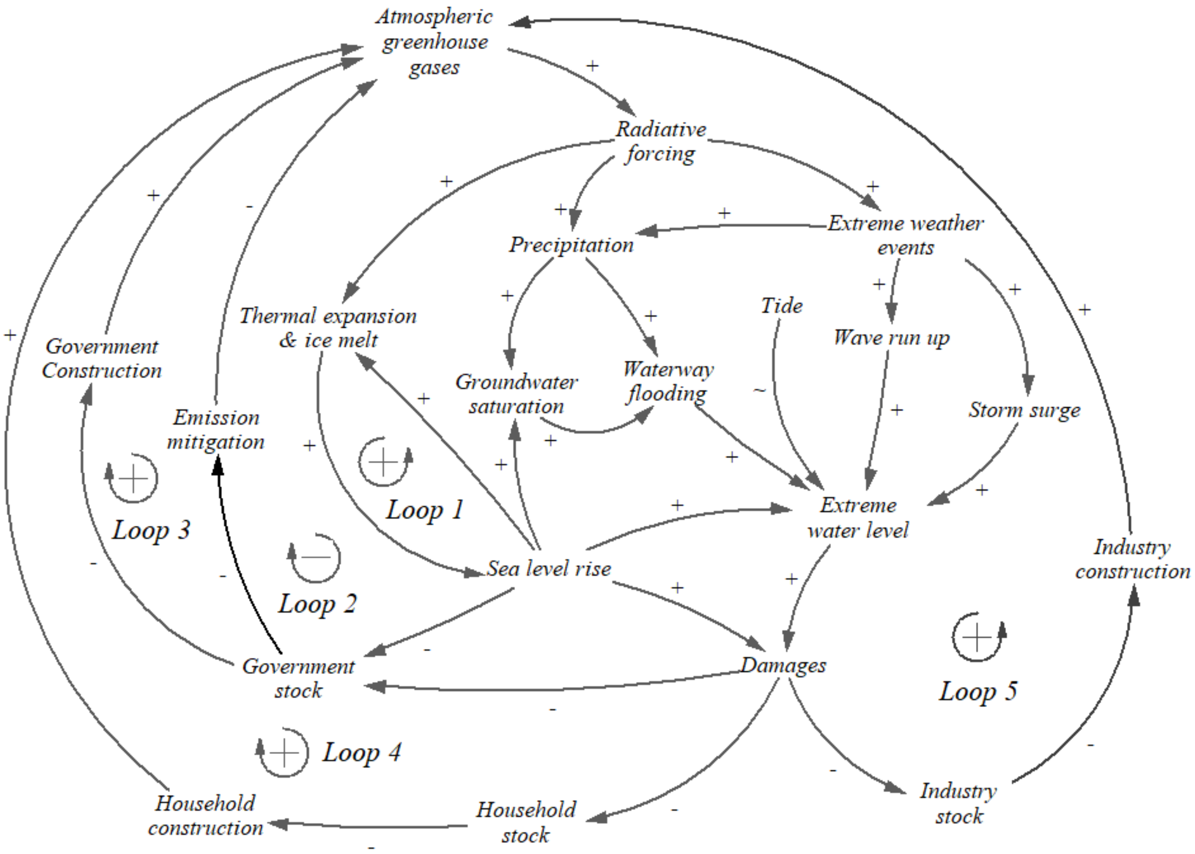



**Figure 3.2** The detailed global-scale CLD applied to this thesis. Here the CLD depicts interactions that are more complex in the environment-economy system with climate change than in Figure 3.1. Built capital stocks for households, industries and government are negatively impacted, leading to increased construction (repair, rebuild, replace). Reinforcing (+) and balancing (-) loops illustrate system feedback that enhances or reduces climate change.

Finally, the CLD in Figure 3.3 depicts the environment-economy system under baseline (i.e. status quo) conditions at the regional scale where government intervention is not forthcoming, but decisions around adaptation still need to be made. Under this baseline, where insurance is available, firms and households repair and remain in-situ following floods (loop 1). Where insurance is not available, firms and households must choose to repair and remain or relocate away *ad hoc* (loop 1 or loop 2). Simultaneously, land (natural capital) is removed from the human-use system forcing a retreat (loop 3).

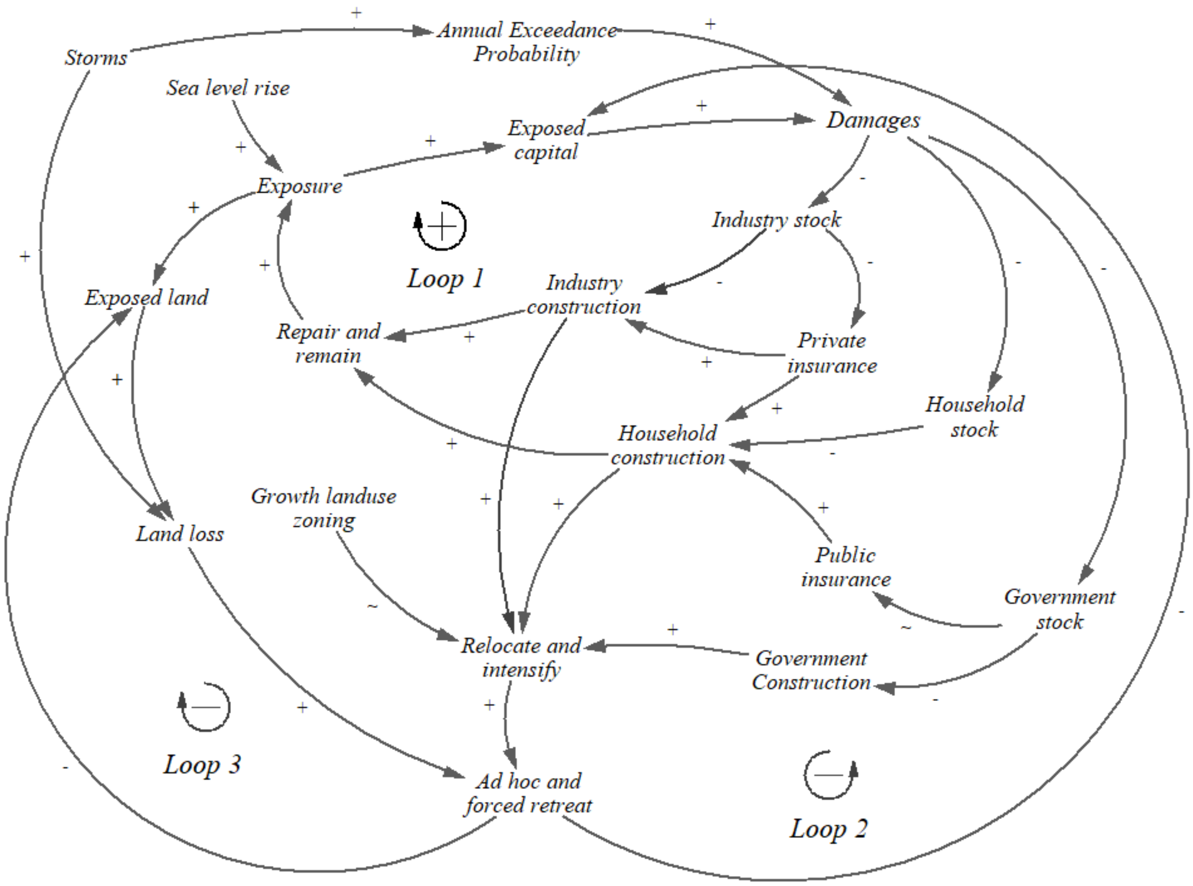



**Figure 3.3** The baseline CLD at the regional scale. This CLD depicts the baseline relationship between the environmental and economic systems. Without government intervention, firms and households have four pathways 1) repair and remain in the CHZ following floods with insurance (loop 1), 2) repair and remain without insurance (loop 1), 3) voluntarily retreat *ad hoc* (loop 2), or 4) forcibly retreat as land disappears from the CHZ (loop 3).

## 3.2 Assessing futures: Scenario Planning, Robust Decision Making and Dynamic Adaptive Policy Pathways

Now the CLDs have set the scene; the following section addresses how Scenario Planning, RDM and DAPP can be integrated to explore futures for managed retreat. It illustrates the usefulness of each approach and how their integration can obtain synergy. In short, Scenario Planning allows for insights from expert workshops and conversations, RDM provides statistical analysis to scenario modelling, and DAPP allows for the development and comparison of policy pathways. A critical review of their synergy follows an explanation of each approach. Finally, thresholds and tipping points are introduced, given their importance in determining adaptation pathways.

### 3.2.1 Scenario Planning

A scenario is an internally consistent view of how the future might eventuate (Porter, 1985). Scenarios are an alternative approach to predictions and forecasts whereby plausible future worlds are compiled from expert judgement and analysed to develop consistent stories of how the future might eventuate through reframing the system when faced with decision-making under uncertainty (Gong et al., 2017; Ramirez & Wilkinson, 2016). Unlike predictions, scenarios are uncertainty based, illustrate risk and are applicable over longer time intervals (Lindgren, 2003). Scenarios allow stakeholders to understand the potential impacts of decisions and policies by exploring their implications on a range of possible futures (IPCC, 2014c). Using scenarios is now a preferred local government approach to managing exposed assets in New Zealand (Local Government New Zealand, 2019).

Scenarios allow modellers to account for different perspectives on specific issues and opportunities (Frame et al., 2005). They cover situations that explore the unfolding of futures given various drivers under baseline conditions (problem exploration) and scenarios that examine how various interventions might eventuate (solution exploration) (IPCC, 2014c). By design, they should look more than a decade ahead and address changes across many aspects of society (Frame et al., 2005). Scenarios should have technical credibility and adequacy through scientific evidence and arguments, relevance to the assessment process required by decision-makers, and legitimacy through objective information (Cash & Moser, 2000).

Adaptation scenarios require modellers to integrate, where appropriate, interacting factors such as human behaviour, policy choices, land-use changes, population trends, economic conditions, technological advances, and international competition and cooperation (Moss et al., 2010; Turner, 2000). However, managing all of these factors simultaneously is beyond the scope here. The scenarios modelled in this thesis address human behaviour concerning insurability and coastal amenity value, policy choices to finance managed retreat, changing land-use as coastal hazards remove land from the economic system, population trends, and regional economic conditions.

This research adopts a particular approach called Scenario Planning, where scenarios concentrate on a few dominating issues of concern for a select audience and provide new knowledge that reframes the situation with future perspectives (Ramirez & Wilkinson, 2016). However, given its rationale as a research thesis, the full implementation of Scenario Planning by reframing the audience was not administered during the period. Yet, this thesis, in time, will reframe perceptions held by coastal stakeholders on its completion and their review.

Scenario Planning is the link between futures thinking and strategic action (Lindgren, 2003). It seeks to manage ‘conditions of turbulence, uncertainty, novelty and ambiguity’ (TUNA) to create a new strategy on which a new behaviour can be based (Ramirez & Wilkinson, 2016). Therefore an ideal approach to manage the complexity of futures for coastal communities. There are two main ways to define the future context: 1) a system map of causally linked variables or 2) linking the future to the present by telling a story of what will happen and why (Ramirez & Wilkinson, 2016). Thus, Scenario

Planning integrates well into System Dynamics CLD, and in this research, both ways are applied. Scenario Planning does not seek to map the entire contextual environment, but analyse typically three or four future systems for the strategic planner to focus on for a particular audience (Ramirez & Wilkinson, 2016).

Scenario modelling requires that models are populated with a wide range of data to develop meaningful scenarios architecture, ideally with consistent assumptions (Frame & Reisinger, 2016). Where data is not available, inference can be made from expert workshops, peer-reviewed literature or grey literature, as described by Smith et al. (2016). Data may include: a) inferences from global datasets; b) extensions of current shorter-term datasets; or c) inferred extensions of datasets based on declared suppositions (Frame & Reisinger, 2016). The data development process and the underlying assumptions also need to be recorded and accessible so that as new information comes to light, it can be challenged (Frame & Reisinger, 2016).

Traditional planning approaches have tried to predict the future and prepare a static and anticipatory plan to meet this future (Hamarat et al., 2014). However, static policies prove ineffective at managing complexity under uncertainty (Hamarat et al., 2014). Conversely, Scenario Planning anticipates that the future is uncertain, and multiple futures could exist (Lindgren, 2003). Therefore, Scenario Planning goes beyond defining iterative models with quantifiable facts of the past. It acknowledges and defines novel developments and dynamic feedback of interconnected environmental, social and institutional structures in possible futures (Ramirez & Wilkinson, 2016).

However, Scenario Planning is not without its flaws. Many decision-makers seek security in single definitive answers about the future, which is not offered by Scenario Planning (Lindgren, 2003). Opposing ideological positions can lead to conflicts around strategic reframing and hinder the process of a shared understanding of the future (Ramirez & Wilkinson, 2016). The process can also fail when all the energy focuses on creating the “perfect” scenario (Ramirez & Wilkinson, 2016). Similarly, Scenario Planning can be rendered useless by 1) being vague about the use and user of the scenarios, 2) applying probabilities to the intended scenarios, 3) decreasing the clarity of a scenario and confusing or befuddling the end users’ thinking, 4) believing in pop-up scenarios (scenarios put together in a matter of hours) with little input from others, 5) seeking to foretell a definitive future amongst a myriad of uncertainty, and 6) downplaying Scenario Planning to be an incomplete methodology by nature as they are ‘only stories’ (Ramirez et al., 2021). Therefore, in this research, creating a definitive ‘perfect’ scenario was not the aim but to tease out likely pathways for managed retreat.

Finally, Scenario Planning provides plausible futures that can then be stress-tested through RDM to give confidence in the outcomes and provide communities with a range of pathway opportunities. Further detail on Scenario Planning and the scenarios themselves are covered in Chapter 5. They highlight baseline scenarios for different RCPs, central government bonds interventions, local government rates interventions and coastal defence strategies.

### 3.2.2 Robust Decision Making

RDM is a process whereby models are iterated hundreds or thousands of times under different inputs and assumptions to discover plausible futures through minimising regret and statistical uncertainty (Lempert et al., 2013). Statistical analyses and visualisations of the results facilitate the decision-maker's assessment to compare scenario performance across a wide range of future conditions (Lempert et al., 2013). The idea is that multiple runs will identify vulnerabilities in policies, and then the evaluation of potential robust policy responses will address those vulnerabilities (Lempert et al., 2013). It effectively deals with deep uncertainty and complex situations through computer modelling and evaluating alternative decision options (Lempert et al., 2013). Operationalising robustness, or finding a successful strategy to minimise vulnerability across a broad range of climate futures, selects a pathway that minimises the maximum risk, or the solution with the least maximum regret, or least regret (Costanza, 1989; Hamarat et al., 2014; Wreford et al., 2020). Thus, a robust design seeks to optimise futures, avoid regret and minimise uncertainty over a broad range of anticipated climates rather than optimising for any single climate outcome (Callaway, 2014).

Here algorithms identify robust strategies through regret functions which compare the various strategies with the best-performing strategy (Stern et al., 2014). They seek strategies that meet the decision-makers objectives over many plausible futures (robustness) rather than optimising toward any single best option for the future (Lempert et al., 2013). However, extensive model runs, complicated computer algorithms and software, project specificity, and organisational training can be challenges to its implementation (Lempert et al., 2013; Stern et al., 2014).

### 3.2.3 Dynamic Adaptive Policy Pathways

Pathway planning allows management agencies to implement strategic, individually styled long-term plans for vulnerable areas that achieve greater integration for managing coastal risks in land-use management (Manning et al., 2015) when exposure becomes critical. DAPP are a sequence of strategies or policy actions required over time to achieve specified objectives (Haasnoot et al., 2014a). Alternative future scenarios are evaluated and impacts compared to provide society with options for coastal hazard mitigation and adaptation (Haasnoot et al., 2014a). DAPP makes it possible to assess numerous scenarios that can be adapted over time to provide a staged decision-making process that includes identifying tipping and trigger points (Haasnoot et al., 2012; Kwakkel et al., 2015). However, the lifetime allocated for an adaptation decision also needs to consider the rate of change of the climate risk over time to result in more resilient options (Manning et al., 2015). Thus, a specific pathway emerges given time-varying conditions where impacts and policy responses are actioned (Haasnoot et al., 2014a). This approach allows for adjusting actions as operating conditions, objectives or policies change or fail over time, leading to a change in form and function (Haasnoot et al., 2014a; Kwadijk et al., 2010).

However, DAPP has drawbacks: the unpopularity of alternative actions; failure through the singularity of a preferred pathway; contested goals and values of society; implementation of maladaptive pathways to protect private amenity values; evaluation of complex trade-offs; stakeholders gaming the system to suit well-entrenched views on coastal management and treating adaptation as a process issue rather than addressing its underlying structures (Gorddard et al., 2012; Imura & Shaw, 2010; Peck et al., 2014). Similarly, the reversibility of pathways is a contentious issue, as this may not always be the case given irreversible environmental changes, substantial financial costs and legal barriers. Often DAPP in New Zealand are implemented into a broader process, or fail to include key drivers such as funding mechanisms, which can stall the decision-making process or negate its effectiveness (see HBcoast, 2017; Sharpe, 31 January 2020).

Nonetheless, DAPP is not a new concept used for coastal hazard management in New Zealand. It has been deployed in Hawkes Bay and Buller Bay, with its effectiveness not fully known for many years once action triggers have been implemented. A Technical Advisory Group was established in the Hawke's Bay to investigate possible long-term options for communities susceptible to coastal hazards by providing a more formal, scalable, inclusive and transparent approach. To facilitate the decision-making process toward sustainable long-term outcomes for communities, the three councils (Hawke's Bay Regional Council - HBRC, Napier City Council - NCC and the Hastings District Council - HDC) developed a collaborative process known as "The Clifton to Tangoio Coastal Hazards Strategy 2120" (HBcoast, 2017). This strategy aims to develop adaptive responses to coastal issues for at least 100 years, utilising a structured and inclusive DAPP process (HBcoast, 2017). Similarly, Carters Beach on the West Coast has employed a spatial DAPP process to determine its future given physical erosion and overtopping thresholds of the beach profile (NIWA, 2017a). Hawke's Bay has also employed DAPP to enable primary industries to adapt to climate change (Cradock-Henry et al., 2019).

This research strives to replicate the DAPP process but fails to achieve some of its objectives. Failure is because the development of DAPP aims to maintain the accessibility to new options as they become apparent over time. From a theoretical viewpoint using an Evolutionary Economics lens, accessibility to new options becomes increasingly difficult as evolving complex systems exhibit a state of irreversibility or pathway dependence. Thus, implementing a coastal managed retreat is not reversible due to cost and the physical loss of property and therefore managed retreat determines some level of path dependence. It is also difficult to switch pathways over the short to medium-term, the thesis's operational timeframe, given the long and deliberative decision-making process around consensus on expensive mitigation or adaptation processes. Nonetheless, managed retreat should be viewed as a step-change in eliminating risk for exposed communities rather than a timeline of temporary stages to stave off the inevitable.

### 3.2.4 Contrasting Scenario Planning, RDM and DAPP

Traditionally, managing coastal hazards has involved long deliberation by officials, experts and communities to tease out an appropriate and cost-effective method to manage impending asset damage or loss (Hayward, 2008). Analysing a system's sensitivity to different scenarios can determine its long-term capacity, effectiveness and success (Manning et al., 2015). However, exposed communities must first plan appropriate scenarios of what they envisage. DAPP delivers a means to operationalise and explore both a large ensemble of possible futures and many alternative policies within a framework of multi-objective robust optimisation (Kwakkel et al., 2015) such as RDM. Yet, RDM requires scenarios as the input to define plausible future conditions for consideration when making decisions with a significant amount of uncertainty (Gong et al., 2017). Integrating the three can help eliminate inappropriate or impossible pathways toward managed retreat.

Combining the three can also provide probabilities and confidence in the outcomes generated from diverse scenarios and policies. Scenario Planning can bring low-probability, high-consequence outcomes to decision-makers' increased attention, but it can also lead to their over-weighting in the analysis (Gong et al., 2017). RDM reveals any vulnerabilities in plans and helps make them more robust (Lempert et al., 2013). Thus, RDM feeds back into Scenario Planning to manage statistical uncertainty around climate change adaptation. At the same time, scenarios are effective for planning challenges and responses with a high level of deep uncertainty (the unknown unknowns, black swan events) (Lempert et al., 2013), which RDM cannot manage alone as it is outside the decision space (Bhave et al., 2016). Because RDM is driven by the scenarios, the decision space on which it impacts is limited, leading to limited applicability for decision-making (Bhave et al., 2016). The limited decision space of a handful of scenarios often leads to adopting robust conservative solutions over worst-case scenarios (Bhave et al., 2016).

Similarly to scenarios, DAPP does not predict the future; it provides a range of plausible futures to support decision-making (Kwakkel et al., 2015). Here it is useful to combine with RDM to define adaptation and risk management goals to assess pathways through the success or failure of multiple performance metrics for the range of scenarios (Bhave et al., 2016). Finally, RDM has strength over the other two approaches as it adopts the philosophy that "it is better to be roughly right than precisely wrong" (Bhave et al., 2016, p. 3).

However, there are weaknesses to these approaches. First, all three require pathways planning to accommodate and respond to new knowledge and information over time to provide more robust plans (Kwakkel et al., 2015; Lempert et al., 2013; Ramirez & Wilkinson, 2016). In theory, this assumption is ideal, but funding constraints or changes in governance may disrupt the ongoing provision of such intensive assessment and consultancy. Therefore, the approach requires a timeline of changing risk on which to act that is regularly updated and a timeline for deliberation and finance to maintain the work stream's existence into the future. Weissenberger (2015) summarises that implementation strategies require adaptation tools that cover legislative, management, economic, financial, scientific, communication, technological, engineering, and decision support categories, the management of which is an arduous task. Second, considering path dependency and the irreversibility of options is also critical when undertaking risk assessments and analysing policy options (Boston, 2017). Again, this works in theory, but many funding options for managed retreat require significant investment ahead of time, and reversing decisions undermines integrity in the decision-making process. Provision of public goods (or the implementation of managed retreat) requires a combination of markets, government intervention, research funding and the removal of social, political and legal constraints to ensure efficient outcomes (Peck et al., 2014). Decision-makers are thus creating a seemingly irreversible process once funding is established.

### 3.2.5 Thresholds and tipping points of change

One key to developing a successful adaptation strategy is understanding adaptation thresholds and tipping points. DAPP calls for early identification of thresholds at which communities can no longer cope or where the ongoing costs become unmanageable (Manning et al., 2015). A tipping point occurs when an action no longer meets its objectives, which can be mitigated by installing a sell-by-date (when an action no longer leads to success) that is scenario dependent (Haasnoot et al., 2014a). Environmental anomalies and extremes precipitate tipping points alongside economic drivers such as housing affordability or business disruption. A new policy pathway is then actioned once its predecessor no longer addresses the issues it was designed to alleviate (Kwakkel et al., 2015).

Tipping points activate adaptation triggers that are critical for implementing plans and actions once thresholds are breached (the process of saltation) or new systems emerge (bifurcation) (Stam, 2006) over time. Tipping points should cover a wide range of extreme events and a range of projected sea levels. They require that an adaptation plan has an internal monitoring requirement of system developments that determine a contingency action where a shift to a different policy action occurs (Kwakkel et al., 2012). Thresholds are then considered a socially tolerable level of risk from environmental change for communities and provide certainty around the timing of actions (Barnett et al., 2014). Observable thresholds such as road flooding or breach of a barrier dune provide decision-makers with a 'social licence' to act with minimal contestation by communities (Barnett et al., 2014) as the trigger and response were debated ahead of time. Similarly, thresholds and tipping points provide owners and asset managers with a point at which they can reduce depreciation, phase in investment, and plan for adaptation or abandon assets (Barnett et al., 2014; Local Government New Zealand, 2019).

## 3.3 Modelling of dynamic systems for insights into futures and enhance our understanding

Modelling future long-term economic impacts of policy decisions on systems that enable managed retreat can help provide a robust approach to base decisions. Consideration of the estimated long-term costs of maintaining the status quo is also needed for comparison. Thus, effective policy solutions with broad societal support require data-intensive empirical work to strengthen the foundations upon which policy-relevant decisions are based (Burke et al., 2016). Planning and financial interventions can then be implemented ahead of time to provide communities with possible options when thresholds are breached, and action is critical. Modelling should also enhance policy practices rather than replace well-embedded ones and allow for transparency and flexibility to address real planning problems (van Delden, 2009).

Economic modelling of adaption decisions is valuable for evaluating trade-offs between economic, social and environmental systems and coordinating strategies for land use planning, environmental management, and infrastructure provision (Gorddard et al., 2012). Economic models provide a technical approach to defining coastal adaptation. Models simplify the reality of a complex world through abstraction while containing the relevant structures of reality (Foster & Hölzl, 2004). The model must fit with real-world observations and the modeller's previous theoretical knowledge (Ebersberger & Pyka, 2009). Although as Ruth and Hannon (1997) note, models are often prone to context-dependence and scale associated with human activities and any variability in rules used in the decision-making process can limit the applicability of models for predictive evaluation. Here, Scenario Planning, RDM and model testing can minimise bias and uncertainty.

Similarly, integrated assessment models should allow for the analyses of trade-offs, rank actions to achieve objectives, support the improvement of dynamic adaptive plans, be computationally efficient enough to simulate long periods and provide a relevant output to the decision-making process (Haasnoot et al., 2014a). They should also have an appropriate spatial scale and detail to represent the whole system in an integrated way to support decision-making (Haasnoot et al., 2014a). However, the closed system used in modelling is limiting, as new information is not autonomously integrated and replacing exogenous factors with constants reduces dynamic capacity. Therefore, models require ongoing updates, calibration and refinement to maintain objectivity and relevance (Foster & Hölzl, 2004; Trucano et al., 2006). The modelling process should maintain simplicity and sophistication through iteration and sensitivity testing to overcome flaws and uncertainty (Trucano et al., 2006). Models should highlight trends, orders of magnitude and non-trivial variable interrelationships rather than provide one-point definite estimates (Bosello, 2014). Similarly, system models, evaluations and scenarios should never be treated as the best representation as they require iterative consideration (Hamarat et al., 2013). Ideally, multi-disciplinary research teams engaged with stakeholders in various sectors provide the ideal platform for forming adaptation scenarios and model rules (Frame & Reisinger, 2016).

### 3.3.1 Traditional local-scale economic modelling at the coast

Traditionally, evaluation of mitigation or adaptation alternatives at the coast has been done through Cost-Benefit Analysis or to measure projects' costs over their life cycle and any economic benefits (Infometrics Consulting Limited, 2017a; IPCC, 1990). Cost-Benefit Analysis applied to SLR mitigation options tends to be characterised by investment decisions having non-simultaneous exchanges of immediate costs with distant benefits (Boston, 2017). Cost-Benefit Analysis often fails to assess broader interdependent social issues, and within these assessments differing estimates can arise from the methodology, discounting, data used, and the management of uncertainty (Losada & Diaz-Simal, 2014) while ignoring important distributional and equity impacts by averaging outcomes (New Zealand Treasury, 2015a). One relatively modern alternative to this is Real Options Analysis, an expanded Cost-Benefit Analysis that assesses whether to wait for more information before investing in possibly irreversible and costly actions and what alternative investments might suffice in the meantime (Infometrics Consulting Limited, 2017a).

### 3.3.2 Stepping up to regional Computable General Equilibrium Models

CGE modelling is a significant step forward in economic analysis. Rather than accounting for benefits and costs, they focus on a holistic view of markets accounting for all sectors in an internally consistent way (Heer & Maußner, 2009). More importantly, they account for the circular flow of money, including dynamics between key economic agents, characterised by non-linear feedback (Heer & Maußner, 2009). They provide for multi-agent interaction within markets by changing prices for the supply and demand for goods and services until an equilibrium is reached, otherwise known as efficiently allocating resources through market price adjustments (Bosello, 2014).

There are many types of CGE models which view the future from different perspectives. Traditionally, the most common CGE models use 'comparative statics' of the Walrasian persuasion (Devarajan & Robinson, 2013). These models typically compare the baseline equilibrium results for key economic aggregates with shocks to the economy, with and without policy interventions (Dellink et al., 2020). Comparative statics models do not consider the timing of impacts (Partridge & Rickman, 2010), i.e. the travel path to the equilibrium is unknown. A key strength of comparative static CGE models is that they account for economic interdependence, capturing flow-on (that occur between industries within an economy) and higher-order impacts (that occur through the circular flow of money between economic agents within an economy) (Smith, McDonald, et al., 2016). Comparative static CGE models can accommodate economic fluctuations through, for example, demand and supply shocks that substitute commodities to converge at an equilibrium (Bosello, 2014; Heer & Maußner, 2009).

More recently, dynamic CGE models have become more commonplace. There are many different types of these. Most common are 'dynamic recursive' models (see The Climate Change Commission, 2021), which assume that agents (households and firms) base their behaviour on the information of the past and are undecided about the future (Dellink et al., 2020). On a year-to-year basis, they typically assume that markets clear, utility is maximised in the present and the economy is in equilibrium at the end of the financial year (Dellink et al., 2020). Conversely, perfect foresight models are solved over the whole time horizon by maximising utility value in the present and the future (Dellink et al., 2020). The simplest dynamic CGE are the steady-state or balanced growth path models, which assume that all the key variables are growing simultaneously over time (Dellink et al., 2020). The savings rate, depreciation, and technological change are the only data requirements (Dellink et al., 2020). Yet, these are at odds with models applying Social Accounting Matrices (SAM) such as MERIT, which are generally not balanced in the base year (Dellink et al., 2020).

Of note, Bossello et al. (2007) used CGE models to estimate the implications of SLR in 2050 on the global economy, which was deconstructed by region and industry. As expected, results show that general equilibrium effects increase welfare costs, but not in every industry or region (Bosello et al., 2007). Bosello (2007) found that heavily agricultural economies will be the hardest hit where coastal protection does not exist. Meanwhile, in New Zealand, Landcare Research developed a top-down dynamic recursive, multi-sectoral and multi-regional CGE model over a decade ago to describe the global economy and greenhouse gases by sector called CLIMATDGE (Frame & Reisinger, 2016). They coupled Shared Socio-Economic Pathways and RCP projections within a CGE model to demonstrate alternative impacts based on climate change trajectories (Frame & Reisinger, 2016), an approach similar to developing baseline scenarios in this thesis.

### 3.3.3 Measuring the Economic Resilience of Infrastructure Tool (MERIT)

An extension of the CGE model is the dynamic computable general equilibrium model (DCGEM), which allows for exogenous changes to manifest more organically over time. MERIT, co-developed by Market Economics, Resilient Organisations and GNS Science, is a quasi-DCGEM. It derives a 'transitional pathway towards equilibrium' to which the economic system moves, which may continue to change over time (Smith & McDonald, 2016a). This pathway is based on equilibrium seeking algorithms that account for the adaptive behaviour of agents.

MERIT offers a unique approach to economic impact analysis of natural hazards. It allows for continual readjustment of the economy over time through CGE theory and system feedback (Smith, McDonald, et al., 2016). Thus, it is more temporally flexible than a standard CGE model, and unlike many DCGEMs, it: 1) captures out-of-equilibrium dynamics, often typically a coincidence of cascading natural hazard events and arguably; 2) is easily adjusted for resilience building initiatives and adaptations; and 3) due to its graphical user interface based on stock-flow diagrams, is easily interfaced with other models. MERIT relies on finite difference equations, rather than optimisation, to move toward equilibrium. The Dynamic Economic Model, which resides at the heart of MERIT, is described fully in McDonald and McDonald (2020), with full technical specifications given in Smith, McDonald, et al. (Smith, McDonald, et al., 2016).

Given MERIT's dynamic flexibility, it is more in line with the evolutionary economic theory that inertia, selection and development (innovation) are the primary drivers of systemic change and disrupt any market equilibrium rather than the Keynesian General Equilibrium Theory of market clearance. The dynamic evolution is due to price and time lags in MERIT. Therefore, it does not compute (using mathematical optimisation) the price necessary to achieve equilibrium but instead adjusts (oscillates) prices upward when demand exceeds supply and vice versa over the whole system simultaneously for each model time step (i.e. every 1.8 days) (Smith, McDonald, et al., 2016). Price-balancing feedback loops for demand and supply are crucial to making the model dynamic (Smith, McDonald, et al., 2016). Nested Constant Elasticity of Substitution and Constant Elasticity of Transformation functions represent alternative demand and supply choices that react to imbalances in commodities or factors by substituting demand or production (Smith, McDonald, et al., 2016). As outlined in this thesis, this makes it ideal for computing and quantifying non-linear behaviour and feedback associated with complex economic-environmental systems.

As noted above, most standard CGE models are comparative static in nature (Heer & Maußner, 2009), while most dynamic recursive DCGEMs utilise the equilibrated results from the previous model iteration and dynamic changes in labour and capital stocks to evolve the economy over time (Heer & Maußner, 2009). Fully dynamic CGE models (of which MERIT has many characteristics) are rare, requiring calibration across scales and through time - a notoriously tricky task. By contrast, MERIT employs finite difference equations for solving differential equations (by approximating derivatives using finite differences) based on the Euler's method or Runge-Kutta 4 (RK4) method (Smith, McDonald, et al., 2016). RK4 is a fourth-order time integration technique that allows DCGEM to discover a point solution based on the weighted average of four timesteps; this method is used for accuracy and stability, but not necessarily efficiency (Zeltkevic, 1998).

### 3.3.4 The value of MERIT for climate change

MERIT is a novel economic framework that helps analysts overcome shortfalls in standard CGE models. In MERIT, shocks (including coincident and cascading hazards) to the economy can be included for any period and may cause temporal lags that, in turn, may result in new dynamic equilibrium states (Heer & Maußner, 2009; Smith, McDonald, et al., 2016). This is because, during disruption, it is generally not practical to reach an equilibrium, as the economy will probably exhibit non-equilibrium market behaviour, such as operational losses, and therefore any pre-conditions for equilibrium will not be met (Smith & McDonald, 2016a).

MERIT's dynamic nature makes it useful for assessing economic impacts and policy interventions of out-of-equilibrium shocks including cascading or higher-order impacts such as changes to household consumption or demand for intermediate goods (Smith, McDonald, et al., 2016). It is, therefore, able to assess transactional changes in commodities due to disruptions. It is also crucial to model the growth or decay from the economic impacts of climate change as the economy changes over the long-term (Batten, 2018). Growth or recession is implicit in MERIT by including factors such as an interest rate, exchange rate, and cost of capital and investment. Thus, MERIT can model two or more dynamic modes outlined by Forrester (1982): 1) the economic long-wave, or the Kondratieff cycle of 45-60 years (Forrester, 1982), and 2) the regular short-term business cycle. This thesis falls short of capturing a complete oscillation of a Kondratieff cycle given the 44-year timeframe modelled, but it does illustrate partial oscillations. Therefore, the thesis covers the economic short to medium-term.

Another benefit of MERIT is its formulation of industry structure using the building blocks of System Dynamics, an analysis not seen for coastal managed retreat. Statistical models tend to ignore industry structure, and therefore industry behaviour is defined by changes to exogenous macro-economic factors (Lyneis, 2000). Conversely, Input-Output models define industry structure but fail to capture spatial or temporal dynamics (Miller, 2009). Structural and dynamic models, such as MERIT, can provide more accurate simulations when faced with noise and uncertainties from exogenous factors (Lyneis, 2000).

Batten (2018) highlighted three trends following a climate shock on GDP, as shown in Figure 3.5. One illustrates no long-term recovery to the economy—the second as a recovery to the previous trend. A third is a positive influence of 'creative destruction'. This type of analysis is a strength of MERIT. The assessment of baseline and intervention scenarios can define the effects on Total Value-Added (a proxy for the Gross Domestic Product metric, which excludes taxes on products but includes subsidies as a deduction). Ideally, managed retreat produces 'creative destruction' for society, where resilient communities prosper after the relocation. In MERIT, relocation can be included through delays in decision-making and reduced business operability during the relocation period (Brown et al., 2015) and transfers in built capital, natural capital, labour, investments, savings and taxes. Concurrently, MERIT diverts resources usually allocated for innovation or investment to reconstruction, replacement or managed retreat, whatever the scenario may be.

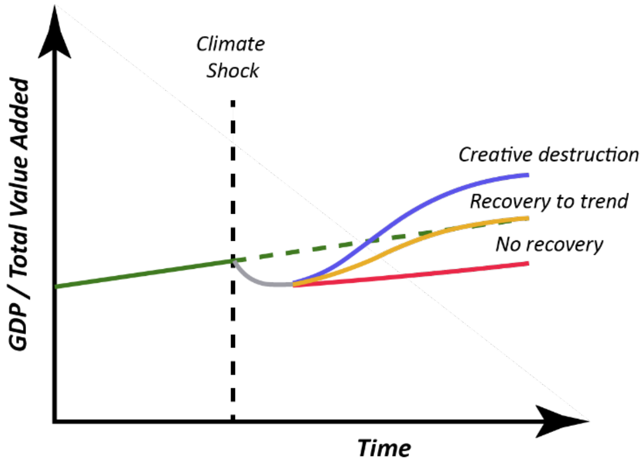



**Figure 3.5** Possible effects of natural disasters on GDP / Total Valued-Added adapted from Batten (2018). Similarly, scenarios modelled in MERIT illustrate changes in economic productivity.

### 3.3.5 Integrating Evolutionary Economics in decision-making

Once model trends, such as those in Figure 3.5, are established in MERIT, the analysis must then turn back to the principles of integrating Evolutionary Economics and System Dynamics to understand the complex system. First, System Dynamics must quantitatively define the system and variable interactions over time to establish a possible dynamic equilibrium. Second, Evolutionary Economics can then assess the stability of the system's dynamic equilibrium under varying scenarios over the economic medium-term. The notion of dynamic equilibrium can refer to a population oscillating around a stable or an unstable state (DeAngelis & Waterhouse, 1987). Such oscillations are dependent on interactions within the complex system and therefore become a metric for this research. Ford

(2010) describes these oscillations in three phases: 1) A Stable Equilibrium, where a steady-state may fluctuate around a dynamic equilibrium; 2) An Unstable Equilibrium, where a dynamic state is brought on by a sudden system shock or positive reinforcement from a chaotic perturbation; and 3) A Neutral Equilibrium, where shocks and perturbations in an already disturbed state lead to a new stable state (Ford, 2010). Bifurcation can often arise from an evolving state (Rosser, 2011), leading to multiple future pathways.

Changing states are the result of reinforcing (positive) system feedback. The positive feedback from coastal hazards (produced by significant stochastic effects) can precipitate a threshold response leading to hysteresis, a flow-on cyclical effect, or a catastrophic system collapse (DeAngelis & Waterhouse, 1987; Hughes et al., 2017). Alternatively, multiple weak feedbacks (with few stochastic effects) that act simultaneously may induce a regime shift (Hughes et al., 2017). Environmental variations (storms, SLR, etc.) control the former. In contrast, biotic forces, such as self-regulating population growth or compensatory interactions, control the latter (DeAngelis & Waterhouse, 1987). Reducing system drivers of positive feedback can mitigate the crossing of thresholds, while promoting drivers that stimulate negative feedback, such as social change toward sustainability and resilience, are effective intervention responses (Hughes et al., 2017).

However, evolutionary economic solutions for long-term planning alone do not guarantee socially optimum outcomes (van den Bergh, 2004) for coastal communities. As mentioned earlier, policy integration, stakeholder participation, financial initiatives and land-use planning are a few critical issues that need resolving to enable resilience through managed retreat. However, Evolutionary Economics gives society a new perspective to view a pertinent problem by allowing decision-makers to be more informed of economic interdependencies and dynamics outside of mainstream neo-classical economics of the Keynesian variety. The neo-classical approach focuses on the macro-economy, aggregated demand defining economic output and government intervention as key to moderating economic fluctuations (see Keynes, 1936). Whereas System Dynamics provides leverage points for decision-makers to influence systems and understand their connection to systems (Stave, 2002). Although the term over which modellers apply a system intervention is fundamental, short-term interventions can degrade the system long-term, long-term interventions can depress the system short-term (Forrester, 1971). Forrester (1971) referred to this as solutions to treat symptoms instead of the cause and creating new problems that can defeat our well-intentioned policy interventions.

### 3.3.6 Uncertainty in modelling

Unfortunately, with the abstraction of reality into models, weaknesses exist due to the simplification of the real world (Foster & Hölzl, 2004), and therefore, either uncertainty increases in models with greater timescales or the unknowable is omitted. Generally, risks are the known unknowns that are measurable and knowable and thus a probability distribution can be formed (Rosser, 2011). Deep uncertainties are the unknown unknowns on which no observable information is available (Rosser, 2011). Deep uncertainty can arise from multiple possible futures with unknown relative probabilities, inappropriate models for describing interactions between a system's variables, or multiple worldviews with different values to assess the system (Haasnoot et al., 2014a; Lempert, 2007). Rosser (2011) claims that climate change complicates probability distributions (such as risk or loss) with 'fat tails' through complex non-linear dynamics that manifest as unknown unknowns, and therefore, society is facing genuine deep uncertainty with climate change.

Climate variability, economic unknowns, technological advances, perverse capital valuations, unforeseen tipping points, system variability, cognitive bias, lifestyle, asymmetric information, funding constraints or political intervention are issues that are difficult to model but need consideration in integrated assessment modelling to minimise uncertainty (Fitzharris, 2007; Gorddard et al., 2012; Jevrejeva et al., 2014; Kartez & Merrill, 2016; Turner, 2000). Alternatively, societal characteristics such as population, land-use, resource use, infrastructure projects and economic activity are very dynamic (and highly interdependent) over a scale of one or two decades (IPCC, 2014c), which can lead to model errors. As the model timeframe extends, so does the uncertainty in establishing a reliable baseline scenario (Smith, Orchiston, et al., 2016). Quantifying variables with incomplete knowledge, or are inherently non-market such as socio-economic behaviour, technological innovation or changing ecosystem services, are problematic for top-down economic models (Bosello, 2014). Similarly, technical breakthroughs constitute a discontinuity of the normal predicted process (Bosello, 2014), leading to an unforeseen abrupt change in the system (or an unknown tipping point), which exacerbates deep uncertainty.

Achieving resilience is difficult through modelling, as deep uncertainty exists for futures that we cannot reliably quantify (Smith, McDonald, et al., 2016). It is often left to best guesses or mathematical equations to reduce these errors (Ranger et al., 2013; Stern, 2007). Incorporating dynamic feedback loops synonymous with System Dynamics seeks to minimise uncertainty by developing a deeper understanding of system behaviour (Lyneis, 2000). Similarly, integrating socio-environmental resiliency within economic models does not often approximate methodically (Smith, McDonald, et al., 2016). Although, an approximation can lead to the inclusion of separate analysis or the creation of specific modules to ameliorate the surrounding complex processes (Smith, McDonald, et al., 2016). An approach applied to this research is the incorporation of modules to expand MERIT.

Alongside deep uncertainty are important and unresolved methodological constraints in adaptation planning, which involve choosing several plausible scenarios to summarise futures from what is often a wide range of uncertainties and assumptions, and how to include probabilistic information when judging scenarios (Bosello, 2014). Scenarios tend to reduce uncertainty compared to predictions' firm outcomes by presenting information as possibilities (Gong et al., 2017). Generally, decision-makers find scenarios less psychologically threatening when faced with a range of inconvenient or contentious futures (Gong et al., 2017).

Models can also accommodate parametric or statistical uncertainty through iteration, real-world calibration and sensitivity analyses to provide confidence in the outcomes (Bosello, 2014; Kwakkel et al., 2015). An example of parametric uncertainty is where damage functions express a bandwidth of plus or minus 10% grounded in evidence (Kwakkel et al., 2015). Similarly, sensitivity analyses can be conducted through Monte Carlo sampling (or, in this thesis, Latin Hypercube sampling) over probability distributions of input parameters to investigate uncertainty propagation (Bosello, 2014). Latin Hypercube sampling is more efficient at exploring input parameters as it stratifies their cumulative probability distributions to select samples more strategically from each proportion of the distribution iteratively (Kucherenko et al., 2015). Strategic sampling makes it more helpful in assessing climate-economy extremes, as the probability of sampling these extremes is more likely given the stratification of the range of input parameters.

Finally, communicating the uncertainty around environmental and socio-economic issues is critical when evaluating policy interventions (Bosello, 2014). Therefore, economic evaluations to manage uncertain futures must accommodate 1) multiple and unpredictable futures and 2) a flexible schedule of policy options (Gorddard et al., 2012). Fortunately, modelling through RDM or DAPP can manage some uncertainty (Lawrence et al., 2013). These approaches seek policy interventions that can adapt well to many plausible futures and minimise uncertainty through sensitivity analyses. RDM has the added strength of model iteration to give it an advantage over DAPP.

### 3.3.7 Adjusting to scale, diversity and discordance between systems

The scale of a study to research a pertinent issue is often seen as contentious and requires knowledge and information generated by models to be useful to both assessor and decision-maker (Cash & Moser, 2000). Traditionally, disciplines or sectors analyse climate change independently, which is ideal for managing complexity, but this creates challenges for assessment by decision-makers who must adopt a holistic approach (Cash & Moser, 2000). Of particular interest here are the fundamental scales of space and time, as both affect the interaction between the environmental and economic systems (Cash & Moser, 2000). Often, spatial and temporal scales are beyond central governments' managerial capacity, let alone local councils' capacity to manage coastal hazards (Hayward, 2008). The lack of capacity is because the effects of climate change at the coast can extend beyond the electoral cycle or catchment boundary, culminating in traditional planning responses falling short (Hayward, 2008).

Assessing the spatial scale identifies two significant issues for modelling managed retreat. First, granular scales can inflate or obfuscate signals used for system analysis which can mislead decision-making (Cash & Moser, 2000). Second, communities require unique adaptive strategies tailored to their needs (Gibbs, 2015). As mentioned earlier, System Dynamics and Evolutionary Economics perform better at the national or regional scale as aggregation leads to a more robust system structure assessment. Although knowledge generated at this scale creates contestation between communities requiring unique resettlement versus a 'one size fits all' approach desired by the central government. Nonetheless, aggregation does overcome the inflation or obfuscation of signals issues, as stated earlier. Gibbs (2015) argues that adaptation should occur at the community or infrastructure scale and therefore become the responsibility of local councils to develop a unique adaptation strategy for managed retreat. However, a regional approach is necessary to achieve efficiency, so economies of scale can be honoured. For example, economies of scale in the construction industry (or a falling long-run average cost curve generated by gains in efficiency, purchasing or technology) are realised where managed retreat reflects a sizeable spatial scale or significant property aggregation (Hillebrandt, 1985). Thus, a progression from local-scale management towards multi-scale governance of system drivers, thresholds and feedbacks at applicable scales is becoming critically important (Hughes et al., 2017).

As mentioned earlier, not only is the spatial scale significant, but also the temporal scale. Here, this section embeds the temporal scale of economic analysis for managed retreat within a traditional framework. Williamson (1998) provides a valuable description of economic exchange as it covers the full range of economic transactions through time in Figure 3.6. It is adapted for this thesis with the blue font to describe the temporal scale for economic assessment at the coast.

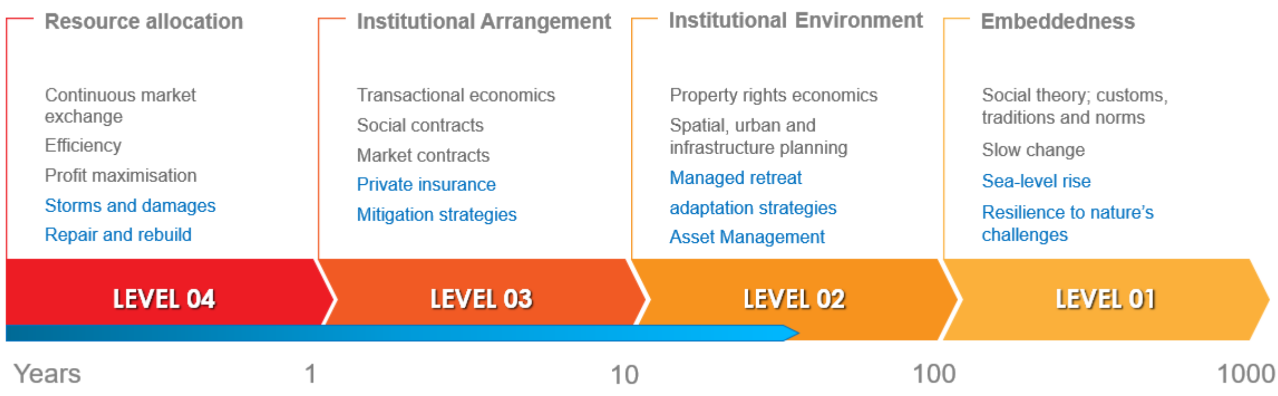



**Figure 3.6** The logarithmic scale of timeframes for economic analysis adapted from Williamson (1998). The blue font represents environment-economy actions on the coast. The blue arrow represents the modelling in this thesis straddling levels 4 and 3 for insights into level 2.

The following deduction of Williamson's timeframes is described by Murray et al. (2015) and applied to the economics of coastal managed retreat. First, level 4 operates from minutes to one year and covers everyday market exchanges of commodities and resources. At this level, storms damage assets (direct impacts) and property owners employ the construction industry to repair and rebuild in the aftermath. Many higher-order impacts also occur, such as constraints on intermediate goods or increased employment. Level 3 (1-10 years) is the timeframe where more significant contractual agreements occur. For example, there may be risk transfer from property owners to insurers or the introduction of mitigation strategies such as sea walls to reduce risk and increase the planning time horizon. Level 2 (10-100 years) is dominated by the institutional environment where the political and legal process defines economic activity rules (Murray et al., 2015). policy-making, property rights, resource allocation and built capital dominate (Murray et al., 2015). Adaptation strategies such as managed retreat operate at this level as it requires the alignment of institutional planning, private property rights and risk minimisation. Also acting at this level are the intergenerational costs or benefits of adaptation. Finally, level 1 (>100 years) sees the normalisation of social theory, or embeddedness, where institutional change is slow (Williamson, 1998). SLR continues, and society is resilient to nature's challenges. Cultural precedence normalises societal reactions to natural disasters (Murray et al., 2015). Concerning this thesis, the assessment covers thirty years with an initial calibration of 14 years, so it concentrates mainly on levels 2-4, but aims to advance our understanding into Level 1.

#### *3.3.7.1 Limitations of scale*

Spatial scale and detail to represent the whole system in an integrated way will support the decision-making process (Haasnoot et al., 2014b). Traditionally, System Dynamics and Evolutionary Economics are tailored to national or global-scale assessments, where greater aggregated information exists, and generalisations hold (Forrester, 1971; Foster & Hölzl, 2004). However, systems thinking (and, to a lesser degree, Evolutionary Economics) need to manage complex problems at the regional or local scale while maintaining a cohesive view of the whole system (Bosomworth et al., 2017). However, the complexity of relationships between variables at the local scale may make model refinement impossible (Bosomworth et al., 2017).

Consequently, when modelling dynamic systems at a local scale, the prognostic approach of Scenario Planning is helpful in representing the futures of localised complex systems. Often System Dynamics applies a probabilistic approach, as outlined by Ford (2010) and Hannon and Ruth (1994), to manage uncertainty and define general rules and relationships. Still, it struggles to apply these rules to a specific localised system accurately, say at a community scale of a census area mesh block — an area at which the environmental system applies discrete coastal inundation and erosion to the economic system. System Dynamics, in its traditional form, lacks a spatially explicit nature to model complex human-environment systems, with variable interactions differing depending on their whereabouts in the system (Allison, 2020). However, there are spatially explicit software packages suitable for building System Dynamic models such as Simile® and GIS extensions such as Peck et al. (2014). Greater integration of System Dynamics with GIS is an avenue for computational development given the complex datasets and analyses tools available in GIS and the elementary gridded neighbourhood approach offered by Simile® (see Simulistics Limited, 2017).

Similarly, when analysing disruptive events, it is useful to acquire data that have reasonably fine-grained spatial and temporal resolutions because while many events may be quite significant at a local scale, at a national scale, the impacts may be less significant or noticeable (Smith, Orchiston, et al., 2016). Meanwhile, the development of SAMs to manage this problem proves to be an increasingly labourious process as more downscaling is required (Smith, McDonald, et al., 2016). Alongside difficulties in increasing the granularity of SAMs in MERIT, there are a set number of 'average commodities' traded by 'representative agents'. It is currently impossible for MERIT to capture changes to a sub-class given government agencies' aggregation of economic and statistical data. Therefore, 'averages' must apply across the whole class within a regional economy (Smith, McDonald, et al., 2016).

Here Scenario Planning offers granular detail to the IAM by focussing on a particular audience and facilitating the ability to reframe the system and guide the behaviour of the stakeholders toward a resilient future (see Ramirez & Wilkinson, 2016). Yet, this research requires further intensive planning and implementation with stakeholders and communities to adopt its outcomes and see the successful realisation of managed retreat. Thereby fulfilling all the objectives of Scenario Planning as outlined by Ramirez and Wilkinson (2016).

# 4. Study area

Hawke's Bay, New Zealand was selected as the case study for this thesis owing to extensive research into coastal hazards and mitigation and adaptation strategies that have already been undertaken (see HBcoast, 2017; Infometrics Consulting Limited, 2017a; Kench et al., 2018; Komar, 2010; Komar & Harris, 2014a). Hence, as a case study for managed retreat, it is consistent with Callaway's (2014) study area characterisation, where an area should encompass natural science (environmental change scenarios), social science, economic activity patterns, management strategies and system drivers and boundaries. The following chapter describes the study area with regard to the geographic setting, coastal exposure and the regional economy.

## 4.1 The Hawke's Bay

The study area, shown in Figure 4.1, is defined by the coastal inundation extent modelled by HBRC and CDEM (2017a) (or the 1% AEP projected for 2120) as the CHZ for land use planning and economic impact assessment. Figure 4.1 also shows the properties used for valuation and industry analysis, authoritative boundaries, future zoning, and the cell boundaries for proposed defensive structures.

The study area covers a long stretch of exposed coast (37 km), with the CHZ (18 $km^2$) spanning three municipalities, two local councils (HDC and NCC) and one regional council (HBRC). These councils have integrated a long-term vision for the CHZ represented by the Hawke's Bay Clifton to Tangoio Coastal Hazards Strategy 2120 (HBcoast, 2017). The Strategy has divided the area into cells, each with a unique economic action plan. However, a bespoke area for economic analysis was created for this study that incorporated all properties within the CHZ and many adjacent reference properties. The area analysed has 9,618 properties, with the CHZ consisting of 3,249 buildings from the Riskscape database (NIWA, 2017b) and 2,451 properties registered with the local government. NIWA (and embedded in the original Riskscape™) has a good built capital dataset for Hawke's Bay as of 2009, making it ideal for analysis.

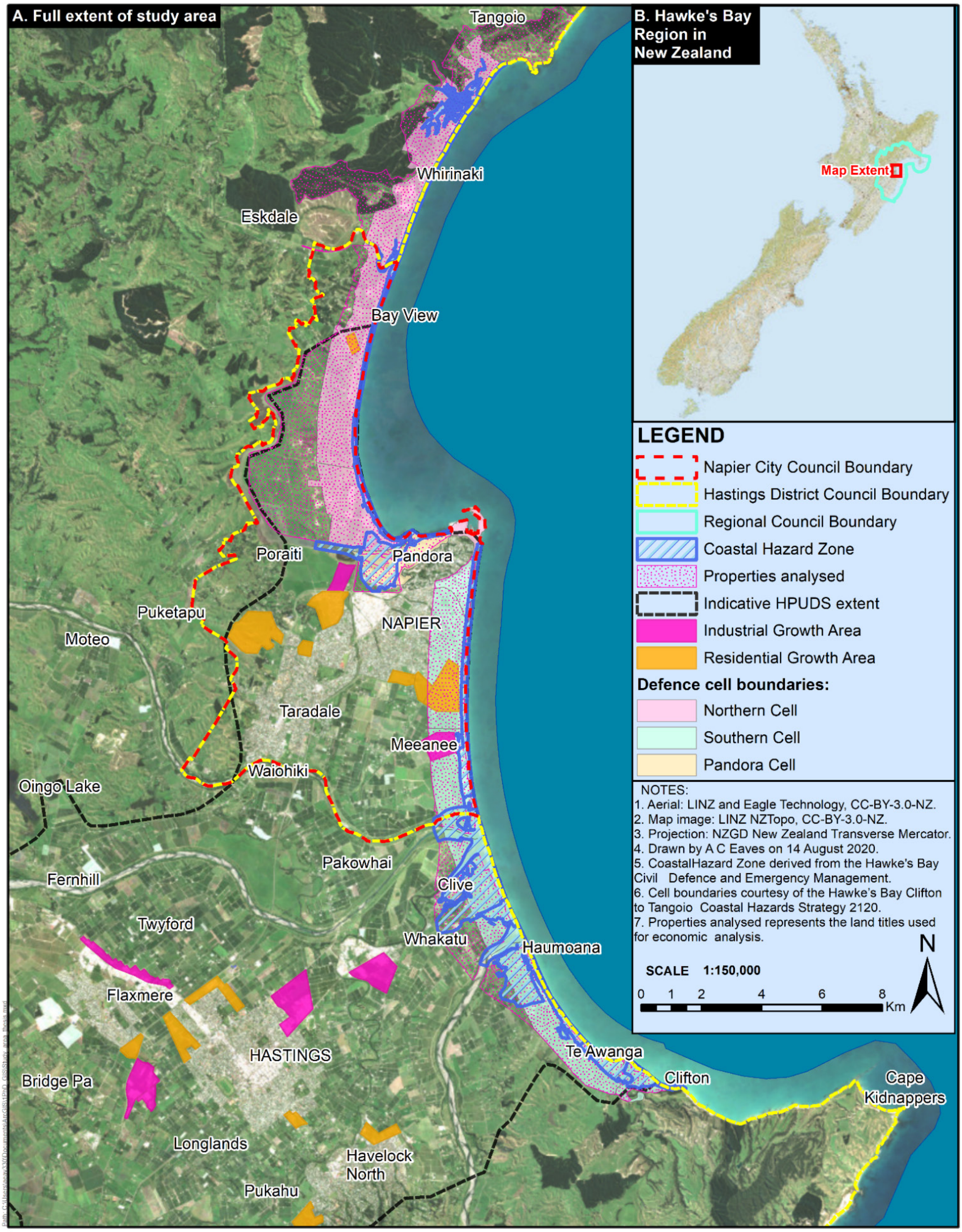



**Figure 4.1** Map of the geographic setting showing the CHZ, the properties analysed, the authoritative boundaries and future urban growth areas.

## 4.2 Coastal setting and risk exposure

Hawke's Bay has a dynamic coastline that underwent a significant change due to a major earthquake in 1931 (Komar & Harris, 2014a). The earthquake led to variable changes in the coastal structure and configuration due to differential uplift and subsidence and increased sediment supply to the coast from landslides (Brown et al., 2019; Komar & Harris, 2014a). These geomorphically modified barrier beaches were subsequently developed as towns and cities expanded. Short-term shoreline accretion occurred in some areas, but there has been long-term erosion alongside SLR (Brown et al., 2019; Komar & Harris, 2014a).

Many properties now face increasing exposure to coastal hazards due to the proximity of capital assets to the MHWS tide level (HBRC, 2014). Nationally, SLR, the increasing frequency and intensity of storms and land subsidence will exacerbate multiple local-scale coastal hazards such as storm inundation, erosion, waterway flooding and rising groundwater (Ministry for the Environment, 2017). These hazards threaten the continued long-term occupation time of the CHZ as the structural integrity of the land yields to ocean forces.

Nonetheless, it is a priority for local governments to assess their level of risk and exposure within the NZCPS 2010 and the RMA 1991 to inform their coastal hazards response (NIWA, 2015). Therefore, evaluating exposure to flooding and inundation requires identifying all the hazardous elements (Foudi & Nuria, 2014). NIWA (2019) has quantified the number of assets exposed using their Riskscape model (NIWA, 2017c) for all coastal assets in New Zealand, where LiDAR is available (Table 4.1). The results show classifications of assets, land and populations exposed to varying scenarios of SLR and storms for both Hawke's Bay and New Zealand. It becomes abundantly clear that it does not take a large amount of SLR coupled with a significant storm for people, assets, and land to be adversely impacted for the region and the nation.

*Table 4.1 Hawke's Bay and national exposure to SLR (NIWA, 2019)*

| Region | Scenario | Population (#) | Building (#) | Building value ($NZ\$_{2016}$ B) | Roads (km) | Railway (km) |
|---|---|---|---|---|---|---|
| **Hawke's Bay** | 2019 MSL & 1% AEP event | 6,152 | 4,574 | 1.02 | 87.1 | 1 |
| **NZ Total** | 2019 MSL & 1% AEP event | 72,065 | 49,709 | 12.4 | 1,414 | 86 |
| **Hawke's Bay** | 2019 MSL +0.3 m SLR & 1% AEP event | 11,875 | 9,315 | 2.06 | 133.9 | 1.5 |
| **NZ Total** | 2019 MSL +0.3 m SLR & 1% AEP event | 98,782 | 69,845 | 18.49 | 1,823 | 112 |
| **Hawke's Bay** | 2019 MSL +0.6 m SLR & 1% AEP event | 18,008 | 14,302 | 3.19 | 178.5 | 2.9 |
| **NZ Total** | 2019 MSL +0.6 m SLR & 1% AEP event | 132,650 | 93,891 | 26.18 | 2,273 | 142 |
| **Region** | **Scenario** | **Airports (km)** | **High Voltage Electricity Lines (km)** | **3 Waters Pipelines (km)** | **Land Cover Production ($km^2$)** | **Land Cover Natural ($km^2$)** |
| **Hawke's Bay** | 2019 MSL & 1% AEP event | 1 | 0.8 | 484.8 | 38.2 | 27.4 |
| **NZ Total** | 2019 MSL & 1% AEP event | 13 | 122 | 3,179 | 1,457 | 529 |
| **Hawke's Bay** | 2019 MSL +0.3 m SLR & 1% AEP event | 1 | 0.9 | 697.3 | 49.4 | 30.1 |
| **NZ Total** | 2019 MSL +0.3 m SLR & 1% AEP event | 14 | 144 | 4,307 | 1,612 | 569 |
| **Hawke's Bay** | 2019 MSL +0.6 m SLR & 1% AEP event | 1 | 1 | 904.9 | 60.7 | 32.8 |
| **NZ Total** | 2019 MSL +0.6 m SLR & 1% AEP event | 14 | 165 | 5,572 | 1,765 | 605 |

In short, the value of exposed capital assets and replacement costs in Hawke's Bay was calculated at $NZ\$_{2007}$2.4Bn[1] for the integrated assessment modelling from Riskscape™, HDC and NCC valuations (Hastings District Council, 2017b; King & Bell, 2005; Napier City Council, 2017b; NIWA, 2017c; Reese & Ramsay, 2010). There is also 1,094 Ha of vulnerable land in ownership, totalling $NZ\$_{2007}$248M (NIWA, 2017c) and a further 702 Ha of vulnerable land used for infrastructure, ecosystem services, and amenities not in ownership. The value of exposed capital assets in the CHZ is highlighted in Figure 4.2.

[1] Note: Dollars are nominal $NZ\$_{2007}$. $NZ\$_{2007}$ 1.00 = $NZ\$_{2021}$ 1.31 and $NZ\$_{2007}$ 1.00 = $US\$_{2021}$ 0.70.

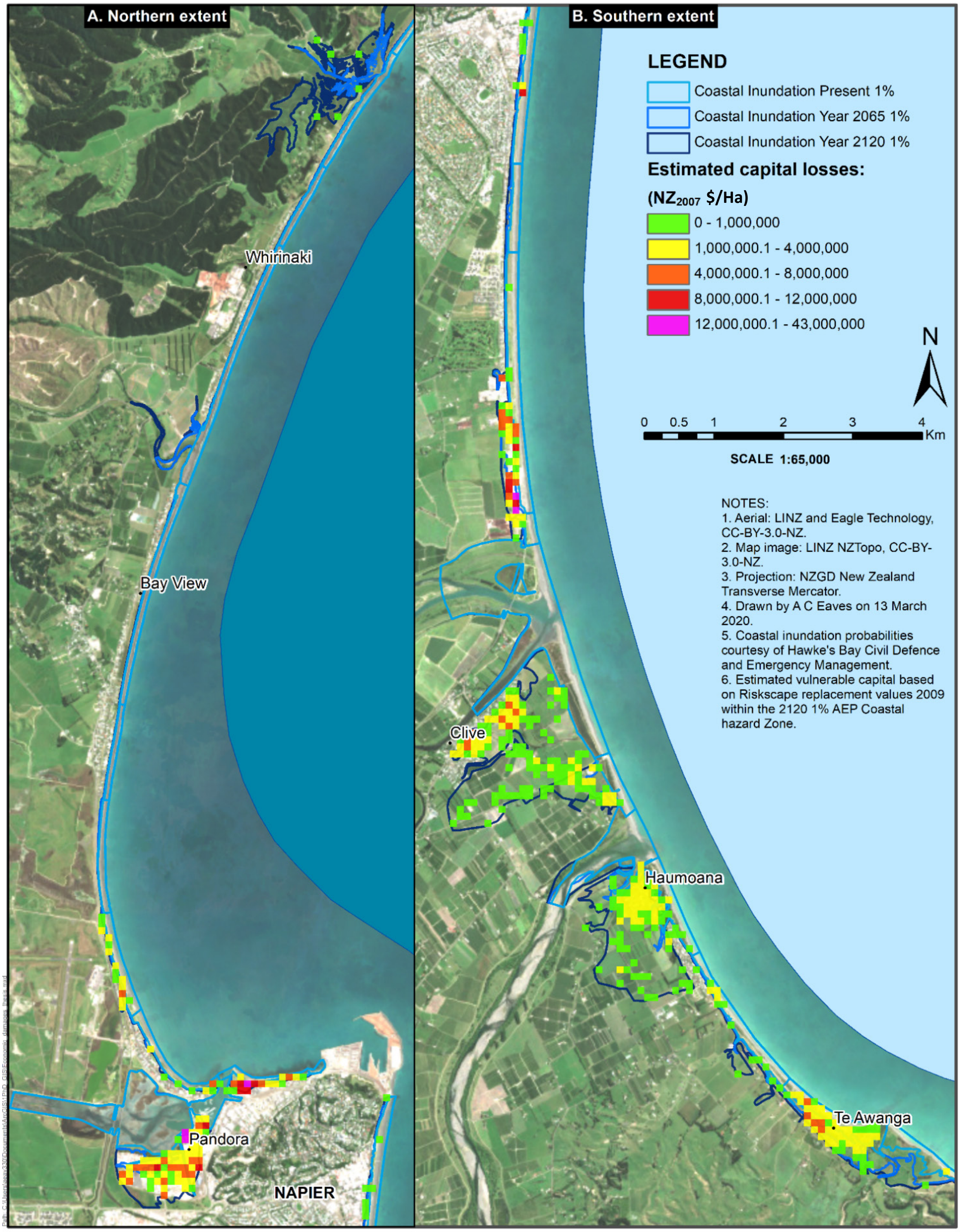



**Figure 4.2** The coastal inundation probabilities and estimated capital asset losses by a hectare (Ha). The Coastal Inundation Year 2120 1% polygons denote the CHZ for the calculation of loss using the 2009 Riskscape Coastal Vulnerability Assessment, a tool to estimate impacts and losses from natural hazards (HBRC, 2017a; King & Bell, 2005; NIWA, 2017b, 2017c; Reese & Ramsay, 2010). Panel A shows the northern extent, Panel B the southern extent in Hawke's Bay.

Given the large scale of the CHZ, two ‘hot spots’ are highlighted to illustrate the spatial exposure of industries and infrastructure to coastal hazards in more detail. First, is the commercial and industrial hub of Pandora in the Napier City jurisdiction (Figure 4.3), and second is the coastal settlement of Haumoana in the Hastings District (Figure 4.4).

Pandora is a sheltered industrial/commercial precinct aligned along the Ahuriri Estuary’s eastern fringe, exposed to flooding and coastal inundation. There are significant capital and infrastructure assets within 2 m of MHWS, and being adjacent to the Ahuriri Estuary increases the vulnerability to the river and estuary flooding during extreme weather events (Figure 4.3). Expansion and intensification of Pandora are ongoing (Napier City Council, 2017a), and considerable wealth has been invested in this area over the past two decades.

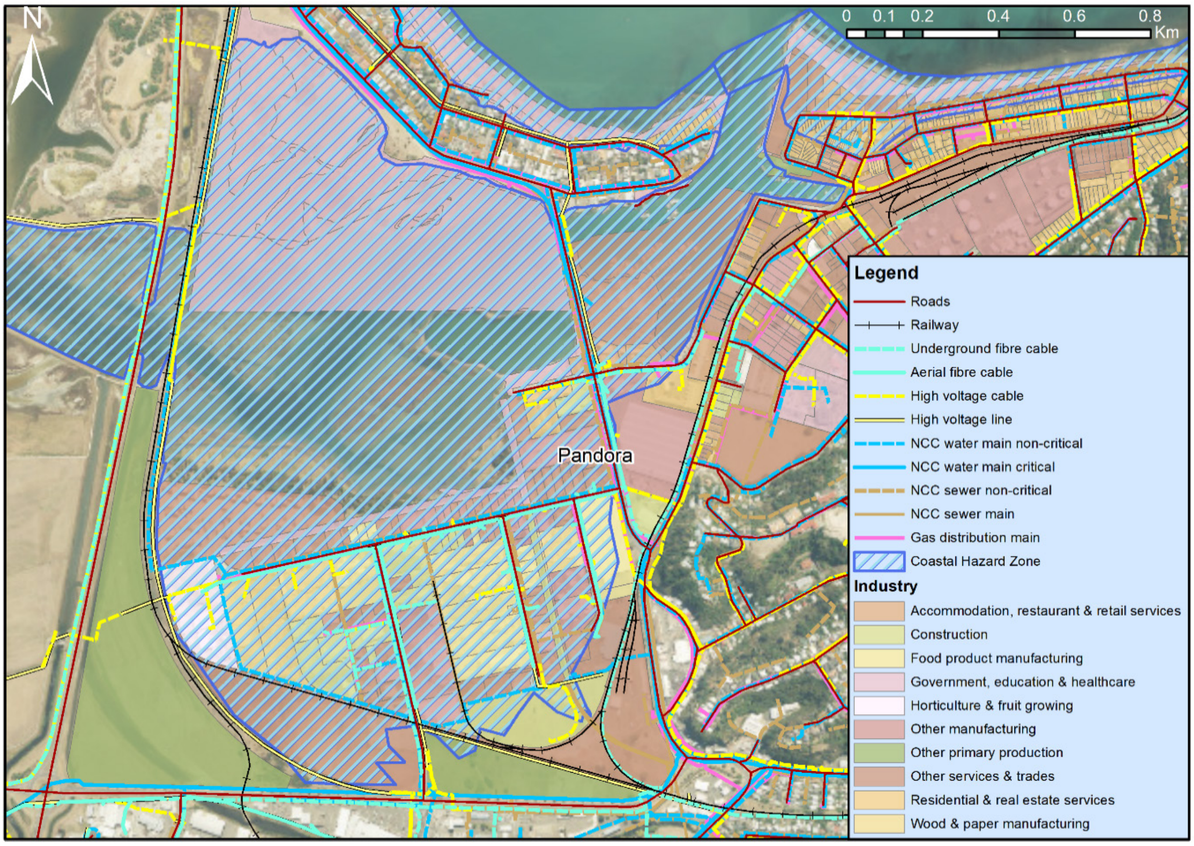



**Figure 4.3** Exposed infrastructure and industries to inundation in and around the Pandora Precinct of Napier.

Conversely, Tangoio to Ahuriri and Napier to Clifton are open coast environments exposed to extreme weather events, coastal erosion and SLR. They generally encompass residential properties, primary and secondary industries and their associated infrastructure. Preliminary GIS analysis discovered intensification along this stretch of coast from predominantly rural and rural-residential land use to residential, commercial, and horticultural purposes outside Napier's older suburbs and the small towns dotting the coast over the past 40 years. State Highway 2 and the main rail link for the lower east North Island adjoin the CHZ. Haumoana is a typical coastal community situated on the Hawke's Bay coastline (Figure 4.4). Although there is not as much infrastructure and asset wealth in the town, it has high amenity value given its proximity to the coast and the nearby Tukituki River. Other significant 'hot spots' for erosion or inundation include Westshore, Ahuriri, Clive, Te Awanga and Clifton.

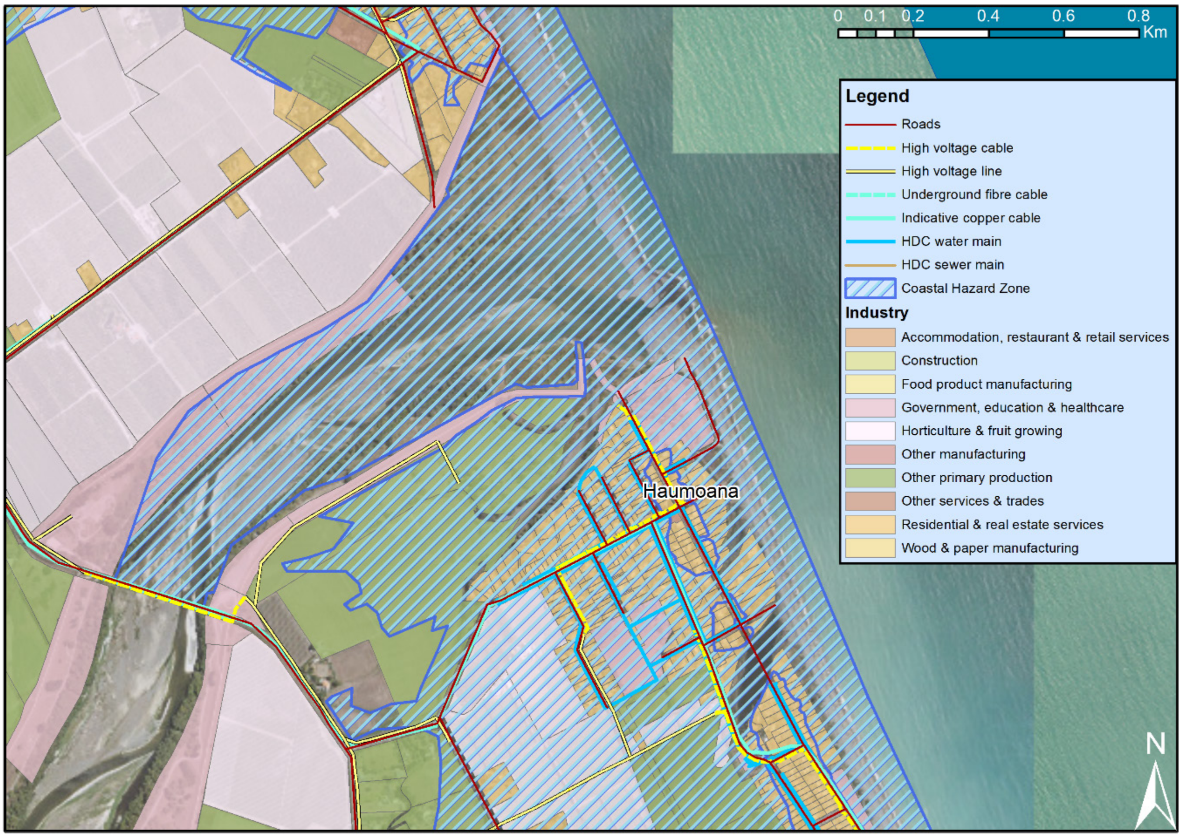



**Figure 4.4** Exposed infrastructure and industries in and around the seaside community of Haumoana, Hastings District.

## 4.3 The Hawke's Bay Economy

The following section covers the region's economy and its present-day activities to provide a background for economic impact modelling. It breaks down into two parts: 1) current sector and industry composition, and 2) household income, employment and population projections.

### 4.3.1 Industry output and sector composition

The Hawke's Bay region made up 2.8% of national GDP (NZ$$_{2020}$11.37Bn) to the year ended March 2020 (StatsNZ, 2020d). In 2020, Hawke's Bay's Regional Domestic Product (RDP) increased by 4.8%, whereas the national average was 5.4% (StatsNZ, 2020d). Increases in construction, health care and social assistance, and owner-occupied property operation drove this increase (StatsNZ, 2020d).

Hawke's Bay has seen RDP growth at around 10% since 2009, which currently exceeds the population and household growth rates for the Heretaunga Plains (HBRC et al., 2017), a sub-region of Hawke's Bay that includes the study area. Figure 4.5 illustrates the trends for RDP for Hawke's Bay and GDP for New Zealand for 2000-2020.

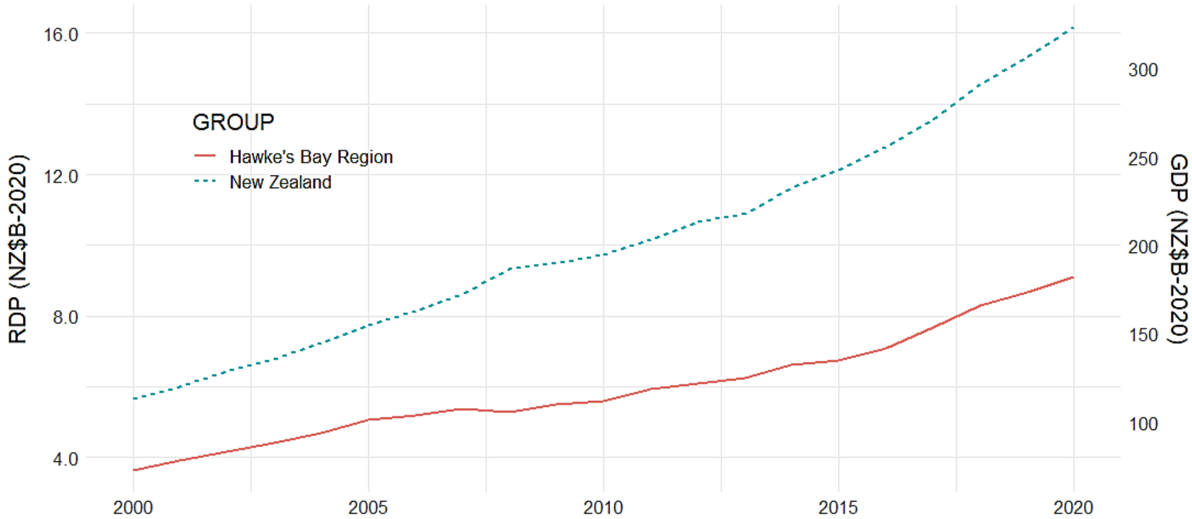



**Figure 4.5** The Regional Domestic Product (RDP) of Hawke's Bay and the national Gross Domestic Product (GDP) from 2000-2020 (StatsNZ, 2020b). Both RDP and GDP illustrate similar trends over the period.

Since 1972, the national trend in GDP composition has seen a reduction in the primary and secondary sectors and an enhancement in the tertiary sector (StatsNZ, 2019b). Currently, agriculture (including horticulture and fruit growing; and grain, sheep, beef; and dairy cattle farming) and manufacturing sectors are the key drivers for the overall performance of the Hawke's Bay economy, sharing 30 - 40% of total RDP (HBRC et al., 2017). Figure 4.6 shows a similar pattern for Industry Value Added and sector composition derived from the SAM in MERIT for 2020 (see StatsNZ, 2007, 2013b, 2018b). The regional SAMs derived by Market Economics form the base economic accounts used in MERIT from 2007 to 2018 (Smith, McDonald, et al., 2016). In Figure 4.6, the regional industry and sector composition were projected for 2020. SAMs are calculated from the Statistics New Zealand (StatsNZ) 'Australia and New Zealand Standard Industrial Classification' tables (StatsNZ, 2006) and aggregated from 106 industries and 205 commodities to 10 industries and 10 commodities of interest for this research. Therefore, it should be noted that these values are modelled values. Here the inner rings illustrate the composition of the Hawke's Bay economy, where the outer rings represent the rest of New Zealand. The primary and secondary sectors make up 34% for Hawke's Bay, whereas they make up only 19% for the rest of New Zealand.

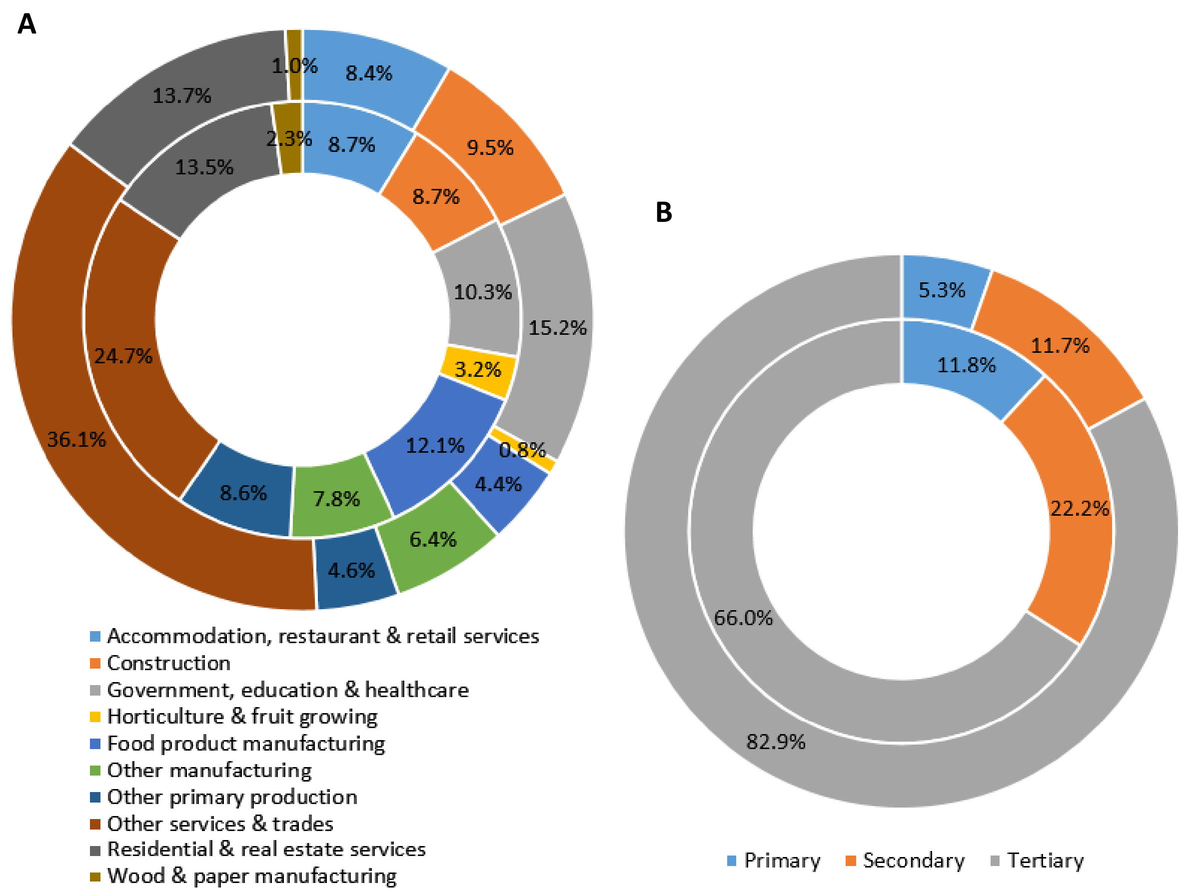



**Figure 4.6** Share of Value Added modelled by industry (A) and sector (B) developed from MERIT and the underlying Social Accounting Matrix (SAM) for 2020. Here the inner circle represents Hawke's Bay, and the outer circle represents the rest of New Zealand.

### 4.3.2 Population, households, income and employment

When analysing the demographics, the CHZ contains approximately 2332 (2007) people, whereas the regional population of Hawke's Bay is 152,940 (2007), making it 1.5% of the regional population. The Hawke's Bay population is set to increase from 161,800 people in 2020 to 191,100 people by 2050, as forecasted by StatsNZ (2019a), an 18.1% increase. It slightly deviates from the national population trend as there is a larger increase in the regional population than the national population over the latter half of the period, illustrated by the increasing steepness of the curve (Figure 4.7) (2019a). These StatsNZ projections are programmed into MERIT and conform with technical reports produced for HPUDS, where current population data and projections illustrate a significant population increase over the next 30 years and a 30% increase in the number of dwellings (HBRC et al., 2017). The population increase will provide a reasonable labour force to achieve future growth targets in productivity and achieve an aim of the Matariki Plan (the regional economic development strategy and action plan for Hawke's Bay) "to increase the median household income above the national median, for equitable growth" (HBRC, 2016a, p. 7). The Matariki Plan covers all of Hawke's Bay, whereas HPUDS covers the Heretaunga Plains only.

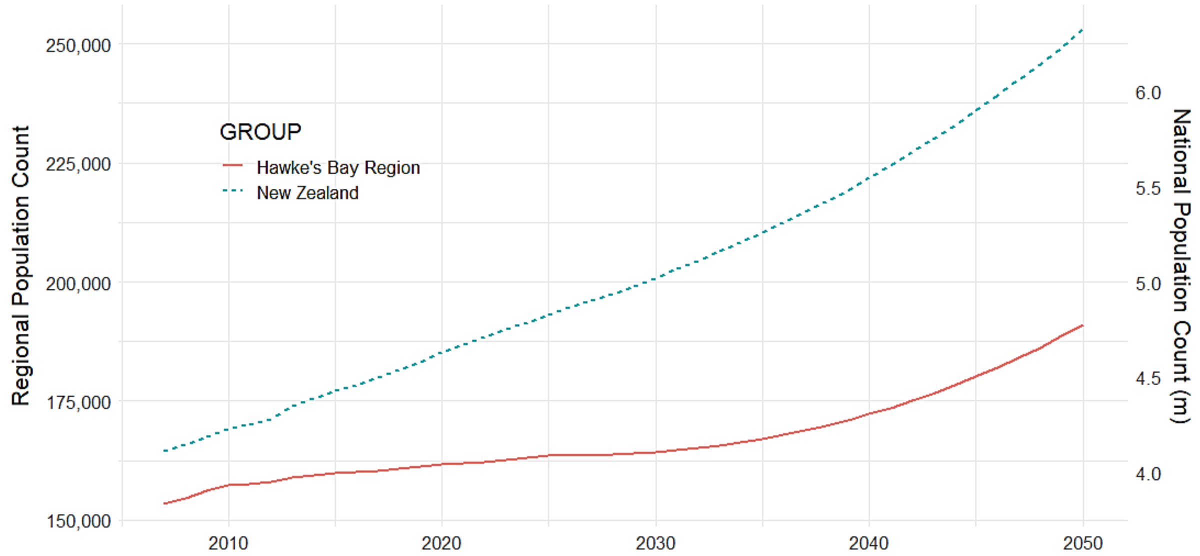



**Figure 4.7** Population forecasts for Hawke's Bay and the national population scaled for comparison. The Hawke's Bay population sees a more significant acceleration after 2030 than the national population. Projections courtesy of StatsNZ (2019a) and applied to MERIT.

As of 2007 (the starting point for model calibration), there were 1508 households and 943 businesses in the CHZ, totalling 2451 properties. The total number of households in the wider HPUDS area increased by 6.3% between 2009 and 2015, which exceeded the projections (HBRC et al., 2017). Future households will need to be provided for within a smaller land footprint through increased densities in new residential developments and intensive redevelopment of existing areas while providing amenity values (HBRC et al., 2017).

The average annual household equivalised disposable income (after tax and transfer payments) was $NZ_{2019}$\$47,517 nationally and $NZ_{2019}$\$42,200 for the combined Hawke's Bay/Gisborne area in June 2020 (StatsNZ, 2020a). Therefore, below the national average. The equivalised disposable income method is helpful as it reflects the diversity in household size and composition by dividing the net household equivalised income over the number of 'equivalent adults' (StatsNZ, 2020a). From 2007 to 2020, the household income increased 4.6% per annum from $NZ_{2019}$\$23,987 to $NZ_{2019}$\$42,200 for the Hawke's Bay region (StatsNZ, 2020a). Over the same period, the average annual household equivalised disposable income increased 4.5% per annum from $NZ_{2019}$\$29,925 to $NZ_{2019}$\$47,517 (StatsNZ, 2020a).

The household income distribution for both the New Zealand population and Hawke's Bay is represented in Figure 4.8 using Lorenz curves. Lorenz curves are a convenient way to represent the size distribution of income and wealth, from which one can infer economic and social welfare (Kakwani, 1977). It would appear that between 2013 and 2018 that inequality is on the rise for both the New Zealand population and the Hawke's Bay population. The Gini coefficients (areas under the curve) are also an acceptable way to measure inequality as they provide a singular indexed number

(Kakwani, 1977). For 2018 they were a) 20.5 for Hawke's Bay and b) 33.1 for New Zealand (with StatsNZ (2020b) defining the same period as 33.2), where 0 equals perfect equality, and 1 equals perfect inequality. Therefore, Hawke's Bay's society exhibits more equality than the national average.

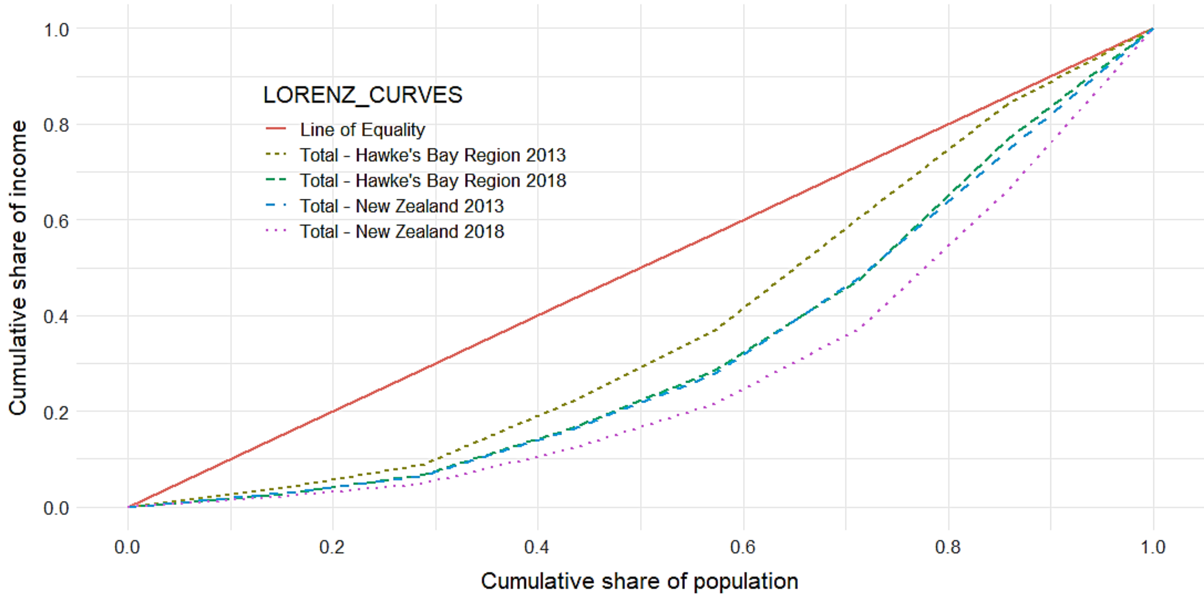



**Figure 4.8** Lorenz curves prepared from StatsNZ census data for 2013 and 2018 (StatsNZ, 2020b) to develop the Gini coefficient for Hawke's Bay and New Zealand. The further the distribution is from the Line of Equality, the more unequal a society is. Hawke's Bay has a favourable position over the New Zealand average in these cases.

Finally, over the past two decades, the unemployment rate in Hawke's Bay has been higher than the national average (Figure 4.9). Yet, history shows regional employment has increased by 1-1.5% over the 2000-2015 period (HBRC et al., 2017), with the trend continuing through to 2020. The future focus is for substantial regional employment of the local workforce in public capital projects to increase the population's resiliency (HBRC, 2016a). Thus, even with a higher unemployment rate, Hawke's Bay is a more egalitarian place to live than the national average.

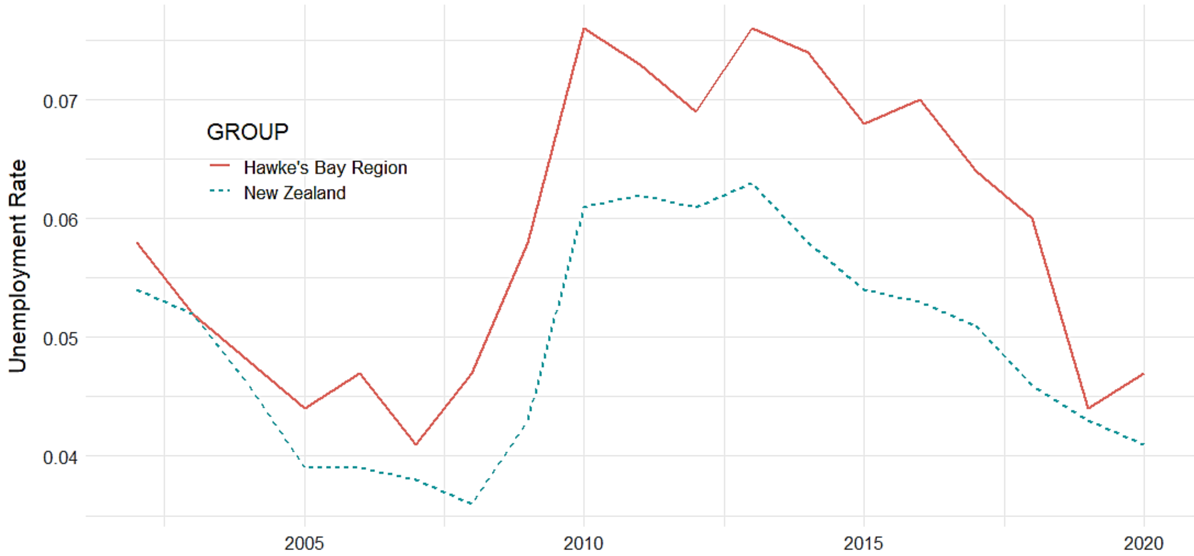



**Figure 4.9** Unemployment Rate for the Hawke's Bay Region and New Zealand between 2002-2020 (StatsNZ, 2021). The Hawke's Bay region has sustained a higher unemployment rate than the national average over the period. Note the steep increase in both lines around 2008 as the Global Financial Crisis sets in.

# 5. C-ADAPT: A new Integrated Assessment Model for analysing the economic impacts of managed retreat

Chapter five describes a new IAM to explore coastal managed retreat called C-ADAPT. It explores funding and land-use planning scenarios for managed retreat in Hawke's Bay alongside what happens if society does nothing. C-ADAPT aims to operationalise the conceptual framework described in Chapter 3. This chapter first describes the Scenario Planning needed to identify a plausible view of the system now and into the future. Second, gathered knowledge and information are incorporated into System Dynamics to create input modules that integrate with MERIT. Third, MERIT quantifies regional economic impacts from baseline, mitigation and adaptation scenarios. Finally, RDM assesses model outputs or key performance indicators (key aggregates) to identify DAPP of least regret for coastal communities.

## 5.1 IAM development

Integrated assessment analyses interacting systems to define states, impacts, and feedback that result from policy intervention (Haasnoot et al., 2014a). Evaluation of impacts given climate pressures, socio-economic developments or policy options determines the usefulness of an IAM (Haasnoot et al., 2014a). The IAM C-ADAPT achieves this by using Ventana Systems' Vensim® DSS System Dynamics software to simulate the influence of coastal flooding and inundation on the local and regional economy and implement adaptation strategies for managed retreat. The impact of coastal hazards on the local and regional economy defines the problem the IAM seeks to resolve, which can then be broken down into the baseline, or reference modes, against which the policy interventions are measured. Next endogenous and exogenous variables are defined through iteration, and the 'bull's eye' approach outlined by Ford (2010) is applied. Iteration in System Dynamics, calibration, verification, and model validation are also outlined below. The C-ADAPT Vensim® model, the technical report, its equations and the source data are accessible from Gitlab at https://gitlab.com/aceaves/c_adapt.

C-ADAPT is based on the down-scaled CLD outlined in Figure 5.1, which defines crucial cause and effect relationships through balancing (-) and reinforcing (+) feedback loops within the environment-economy systems. The CLD rationale was obtained through Scenario Planning and System Dynamics. Next, the modelling phase developed quantitative stock-flow diagrams (modules) from the CLD, which were tested for robustness through calibration, iteration and sensitivity analyses. Modules combine local-scale geospatial information with time-dependent hydrological and socio-economic data to infer impacts propagating into MERIT. Finally, RDM was employed by developing a Python matrix - PYRDM (https://gitlab.com/aceaves/dappy) to explore DAPP of least regret from the evaluation of key aggregates (e.g. Annual Expected Loss, Total Value Added and government consumption).

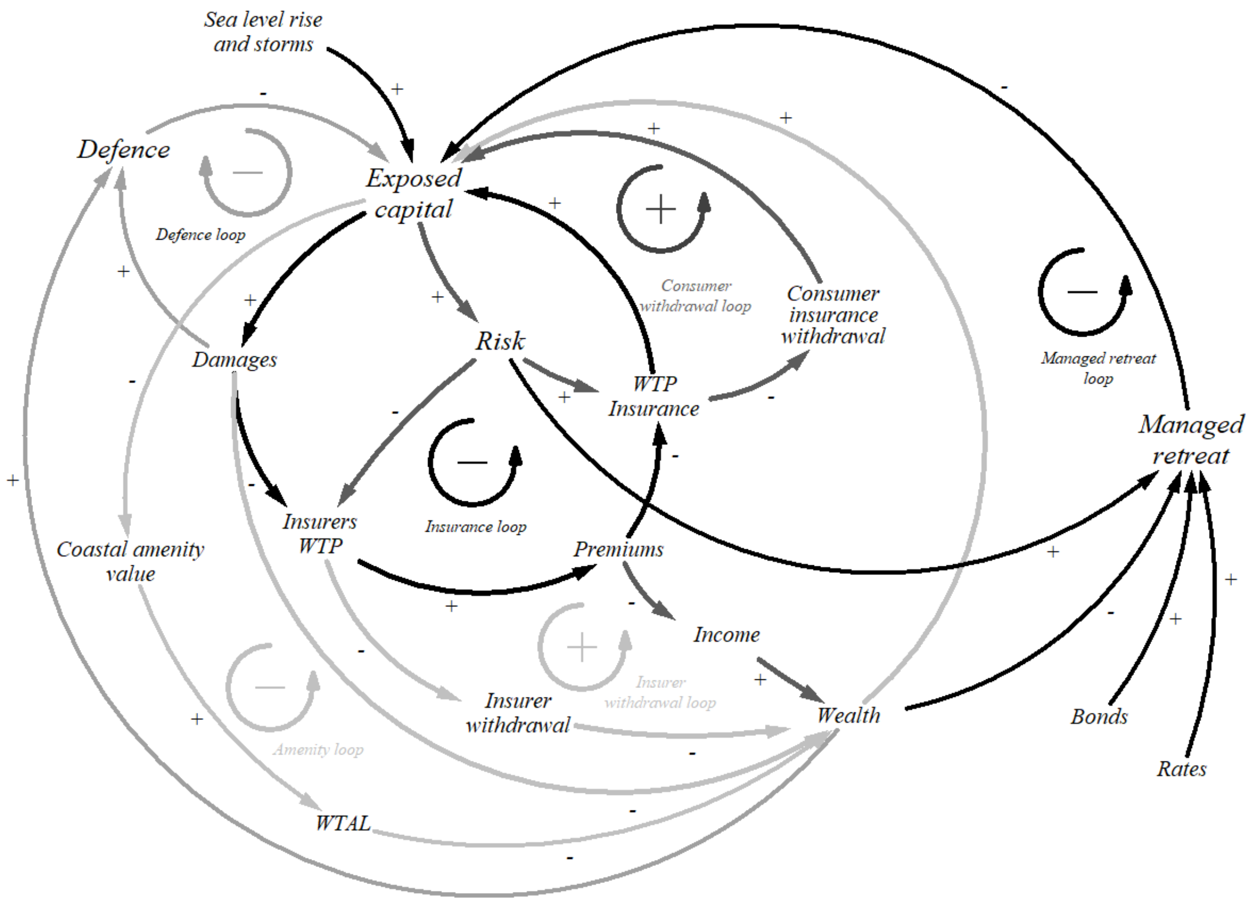



**Figure 5.1** The overarching Causal loop diagram for C-ADAPT. Central to the diagram are insurance mechanisms that maintain the status quo. Under the baseline scenario, the central loop is the 'Insurance loop', where communities transfer coastal hazard risk by insuring against storm damages. Insurer's WTP for increasing damages and losses leads to their market withdrawal (Insurer withdrawal loop). Similarly, growing premiums become intolerable for consumers, leading to withdrawal (Consumer withdrawal loop). An 'Amenity loop' preserves capital exposure as property owners are WTAL for coastal living benefits. On the top left is the mitigating coastal defence balancing loop (Defence loop), and on the right, the managed retreat balancing loop through government adaptation interventions.

The CLD can be explained as follows. The central loop in the diagram is the 'Insurance loop', where communities offset coastal hazard risk by insuring against built capital damages and losses from storms which somewhat maintains their capital value. However, as the sea level rises and storms increase in frequency and magnitude, storms increasingly remove built capital and land, reducing property owners' wealth. The insurer's unwillingness to pay ((un)WTP) for foreseeable increasing damages and losses leads to their withdrawal from the insurance market (Storey et al., 2017) which subsequently reduces the value of exposed capital. Similarly, consumers in the CHZ are unwilling to pay an endless share of income for insurance as risk-based premiums rise. Consequently, insurance becomes intolerable; they also withdraw from the market. These outcomes fail to reduce capital exposure to coastal hazards (as they maintain the original state by remaining in harm's way). Finally, exposure to hazards is accentuated by amenity value as exposed property owners are willing to accept loss (WTAL) of capital wealth to maintain the benefits of coastal living (Bin & Kruse, 2005; Penning-Rowsell et al., 1992). However, mitigation is a scenario where the local government installs coastal defence structures to maintain exposed habitation. Similarly, governments can intervene through adaptation and provide managed retreat by implementing financial mechanisms, such as property rates or climate bonds.

C-ADAPT requires a structured process for model development. Therefore, it applies the Agile Development Methodology (ADM) outlined by Sawalha and AbdelNabi (2020) (Figure 5.2). ADM is a structured process for technological development that computer programmers use to provide transparency to their automation and an audit trail of activity, testing and consultation (Sawalha & AbdelNabi, 2020). The IAM evolved through numerous iterations involving supervisory feedback, expert workshops and external expert input.

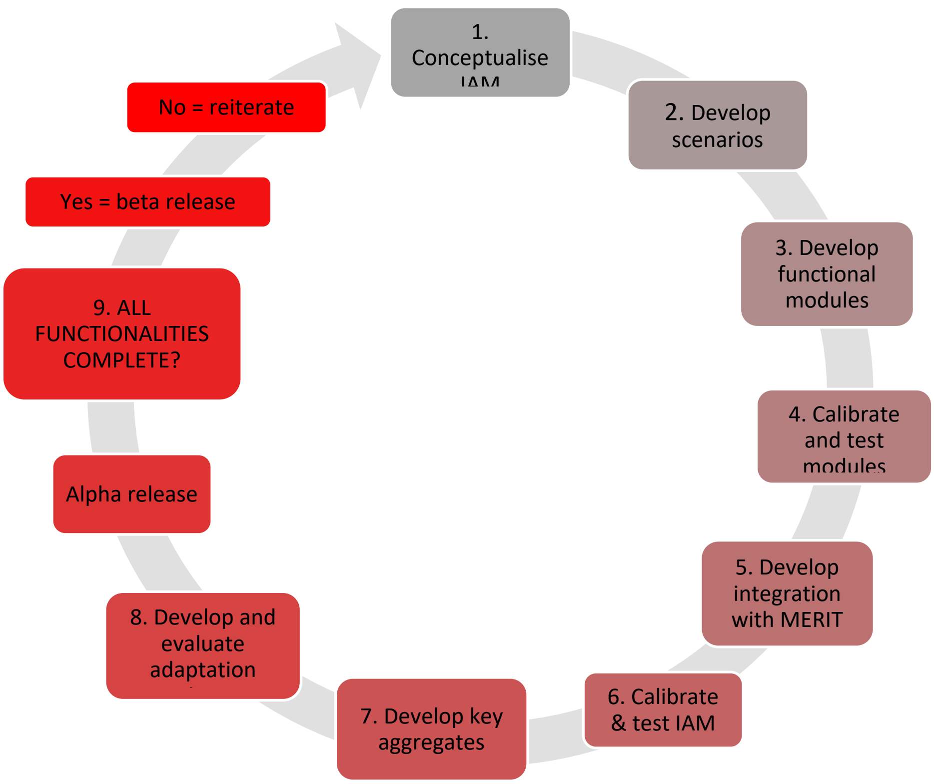



**Figure 5.2** The Agile Development Methodology used to develop C-ADAPT.

## 5.2 Scenario Planning

Modelling future options for a coastal managed retreat for sub-regional Hawke's Bay draws on Scenario Planning developed using census information, expert workshops, expert conversations, questionnaires, government planning documents and datasets, utility datasets, reports, industry practice, model feedback and finally, knowledge obtained through the National Science Challenge: Living at the Edge project (see Kench et al., 2018).

Expert workshops were held with the Hawke's Bay Technical Advisory Group and the Reserve Bank of New Zealand (ethics approval reference 021706) to provide a range of plausible scenarios. External expert input was conducted with Market Economics, EQC governance, Climate Sigma, NIWA coastal engineers, consulting engineers and district planners. Smith, Orchiston et al. (2016) applied a similar approach to developing system variables exogenous to the MERIT model that reflected stakeholders' narratives. The audience for the Scenario Planning was considered to be government decision-makers, coastal managers and stakeholders in Hawke's Bay. These workshops were participatory rather than collaborative, an approach outlined by Allison (2020). The participatory approach was considered appropriate as incentivising subject matter experts to part with many hours of their time to collaborate in multiple workshops is not feasible without a significant reward being offered to participants – an option not available to this research project.

Iteration, sensitivity analyses and model feedback also design the plausibility of the scenarios through model refinement. Thus, a hybrid approach was developed that tested predetermined scenarios developed with experts as described by Scenario Planning and the use of model refinement in System Dynamics. The scenarios are:

1. The Baseline Scenario (status quo, counter-factual or reference mode);
2. The Defence Scenario;
3. The Climate Bonds Scenario;
4. The Property Rates Scenario;
5. The Land-use Planning Scenario.

C-ADAPT is set up with the scenarios shown in Table 5.1. Three baseline scenarios (Table 5.1, 1 - 3) illustrate a world where we do nothing and continue to live with communities at risk from coastal hazards: storms impact the coast, inundating assets and eroding foundations. Eventually, depending on the two RCP driver conditions, risk-averse insurers withdraw from exposed markets and communities are forced to retreat from the coast as their savings evaporate and the land yields to erosion and flooding. Two engineering intervention scenarios (Table 5.1, 4 & 5) examine the effects of installing coastal defence structures (see HBRC, 2019, 2020), and four financial intervention scenarios (Table 5.1, 6 - 9) examine the plausibility of financial planning mechanisms that could enable managed retreat. The first set of adaptation scenarios (Table 5.1, 6 & 7) involves the financial intervention of central government acting as a 'Development Partner' (Hall & Lindsay, 2017) by purchasing at-risk properties through climate bonds. In contrast, the second set of adaptation scenarios (Table 5.1, 8 & 9) considers the possibility of no central government contribution. Instead, the local government comes to the aid of exposed communities as a 'Direct Investor' (Hall & Lindsay, 2017) by financing and managing relocation through a property rating tax. Two other scenarios (Table 5.1, 10 & 11) are examined in Chapter 7 only, representing a view where insurers remain in the market indefinitely to discover when consumers are no longer WTP for insurance as premiums rise. They are surplus to the primary analysis but provide insight into an alternative baseline scenario.

All scenarios integrate current global and national climate change science alongside operative regional planning documents. The IPCC (2019) RCP projections define future physical exposure to SLR and storm impacts that reflect projections by the Ministry for the Environment (2017) under RCP4.5. Conversely, under RCP8.5, the IPCC defined SLR, whereas storm impacts reflect a greater magnitude than reported by the IPCC to reflect New Zealand's exposure to extreme storms in the South Pacific.

***Table 5.1 Climate, baseline and intervention scenario details for C-ADAPT***

| Scenario | RCP driver | SLR (mm $a^{-1}$) | Increase in Storm Intensity (% $a^{-1}$) | Increase in Storm Frequency (% $a^{-1}$) | Interventions / Comments |
|---|---|---|---|---|---|
| 1. | RCP0 | 0 | 0 | 0 | **No SLR**<br>Properties are exposed to infrequent storms without climate change |
| 2. | RCP4.5 | 6 | 0.23 | 1.86 | **Baseline**<br>Baseline scenario in which property owners remain in situ until insurers withdraw from the market or three significant storms force an *ad hoc* relocation financed by public insurance. |
| 3. | RCP8.5 | 8 | 0.98 | 2.75 | **Worst-case baseline**<br>Property owners follow the same behaviour as (1) but are subject to higher SLR and more intense storms earlier in the model period. |
| 4. | RCP4.5 Defence | 6 | 0.23 | 1.86 | **Defend**<br>Baseline scenario (1) modified with defence structures installed along the coastline.<br>Pandora cell cost is $NZ_{2007}$\$39M (inundation trigger level).<br>Northern cell cost is $NZ_{2007}$\$6M (erosion trigger level).<br>Southern cell cost is $NZ_{2007}$\$55M (erosion trigger level). |
| 5. | RCP8.5 Defence | 8 | 0.98 | 2.75 | **Worst-case defend**<br>Identical to (3) but subject to higher SLR and more intense storms. |
| 6. | RCP4.5 bonds | 6 | 0.23 | 1.86 | **Managed retreat (bonds)**<br>$NZ_{2007}$\$35Bn national bond issued by the central government.<br>$NZ_{2007}$\$2.4Bn allocated to Hawke's Bay. |
| 7. | RCP4.5 rates | 6 | 0.98 | 1.86 | **Managed retreat (rates)**<br>Targeted, general and household property rates are generated by the local government.<br>$NZ_{2007}$\$2.4Bn generated for Hawke's Bay. |
| 8. | RCP8.5 bonds | 8 | 0.23 | 2.75 | **Worst-case managed retreat (bonds)**<br>Identical to (5) but subject to higher SLR and more intense storms. |
| 9. | RCP8.5 rates | 8 | 0.98 | 2.75 | **Worst-case managed retreat (rates)**<br>Identical to (6) but subject to higher SLR and more intense storms. |
| 10. | RCP4.5 Insure | 6 | 0.23 | 1.86 | **Insure**<br>Baseline scenario (2) modified so insurers remain in the coastal property market (until the AEP = 5% approximately) to define when property owners themselves retreat.<br>Chapter 7 only. |
| 11. | RCP8.5 Insure | 8 | 0.98 | 2.75 | **Worst-case insure**<br>Identical to (4) but subject to higher SLR and more intense storms.<br>Chapter 7 only. |

The indicative timing of adaptation scenarios through changes to the number of structures affected and finance installations are illustrated in Figure 5.3 to provide context around CHZ occupation. It shows the occupation through property count to illustrate when any *ad hoc* or managed retreat occurs under the different scenarios (A) and the associated government expenditure on intervention scenarios (B), as explained in Table 5.1. As flooding forces an *ad hoc* retreat, the number of properties in the CHZ reduces after 2040 under baseline scenarios (2 & 3). Still, the percentage loss is more significant under RCP8.5 owing to higher SLR and more intense storms (Figure 5.2A). Properties in the CHZ reduce to zero under the RCP8.5 managed retreat scenarios (8 & 9) and RCP8.5 (3) but not under the RCP4.5 scenario (2). In contrast, defence scenarios and the No SLR scenario result in all properties remaining (1, 4 & 5). A delay in the baseline scenarios occurs when insurers remain in the market (10 & 11). Figure 5.2B illustrates the timing and cost of interventions. All managed retreat scenarios cost significantly more than defence scenarios, as outlined earlier, as the cost of community relocation far outweighs that of defensive structures.

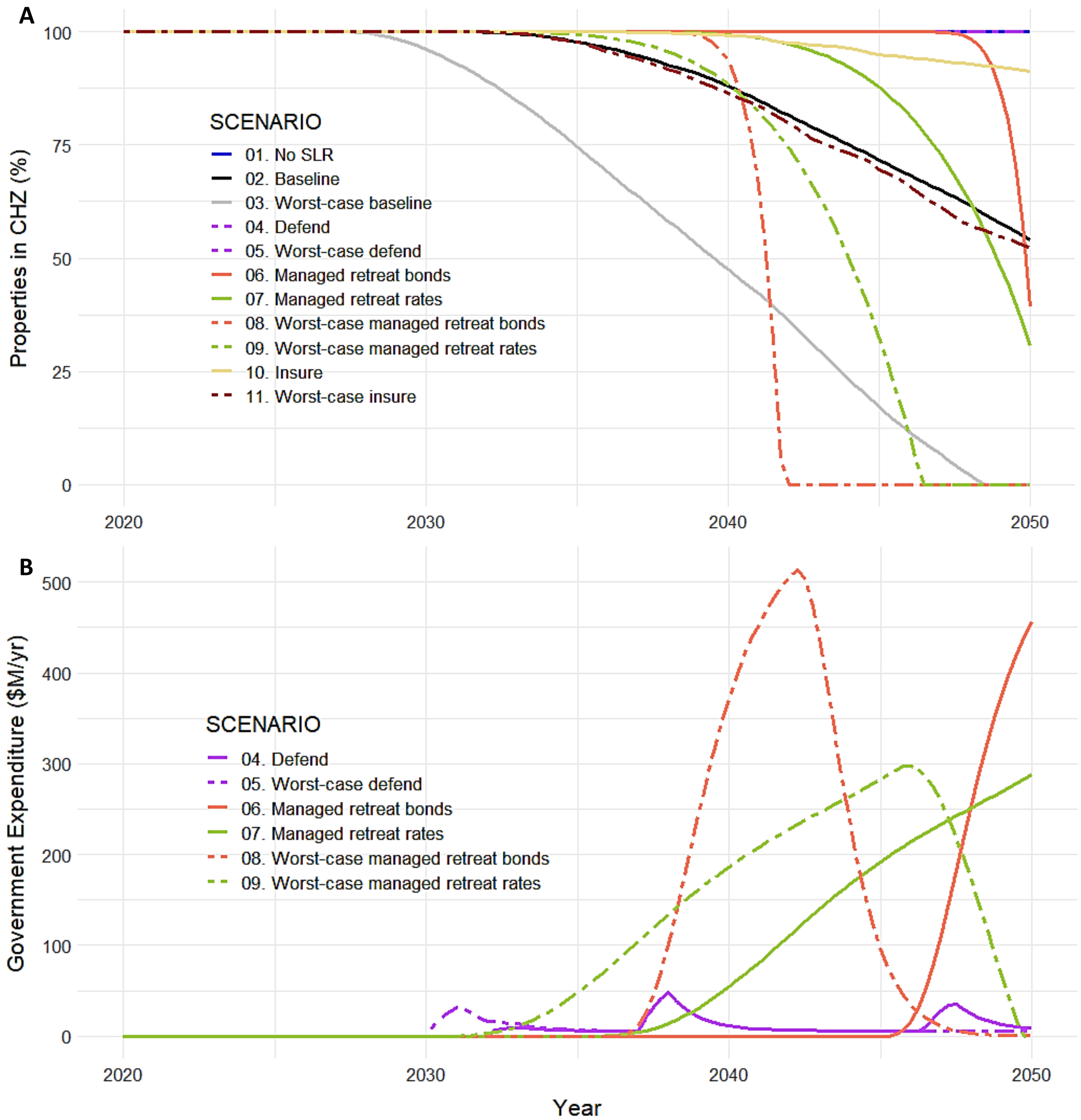



**Figure 5.3** Indicative timing of scenarios (A) and the implementation of intervention funding (B) based on the median of 100 simulations. Note that baseline scenarios are missing in (B) as they do not require government expenditure.

The model's decision tree is outlined in Figure 5.4 for the various scenario pathways. Whereas Table 5.2 describes the associated distributional impacts implicit in the modelling on households, industries and governments.

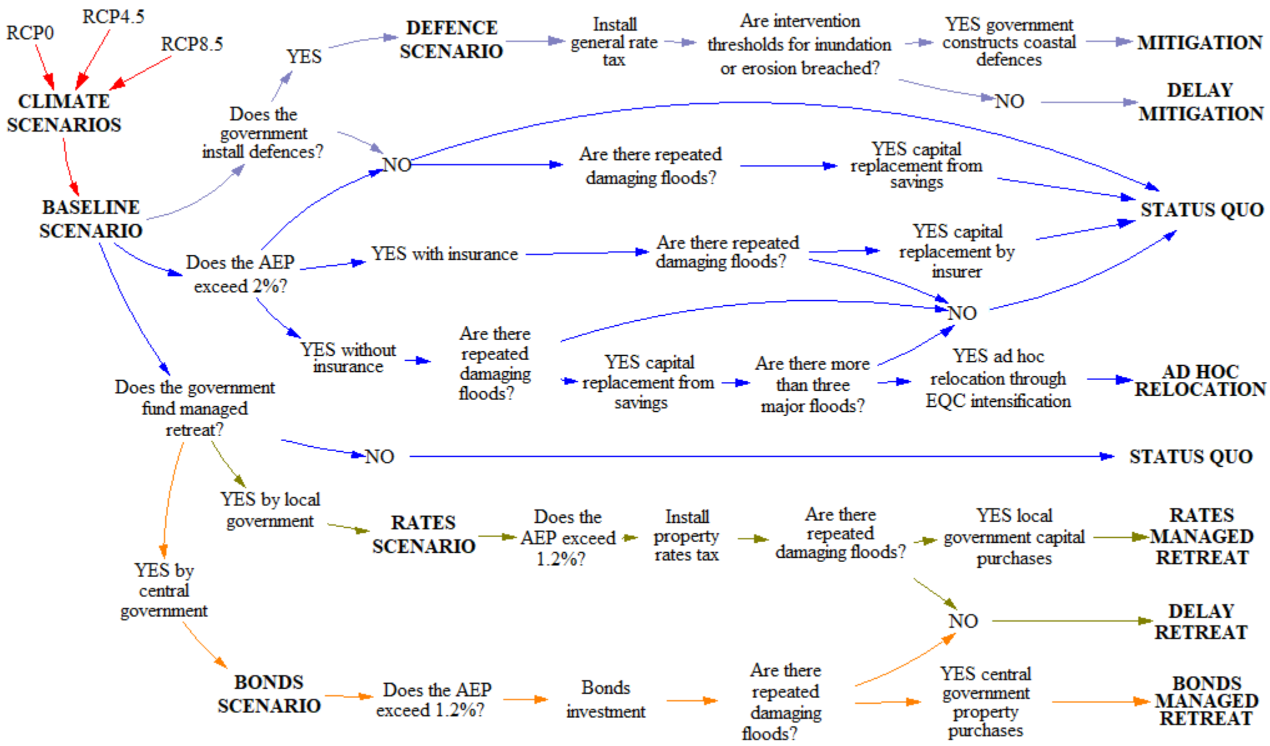



**Figure 5.4** Decision tree of the scenario pathways over time in C-ADAPT.

***Table 5.2 Distributional impacts of scenarios for managed retreat (NB: HHLD = Households, IND = Industries, GOVT = Government)***

| Scenario | Distribution on HHLD | Distribution on IND | Distribution on GOVT | Other |
|---|---|---|---|---|
| **Baseline** | • High impacts on a few individuals | • More long-term impacts than managed retreat | • Significant impact on public insurance | • Minimal moral hazard |
| **Defence** | • Households gain at the expense of the region | • Industry gains at the expense of the region | • Medium impact on local government | • Long-term hazard remains<br>• Intergenerational and spatial risk transfer |
| **Rates** | • Performs poorly for households<br>• Affects low-income earners more than higher earners | • More spread of impacts onto businesses than Baseline<br>• Invigorates manufacturing | • Local GOVT consumption significantly outweighs revenue | • Large moral hazard |
| **Bonds** | • Performs well for households<br>• Reduces unemployment | • Diverts investment expenditure lowering capital growth regionally & nationally<br>• Exchange rate impacts | • Minimal impact on Central GOVT<br>• Requires a favourable bond market | • Large moral hazard<br>• Equity issues |

### 5.2.1 The Baseline Scenario

The baseline scenario invokes the status quo and broadly follows the expectation outlined by Maven Consulting Limited (2017, p. 9) for the Hawke's Bay Cape Coast area where:

> "Property owners take individual responsibility for the protection of their properties and assets. Councils do not construct any defensive works along the coastline. Essential services (power and water supply, etc.) will continue to coastal properties in the erosion and inundation hazard zone for as long as it is viable to do so".

Industries and households remain in the CHZ through repeated inundation events of varying magnitude. However, once the TWL exceeds 1.23 m above three times the MHWS (12 m NZVD2016), households and firms abandon the CHZ through *ad hoc* or forced relocation. In this instance, the relocation is supported by the public insurance provider EQC, which underwrites lost land with a modest section away from hazards. Households and firms internalise direct impacts or transfer risk through public and private insurance schemes. However, insurance providers stop covering exposed households once the AEP exceeds 2%. If capital is uninsured, then households and firms cover damage and clean-up costs after floods from savings.

Concurrently, exposed properties' capital values decline over the medium-term with no new development in the area. Again, Maven Consulting Limited (2017, p. 45), under their status quo scenario, contest that "discounts on a property in an area that is subject to natural hazards will remain for as long as the hazards exist (and may increase if the perceived risk becomes higher)". In contrast, Filippova et al. (2020) illustrated that property prices in hazard zones are not so simple as people are willing to tolerate coastal risk in the short term for the added amenity value of coastal living.

Outside the CHZ, projections for Hawke's Bay are optimistic, with growth in primary production and manufacturing sectors (Hawke's Bay Today, 2018). Population growth is greater than the national trend as people seek the amenable lifestyle of Hawke's Bay (StatsNZ, 2019a). However, the increasing demand for quality land from many competing interests forces land prices higher (Radio New Zealand, 2020).

### 5.2.2 The Defence Scenario

The defence scenario is the 'historical practice scenario' where communities choose to defend the shoreline against coastal hazards. The local government mitigates the hazard through defence structures along the coast. The Clifton to Tangoio Coastal Hazards Strategy 2120 (2017) outlines a series of preferred options for each community. The options predominantly favour short to medium-term coastal defence through control/defence structures, followed by managed retreat long-term (HBcoast, 2017). However, this scenario only focuses on the short-term pathways for coastal defence outlined by the Strategy. There are two pertinent issues for coastal defence: cost and timing. HBRC (2019, 2020) estimate the costs, which are in Appendix 1. Coastal engineers put forward scenarios to define the trigger levels for the timing of implementations. Defence structures are assumed to last 20-30 years (Infometrics Consulting Limited, 2017a) with an ongoing maintenance program outlined by HBRC (2019, 2020) once installed. The general synopsis is:

1. The local government installs a property rating tax on the district and region to pay for coastal defence. The local government introduces a general rate as outlined by HBRC in Sharpe (28 May 2019).
2. In the short-term, communities endure nuisance flooding until the local government installs defence structures.
3. The module integrates capital and maintenance costs (Appendix 1).
4. The local government successively installs the coastal defence structures when repeat flooding or erosion exceeds trigger levels.
5. Defence structures last 20-30 years before replacement or retreat is required.

Trigger levels determine the implementation of defence strategies before significant exposure is imminent and were designed with coastal engineers' knowledge. Given the diversity in spatial extent, each management cell requires a different implementation timeframe given various environmental factors affecting each community. Therefore, Pandora requires a trigger level based on water level due to its estuarine environment. In contrast, all other cells are open coast and therefore trigger levels are quantified from the erosion rate. HBRC (2019, 2020) determined Inundation levels and erosion rates. Thresholds were identified through conversations with coastal experts, including NIWA, HBRC, Tonkin and Taylor and planning guidance from the Ministry for the Environment (2017).

The inundation trigger level for Pandora is when 1-2 10% AEP events affect property foundations over ten years, as suggested by NIWA (M. Allis, coastal engineer, personal communication, 29 October 2020). Trigger levels should not be based on episodic extremes, which may only reflect natural climate variability. Instead, they should reflect the slower onset or trend of the natural system responding to climate change, such as multiple inundation events over time, salinisation or chronic erosion (M. Allis, personal communication, 29 October 2020).

The erosion trigger level for the northern and southern cells required establishing distances between structures and the sea and the current rate of change for the coastline. The approach used here is similar to that used by NIWA (2017a) at Carters Beach, West Coast. GIS analysis averaged the distance from MHWS to exposed dwellings for each cell and then applied the annual erosion rate to determine the period before a buffer was breached. However, isolated buildings (surf clubs, campgrounds, boat sheds, etc.) and utility infrastructure were exempt. A building buffer or offset also provides time for planning, community inertia and implementation, an approach advocated by the Ministry for the

Environment (2017). A buffer of 7 m as suggested by Tonkin and Taylor (T. Shand, coastal engineer, personal communication, 28 October 2020), which is based on a subdivision ruling by the Environment Court at Mahanga Beach, Mahia (NZEnvC 83 "Mahanga E Tu Inc v Hawkes Bay Regional Council," 2014).

### 5.2.3 The Climate Bonds Scenario

The Climate Bonds Scenario covers the procedure outlined by the Climate Bonds Initiative (2019), Climigration (Taylor-Hochberg, 2017) and Treasury's Acting Director of capital markets at the time of writing, Kim Martin (Maoate-Cox, 14 June 2020). Bonds are the most common way for governments to generate capital, and a system for generating and repaying bonds is already in place (Maoate-Cox, 14 June 2020). A bond is a type of loan which institutions and companies use to finance projects (Climate Bonds Initiative, 2019). "The issuer (the borrower) of the bond owes the holder (the creditor) a debt and, depending on the terms they agree on, is obliged to pay back the amount lent within a certain time and with a certain interest" (Climate Bonds Initiative, 2019). The capital generated is then invested in high-return markets until it is spent on climate-related ventures across the country on an 'as required' basis. Here the central government takes the role of development partner' (Hall & Lindsay, 2017) by purchasing exposed properties from households and firms so they can invest elsewhere.

Central government funding was the preferred intervention scenario from the TAG expert workshop (8 November 2018). The RBNZ expert workshop (5 December 2018) also considered this as a viable option but were unwilling to comment further, given their close links to central government. The general synopsis is:

1. Banks create an investment fund to raise capital; for example, the New Zealand Green Investment Finance fund (Herd, 5 December 2018).
2. The investment fund issues a 10-year Climate Bond when the AEP > 1.2% to finance projects that address climate issues (Climate Bonds Initiative, 2019). The government manages bonds under the existing mechanism for issuing New Zealand Government Bonds (Maoate-Cox, 14 June 2020).
3. Issuance of a NZ$$_{2007}$35B bundle at the national level is implemented to cover all climate emergencies (NZ$$_{2007}$35Bn based on model sensitivity analyses using Latin Hypercube sampling).
4. The government auctions bonds to registered tender counterparties, such as domestic or offshore banks (Maoate-Cox, 14 June 2020).

5. Tender counterparties then seek investors, such as fund managers, central banks, pension funds or individuals, to purchase bonds as a legal contract with the central government (Climate Bonds Initiative, 2019; Maoate-Cox, 14 June 2020).
6. Capital generated from lenders is invested in high-yield corporate bonds with an interest rate of 5% return to increase capital (Latin Hypercube sampling).
7. Bonds mature after ten years with a fixed interest rate (coupon payment) of 3.13% p.a. This represents the average annual return on investment from seven issues by the Climate Bonds Initiative (Tapley, 2016). The coupon payment to investors is generally twice a year, usually based on the prevailing market interest rate (Maoate-Cox, 14 June 2020). However, under this scenario, a monthly payment is made based on the fixed interest rate.
8. The central government then draws down on its available funds to purchase the exposed properties (TWL>12 mRL, or MSL>3.183 m, on two occasions).
9. Bond funding seeks to cover the $NZ_{2007}$\$2.4B of assets exposed in Hawke's Bay.
10. Finance generated is directed into purchasing exposed properties by the central government. The owner can then use the payment to buy another property elsewhere.
11. Land-use zoning increases to meet the supply for managed retreat.

### 5.2.4 The Property Rates Scenario

Under this scenario, local government is a 'Direct Investor' (Hall & Lindsay, 2017), generating capital to finance managed retreat through general and targeted rates or property taxes. The two rates are 1) a general rate for all property owners within the region and district, split into an enterprise rate and a household rate, and 2) a targeted rate. The general rate split is so a higher weighting is imposed on enterprises with more cash flow to absorb the tax than households are. The targeted rate applies a 'beneficiary pays' approach, where some managed retreat costs are recouped from beneficiaries. Thus, differential (targeted) property rates are similar to a user fee as "they impose the heaviest cost burden of a project on residents who have the highest demand" (Mullin et al., 2019, p. 277). The local government already employs general rates in Hawke's Bay to generate capital to defend against SLR and coastal erosion (Sharpe, 28 May 2019). A local government Council Controlled Organisation (CCO) administers and manages the retreat (TAG communication 8 November 2018). After leaving it up to the household, there was firm support for property rates from the TAG expert workshop (8 November 2018) as the third, most acceptable option. The RBNZ expert workshop (5 December 2018) also considered this as a viable option. The general synopsis is:

1. Local government levies a targeted and general rate on properties when the AEP > 1.2%.
2. The general rate includes a differential between households and businesses for each property in the rating district.

3. A local rate is set by property in the NCC and HDC jurisdictions, and a regional rate by property in the HBRC region.
4. The rate is a fixed charge rather than based on land or capital value. A fixed-rate model was preferred by respondents of a proposed Water Quality Targeted Rate by Auckland Council (2017).
5. All rates increase at 5% p.a. and are subject to changes in the rating base. The targeted rate also proportionally increases as properties leave the CHZ, which incentivises withdrawal.
6. Similar to bonds, the cumulative rates funding peak at NZ$$_{2007}$2.4B.
7. Rates revenue gathered is invested by local government into capital projects for enterprises and households (TWL > 12 mRL, or MSL>3.183 m, on two occasions).
8. The module also applies a 2-year lag between tax generated and capital expenditure.
9. The CCO undertakes land purchase and builds capital for managed retreat. Both the NCC and the HDC have departments for managing economic development (see Hastings District Council, 2020; Napier City Council, 2020), which require integration into a CCO to reflect the objectives of Heretaunga Plains Urban Development Strategy (HPUDS) and the Matariki Plan to manage the retreat.
10. The CCO allocates built capital to the private sector in collaboration with enterprises and households to match demand.

### 5.2.5 Land-use Planning Scenario

Land-use planning determines the amount of land required under each scenario, whether greenfield conversion or zone intensification. However, for managed retreat scenarios, legislative change is required. Thus, councils require an ‘Enabling Act’ from the central government that provides powers to: condemn buildings unfit for habitation, streamline land-use zoning, enforce relocation and provide enforcement action for non-compliance (TAG communication 8 November 2018). Therefore, if withdrawal from an exposed area is required before risks become significant, then bespoke legislation to enable relocation should be considered (Grace et al., 2018). The Enabling Act, alongside amendments to the RMA, as outlined by Grace et al. (2018), provide an avenue for effective implementation. The general synopsis is:

a. Amend the RMA1991 so that regional rules and regional policy statements can manage existing uses, existing development, future development and risk reduction (Grace et al., 2018):
    i. Introduce rules to manage the rebuilding of damaged dwellings, such as requiring buildings to be set back within site.
    ii. Introduce rules to require existing uses to necessitate resource consent, with a finite duration that aligns with a particular SLR. Permitted activities in the CHZ change to become

discretionary activities in the medium-term, given prohibited activity status over the long term (Tasman District Council, 2011).

iii. Enhance risk reduction through rules that make existing uses prohibited activities.

b. The Local Government Long Term Plan modifies the CHZ to a residential, commercial, industrial or rural Closed Zone for future development and subdivision (Tasman District Council, 2011).

c. The Long Term Plan provides new zones in the District Plan of habitable land close to the CHZ to suit the community's adaptation needs (Tasman District Council, 2011).

d. The Long Term Plan contains strategic structure plans that enable industries to relocate with similar business viability factors.

e. The Long Term Plan goes beyond the usual ten years to follow similar timeframes to the Urban Development Strategy and asset management plans of 30 years.

f. Exceeded trigger levels (see Defence Scenario) lead to a scaling back of council service provision in the CHZ allowing the redirection of resources to new locations.

## 5.3 Developing input modules for MERIT

From the scenarios, input modules are constructed that concentrate on causal relationships between variables to understand exogenous system drivers for integration into MERIT. Initial causal mapping derives the modules to provide a theoretical framework of relationships, influences, external factors, lags and delays in the system (Smith, Orchiston, et al., 2016). Modules can represent activity models, natural systems models and valuation models (Turner, 2000) that allow for processing data and developing system relationships through System Dynamics.

Modules incorporate a) risk through assessing physical system drivers, spatial asset data and hydrologic data; b) household and firm behaviours through socio-economic data and logic from Scenario Planning; c) the cost of defending the shoreline; d) finance and insurance interventions from Scenario Planning and e) land use planning projections. The modules are the following:

1. Risk Assessment Module;
2. Socio-Economic Module;
3. Infrastructure Interdependencies Module;
4. Defence Module;
5. Climate Bonds Module;
6. Rates Module; and
7. Land use Zoning Module.

The modules are hard-linked into MERIT to create an integrated (closed) system using Ventana Systems' Vensim® DSS, as shown in Figure 5.4. A hard-linked IAM's strength is internal consistency, rigorous mathematical foundations, and the execution of long-term, multi-dimensional policy optimisation useful for risk and damage computations (Bosello, 2014).

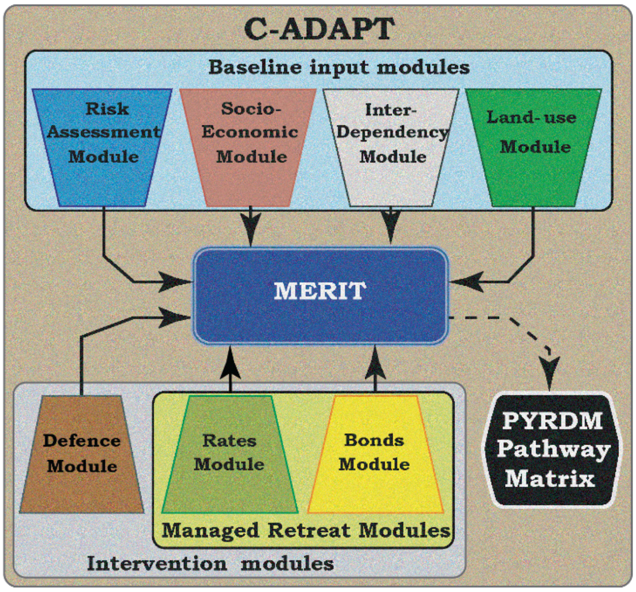



**Figure 5.4** C-ADAPT workflow from modules into MERIT and then to the PYRDM pathway matrix.

Note that variables in the simplified stock-flow diagrams and equations are formatted as:

- Bold for stocks;
- Italics for auxiliaries;
- Capitals and italics for constants or exogenous datasets.

### 5.3.1 The Risk Assessment Module

Hazard and risk identification represent the magnitude and probability of flooding that threaten life, infrastructure and the economy. In contrast, vulnerability and exposure assessments characterise the population exposed to the danger and the resulting damage (Williams & Micallef, 2009). The Risk Assessment Module calculates the physical hazard and economic exposure by applying stochastic floods to create localised direct impacts (damages and losses) to land and built capital under different climates. The inundation of coastal communities is assessed through the effects of SLR, marine storm surge, breaking waves, river flooding and tides. The changing hazard scape provides the economic system with stochastic shocks through damage and loss from increasingly higher water levels through linear operators. Therefore, the escalation of these hazards through time is the critical driver of system change. However, there is dynamic feedback from the retreat of properties occupying the CHZ. Conceptually, the modelling approach is similar to Johnson et al. (2013), who modelled risk assessment through spatial flood depth and economic exposure to quantify the estimated annual damage and Peck et al. (2014), who coupled ESRI ArcGIS® with Vensim® for flooding and infrastructure outages. The module also follows the approach of Baron et al. (2015) for assessing community exposure to a changing TWL. The Risk Assessment Module is illustrated in Figure 5.5.

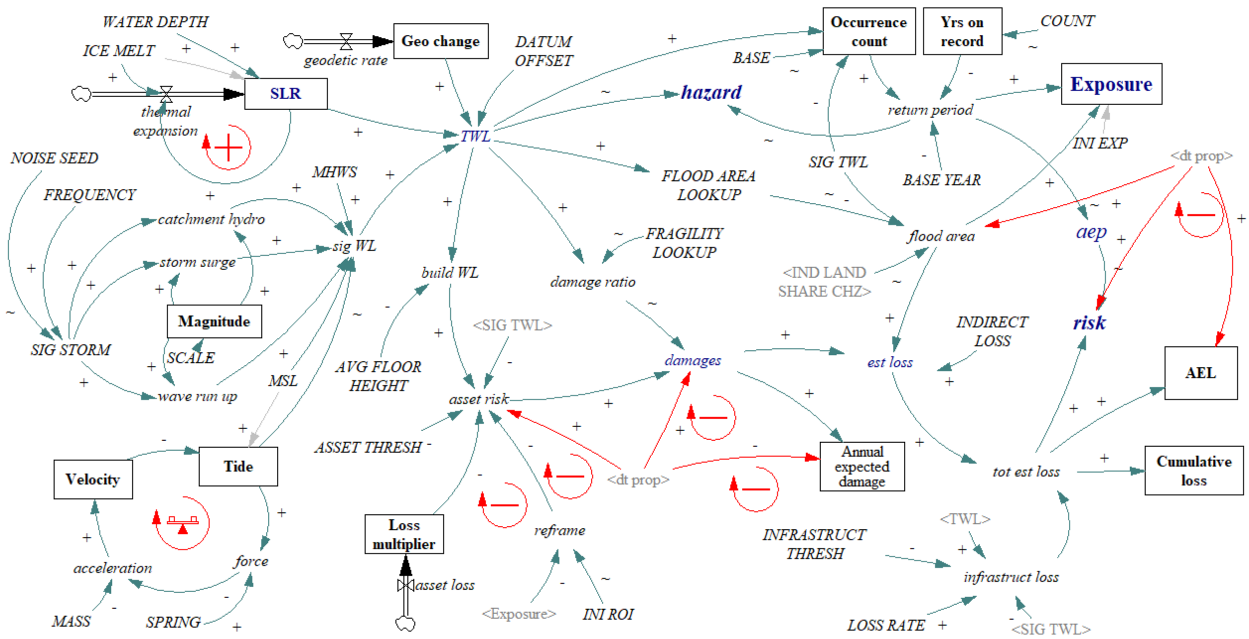



**Figure 5.5** The stock-flow diagram of the Risk Assessment Module. It features linear operation from significant total water levels (*TWL* and *SIG TWL*) to damages (*Annual expected damage*) and losses (*AEL* and *Cumulative loss*) incurred. Balancing dynamic feedback occurs through *dt prop,* or the percentage of properties in the CHZ, and behavioural reframing (*reframe*) of property investment decision making based on *exposure* and return on investment (*INI ROI*). *SLR* illustrates reinforcing environmental feedback from *thermal expansion.* Significant TWLs are triggered by a random *noise seed* acting on the frequency of storms and the *magnitude* of the event. The *tide* operates expectedly as a diurnal oscillation. Red arrows represent external module influence.

The sea level is based on historical data supplied by Napier Port and adjusted to NZVD2016. SLR projections were accommodated from the IPCC (IPCC, 2014b, 2019) RCPs, corrected with the national and regional offset (Ministry for the Environment, 2017). Thus, changes to the current water level were calculated using trends for future SLR (IPCC, 2014b; Ministry for the Environment, 2017), storm surge (Komar & Harris, 2014a), waves (Komar & Harris, 2014a), river flooding (HBRC, 2018), tide (LINZ, 2012) and land subsidence as described in Beavan and Litchfield (2012) to define significant TWLs during future storms. SLR and significant TWLs that drive damages and losses are visible in Figure 5.6.

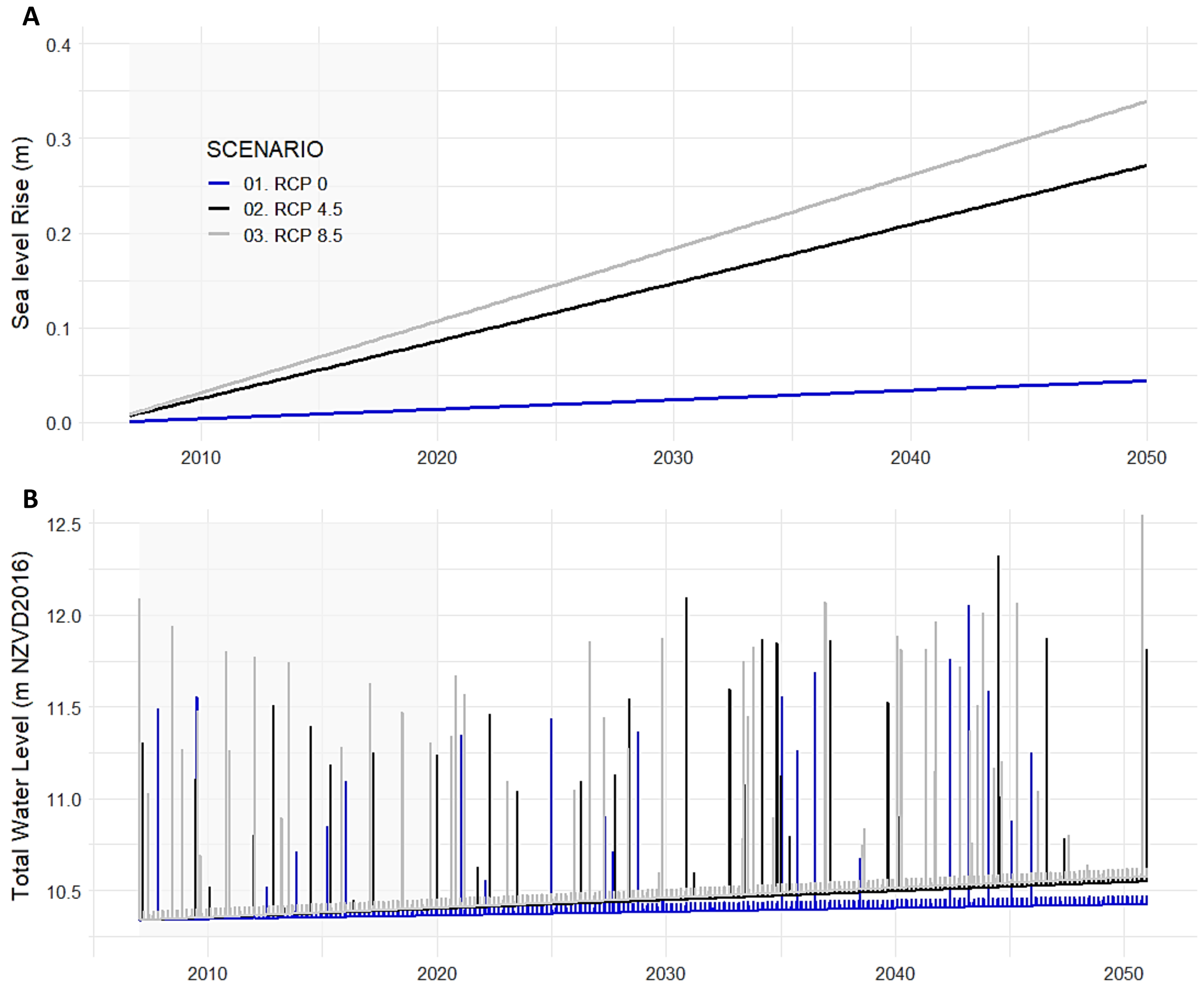



**Figure 5.6** Indicative sea level rise (SLR) (A) and stochastic TWL (B) that drive damages and losses to the CHZ under varying climate projections. As the land subsides, there is an increase in SLR under the RCP0 scenario. Note the grey box denotes the calibration period.

Equations 5.1 and 5.2 represent the *AEP* and *return period* adapted for System Dynamics (where *Yr* refers to years).

$$aep = \left(\frac{1000}{return\ period}\right) - 10 \qquad \textbf{(5.1)}$$

$$\boldsymbol{Where}:$$

$$return\ period = -\left(\frac{\textbf{Occurrence count}^2}{\textbf{Yrs on record}}\right) + BASE\ YR \qquad \textbf{(5.2)}$$

Flood risk fragility, or damage ratios, are fundamental to defining the possible direct economic impacts from coastal hazards. They define the percentage of buildings damaged based on a given water level. In New Zealand, the methodology for building flood fragility curves is outlined by Reese and Ramsay (2010). The methodology features curves (represented using a series of damage ratios) used for assessing direct flood impacts as in Riskscape (NIWA, 2017c). Building floor height and construction type define damage ratios, as shown in Figure 5.7. The damage ratio used to calculate the residential building content value from the Riskscape database and the average construction type is also visible in Figure 5.7. The residential calculation is similar for most commercial premises but not for industrial premises, where a linear relationship between water level and damage is more appropriate (Reese & Ramsay, 2010).

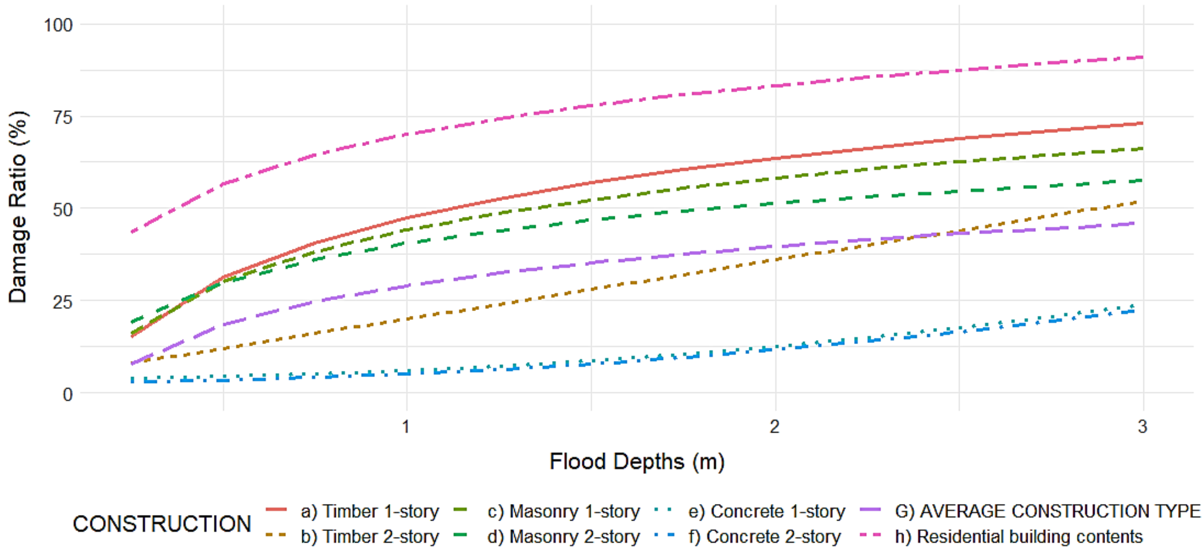



**Figure 5.7** NIWA flood damage ratios adapted from Reese and Ramsay (2010). Given the size of the study area, the building construction types were averaged (line G) and applied.

Next, the direct physical impacts are calculated. The direct impacts include built capital damage and loss from flood fragility curves, land loss, clean-up costs and remediation costs. Direct impacts are commonly measured as changes in capital stock values at a single point in time (Boston, 2017), as described by NIWA (2019). The estimated capital damage, which accounts for replacement costs, stock, plant, and contingent values, was calculated from Riskscape (see NIWA, 2017b; NIWA, 2017c) and 2017 local government property valuations. It achieves this by overlaying the spatial vulnerability in GIS, or the CHZ the CDEM 2120 1% AEP (HBRC, 2017a). The inundation's aerial extent is modelled through step changes in inundation levels aligned with the 1% AEP at 2065 and the 2120 1% AEP. See Appendix 2A for the industry breakdown of assets at risk for the a) CDEM 2065 1% AEP coastal inundation, b) CDEM 2120 1% AEP coastal inundation and c) the regional asset value expressed in MERIT.

Similarly, infrastructure assets were valued in GIS and added to the risk assessment (see Appendix). Local Government provided information on roads, rail and the three waters network, Unison provided electricity and communications network information, and Powerco provided the information on the gas network. Network valuation followed the same approach as Local Government New Zealand (2019), which quantified exposed infrastructure by overlaying GIS polygons of SLR elevations with council infrastructure information to define replacement value.

Finally, the annual estimated loss (AEL) accounts for damages, losses, clean-up and remediation costs previously mentioned and land losses (a derivative of total estimated loss or *tot est loss*). Land losses are set at 1% of government land valuations for each storm event. C-ADAPT assumes that subsequent storms incrementally remove a share of the land area (*flood area*) and value per hectare (*indirect loss*). The 1% AEP has an annual recurrence interval of 100 years (Pacific Region Infrastructure Facility, 2017) which is the assumed inundation of the CHZ over 100 years (see HBRC, 2017b). Therefore for simplicity, the model assumes each storm event incrementally costs a share of the land value. There are approximately 40 significant storm events (TWL > 11.5 m) over the 44 years (2007-2050), accounting for 40% of the land value. Tonkin and Taylor's (2016) land inundation mapping estimated approximately a 30% reduction in the area over 100 years, a more conservative estimate. Equations 5.3 and 5.4 illustrate the calculation of *AEL* from estimated loss (*est loss*) with a Vensim® SMOOTH function to induce a temporal system lag of 5 years. The SMOOTH function acts to enforce a time delay called psychological smoothing, a form of information delay that occurs whenever a decision forms part of a system's feedback structure, which is influenced by gradual adjustments of beliefs or perceptions (Forrester, 1961; Smith, McDonald, et al., 2016).

$$\frac{d}{dt}\mathbf{AEL}_{SMOOTH\ 5} = \sum tot\ est\ loss_{IND} \times dt\ prop \times \mathbf{Time} \times CALIBRATION - \mathbf{AEL} \qquad \textbf{(5.3)}$$

$$\mathbf{AEL}(t_0) = 0$$

$$\boldsymbol{Where}:$$

$$est\ loss_{IND}$$

$$= damage + flood\ area \times INDIRECT\ LOSS \qquad \textbf{(5.4)}$$

### 5.3.2 The Socio-Economic Module

The Socio-Economic Module captures behaviour that emerges when communities are faced with complex dynamic feedbacks present within an economy resulting from an increasing coastal risk and storm damage. It takes the stochastic shocks and losses from the Risk Assessment Model and then simulates the response of the local property and insurance markets to multiple complex economic interactions. This module focused on understanding stakeholder behaviour, accommodating known risk through multiple loop feedback in System Dynamics based on Scenario Planning outcomes. Insurance is central; therefore, the module defines increasing risk-based insurance premiums and excesses, and when insurers or consumers withdraw from the market, it drives an *ad hoc* retreat. High-risk areas may face insurance retreat, while some property owners opt to remain in high-risk areas to enjoy coastal amenity values (Bin & Kruse, 2005; Penning-Rowsell et al., 1992). Compulsory public insurance also helps vulnerable residents from flooding and inundation. It focuses on the interactions between household wealth, income, coastal property amenity, exposed capital and insurance. The stock-flow diagram for the Socio-Economic Model is illustrated in Figure 5.8.

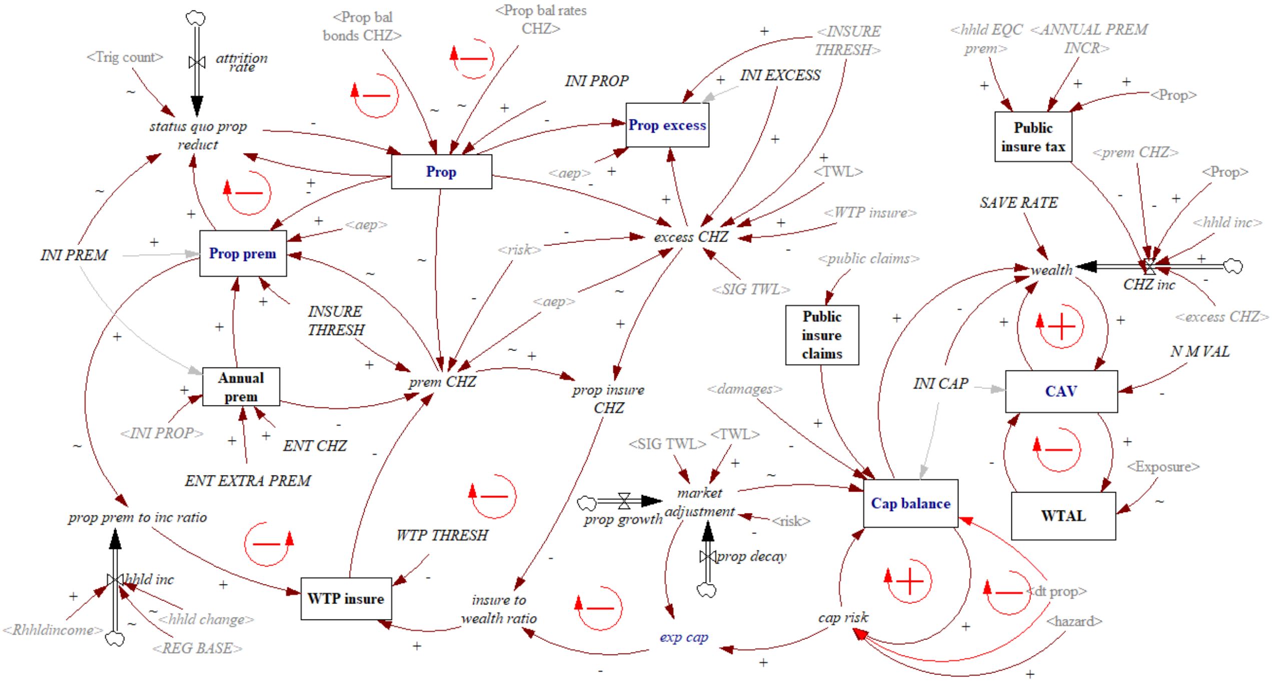



**Figure 5.8** The stock-flow diagram of the Socio-Economic Module. The left-hand side operators represent insurability (*Prop prem, Annual prem, prop excess,* and *WTP insure*) and properties (*Prop*). In contrast, the right-hand side loops represent capital in the Coastal Hazard Zone (*wealth, Cap balance, market adjustment*, and *exp cap*) and coastal amenity value (*CAV, N M VAL*-non-market value, and *WTAL*-willingness to accept loss). As risk increases, insurers increase premiums (*prem CHZ*) and excesses (*excess CHZ*) to a point where they become unaffordable to owners (*WTP THRESH* and *WTP insure*). The scenario alters the property balance (*Prop bal bonds CHZ, Prop bal rates CHZ* or *status quo prop reduct*), where implemented rates and bonds scenarios reduce the property count and repeated flooding (*Trig count*) influences the baseline scenario. Coastal amenity is reinforced by WTAL, wealth and the non-market value of coastal living developed from hedonic pricing. Next, the capital balance is influenced by impending hazard, changing property count (*dt prop*) and the risk-based rationalisation of the market (*market adjustment*). Light red arrows represent external module influence.

Data to quantify exposed capital is sourced from Riskscape (NIWA, 2017b), StatsNZ (2020b), property sales (The University of Auckland, 2017), capital vulnerability assessments (NIWA, 2019) and government property valuations (Hastings District Council, 2017b; Napier City Council, 2017b) which are required for calculation of Equations 5.5 and 5.6. Here exposed capital (*exp cap*) is a function of the AEP and the insurability threshold (*insure*). The *market adjust* features here to adjust capital values (*cap bal*) to a return on investment (*ROI*) with and without risk as a function of the number of significant floods experienced (*trig count*).

$$exp\ cap(aep)_{SMOOTH\ 1}$$

$$= \begin{Bmatrix} \textbf{Cap bal} \times market\ adjust + \textbf{Tot damage} \\ for\ aep < \ INSURE \\ \textbf{Cap bal} \times market\ adjust - \textbf{Tot damage} \\ for\ aep > \ INSURE \end{Bmatrix} \quad \textbf{(5.5)}$$

$$\boldsymbol{Where}:$$

$$market\ adjust(\textbf{Trig count}\,)$$

$$= \begin{Bmatrix} ROI\ for\ \textbf{Trig count}\ \leq 2 \\ ROI - \left[ROI \times \left(\frac{risk}{100}\right)\right]\ for\ \textbf{Trig count} > 2 \end{Bmatrix} \quad \textbf{(5.6)}$$

Insurability was defined with Scenario Planning through the expert workshops and conversations and incorporated into the module alongside insurance policies, census data (StatsNZ, 2020b) and spatial data (LINZ, 2018). It then defines the premiums and excesses in the CHZ. Anecdotally, insurers are only willing to cover properties where the AEP is < 2%; above this amount, insurers withdraw from the market (Daalder, 2 December 2020). Conversely, households are only willing to pay up to 5% of household income toward insurance (quantified from model sensitivity analyses); otherwise, consumers withdraw from the market. Similarly, they are only willing to lose 5% of their capital wealth, which is an assumed arbitrary value to reflect consumer behaviour as insurance costs and exposed capital rise. C-ADAPT initially calculates the household insurance premium at $NZ\$_{2007}$1,000 and calibrates to $NZ\$_{2007}$1,500 by 2018 to conform with Corelogic Inc (2018). During the 2016 financial year, New Zealand households, on average, spent 17.6% of their income on housing costs (mortgage or rent expenses, property rates and building-related insurance) (StatsNZ, 2016). Given that Hawke's Bay's median household income was $NZ\$_{2013}$53,200 (StatsNZ, 2020b) in 2013, 5% represents a tolerable percentage when 21% of household income is spent on household costs on average nationally (StatsNZ, 2020a). Equations 5.7 and 5.8 show the calculation for property premiums (*prop prem*) and property excesses (*prop excess*) as a function of the *AEP* and the insurance threshold. Note that *INI* refers to the initial starting amount.

$$\textbf{Prop prem}(aep\,)_{SMOOTH\ 1} = \begin{Bmatrix} 0\ for\ aep > INSURE \\ \left(\frac{prem\ CHZ}{PROP} \times (1 + risk)\right) for\ aep \leq 2 \\ -\textbf{Prop prem} \end{Bmatrix} \quad \textbf{(5.7)}$$

$$\textbf{Prop prem}\ (t_0) = \textbf{Annual prem}$$

$$\frac{d}{dt}\textbf{Prop excess}(aep\,)$$

$$= \left\{ \begin{matrix} -\mathbf{Prop\ excess}\ for\ aep > 2 \\ \left(\frac{excess}{PROPERTIES} \times (1 + risk)\right) for\ aep \leq 2 \end{matrix} \right\} + \mathbf{Prop\ excess} \tag{5.8}$$

$$\mathbf{Prop\ excess}(t_0) = \left\{ \begin{matrix} 0\ for\ aep > 2 \\ INI\ EXCESS\ for\ aep \leq 2 \end{matrix} \right\}$$

Amenity values (e.g. recreation, coastal access and views, ecosystem services) were developed using hedonic pricing, a contingent valuation that estimates the monetary benefits through property market values to overcome specific non-market valuations (Filippova, 2009; Ojea, 2014). It determined the added value for coastal amenity, a non-market environmental service (Ministry for the Environment, 2004; van den Belt & Cole, 2014) (See Appendix 3). Calculating the amenity value helps define property owners' behaviour, given knowledge of the increasing risk of coastal hazards. This study's hedonic pricing method of valuation performed multiple linear regression analysis on 53,800 property sales within commuting distance of the study area using the University of Auckland's Property Database (2017) (see Appendix 3). The sales price was the dependent variable, and the distance from the coast was one of the independent variables to define the multiplier non-market value (*nm val*). Equations 5.9 and 5.10 illustrate the calculation of coastal amenity value (*CAV*) and *wealth*.

$$CAV = \mathbf{Wealth} \times N\ M\ VAL \times (1 + \mathbf{WTAL}) - \mathbf{Wealth} \tag{5.9}$$

$$\boldsymbol{Where}:$$

$$\frac{d}{dt}\mathbf{Wealth} = \mathbf{Cap\ bal_{IND9}} + CAV + EQC\ claims$$
$$+(CHZ\ income \times SAVINGS\ RATE) - \mathbf{Wealth} \tag{5.10}$$
$$\mathbf{Wealth}(t_0) = INI\ CAP$$

### 5.3.3 The Infrastructure Interdependency Module

The Infrastructure Interdependency Module determines industry operability given infrastructure outages, or a drop in the level of service provided by infrastructure providers to consumers due to floods. As expected, the level of service provided by critical infrastructure is determined by its reliance on other critical infrastructures for normal operation, with relationships developed by McDonald, Buxton and Fenwick (5 November 2014) and presented at the 2014 New Zealand Lifelines Forum. The loss of service in one infrastructure affects the level of service provision of other infrastructures, which, in turn, affects other infrastructures. Understanding these interdependencies can be achieved by simulating the reliance and volume of financial exchange between interconnected infrastructure, assumed through measured economic transactions in national accounts (Zorn, 2017b).

It operates as follows. Once a significant TWL drives an outage, each infrastructure cycles through its dependency on the other infrastructures. The interdependent level of service for each type of infrastructure is discovered, with the delta time playing a critical role in module accuracy given the timestep of 1.8 days. Such a timestep is not a problem where damages take longer than 1.8 days to repair. However, communication and electricity networks are rapidly repaired or have inherent redundancies reducing the impact to negligible (Zorn, 2017b). The individual infrastructures are averaged to discover an 'average' outage given the size of the study area. Any changes to the number of properties in the CHZ due to *ad hoc* or managed retreat are also incorporated by increasing an infrastructure's level of service. The infrastructure are:

- *Electricity*
- *Water*
- *Sewer*
- *Gas*
- *Port*
- *Airport*
- *Communications*
- *Petrol*
- *Rail*
- *Road*

For example, Equation 5.11 represents the operability of electricity infrastructure (*elec out*) based on TWL.

$$elec\ out(tot\ WL)_{SMOOTH\ 0.005} = \left\{\begin{matrix} 1\ for\ TWL < 11.5 \\ ELEC\ OUT\ 1\ for\ 11.5 \geq TWL \ \leq 12 \\ ELEC\ OUT\ 2\ for\ TWL \ > 12 \end{matrix}\right\} \qquad \textbf{(5.11)}$$

If the TWL is less than 11.5 m, then the electricity network operates at full capacity. Conversely, where the TWL is greater than 11.5 m or 12 m, then spatially derived outage datasets are integrated through Vensim® functionality and iterated until normal operation resumes. Once there is an outage in one part of the network, it propagates to other interdependent infrastructure inducing further vulnerability. This process can be seen in Equation 5.12, where the electricity level of service (*elec LoS*) depends not only on the outage but also on interdependent infrastructure.

$$elec\ LoS(elec\ out) = \left\{ \begin{bmatrix} 1\ for\ elec\ out\ \geq 1 \\ min\ Ptrlm - Elec \\ min\ Gas - Elec \\ min\ Tele - Elec \\ min\ Water - Elec \\ min\ Sewer - Elec \\ min\ Roads - Elec \\ min\ rail - Elec \\ min\ Ports - Elec \\ min\ Airports - Elec \\ 1 - \left( (1 - elec\ outage) \times \frac{REDUCTION\ IN\ OUTAGE}{100} \right) \\ for\ elec\ out\ < 1 \end{bmatrix} \times \left( \frac{1}{ELEC\ RECOVERY\ DELAY} \right) \right\}$$

The spatial vulnerability, or geographic density of the infrastructure network, was adapted from Zorn (2017b) using the ESRI ArcGIS® Kernel Density Tool to develop time-stamped outage maps (see Appendix 4). Zorn (2017b) describes how the co-location of infrastructure assets increases their vulnerability to localised disruptive events. Therefore, the module provides time-stamped geospatial outage maps for Hawke's Bay. The GIS calculates the density per unit area by aggregating multiple grids and adapting the quartic kernel function described by Silverman (1986). These estimates were adapted for use in Vensim® by utilising Equation 2. 1 in Zorn (2017b) and Equation 16 in Brown et al. (2015) to form Equation 5.13.

$$y_j^i = 1 - e^{-x} \tag{5.13}$$

Where *i j* refer to the infrastructure type and *x* the spatial output, the log scalar determines a percentile relationship for density between 0 (very distributed) and 1 (very clustered). The search radius was 2 km to account for the CHZ and the infrastructure in the broader area servicing the CHZ.

### 5.3.4 The Coastal Defence Module

The Coastal Defence Module is where communities choose to defend the shoreline against coastal hazards with the aid of local government. Trigger levels activate short-term coastal defence costs introduced by a series of time delays for temporal accuracy. The Pandora cell activates on random flood events (TWL > 12 mRL on two occasions). In contrast, the Northern and Southern cells activate on erosion (approximately 2033 and 2038, respectively), with timing implemented through delays activated by Vensim®'s *Time* variable. The maintenance cost of defence structures is activated after structure implementation. As outlined earlier, defence cost is paid for through a rates tax and therefore utilises the Property Rates Module. The Clifton cell cost is accounted for at the time of construction (2018) as the cost is incurred during the calibration period.

For this module, three equations are central. First, C-ADAPT needs to calculate the cost over time for each cell. For example, in equation 5.14, the cost of the northern cell is calculated as the initial value for defence structures (*nor cell short*) multiplied by the investment composite commodity consumption price (*pinvestcc*) and the time delay (*delay north*) determined by the erosion trigger. Note that * represents MERIT variables.

$$cost\ north_{SMOOTH1} = NORTH\ CELL\ SHORT \times pinvestcc^{*} \times DELAY\ NORTH \tag{5.14}$$

The total defence cost (*tot def*) in Equation 5.15 sums the three cell costs (*c short, c north* and *c south*) and multiplies the value by the binary operator *Def Switch* to turn the future defence scenario on or off. Then the current cost of existing defence for the Clifton cell is added.

$$tot\ def = \left[\begin{matrix}(c\ short + c\ north + \mathrm{c}\ south) \\ \times\ DEF\ SWITCH\end{matrix}\right] + existing\ def \tag{5.15}$$

Finally, the cost of maintenance calculates when the defence structures are implemented. *Dtmaintenance* represents the changing cost through time and takes the initial calculations from HBRC in Appendix 1 and multiplies it by the Consumer Price Fisher Index (*cpif*), as shown in Equation 5.16.

$$dtmaintenance(c\ short) = \left\{\begin{matrix} 0\ for\ c\ short < 0 \\ 0\ for\ c\ north < 0 \\ 0\ for\ c\ south < 0 \\ MAINTENANCE \times \left(\frac{cpif^*}{1000}\right) \\ for\ c\ short > 0 \\ for\ c\ north > 0 \\ for\ c\ south > 0 \end{matrix}\right\} \tag{5.16}$$

### 5.3.5 The Climate Bonds Module

The Climate Bonds Module allows the central government to raise capital by issuing a $NZ\$_{2007}$35Bn bundle of climate bonds to cover all climate disasters facing New Zealand. Approximately NZ$20072.4Bn is allocated to Hawke's Bay following two flood events. The stock-flow diagram and the various components that generate climate bonds are illustrated in Figure 5.9.

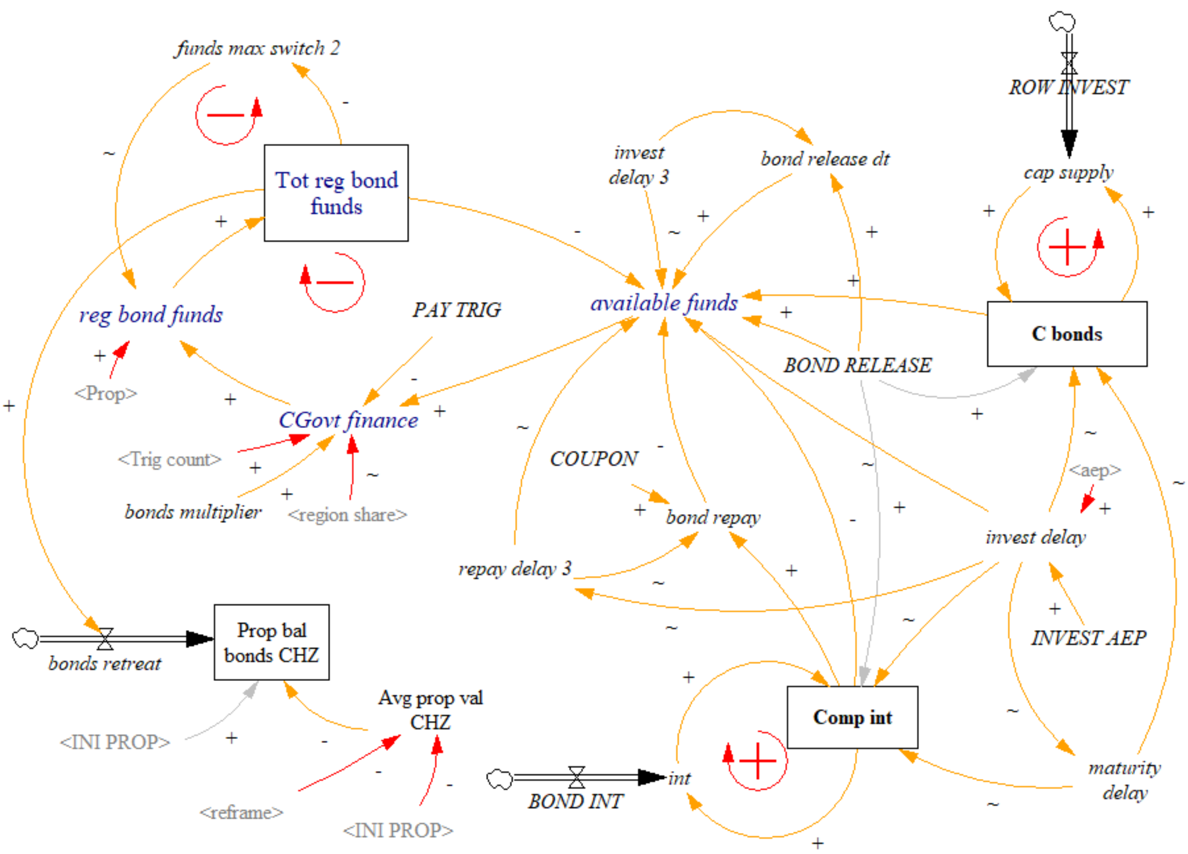



**Figure 5.9** The stock-flow diagram for the Climate Bonds Module operating at the national scale through central government by utilising Vensim® subscripting for governments. Reinforcing loops exist for Compound interest (*comp int*) and Climate bonds (*C bonds*) to generate increasing capital for relocation and loan repayment, with a balancing loop in place as *available funds* are drawn down for use in managed retreat (*reg bond funds*). As funds are spent (*bonds retreat*), the property balance in the CHZ is reduced (*Prop bal bonds CHZ*). A series of delays (*invest delay, maturity delay and repay delay*) enable the timing of transactions to suit the dynamic environmental change. The red arrow represents external module influence.

There are three fundamental exogenous system drivers in this module; 1) the Rest of World (ROW) investment rate, 2) the bond interest rate, and 3) the property balance in the CHZ given the bonds scenario. The investment and interest rates are set as exogenous inputs so that the module is operable with varying financial drivers given the current market uncertainty. The other main system drivers are the delay in investment timing, coupon repayments and the allocation of available funds at both the national and regional scale to meet the desired funding. Equation 5.17 shows the calculation for the stock of climate bonds (*C bonds*) as a feedback loop with capital supply (*cap supply*), which is developed from the *ROW Investment Rate*. At $t_{0,}$ *C bonds* equal the initial *bond release,* which are only activated as investment and maturity delays (*mat delay*) are realised.

$$\frac{d}{dt}\mathbf{C\ bonds} = cap\ supply \times invest\ delay \times MAT\ DELAY$$
$$\mathbf{C\ bonds}(t_0) = BOND\ RELEASE \qquad \textbf{(5.17)}$$

Similarly, Equation 5.18 calculates compound interest (*comp int*), where interest (*int)* is developed from the bond interest rate.

$$\frac{d}{dt}\textbf{Comp int} = int \times invest\ delay \times MAT\ DELAY \qquad \textbf{(5.18)}$$

$$\textbf{Comp int}\ (t_0) = BOND\ RELEASE$$

Equation 5.19 divides the compound interest into monthly coupon payments (*coup*) to calculate the bond repayment (*bond repay*) once delays are realised and activated by the binary *bond switch*.

$$bond\ repay(REPAY\ DELAY\ 3) = \begin{Bmatrix} 0\ for\ repay\ delay = 0 \\ \textbf{Comp Int} \times Coup \\ \times BOND\ SWITCH \\ 1\ for\ invest\ delay = 0 \end{Bmatrix} \qquad \textbf{(5.19)}$$

On the other side of the ledger, the available funds (*avail funds*) react to changes in climate bonds, compound interest, the expenditure of funds regionally (*Tot reg bond funds*) and a system lag of 10 years (Vensim® *SMOOTH* function), as shown in Equation 5.20.

$$avail\ funds_{SMOOTH3\ 10} = \begin{Bmatrix} \begin{bmatrix} (\textbf{C bonds} - \textbf{Comp int}) \\ +(bond\ release\ dt - bond\ repay) \\ +BOND\ RELEASE \\ -\sum \textbf{Tot reg bond funds}_{DREGIONS} \end{bmatrix} \\ for\ repay\ delay\ 3 = 3\ or\ invest\ delay \\ 3 = 1\ or\ BOND\ SWITCH = 1 \\ 0\ for\ repay\ delay\ 3 \neq 3\ or\ invest \\ delay\ 3 \neq 1\ or\ BOND\ SWITCH = 0 \end{Bmatrix} \qquad \textbf{(5.20)}$$

Equation 5.21 shows the calculation of *CGovt finance* allocating funds to Hawke's Bay (*reg bond funds*) given the region share (*reg share* derived from the proportion of regional enterprise savings to national enterprise savings in MERIT) and the trigger count (*trig count*) for allocation timing.

$$CGovt\ finance(aep) = \begin{Bmatrix} 0\ for\ \textbf{Trig count} < PAY\ TRIG \\ \left(\frac{avail\ funds}{DENOMINATOR} \times REG\ SHARE\right) \\ \times bonds\ multiplier \\ for\ \textbf{Trig count} \geq PAY\ TRIG \end{Bmatrix} \qquad \textbf{(5.21)}$$

Finally, Equation 5.22 describes the hypothetical reduction in properties in the CHZ as funds are allocated. It utilises an *average property value* defined by the *desired funding* for managed retreat divided by the tally of properties in the CHZ. The *property bal bonds CHZ* scales to zero as total funding allocation for managed retreat is realised. It is then used for dynamic feedback in other modules.

$$Prop\ bal\ bonds\ CHZ_{SMOOTH\ 10} = \left\{ \begin{matrix} 0\ for\ \textbf{Prop bal bonds CHZ} < 0 \\ \dfrac{-bonds\ retreat}{avg\ prop\ value\ CHZ} \\ for\ \ \textbf{Prop bal bonds CHZ} \geq 0 \end{matrix} \right\} \quad \textbf{(5.22)}$$

$$\textbf{Prop bal bonds CHZ}\ (t_0) = INI\ PROP$$

### 5.3.6 The Property Rates Module

The Property Rates Module implements a general rate on businesses and households and a targeted rate on CHZ properties by the local government, again when two flood events occur. It then uses these funds to relocate exposed properties to planned urban growth zones. The stock-flow diagram is illustrated in Figure 5.10.

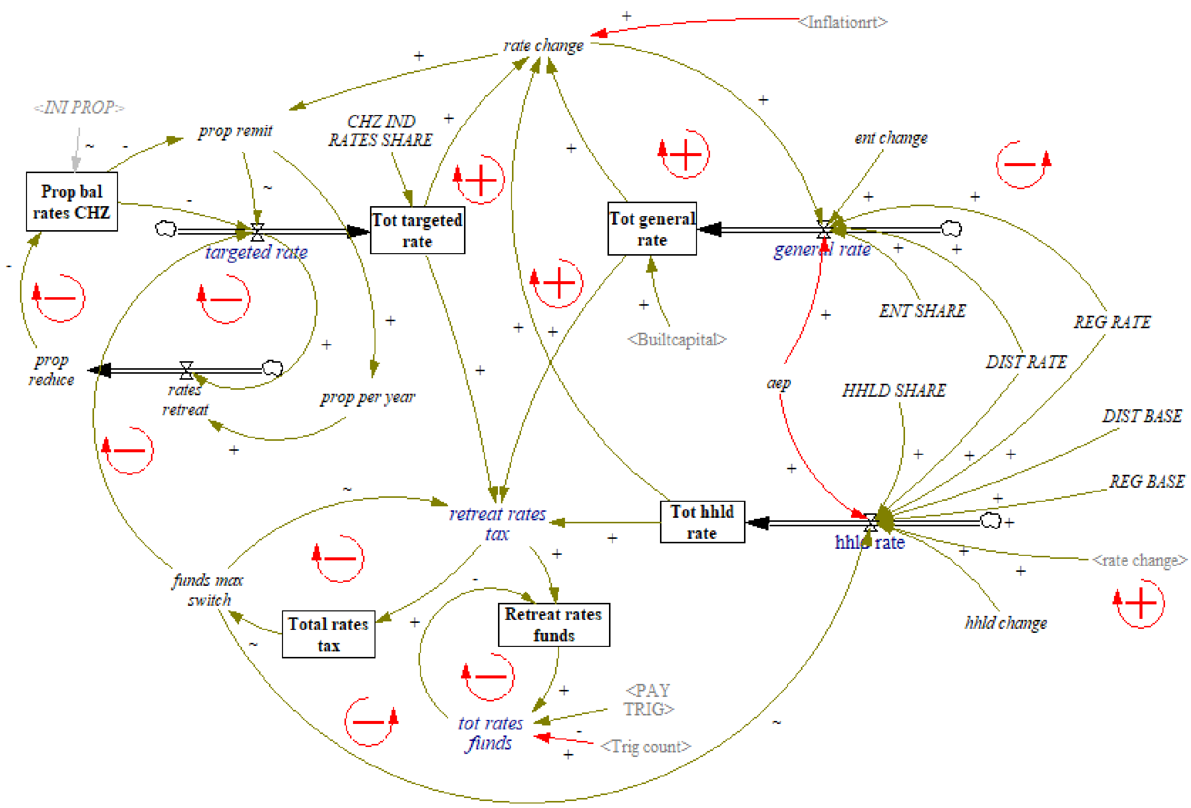



**Figure 5.10** The stock-flow diagram for the Property Rates Module operating at the regional scale through local government by utilising Vensim® subscripting for governments. The *targeted rate*, *general rate,* and the *hhld rate* respond to changes in the *Inflationrt* with feedback from each rate stock to limit the amount to the desired level of funding (*Total rates tax*) for managed retreat. First, the targeted rate disincentivises capital exposure by increasing over the period. Second, the general rate represents the proportion of rates paid by enterprises (*ENT SHARE* and *ent change*). Third, households pay less in the household rate (*HHLD SHARE*), allocated over the regional and district rating base (*DIST RATE, REG RATE, DIST BASE* and *REG BASE*). Funding is then allocated based on environmental triggers (*Retreat rates funds* and *Trig count*). Again, managed retreat funding reduces the properties in the CHZ (*Prop bale rates CHZ*). The module also allows for capturing property rates for coastal defence through cumulative defence cost (*cum def*), where the *funds max switch* uses the cost of defence instead of the retreat cost. Red arrows represent external module influence.

The creation of property rates is firmly entrenched in local government cash flow mechanisms. For example, Equation 5.23 shows the general rate calculation on a dynamic enterprise count (*ent change*) and the increased burden falling on enterprises (*ENTSHARE*) multiplied by the changing rate adjusted for desired funding (*funds cap switch*) and inflation via *rate change*. There is also an *aep* trigger, and trigger and a *rates switch* to enable managed retreat.

$$general\ rate(aep) = \left\{ \begin{matrix} \left( \begin{matrix} REG\ RATE \times ent\ change + \\ DIST\ RATE\ \times ent\ change \times ENTSHARE \end{matrix} \right) \\ \times rate\ change \\ for\ aep > \ RATE\ AEP \\ 0\ for\ aep < RATE\ AEP \\ for\ RATES\ SWITCH = 1\ \ and\ funds\ cap\ switch = 1 \end{matrix} \right\} \qquad \textbf{(5.23)}$$

The household rate calculation is similar and only differs through the dynamic count of households (driven by population growth) rather than enterprises (which grow relative to GDP). Calculation of the targeted rate has similar workings as the general and household rates. However, it differs because it reflects dynamic feedback on the number of properties in the CHZ (*prop bal rates CHZ*) due to the targeted rate's increasing cost. Therefore, it incentivises managed retreat by allocating costs over the properties in the CHZ. As properties retreat, the remaining properties pay a more significant share of the rate (*prop remittance*), which reduces the number of properties. Equation 5.24 illustrates this relationship.

$$targeted\ rate(aep) = \begin{Bmatrix} 0\ for\ aep < RATE\ AEP \\ prop\ bal\ rates\ CHZ \times prop\ remittance \\ for\ \ AEP > RATE\ AEP \\ for\ funds\ cap\ switch = 1 \\ for\ rates\ switch = 1 \end{Bmatrix} \quad \textbf{(5.24)}$$

Finally, the three rates are tallied, *trig count* applied and formatted for use in MERIT. Alongside this operator is a feedback loop to discover when the desired funding has been reached by collecting rates. Equation 5.25 shows the calculation of *total rates funds* as a function of the *pay trig* based on inundation events. *Retreat rates funds* sum the industry and government subscripts, and the Vensim® *SMOOTH* function provides a system lag over four years.

$$tot\ rates\ funds_{SMOOTH\ 4}(PAY\ TRIG) = \begin{Bmatrix} retreat\ rates\ funds \\ for\ Trig\ count \geq PAY\ TRIG \\ 0\ for\ Trig\ count \leq PAY\ TRIG \end{Bmatrix} \quad \textbf{(5.25)}$$

### 5.3.7 The Land-use Module

The Land-use Module tracks spatial changes in land use throughout the model period. It incorporates planned conversion and intensification for growth outlined by the HPUDS and the Matariki Plan (HBRC, 2016a; HBRC et al., 2017). The Land-use Module provides the capacity to constrain industry land use in MERIT through *mobile* or *immobile investment*, and therefore industries cannot meet their full regional capacity. The stock-flow diagram is illustrated in Figure 5.11.

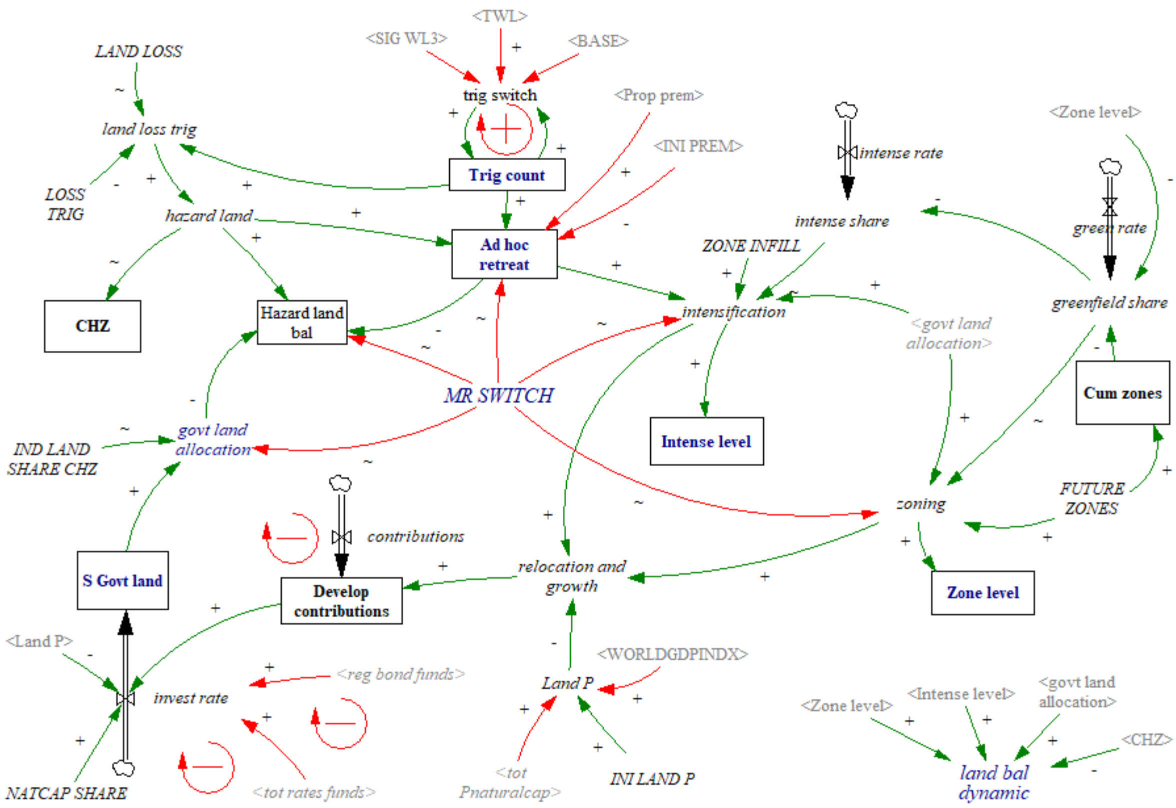



**Figure 5.11** The stock-flow diagram for the Land-Use Module operating at the sub-regional scale. Here the land is allocated by the scenario in hectares before it is converted into dollars (*relocation and growth*). *Adhoc retreat* occurs when multiple triggers are breached (Trig count) or property premiums fail, constraining development. Managed retreat is accounted for through funding from bonds and rates (*total rates funds* or *reg bonds funds*), creating a balancing loop of government land allocation (*S govt land*) to the intensification rate (*intense rate*) and the new zoning rate (*zone rate*). Manged retreat also acts as a logic switch to control land use (*MR SWITCH*). The *land bal dynamic* sums the various land transfers for use in MERIT to alter capital mobility.

The key equations are as follows. First, Equation 5.26 calculates the land retired from the CHZ. *Land loss 1* represents the 1% AEP 2065 inundation spatial extent, and *land loss 2* represents the 1% AEP 2120 inundation spatial extent.

$$land\ loss\ trig\ (aep) = \left\{ \begin{array}{c} 0\ for\ \textbf{Trig count} < 2 \\ LAND\ LOSS\ 1\ for\ 2 \geq \textbf{Trig count} < 3 \\ LAND\ LOSS\ 2\ for\ \textbf{Trig count} \geq 3 \end{array} \right\} \quad \textbf{(5.26)}$$

Second is the calculation of *ad hoc* retreat for the baseline scenario in Equation 5.27. Here the level of *ad hoc retreat* is determined by the rate of change in hazardous land (*hazardous land rate*) and the *trigger count*, *property premium* and the switch for managed retreat (*MR Switch*). It also applies a two-year system delay (*SMOOTH 2*).

$$\frac{d}{dt}\,\mathbf{Adhoc\ retreat}(\mathbf{Trig\ count}, prop\ prem, MR\ SWITCH\ )_{SMOOTH\ 2} = \left\{ \begin{matrix} 0\ for\ \mathbf{Trig\ count} < 3\ or\ prop \\ prem > 1000\ or\ MR\ SWITCH = 1 \\ \left[\frac{hazard\ land\ rate}{DELTA\ TIME} - adhoc\ retreat\right] \\ for\ \mathbf{Trig\ count} > 3\ or\ prop \\ prem < 1000\ or\ MR\ SWITCH = 0 \end{matrix} \right\} \tag{5.27}$$

Third, the *intensification rate* (Equation 5.28), where there is no managed retreat, is purely the addition of the *ad hoc retreat* and the *zone infilling* according to HPUDS. Where there is managed retreat, there is additional *govt land allocation* based on development contributions and is proportioned between zone intensification (*Intense Share*) and greenfields (new) development (*Greenfields Share*).

$$intense\ rate(MR\ SWITCH)_{SMOOTH\ 1} = \left\{ \begin{matrix} (adhoc\ retreat + ZONE\ INFILL) \times DELTA\ TIME \\ for\ MR\ SWITCH = 0 \\ (ZONE\ INFILL + S\ govt\ land) \times \\ INTENSE\ SHARE\ \times DELTA\ TIME \\ for\ MR\ SWITCH = 1 \end{matrix} \right\} \tag{5.28}$$

Equation 5.29 shows the calculation for new zoning, which is similar to Equation 5.28.

$$zone\ rate(MR\ SWITCH)_{SMOOTH\ 1} = \left\{ \begin{matrix} FUTURE\ ZONING \times DELTA\ TIME \\ for\ MR\ SWITCH = 0 \\ (FUTURE\ ZONING + S\ govt\ land) \times \\ GREENFIELDS\ SHARE \times DELTA\ TIME \\ for\ MR\ SWITCH = 1 \end{matrix} \right\} \tag{5.29}$$

The land-use planning tables outlined by HPUDS (HBRC et al., 2017) are adapted into MERIT in Table 5.3. Under the baseline scenario, there is ample future allocation for residential and industrial land uses. Still, the concern is the under-supply of land for commercial, infrastructure (roads and services), and amenity uses. Therefore, the Land-use Module accounts for this by converting development contributions to land for infrastructure, amenities and ecosystem services under the baseline scenario. Development contributions were set at 12% (Napier City Council, 2018), which equals a peak allocation by the end of the period of NZ$_{2007}$22.7M $a^{-1}$ (no-SLR scenario), NZ$_{2007}$23.5M $a^{-1}$ (mid-range scenario) and NZ$_{2007}$26.5M $a^{-1}$ (worst-case scenario). Under the managed retreat scenarios, governments supply land to industries proportionally.

***Table 5.3 HPUDS adapted baseline land-use zoning for MERIT.***

| FUTURE ZONING (Ha) | 2007 | 2016 | 2026 | 2036 | 2046 | 2050 | TOTAL |
|---|---|---|---|---|---|---|---|
| Accommodation, restaurant & retail services | 0 | 0 | 7 | 7 | 7 | 0 | **21** |
| Construction | 0 | 0 | 7 | 7 | 7 | 0 | **21** |
| Government, education & healthcare | 0 | 0 | 7 | 7 | 7 | 0 | **21** |
| Horticulture & fruit growing* | 0 | 0 | 0 | 0 | 0 | 0 | **0** |
| Food product manufacturing | 0 | 0 | 18 | 18 | 18 | 0 | **54** |
| Other manufacturing | 0 | 0 | 18 | 18 | 18 | 0 | **54** |
| Other primary production* | 0 | 0 | 0 | 0 | 0 | 0 | **0** |
| Other services & trades | 0 | 0 | 7 | 7 | 7 | 0 | **21** |
| Residential & real estate services | 0 | 0 | 339 | 164 | 75 | 0 | **577** |
| Wood & paper manufacturing | 0 | 0 | 18 | 18 | 18 | 0 | **54** |
| **TOTAL** | | | **420** | **246** | **157** | **0** | **823** |
| **ZONE INTENSIFICATION (Ha)** | | | | | | | |
| Accommodation, restaurant & retail services | 0 | 0 | 9 | 0 | 0 | 0 | **9** |
| Construction | 0 | 0 | 9 | 0 | 0 | 0 | **9** |
| Government, education and healthcare | 0 | 0 | 9 | 0 | 0 | 0 | **9** |
| Horticulture and fruit growing* | 0 | 0 | 0 | 0 | 0 | 0 | **0** |
| Food product manufacturing | 0 | 0 | 0 | 0 | 0 | 0 | **0** |
| Other manufacturing | 0 | 0 | 0 | 0 | 0 | 0 | **0** |
| Other primary production* | 0 | 0 | 0 | 0 | 0 | 0 | **0** |
| Other services and trades | 0 | 0 | 9 | 0 | 0 | 0 | **9** |
| Residential & real estate services | 0 | 0 | 107 | 85 | 58 | 0 | **250** |
| Wood & paper manufacturing | 0 | 0 | 0 | 0 | 0 | 0 | **0** |
| **TOTAL** | **0** | **0** | **143** | **85** | **58** | **0** | **286** |

Finally, the dynamic land balance (*land bal*) accounts for all the land-use changes to define whether an investment in new capital in MERIT is *immobile* (invested insitu) or *mobile* (invested elsewhere). Equation 5.30 illustrates the relationship. Here the *New zoning level*, *Intensification level* and *government land allocation* are tallied, and the area of the *CHZ* is subtracted.

$$land\ bal = \mathbf{Zone\ level} + \mathbf{Intense\ level} + S\ govt\ land - \mathbf{CHZ} \qquad \textbf{(5.30)}$$

## 5.4 Calibration and module structure tests

During the construction phase, the modules require testing throughout the process before they are accepted. Testing is often incorrectly referred to as validation because all models simplify a reference system; they are never totally valid in the sense of being supported by objective truth (Greenberger et al., 1976). Useful, convincing, or inspiring confidence are more appropriate descriptors of models (Greenberger et al., 1976).

Testing the C-ADAPT modules comprised face validity tests, calibration, validation, sensitivity analyses and System Dynamics testing by utilising the Reality Check feature in Vensim® and the SDM-doc Tool (Bragen & Martinez-Moyano, 2014) recommended by the editorial board of the System Dynamics Review. First, the initial 'face validity' tests establish rational logic or whether the model makes common sense (Ford, 2010). After face validity tests, it relied on the two approaches for fault finding outlined by Goel (1985). First, program calibration examines a sequence of formal and mathematical logical statements (Goel, 1985). Second, program testing through the practical execution of test cases to expose embedded faults (Goel, 1985).

Test results are highlighted in Appendix 5 for the table of tests, Appendix 6 for a summary from the SDM-doc Tool and Appendix 7A for the sensitivity analyses. The table of tests describes the empirical and theoretical direct structure tests (do the modelled trends reflect that of actual data and observable rules over the calibration period), structure orientated behaviour tests (testing through Vensim® Reality Check) and behaviour pattern tests (expectations of the behaviour of the variables over the calibration period) conducted on the modules. Appendix 6 describes the results of the SDM-doc Tool used to test and refine the Risk Assessment Module and the Socio-Economic Module. Similarly, Appendix 7 shows the sensitivity analyses for the Risk Assessment Module and the Socio-Economic Module. The Interdependency, Land use, Defence, Rates and Bonds modules primarily performed linear operations and were only validated for empirical and theoretical direct structure tests, structure orientated behaviour tests, and behaviour pattern tests.

Program calibration was conducted against the baseline period from 2007 to 2018 and applied logic statements to Scenario Planning hypotheses. Calibration enables the refinement of time-dependent variables to maximise model agreement with experimental (or real-world) data (Trucano et al., 2006). Therefore the modules were tested against real-world data (hindcast calibration) to determine whether the outcomes match or diverge from prior knowledge and observations, a process of evaluation outlined by Ebersberger and Pyka (2009). Module calibration uses data from 2007 to 2018, shown in Table 5.4. Models were adjusted where calibration and validation expectations were unfulfilled. Proving also required that the modules met logical statements (using Vensim's Reality Check functionality) to test Scenario Planning outcomes for the future through to 2050.

***Table 5.4 Datasets used for module calibration***

| Module* | Dataset |
|---|---|
| Risk Assessment | Napier Port sea-level data |
| Risk Assessment | Ahuriri Estuary water level recorder |
| Risk Assessment | LiDAR |
| Risk Assessment | NIWA exposure estimates |
| Risk Assessment | IPCC SLR estimates |
| Socio-Economic | The University of Auckland National House Sales Database |
| Socio-Economic | The Insurance Council of New Zealand Insurance claims (2019b) |
| Socio-Economic | Fleming et al. (2018) private and public insurance claims |
| Socio-Economic | Local government property valuations |
| Socio-Economic | StatsNZ household income and unemployment |
| Socio-Economic | Core Logic insurance change |
| Land use | HPUDS and Matariki Plan projections |
| Land use | The New Zealand Land Resource Inventory |

*Note that only modules used for the baseline were calibrated against actual data.

Program testing involved iteration, sensitivity analyses and ‘extreme’ testing to reduce uncertainty. Sensitivity analyses involve the iterative processing of multiple model runs given rational and random distributions of constants given simultaneous changes to multiple parameters to find faults and adjust for uncertainty (Kapmeier & Gonçalves, 2018). Thus, sensitivity analyses in model testing provide probabilistic confidence in the model's numerical accuracy (Trucano et al., 2006). Sensitivity analyses also simplify the IAM by a) removing ineffectual variables or b) deriving constant values as inputs instead of complex tables. This study's sensitivity testing on modules involved 100 Latin Hypercube simulations per scenario in Vensim® using rational and random distributions of constants. Latin hypercube is particularly useful as it allows for automated orthogonal sampling across a grid space whilst remembering what points have already been chosen to minimize repetition and represent real variability (Ford, 2010)  100 simulations were deemed appropriate as the final results produced were statistically significant. Any failure resulted in model adjustment and a further 100 simulations. Sensitivity analyses also accounted for ‘extreme conditions’ to account for dimensional consistency and feasibility, a prerequisite of model testing, according to Barlas (1996) and Macmillan (2012). However, stochastic ‘extreme conditions’ were rationalised to events that could feasibly occur as the simulations fail otherwise. Fully probabilistic and full temporally random simulation approaches account for dependencies between variables, build robustness and include the non-stationarity associated with climate change (H. Baron et al., 2015).

## 5.5 MERIT integration

MERIT operates on embedded regional Social Accounting Matrices (SAM) generated from the New Zealand National Accounts (StatsNZ, 2007, 2013b, 2018b). The SAM are, in turn, based on the ‘Interindustry study of the New Zealand economy' for a given financial year. The study comprises Input-Output tables that describe the New Zealand economy's structure by quantifying the relationship between goods and services produced by industries and who uses them (StatsNZ, 2013b). MERIT allows for an evolving output every 1.8 days through to 2050. The regional SAM constructed for MERIT are from the financial year ending March 2007, the base year for the model (Smith, McDonald, et al., 2016) through to 2018. MERIT structure is summarised by Smith et al. (2016, p. 4) below:

> "For each region, the model describes the behaviour of representative agents [10 industry categories, one household, one enterprise, a Local Government within each region, and a Central Government]. Each industry agent chooses the quantity and type of commodities [aggregated to 10 commodity categories] to produce, based on the prices of those commodities relative to production costs. Household, enterprise, and government agents receive income from a variety of sources (e.g. wages and salaries, business profits, dividends, taxes, and transfers from other agents) and then allocate this income towards a variety of expenditure options (e.g. purchases of goods and services, savings, taxes, and transfers to other agents)."

Readers are directed to Smith, McDonald et al. (2016) for a comprehensive mathematical description of MERIT. In addition, McDonald and McDonald (2020) provide a simplified but fully operational overview of the Dynamic Economic Model that resides at the heart of MERIT. In this thesis, modules are developed that adapt MERIT, including new components and scenarios specific to this thesis, which significantly extend MERIT's usefulness. Thus, MERIT's parameters and equations are altered to reflect the modules' influence (Smith, Orchiston, et al., 2016). Table 5.5 provides an overview of the changes made to MERIT. It illustrates the main action taken under each scenario, which input modules are called upon, and which MERIT modules are influenced.

*Table 5.5 Overview of module integration into MERIT*

| Action | Input Module | MERIT module |
|---|---|---|
| | **BASELINE SCENARIOS** | |
| **Industry operability** | Sub-module Industries | Industries |
| **Infrastructure disruption** | Infrastructure Interdependency | Industries |
| **Lost built capital replacement** | Risk Assessment | Capital & Investment and Savings |
| **Land lost to storms and sea-level rise** | Land use | Capital |
| **Insurers pay storm damages** | Socio-economic | Industries & Capital |
| **Increasing insurance premiums** | Socio-economic | Industries |
| **Development contributions** | Land use | Government & Investment and Savings |
| **Net increase in EQC tax** | Sub-module government | Government & Industries |
| **EQC claims for flooding** | Sub-module government | Government, Industries & Households |
| **Zoning intensification** | Land use | Capital |
| | **DEFENCE SCENARIOS** | |
| **Coastal defence structures** | Defence | Capital & Investment and Savings |
| **Coastal defence cost** | Rates | Government & Industries |
| | **RATES SCENARIOS** | |
| **Local GOVT rating tax revenue** | Rates | Government & Industries |
| **GOVT capital investment** | Rates | Government & Capital |
| | **BONDS SCENARIOS** | |
| **Initial bond release** | Bonds | Investment and Savings |
| **Revenue generated offshore from bonds** | Bonds | Rest of World & Government |
| **Government purchases exposed properties** | Bonds | Government & Industries |
| **Ind invest in new capital** | Bonds | Capital & Industries |
| **Government paying back bonds** | Bonds | Government & Investment and Savings |
| **Government rental income** | Government | Government & Industries |

MERIT then calculates the higher-order impacts (including general equilibrium consequences associated with pricing, factor and commodity substitution and financial lags) on the regional economy of interest and the rest of New Zealand. MERIT was adapted from 41 industries of particular interest to ten in the study area quantified from the Australian and New Zealand Standard Industrial Classification System (ANZIC) tables (see StatsNZ, 2006) as in Table 5.6.

*Table 5.6 Aggregated economic classification*

| Index | Industry | Commodity |
|---|---|---|
| **1** | Accommodation, restaurant & retail services | Accommodation, restaurant & retail services |
| **2** | Construction | Construction |
| **3** | Government, education & healthcare | Government, education & health services |
| **4** | Horticulture & fruit growing | Horticulture & fruit |
| **5** | Food product manufacturing | Food products |
| **6** | Other manufacturing | Other manufactures |
| **7** | Other primary production | Other primary products |
| **8** | Other services & trades | Other services & trades |
| **9** | Residential & real estate services | Residential & real estate services |
| **10** | Wood & paper manufacturing | Wood & paper products |

### 5.5.1 The higher-order impacts on operability

C-ADAPT takes local-scale changes (direct impacts) from input modules and integrates them into MERIT to estimate the higher-order general equilibrium impacts. Under the baseline scenario, disruption to business operability and interdependent infrastructure is an ongoing occurrence. Business disruption calculates as a percentage where zero is complete disruption, and one is no disruption at all (Smith, McDonald, et al., 2016). Therefore, when operability = 1, it is assumed that the industry achieves the maximum level of production (Smith, McDonald, et al., 2016). The length of disruption applied in this thesis is based on a significant storm duration, typically lasting one to several days (Komar & Harris, 2014a). Higher-order general equilibrium economic effects continue for more than a month, with significant building damage (Reese & Ramsay, 2010). Interdependent infrastructure disruption is more far-reaching as critical nodes within the CHZ propagate to users beyond the CHZ. The significant disruptions are the closure of highways at the Ahuriri Estuary, closure of the rail line at the Ahuriri Estuary Bridge, reduction in service at the Napier Airport (30%) and the sewage treatment plant (15%), and gas supply outage (15%).

This situation has been adapted and applied to the MERIT model using the outage curves shown in Figure 5.13. Plot A represents the outage to business operations as a function of TWL, and plot B represents the compounding outage from the interdependent infrastructure that businesses and households depend on for normal operation.

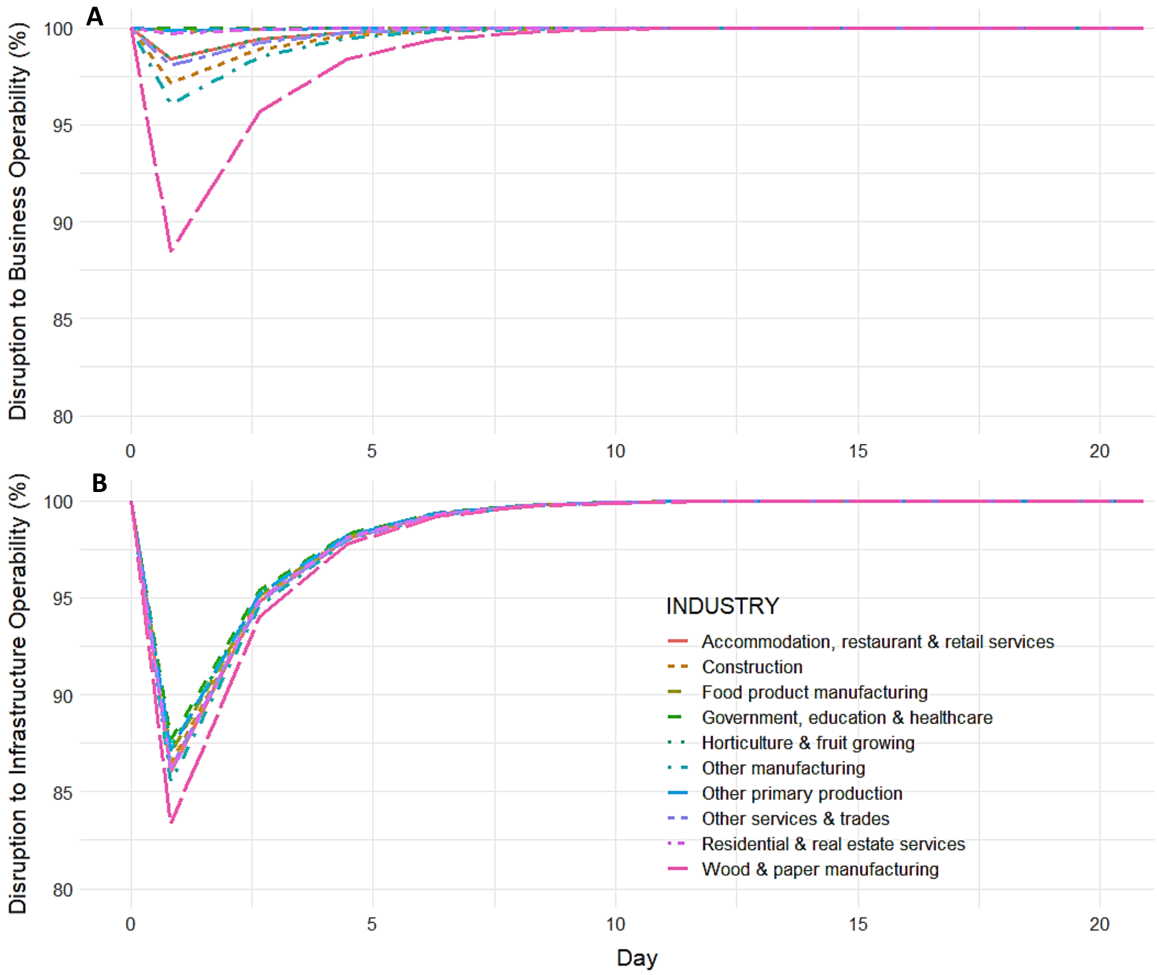



**Figure 5.13** Assumed disruption to business operability by industry following a significant storm. Plot A illustrates the outage to business operation from TWL. Plot B illustrates the reduction in service level of interdependent infrastructure from TWL that businesses and households depend on for everyday activity.

The regional operability by industry is determined by the proportion of employees in the CHZ versus the region as adapted from StatsNZ's (2013a) Employee Count measure. Market Economics (2017b) adapts the Employee Count measure to include working proprietors to provide a more comprehensive measure of total employment known as a 'Modified Employee Count'. The disruption to business and infrastructure initiates with a system shock followed by a logarithmic decay after an event as operability returns to normal using the Vensim® SMOOTH function. It is logically similar to Brown et al.'s (2015) approach (Equation 16), which shows a logarithmic return to normal following a disaster. The modification of operability in MERIT is visible in Figure 5.14, which provides MERIT with an outage timeframe, i.e. the proportion of an industry not operating at full capacity across the region.

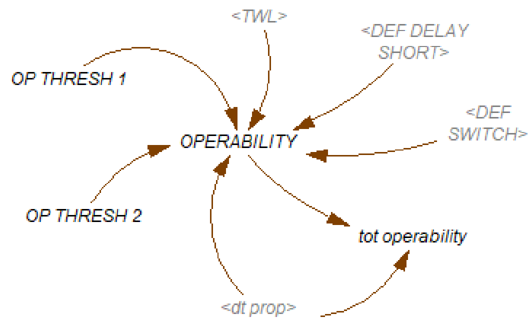



**Figure 5.14** Modified operability function in MERIT for coastal hazards.

Finally, Equation 5.31 illustrates how the Operability is affected by *TWL* and the dynamic count of properties in the CHZ (*dt prop*). The operability thresholds (*OP THRESH*) are defined by the regional percentage of an industry exposed to significant water levels (*SIG WL2* or 11.5mRL & *SIG WL3* or 12mRL).

$$OPERABILITY_{SMOOTH\ 0.005}(TWL) = \begin{Bmatrix} 0\ for\ TWL < SIG\ WL2 \\ OP\ THRESH\ 1\ for\ SIGWL2 \leq TWL < SIGWL3 \\ OP\ THRESH\ 2\ for\ TWL\ \geq SIG\ WL3 \end{Bmatrix} \times dt\ prop \tag{5.31}$$

### 5.5.2 Aggregate and mobile investment

Aggregate and mobile investment deviate from the MERIT economy's regular operation in C-ADAPT (Figure 5.19). Here, immobile investment is constrained by reducing industry land-use supply. Therefore mobile investment takes up the surplus brought on by capital investment in insurance rebuilds or managed retreat. Investment is also dynamically linked to the investment composite commodity consumption price (Pinvestcc), significantly altering composite capital supply. Therefore, as shown in Figure 5.15, *aggregateinvestv baseline* represents standard MERIT, and *aggregateinvestv1* is the module integration of the various scenarios.

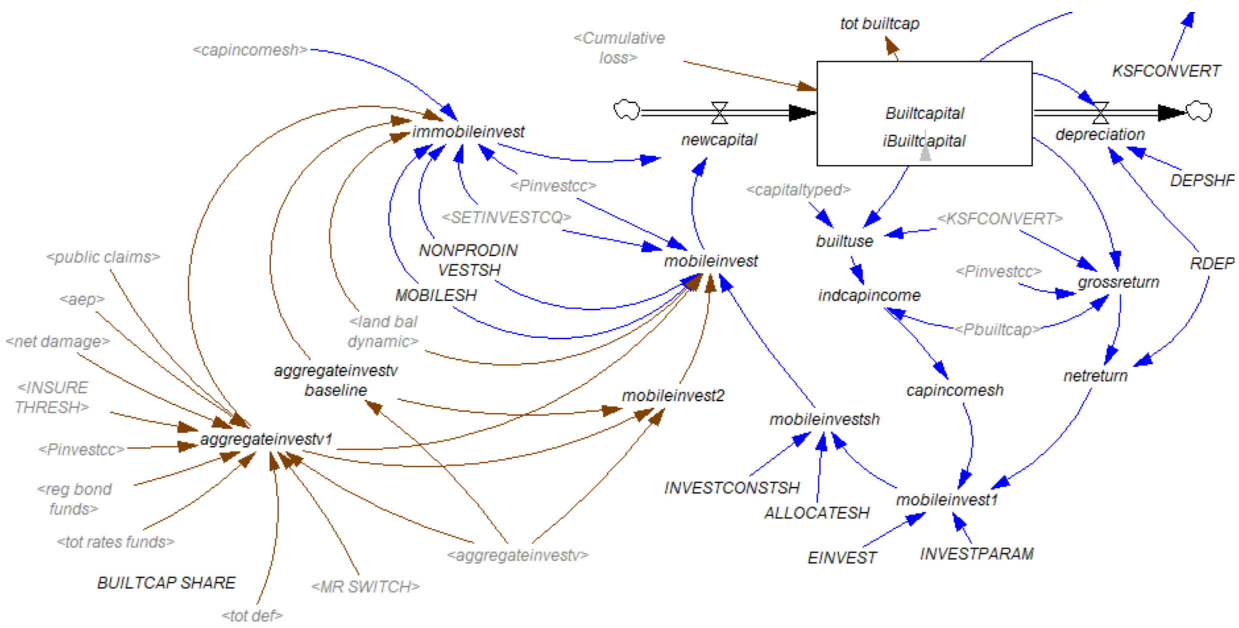



**Figure 5.15** Modified aggregate investment function and the mobility of investment in MERIT (brown) and standard MERIT operation (blue).

The calculation of *aggregateinvestv1* is described in Equation 5.32.

$$aggregateinvestv1_{DREGIONS} = \left\{ \begin{array}{c} aggregateinvestv + tot\ rates\ funds \times BUILTCAP \\ SHARE \times Pinvestcc + reg\ bond\ funds \times \\ BUILTCAP\ SHARE \times Pinvestcc - \\ \left(\frac{\sum net\ damage_{IND}}{1e+006}\right) + tot\ def + public\ claims \\ for\ DREGION1\ and\ where\ aep > INSURE\ THRESH \\ tot\ def\ for\ DREGION1 \\ and\ where\ aep < INSURE\ THRESH \\ aggregateinvestv + tot\ rates\ funds \times BUILTCAP \\ SHARE \times Pinvestcc + reg\ bond\ funds \times \\ BUILTCAP\ SHARE \times Pinvestcc\ for\ DREGION2 \end{array} \right\} \quad \textbf{(5.32)}$$

### 5.5.3 Industry Account

MERIT is also fundamentally altered for industry income and industry expenses by insurability and property rates (Figure 5.16). Under normal operating conditions, industries pay insurers for risk transfer. As climate change exacerbates coastal risk, risk-based insurance or insurance withdrawal are beyond MERIT's regular operation, and therefore the *industry account* requires modification. Similarly, changes to property rates and public insurance from the established baseline tax now account for a changing climate as outlined in the scenarios.

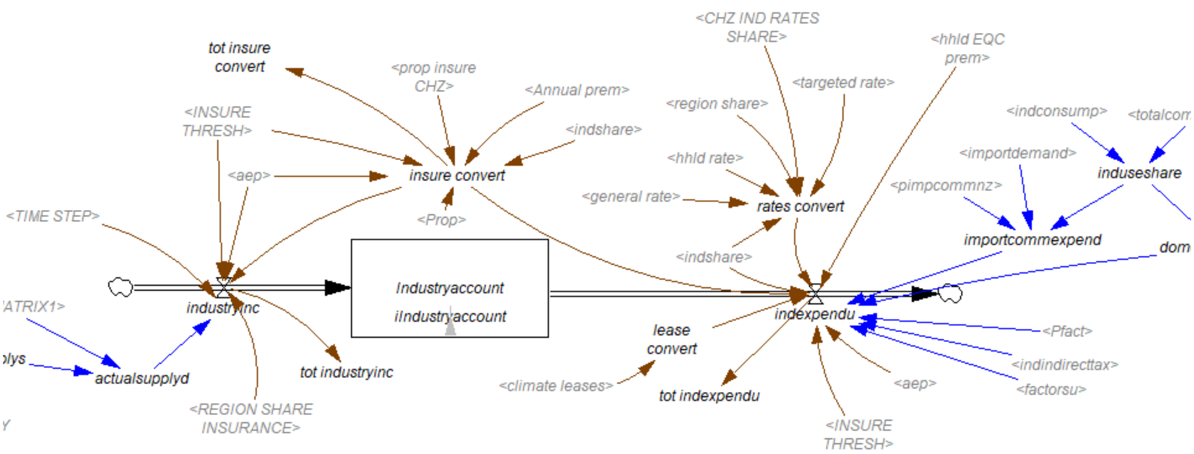



**Figure 5.16** The modified Industry Income (Industryinc) and Industry Expenditure (indexpendu) in MERIT. Modifications adjust the industry account to insurance and rates changes (brown) and standard MERIT operation (black and blue).

Equations 5.33 and 5.34 show the modified calculation for industry income (IND 9 Region 1 only) and expenditure.

$$industryinc_{DREG1\ IND9}(aep) = \begin{cases} \left[\left[\sum actualsupplyd_{COMMODITIESSHORT} + \left(\frac{\sum insure\ convert_{IND\times}\ REG\ SHARE\ INSURE}{1e+006}\right)\right]\right] \times DELTA\ TIME & for\ aep < INSURE\ THRESH \\ insure\ convert_{IND8} & for\ aep > INSURE\ THRESH \\ \left(\sum actualsupplyd_{COMMODITIESSHORT} + insure\ convert_{IND}\right) & for\ other\ IND\ and\ aep > INSURE\ THRESH \\ 0 & for\ other\ IND\ and\ aep < INSURE\ THRESH \end{cases} \tag{5.33}$$

$$indexpendu_{DREGIONS}(aep) = \begin{cases} \left[\sum domcommexpend_{COMMODITIESSHORT} + \sum factorsu_{FACTORS} \times \mathbf{Pfact} + indindirecttax + \sum importcommexpend_{COMMODITIESSHORT} + insure\ convert + lease\ convert \times indshare + hhld\ EQC\ prem \times indshare + rates\ convert\right] & for\ aep < INSURE\ THRESH\ DREGION1 \\ \left[\sum domcommexpend_{COMMODITIESSHORT} + \sum factorsu_{FACTORS} \times \mathbf{Pfact} + indindirecttax + \sum importcommexpend_{COMMODITIESSHORT} + lease\ convert \times indshare + hhld\ EQC\ prem \times indshare + rates\ convert\right] & for\ aep > INSURE\ THRESH\ for\ DREGION1 \\ \left[\sum domcommexpend_{COMMODITIESSHORT} + \sum factorsu_{FACTORS} \times \mathbf{Pfact} + indindirecttax + \sum importcommexpend_{COMMODITIESSHORT} + hhld\ EQC\ prem \times indshare + rates\ convert\right] & for\ DREGION2 \end{cases} \tag{5.34}$$

### 5.5.4 Economies of Scale

Economies of Scale, or a falling long-run average cost curve, adjust multifactor production for the managed retreat scenarios (Figure 5.17). It is calculated as an increase in the productive capacity as the construction industry gains efficiencies through development at scale with managed retreat. C-ADAPT employs a 17.7% increase in economies of scale in the construction sector, developed from the average gain from 12 building construction and civil engineering projects as reported in Ramachandra, Geekiyanage and Perera (02 July 2017).

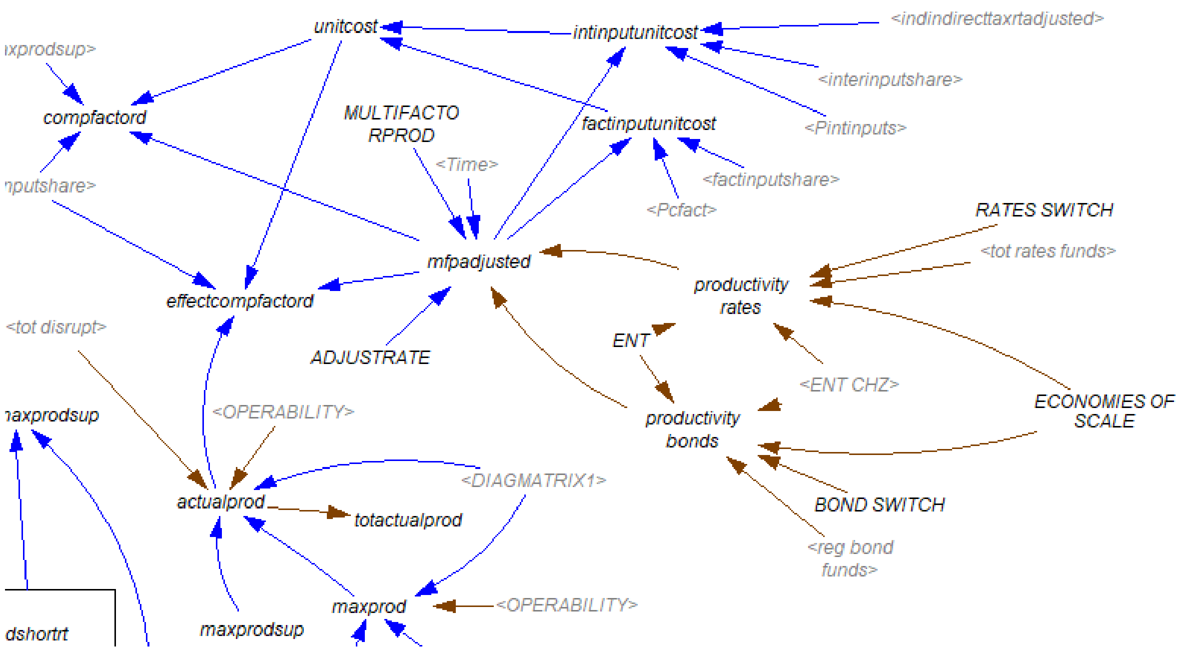



**Figure 5.17** Modified Multifactor Production to enhance the Economies of Scale with the managed retreat scenarios (brown) and standard MERIT operation (blue).

Therefore, the calculation of the economies of scale for the bonds scenario is visible in Equation 5.35.

$$productivity\ bonds_{SMOOTH2} = \begin{Bmatrix} \left[ ECONOMIES\ OF\ SCALE \times \left(\frac{ENT\ CHZ}{ENT}\right) + 1 \right] \\ for\ BOND\ SWITCH = 1\ and\ reg\ bond\ funds > 10 \\ 1\ for\ BOND\ SWITCH \neq 1\ or\ reg\ bond\ funds < 10 \end{Bmatrix} \quad \textbf{(5.35)}$$

The integration of the new economies of scale into MERIT is visible in Equation 5.36. Here *mfpadjusted* refers to the dynamic multifactor productivity.

$$mfpadjusted(t) = \begin{Bmatrix} \begin{bmatrix} MULTIFACTORPROD + \\ 1 \times (1 + ADJUSTRATE)^{((\textbf{Time}-10)-1)} \times \\ productivity\ bonds \times productivity\ rates \end{bmatrix} \\ for\ \textbf{Time} > 10 \\ MULTIFACTORPROD\ for\ \textbf{Time} < 10 \end{Bmatrix} \quad \textbf{(5.36)}$$

## 5.6 Calibrate and test C-ADAPT and apply model feedback

Testing undertaken in Section 5.4 (except those that apply Vensim® Reality Check and the SDM-Doc Tool) repeats once the module-MERIT integration is complete. Standard MERIT is thoroughly calibrated and validated over ten years (2007 to 2018) using several key aggregates and observed datasets (see Appendix 5). Thus, it replicates the essential dynamic behaviour of Hawke's Bay and the rest of New Zealand's economies over this period, although only modules developed and integrated into MERIT as part of this thesis are tested further here. The next step would be to re-calibrate MERIT to the new boundary conditions. However, this was not possible within the scope of this thesis, given time and resource constraints. In addition, C-ADAPT's usefulness was assessed at this step in collaboration with experts and included reflections on functionality and reliability. Again, see Appendix 5 for the table of tests and Appendix 7B for the sensitivity analyses on module-MERIT integration as a measure of the success of the integration. The SDM-Doc Tool failed to produce a result after a month of operation on the entire C-ADAPT model.

The IAM timestep of 1.8 days was also tested against 3.6 and 7.2 days at this step. The latter two timesteps were shown to compromise model accuracy. Therefore, the differential time (*dt*) of 1.8 days is an applicable rate of change because it represents model stability and accuracy in numerical integration proposed by Ford (2010). However, this *dt* leads to over 8,800 timesteps, increasing computational time and data processing time. It also goes beyond the maximum recommended rule of thumb of 1,000 steps (Ford, 2010). Exceeding the recommended timesteps is more the consequence of the long period over which C-ADAPT runs rather than the operation of the model itself.

## 5.7 Defining key aggregates of model outputs for scenario comparison

The key aggregates are outputs from C-ADAPT representing the system's dynamic parts and require being comprehensible and compelling to their audience (Turner, 2000). They should also be drawn from the broadest range of human activities and facilitate tracing management efforts or policy interventions more directly to environmental and social realities (Boston, 2017). They reflect both direct and higher-order general equilibrium impacts and cover the main sectors of household, industry and government (HHLD, IND, GOVT) and land-use changes. The key aggregates should ensure acceptable coverage of the system as a whole. Another goal is to analyse any intergenerational or spatial risk transfer.

Key aggregates can be described by their system type as either being state, impacts or response indicators. State indicators define observable changes in environmental dynamics and functions (Brouwer & Schaafsma, 2013). In contrast, the impacts are the discrete measured changes in condition (Brouwer & Schaafsma, 2013). Response indicators are defined as the institutional response to system changes primarily driven by state and impact indicators (Brouwer & Schaafsma, 2013).

Similarly, it is also helpful to define the variable type. Flow measures, or rates of change, are more illustrative of a disaster's actual cost than stock measures due to being able to account for the disruption and recovery over time (Boston, 2017). In contrast, stock variables value production or assets at a single point in time (Boston, 2017).

The key aggregates in Table 5.7 are model variables described by sector, system type and variable type used to evaluate a scenario's performance. MERIT provides many indicators on which an evaluation of disruptive impacts can be undertaken at an aggregated or industry scale (Smith & McDonald, 2016b). However, as MERIT consists of over 2,000 variables, only a fraction can be fully discussed or reported within the scope of a thesis. Therefore, variables in Table 5.7 were considered to be the most relevant, with regional economic behaviour in MERIT represented by *.

***Table 5.7 Key Aggregates reported***

| | Variable (metric) | Description | Sector | System Type | Variable Type |
|---|---|---|---|---|---|
| **1.** | Risk (%) | The probability of an event occurring multiplied by its consequence | HHLD, IND & GOVT | State | Stock |
| **2.** | Damages ($) | Replacement value of built capital | HHLD, IND & GOVT | Impact | Stock |
| **3.** | Operability (%)* | Business operability is compromised by storms. | IND | State | Flow |
| **4.** | Infrastructure Disruption (%) | The reduction in the level of service to industries by interdependent infrastructure | IND | State | Flow |
| **5.** | Annual Expected Loss ($ $a^{-1}$) | Loss of built capital and land | HHLD | Impact | Flow |
| **6.** | Coastal Amenity Value ($) | Non-market value of coastal living | HHLD | State | Stock |
| **7.** | HHLD Insurance Premiums ($ $a^{-1}$) | Risk transfer | HHLD | State | Flow |
| **8.** | Real HHLD Consumption Rate (%)* | The rate of change in real household consumption. Illustrates whether households are better off to spend or save | HHLD | State | Flow |
| **9.** | Unemployment Rate (%)* | Reflects unemployment in the labour market | HHLD | State | Flow |
| **10.** | Local GOVT Consumption ($ $a^{-1}$)* | The total spending by the government | GOVT | Response | Flow |
| **11.** | Central GOVT Consumption ($ $a^{-1}$)* | The total spending by the government | GOVT | Response | Flow |

| | | | | | |
|---|---|---|---|---|---|
| **12.** | Total Value-Added ($ $a^{-1}$)* | Similar to Gross Regional Product as a measure of productivity, except excludes taxes and includes subsidies | IND | State | Flow |
| **13.** | IND Value-Added ($ $a^{-1}$)* | The gross industry output (sales) less the cost of intermediate inputs | IND | State | Flow |
| **14.** | Totactualprod ($ $a^{-1}$)* | Total actual production | IND | State | Flow |
| **15.** | Pinvestcc ($ $a^{-1}$)* | Investment composite commodity consumption price | IND | Impact | Stock |
| **16.** | Land use Ratio (Ha) | The ratio of greenfield development to zone intensification | Land use | Impact | Stock |

## 5.8 Develop adaptation pathways

Once the indicators have been established, they need to be aggregated and compared to decipher effective pathways toward managed retreat. The methodology follows Callaway (2014), where planners can translate risk parameters into economic costs and aggregate costs based on explicit risk trade-off preferences. It is subsequently possible to aggregate the cost of regret to compare planning designs over some climate futures and select a design that minimises some regrets-based decision-making criteria (Callaway, 2014), as shown in Table 5.8.

***Table 5.8 Calculating economic regret from economic cost described by Callaway (2014)***

a) The ex-post net present value for an ex-ante generic project with four designs and three climate states ($10^6$ €)

| *Project design* | *Expected climates* | | | *Mean and max. (rank)* |
|---|---|---|---|---|
| | *C1* | *C2* | *C3* | |
| D 1 | 120 | 40 | 5 | 55.00 (1) |
| D 2 | 50 | 70 | 20 | 46.67 (4) |
| D 3 | 10 | 50 | 70 | 43.33 (3) |
| D Robust | 50 | 55 | 50 | 51.67 (2) |

b) The ex-post regrets matrix for an ex-ante generic project with four designs and three climate states ($10^6$ €)

| *Project design* | *Expected climates* | | | *Mean and min. (rank)* |
|---|---|---|---|---|
| | *C1* | *C2* | *C3* | |
| D 1 | 0 | -30 | -65 | -31.67 (1) |
| D 2 | -70 | 0 | -50 | -40.00 (3) |
| D 3 | -110 | -20 | 0 | -43.33 (4) |
| D Robust | -70 | -15 | -20 | -35.00 (2) |

C-ADAPT evaluates the key aggregates through RDM in System Dynamics, generalised Boolean operation in Pandas conditional formatting and preference functions of least regret (adapted from Callaway (2014)) to develop a novel DAPP based on the scenarios, similar to Kwakkel et al.'s (2015) Exploratory Modelling and Analysis. Calibration and sensitivity analyses in Vensim® optimise outputs for key aggregates. Statistical preference functions are then calculated in the Python 3 RDM matrix (PYRDM) to discover the scenarios that minimise regret and establish points in time where they perform well or poorly. Thus, the least-regret approach seeks to discover the option that performs better at minimising regret across the range of climate futures, rather than optimising one dominant climate scenario (Callaway, 2014). Figure 5.18 illustrates the workflow.

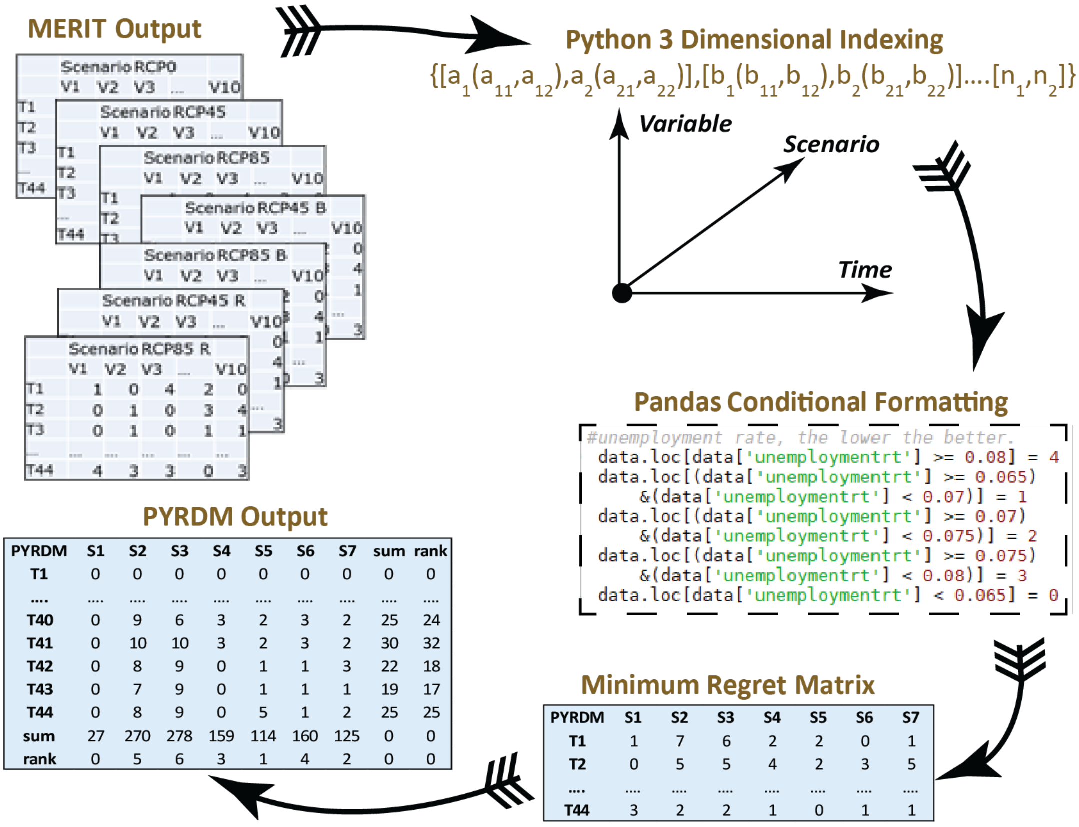



**Figure 5.18** Workflow from Vensim® (MERIT) to the Python 3 (PYRDM) matrix in C-ADAPT. Steps include: 1) condensing output variables into a 3-dimensional index. 2) Applying conditional formatting on variables to enable comparison. 3) Calculating minimum regret matrix (Callaway, 2014) between variables for each timestep. 4) Stack variables by scenario and rank to discover pathways of least regret.

In summary, the least-regret preference function utilises the following steps:

1. Conduct sensitivity analyses in Vensim® (Ventana System Inc, 2015) to produce robust outputs of key aggregates.
2. Import key aggregates into Spyder 3.3.6, the Scientific Python Development Environment (Raybaut, 2009) for use in the Python 3 (Python Software Foundation, 2017), PYRDM script (https://gitlab.com/aceaves/dappy).
3. Sort datasets into a 3-dimensional indexed matrix (key aggregate, time and scenario).
4. Format the data for comparison through Pandas Boolean selection (Pandas Development Team, 2014). The Boolean selection allows the algorithm to satisfy predefined objectives amongst combinations of uncertain conditions—a similar step employed in RDM for scenario discovery by Lempert et al. (2013).

5. Calculate the minimum regret over the matrix based on Callaway (2014) between variables for each timestep.
6. Stack key aggregate matrices by scenario for each timestep, rerun the minimum regret script, and rank scenarios to define DAPP.

Finally, C-ADAPT pathways of least-regret are evaluated for rational logic. If the results are not logical, then the modeller returns to Step 1 of the Agile Development Methodology to examine system failures, abnormal outputs or the irrational timing of events and adjusts the IAM accordingly.

## 5.9 All functionalities complete

Model building is cyclical and dynamic through running, comparing, and changing, which improves the modellers' understanding of reality (Ruth & Hannon, 1997). Therefore the modeller must decide with each iteration of development whether to reject, accept or revise the model in light of new knowledge or experience learned from the real world (Ruth & Hannon, 1997). If all the functionalities pass, then C-ADAPT moves to the beta stage. If not, the modeller reiterates the processes until C-ADAPT and its outputs are robust, a process which took over three years.

## 5.10 Limitations and assumptions

In general, the central assumption is that when coastal hazard risk is low, C-ADAPT assumes that socio-economic wellbeing increases with increasing capital wealth. In contrast, a higher risk is associated with decreased socio-economic wellbeing. However, 'Deep uncertainty' or 'Knightian uncertainty' exists for futures that we cannot reliably quantify (Smith, McDonald, et al., 2016) and therefore, plausible scenarios contain constraining assumptions and trade-offs. The IAM assumptions look more at system structure and scenarios, and the IAM limitations are more mathematical or logical, as shown in Table 5.9.

One limitation that requires explanation is the trade-off between structural detail and data detail to maintain efficiency within a CGE model. Efficiencies are lost in MERIT as structural detail increases from the 10 industries and commodities to the full ANZIC 106 industries and 205 commodities. The model takes days to explore scenarios out to 2050, thus, justifying the aggregation of 10 industries and 10 commodities. Conversely, data detail is constrained by reporting periods. Therefore, data detail has little impact on model efficiency as the model simply ‘looks up’ tables of exogenous values at each timestep. Thus, the timestep is the critical driver of efficiency from a data perspective. Here the timestep of 1.8 days is essential to measure flood impacts, but the accuracy of the MERIT CGE is approximately 90 – 95%. Whereas a standard CGE working to accounting timeframes (monthly) would have increased accuracy, it would be useless to discover an economy's complex operation under disturbed conditions when emergency decisions are made.

*Table 5.9 Key assumptions and limitations of C-ADAPT*

| Assumptions | |
|---|---|
| **General** | ● Households rebuild in-situ after a disaster aided by insurance or savings.<br>● The model uses mathematical constants where source information is limited, such as the Insurance Threshold, Non-market Amenity Value, Desired Funding and District Base.<br>● Appropriate spatial and temporal model resolution to effectively quantify data on impacts (Smith & McDonald, 2016a).<br>● See Smith et al. (2016) for detailed MERIT assumptions.<br>● Weak links in the network limit infrastructure interdependencies. |
| **Spatial** | ● The 2120 1% AEP flood and inundation extents define the CHZ.<br>● The aerial extent of inundation is modelled through step changes in inundation levels aligned with the 1% AEP's at 2065 and 2120.<br>● The geodetic change for the CHZ (see Figure 1) is -0.086m for the model period, aligning with the Ministry for the Environment's projections (Ministry for the Environment, 2017). |
| **Valuation** | ● Estimated built capital losses are quantified from Riskscape, and the damage function is the average of seven different building types as described in Reese and Ramsay (2010).<br>● Land losses are set at 1% of government land valuations for each storm event.<br>● Foreseen risk in the CHZ leads to a decline in the market value of capital. |
| **Insurability** | ● Insurer's tolerance threshold to cover vulnerable properties is where the AEP<2%. Otherwise, insurers withdraw from the market.<br>● Household's tolerance threshold is where they are only willing to pay up to 5% of household income toward insurance or lose 5% of their capital wealth. Otherwise, they withdraw from the market.<br>● Model iteration and feedback defined these values.<br>● Excesses increase with insurance claims following flood events. |
| **Amenity** | ● Amenity value is based on the assumption that the hedonic pricing calculation reflects consumer demand for coastal property in at-risk areas.<br>● Lags and feedback reflect the non-monetary benefits of seaside habitation and behavioural response to capital losses and the coastal environment's reduction. |
| **Adaptation** | ● Once a property floods thrice (where flooding > 12 m NZVD2016, or MSL>3.183 m) under the baseline scenario, households and firms perform *ad hoc* relocation with support from the public insurance provider EQC.<br>● Where *ad hoc* or forced retreat occurs under the baseline scenarios, Central Government, as the public insurer, underwrites lost land with the replacement of a modest section away from hazards. |

| | |
|---|---|
| | • Managed retreat scenarios reduce exposure in the model by reducing the exposed properties as funding becomes available.<br>• Managed retreat scenarios employ economies of scale for the construction sector. Thus, new assets can be provided more efficiently due to scale.<br>• Coastal defence structures eliminate risk, and properties remain in the short to medium-term once installed. |
| **Triggers** | • Environmental triggers act as an early warning system to enact policy decisions.<br>• Logical trigger points are assumed and embedded in the system model based on trends, expert opinions, management plans and logical guesses to initialise the adaptive policy (Secretariat of the Convention on Biological Diversity, 2009).<br>• There are trigger points for planning and trigger points for action, which are crucial to an adaptation policy's performance (Hamarat et al., 2014). |

| **Limitations** |
|---|
| • Future conditions and risks can only be estimated using some type of mathematical model, which are inherently error-prone because of the complexities of the underlying systems and the difficulty of translating that complexity into mathematical statements (Knopman & Lempert, 2016). |
| • Model uncertainty due to limited knowledge, inherent system randomness, dynamic chaos, non-stationarity, and future policy actions (Kwakkel et al., 2015). |
| • Limited timeframe for refinement, reflection, calibration and sensitivity analyses (Smith, McDonald, et al., 2016). |
| • Trade-offs between computational capacity and processing times (Eaves & Doscher, 2015; Kwakkel et al., 2015; Smith, McDonald, et al., 2016). |
| • Quantifying intergenerational and spatial risk transfer. |
| • Uncertainty Analyses is required to better understand and interpret the outputs of MERIT (Smith & McDonald, 2016a). |
| • Uncertainty of the MERIT model between 5-10%. |

# 6. The socio-economic impacts of the baseline scenario for coastal communities

Chapter 6 outlines the economic impacts of the baseline scenario, where a large-scale managed retreat is not available, and communities either endure coastal flooding, erosion, inundation or adapt through relocation in an *ad hoc* fashion. By utilising Scenario Planning and System Dynamics to reduce the total quantity of potential futures, this chapter focuses on the direct impacts on communities in the CHZ and the response of the insurance and property markets. The results expressed are developed from the input modules of C-ADAPT, which are the local-scale inputs to MERIT. The chapter sets up the baseline scenario results for comparison against managed retreat scenarios to answer the research question: What are the socio-economic implications of managed retreat to impacted communities and economic actors through time? The timescale for analysis is from 2020 to 2050, or the economic medium-term, with the model starting in 2007.

## 6.1 C-ADAPT outputs for local-scale impacts

The modelling in chapter 6 to define the direct impacts of coastal hazards concentrates on the input modules that flow into MERIT. Therefore, local-scale direct impacts are isolated to provide context for modelling the regional impacts. The baseline scenario outputs are generated from the Risk Assessment Module and the Socio-Economic Module, which form part of the broader IAM C-ADAPT. They model 1) the direct risk and estimated losses that result from the exposure to coastal hazards and 2) the behavioural response of communities and insurers from balancing economic feedback. The set-up utilises a probabilistic approach in System Dynamics and relies on deterministic Scenario Planning. Thus, rational and random uniform distributions generate input parameters for influential constants for each scenario (Table 6.1). These input modules utilised a probabilistic approach to represent stochasticity in variables, system stability and enhanced feedback rather than investigate a precise community outcome based on a narrow set of input criteria to suit the study area. Two sub-scenarios of the baseline were also examined here only to explore when consumers may exit the insurance market under the condition that insurers remain in the market to transfer risk.

Results illustrate the mean and median statistics of 100 simulations after model testing. The blue ribbon in Figures 6.1 – 6.3 represents the standard error (mean) or the inter-quartile range (median). The ribbon is to illustrate the stochasticity of outputs of the input modules. Monetary values are nominal 2007 New Zealand dollars as measured on 31 March 2007, the starting point of C-ADAPT.

***Table 6.1 Vensim® sensitivity simulation setup***

| Variable | Minimum | Maximum |
|---|---|---|
| Non-Market Value (%) | 0.8 | 1.4 |
| Return On Investment (%) | 0.9 | 1.15 |
| Initial Premium (NZ$$_{2007}$) | 500 | 5,000 |
| Initial Excess (NZ$$_{2007}$) | 500 | 10,000 |
| WTP Threshold (%) | 0.03 | 0.07 |
| Insure Threshold (%) - Baseline | 0.01 | 0.03 |
| Insure Threshold (%) - Insure | 0.04 | 0.06 |
| Attrition Rate (Dimensionless) – Scenario dependent | 0 | 3 |
| Water Depth (m) – Scenario dependent | 0.000 | 0.008 |
| Scale (storm magnitude) – Scenario dependent | 200 | 11,000 |
| Frequency (storm) – Scenario dependent | 0.058 | 0.07 |

### 6.1.1 Direct risks and estimated losses from future coastal hazards

The Risk Assessment Module results show that the frequency and magnitude of coastal flooding of capital assets are likely to increase to 2050 under 0.34 m SLR (worst-case, RCP8.5) or 0.27 m (mid-range, RCP4.5) SLR and increased storminess as shown in back in Figure 5.6. From this hazard, the risk can be quantified. Here the risk is defined as both the likelihood and consequence of a hazard as outlined in the CDEM Act 2002 (New Zealand Government). The increasing likelihood of the hazard occurring is modelled by an increasing AEP, or the inverse of the return period (Auckland Council, 2014), as illustrated in Figure 6.1A. The AEP remains under 2% until 2033 for the 'worst-case' baseline scenario and 2046 for the 'mid-range' baseline scenario. Of note, without SLR, the AEP continues to grow in the CHZ due to tectonic subsidence and storms, leading to a slightly increasing trend under the 'no SLR' scenario.

The AEL is the combined cost of lost land and damaged built capital in the CHZ (Figure 6.1B), or the measure of consequence in monetary terms (Auckland Council, 2014). It increases as flood events become more frequent, prolonged and intense. Two factors drive the overall rise: 1) the magnitude of 'normal' losses increase, and 2) the frequency of loss events increase. It is directly attributable to the extent and occupation of the CHZ. The AEL embeds dynamic feedback in the form of exposure-reduced capital valuations (behavioural reframing), *ad hoc* relocation of properties after repeated flooding and increasing insurance premiums. In essence, behavioural reframing is where knowledge learned from previous floods results in property owners reducing their capital risk over time and the property market risk-adjusting valuations. The dynamic feedback is evident by the stabilising of the worst-case baseline around 2041 (Fig. 6.1B). Notable here is how insurance exacerbates the AEL under the worst-case insure baseline until 2044 as risk transfer to insurers maintains living with risk without significant consequence to property owners.

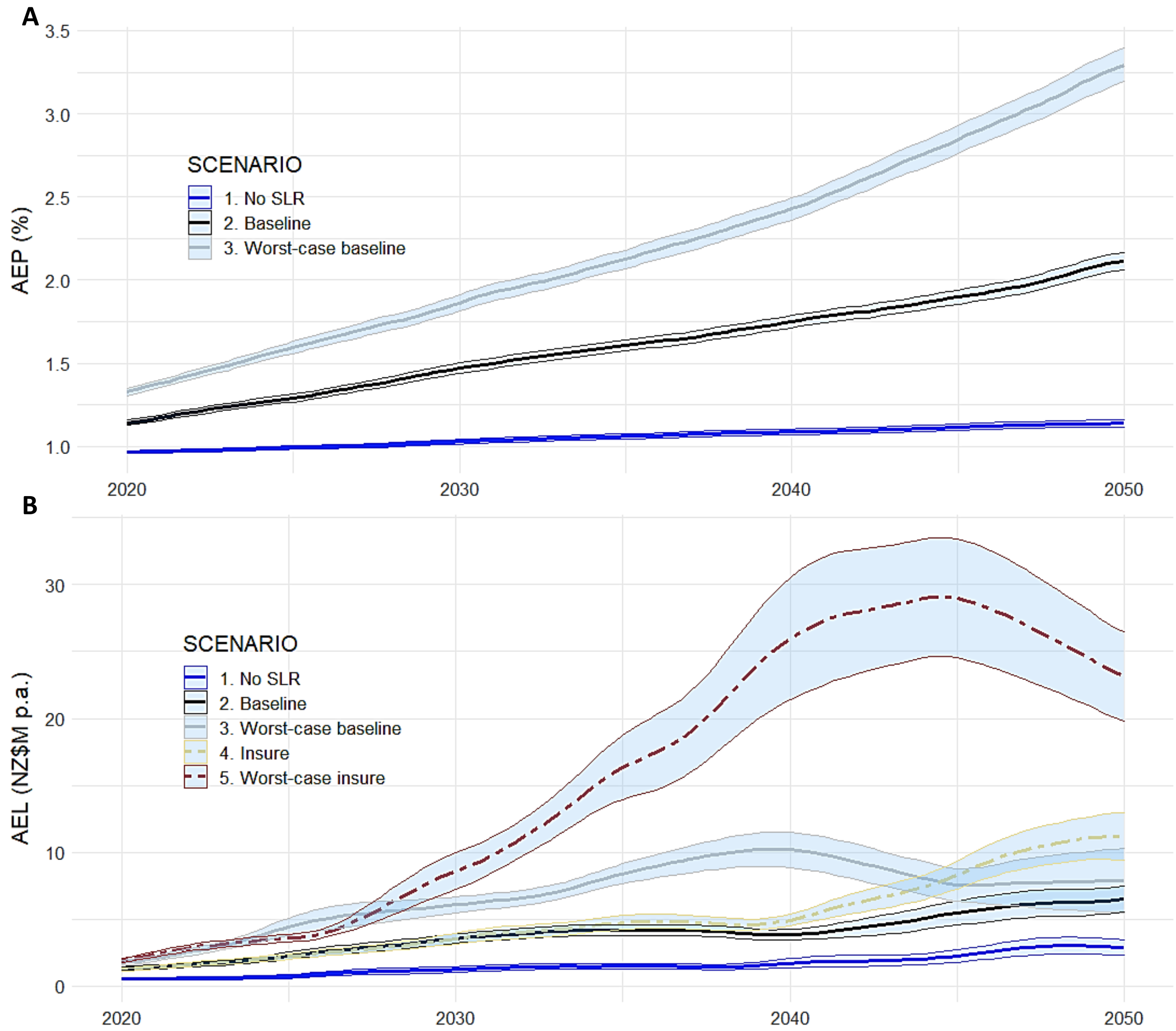



**Figure 6.1** Simulation outputs for the Annual Exceedance Probability (AEP, A) of storms and the Annual Expected Loss (AEL, B) from coastal storms for coastal communities from Tongoio to Clifton in Hawke's Bay. The AEP increases at different rates for each scenario. The AEL increases with the continued occupation of the Coastal Hazard Zone (CHZ) but plateaus under the worst-case baseline (RCP8.5) as dynamic feedback in C-ADAPT reduces risk. Similarly, the worst-case insure scenario peaks around 2044 at a much higher value, given the safety of insurability before it declines. Results are the mean of 100 simulations with the standard error of the mean represented by the blue shading.

### 6.1.2 A behavioural response of communities

Results from the Socio-Economic Module in Figure 6.2 indicate that climate change at the coast negatively influences exposed capital, market return on investment (ROI), and coastal amenity value under worst-case scenarios and, to a lesser degree, under mid-range baseline scenarios. Thus, the hypothetical oscillating dynamic equilibrium of the market in the absence of climate change is transformed through SLR and increased storminess to a system of overshoot and possible collapse of the capital market in exposed areas. However, insurers prop up the market value of exposed capital to maintain a dynamic equilibrium under the baseline insure scenario. Although the worst-case baseline with insurance overshoots and collapses for exposed capital around 2042. Similarly, market ROI and coastal amenity value are heading into an unstable overshoot of the dynamic equilibrium for the worst-case scenarios and the baseline scenario. There also appears to be a minor regime shift around 2027 across most scenarios, as illustrated by the change in the medium-term trend across Figure 6.2, signifying the initiation of a threshold as risk increases.

Results for exposed capital suggest that reinforcing feedback in the IAM reduces exposed capital in the CHZ due to subsequent inundation events (Figure 6.2A). For the baseline mid-range (2) and worst-case scenarios (3), exposed capital peaks around 2042 at NZ$_{2007}$17.74B and 2029 at NZ$_{2007}$5.25B, respectively. This also illustrates the increasing cost of capital over time. However, insurers remain in the market under the mid-range insure scenario to reach NZ$_{2007}$45.47B by 2050. The worst-case insure scenario shows a significant reduction in capital exposure as storms are extensive and frequent under this scenario. It stabilises around 2040 at NZ$_{2007}$11.39B, given the higher capital value than the worst-case scenario. In the absence of significant risk, the no-SLR scenario illustrates accelerating capital growth that reaches NZ$_{2007}$56.66B during the period.

The ROI for market value in the CHZ is influenced by increasing inundation and insurance costs (Figure 6.2B). The 'regular' positive market return of 2.4% (1.024 for modelling purposes) in 2020 adjusts to different exposure rates, except for the no-SLR scenario, which maintains the same positive return. The ROI turns negative for the worst-case scenario around 2032 to reach -7% (0.930) by the end of the modelled period. The worst-case insure turns negative around 2030 to reach -18.9% (0.811) by 2050. It turns negative by 2048 and is -0.8% (0.992) by 2050 for the mid-range baseline and 2043 for the insure scenario, where it is -4.6% (0.954) by 2050. Here the effect of insurers supporting the capital market, which supports CHZ occupation, results in the market adjusting the ROI to match the somewhat larger stock of exposed capital given enhanced insurability. However, the increased capital at risk, as indicated by the risk transfer to the insurance industry (up to an AEP of 5%), forces the market to anticipate future loss as risk increases. This effect is signified by the market ROI reducing at a greater rate for the insure scenarios.

The coastal amenity value of households in the CHZ is highlighted in Figure 6.2C. C-ADAPT assumes that the other nine industries will make decisions to minimise risk based on economic indices and not incorporate amenity value into business decision-making. Therefore, it overshoots the hypothetical dynamic market equilibrium one would expect for the mid-range baseline in 2028 (NZ$_{2007}$0.3B), worst-case in 2026 (NZ$_{2007}$0.27B), and the mid-range insure scenario in 2040 (NZ$_{2007}$0.64B). The worst-case insure scenario does not overshoot during the period but peaks in 2030 (NZ$_{2007}$0.36B). Therefore, insurers remaining in the market significantly stretches out coastal amenity value over time. In the absence of SLR and increased storminess, represented by the no-SLR scenario, the coastal amenity increases to NZ$_{2007}$1.17B in the CHZ. Amenity value still tracks higher under the no-SLR scenario given the allure of coastal living, although the uncertainty range is significant.

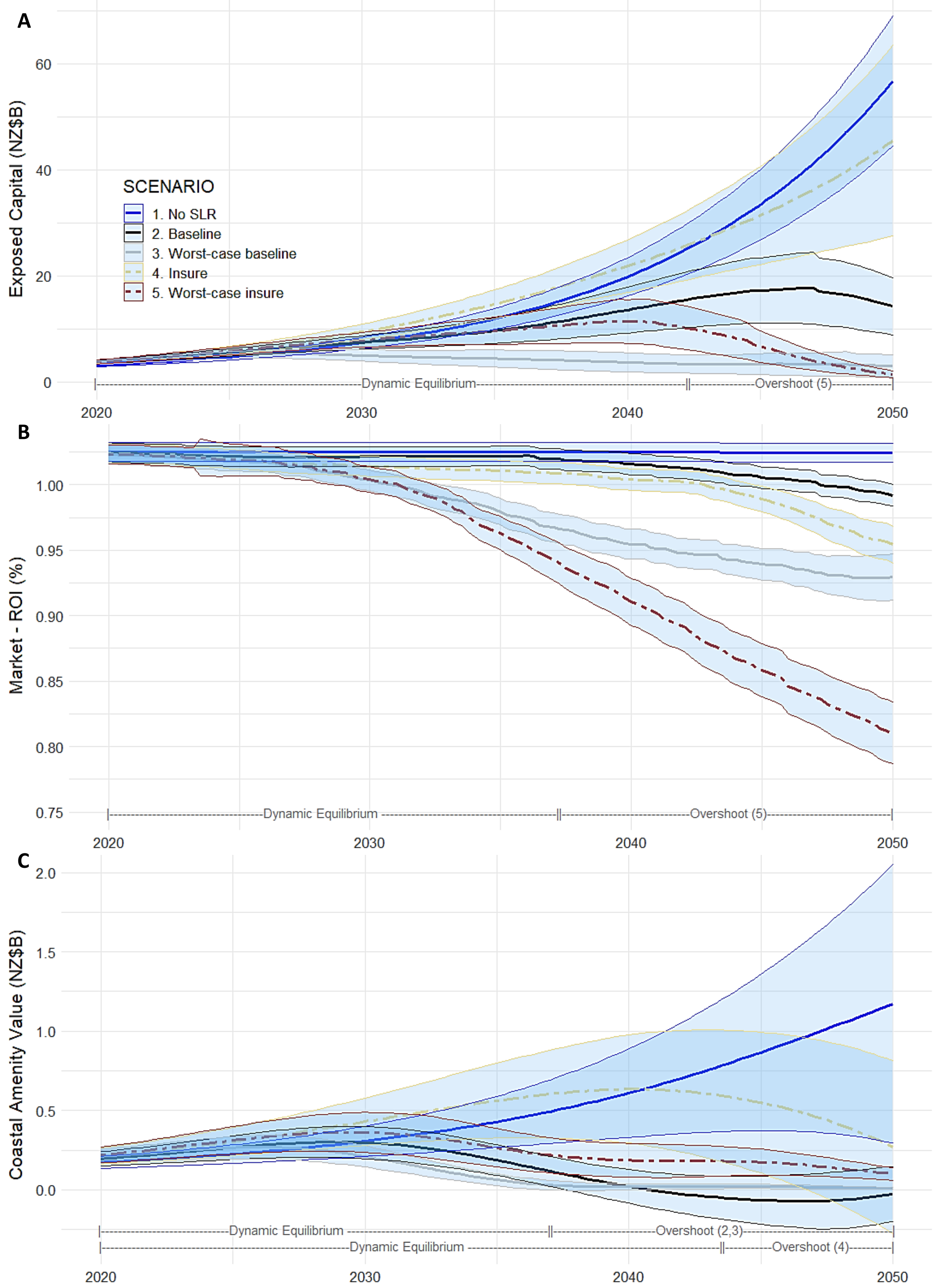



**Figure 6.2** Simulation outputs for exposed capital (A), market adjustment to return on investment (ROI) (B), and the coastal amenity value (C) for the scenarios. The worst-case scenario has a greater negative influence on exposed capital, ROI and coastal amenity value than the mid-range and no SLR scenarios. Under enhanced insurability scenarios, households are worse off for exposed

capital and ROI but are better for amenity value. Subscripts, which enable model structure replication, capture the impacts on different industries here. Households represent a sub-group of the industry Residential and Real Estate Services. Results are the mean of 100 simulations, with the mean standard error represented by the blue shading.

A fundamental driver of the socio-economic results is that insurance premiums and excesses cover the additional annual cost of CHZ living imposed by insurance companies to pool risk. Under all scenarios, C-ADAPT introduces risk-based premiums and excesses. Insurance affordability (as a share of income) by consumers in this demographic influences the scenarios where insurability is guaranteed, and risk motivates insurers to withdraw under the worst-case and mid-range baseline scenarios as described back in Section 5.3.2.

C-ADAPT identifies thresholds where the insurance market fails, as shown by the timing of any overshoot leading to market collapse in Table 6.2. The increasing cost and frequency of events undermine the capability of insurance companies to provide insurance to the CHZ for the mid-range baseline and worst-case scenarios. The increasing cost and frequency lead to insurance market withdrawal when the AEP exceeds 2%, around 2026 for the worst-case scenario and 2032 for the mid-range baseline scenario (Figure 6.3A). If insurers remain in the market indefinitely, consumers are no longer willing to pay for risk-based insurance and start to withdraw around 2029 for the worst-case insure scenario and 2033 for the mid-range insure scenario. When analysing the peak premium, cost drives the threshold for consumer withdrawal (as a fraction of income), whereas risk drives the threshold for insurer withdrawal (the AEP) in the model. This leads to consumers withdrawing earlier (2027) than insurers (2029) under the mid-range baseline and insure scenarios. In contrast, insurers withdraw earlier (2025) compared to consumers (2027) under the worst-case and worst-case insure scenarios (Table 6.2).

***Table 6.2 Withdrawal of insurers and consumers in the CHZ insurance market***

| Scenario | Peak (year) | Peak (Cost, NZ$$_{2007}$ p.a.) | Market collapse (year) |
|---|---|---|---|
| No SLR | 2050 | 5,009 | - |
| Baseline (Insurer withdrawal) | 2029 | 3,308 | 2032 |
| Insure (Consumer withdrawal) | 2027 | 3,514 | 2033 |
| Worst-case baseline (Insurer withdrawal) | 2025 | 3,087 | 2026 |
| Worst-case insure (Consumer withdrawal) | 2027 | 3,355 | 2029 |

Conversely, insurance excesses do not show significant volatility over time except for the gradual decline in excesses under the mid-range baseline and worst-case scenarios (Figure 6.3B). Insurers start to withdraw from the 'riskier' assets in the market under the worst-case around 2024 and mid-range conditions around 2029, as illustrated by the slow decline in excesses to NZ$$_{2007}$0 and NZ$$_{2007}$1,129 respectively by 2050. Excesses remain stable through the period for insure scenarios but dip slightly below the no-SLR scenario. Insurers and consumers remain in the excess market indefinitely under the insure, worst-case insure and no SLR scenarios. Therefore, consumers do not withdraw from the market based on the cost of the excesses alone, given the model set-up. Finally, the no-SLR scenario increases minimally by NZ$$_{2007}$27 from NZ$$_{2007}$5,407 to NZ$$_{2007}$5,434 in the absence of inflation.

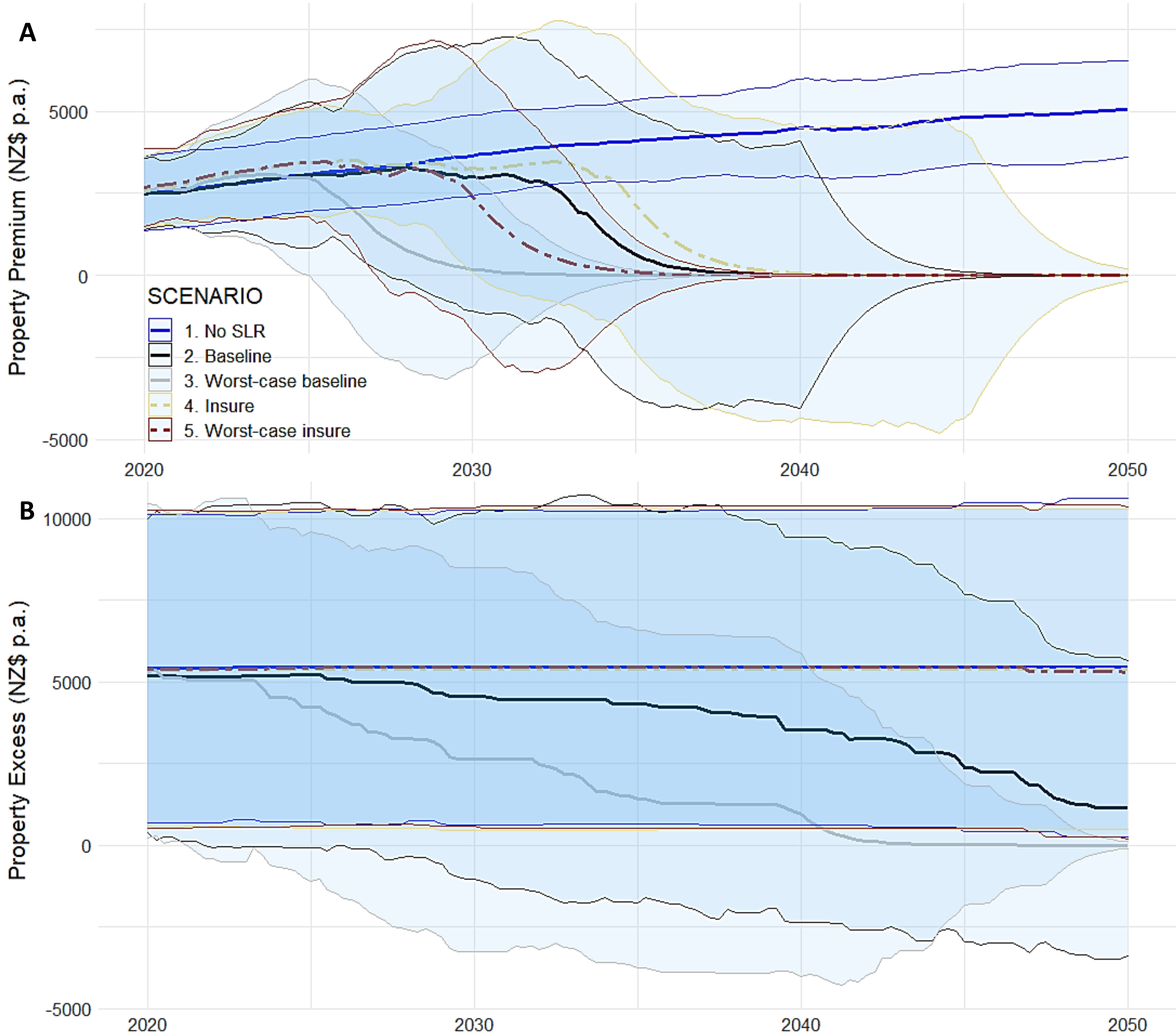



**Figure 6.3** Simulation of property insurance premiums (A) and excesses (B) under baseline scenarios. For premiums, insurers withdraw when the risk becomes intolerable around 2025 under the worst-case scenario, and consumers withdraw when the cost becomes too great around 2027. Under the mid-range baseline scenario, consumers withdraw first around 2027, and insurers withdraw around 2029. For excesses, under mid-range baseline and worst-case scenarios, insurers incrementally withdraw from at-risk assets leading to a decline in excesses to NZ$$_{2007}$1,129 and NZ$$_{2007}$0 respectively by 2050 market. Excesses remain reasonably stable for insure scenarios. Results are the median of 100 simulations, with the error expressed as the interquartile range for (A). The results for (B) are the mean of 100 simulations with the standard error of the mean represented by the blue shading.

## 6.2 Implications for the local-scale impacts

Combining System Dynamics with Scenario Planning in C-ADAPT is a valuable approach to analyse non-linear feedbacks within and between environmental and economic systems. Scenario Planning defines local-scale outcomes for a particular group or audience (Ramirez & Wilkinson, 2016). In contrast, System Dynamics has traditionally been applied globally or nationally (Forrester, 1982). However, developing a methodology embedded within an IAM that accommodates both can be problematic. On the one hand, System Dynamics relies on probability analysis to discover general patterns of behaviour (Ford, 2010). In comparison, Scenario Planning drives a more deterministic outcome by training the model toward an audience and outcome (Ramirez & Wilkinson, 2016).

C-ADAPT was initially set up with unique values for the study area, making it possible to define actual outcomes for events, thresholds and valuations for Hawke's Bay. However, patterns of behaviour were bound to the local scale under this deterministic approach. Subsequent model development expanded the input criterion for sensitivity analyses and simplified the system structure. Iterative development led to new emergent behaviours becoming visible as the system is restructured. Discovering these new emergent behaviours at the local scale through System Dynamics is a significant result, yet they may not reflect the long-term outcomes for the study area. One such generic insight was a more gradual market response to increasing insurance premiums (Figure 6.3A) rather than an abrupt change in system state.

Still, modelling baseline scenarios using this integrated approach enabled the discovery of two stand-out drivers that influence a behavioural response of communities to coastal inundation at the local scale: first, the ongoing likelihood of risk transfer to the insurance industry (Figure 6.3A), and second, the behaviour of households and firms to accept risk for the added value of coastal living (Figure 6.2C).

### 6.2.1 The future of insurance with exacerbated risk

System Dynamics enables the quantification of causal relationships and the implementation of thresholds to discover general patterns of behaviour for the insurance market's response to coastal risk. Patterns of behaviour then allow vulnerable communities and government agencies to plan futures accordingly. Here C-ADAPT investigated the price response of the insurance market to changing coastal risk through economic impact modelling of storm events. This is useful for vulnerable communities to predict the actions of the insurance industry and make decisions as insurers assess policies annually on a case-by-case basis, with differences occurring between insurers and locations (Parker, 19 May 2017). The scenarios modelled indicate that the insurers' response to increasing coastal hazards increases risk-based premiums, higher excesses and inevitably insurance withdrawal. These instruments align with current practice, although insurers may also implement 'market value cover only' or exclude storm water damage (Parker, 19 May 2017).

Modelling suggests that risk-based premiums enable insurance providers to remain in the CHZ over the short-term (1-20 years) until increasing claims reduce acceptable profitability. In the IAM, probabilistic risk (the AEP and AEL) determines profitability, and increasingly disastrous events lead to more claims on insurance policies. Insurers will inevitably withdraw when risks are sufficiently probable and certain (Storey et al., 2017). They will also become more risk discriminating and spatially granular in assessing insurance policies (Storey et al., 2017). The scenario modelling here defines a projected withdrawal point by insurers, or tolerance threshold, when the modelled storm recurrence interval (frequency) or AEP is greater than 2% (Figure 6.1A). However, given the extent of the study area, insurers withdrawal incrementally from the most at-risk areas, followed by total withdrawal (market collapse) from the market, as shown in Table 6.2 and Figure 6.3A.

Similarly, Reguero et al. (2020) refer to the 2% AEP (the annual return interval of a significant event being 50 years) as the insurers' 'exhaustion point', where insurers stop covering losses or the probability of losses. Once the timing of the tolerance threshold is known, property owners can then plan for insurance retreat from the market and implement adaptation strategies. However, disclosure by insurance providers of their risk appetite is desirable to enable vulnerable coastal communities to plan long-term futures through additional savings to mitigate damages or undertake an *ad hoc* retreat.

Alternatively, higher excesses are the preferred choice of insurers to manage hazards in the short term (Storey et al., 2017). Insurers have introduced risk-based excesses in New Zealand of NZ$$_{2007}$2,090-10,000 (Initio, 2019; Parker, 19 May 2017; Storey et al., 2017). However, the modelling here did not achieve such high excesses because the set-up of C-ADAPT only accounts for risk, claims, profit, and an averaged initial excess with a distributional range of NZ$$_{2007}$500-10,000. Here the spatial extent of the study area is fundamental to the outcomes. A more granular insurance approach would see very high-risk properties requiring a NZ$$_{2007}$10,000 excess, whereas properties a street or so back from the coast may require only a NZ$$_{2007}$500 excess. Currently, the risk is pooled to a community level by insurers, which will change in the future with the introduction of risk-based pricing (Huffadine, 2018). Further modelling at a more agent-based and granular level would overcome this issue somewhat, but it would require multiple micro-scale study area investigations.

From the consumer's perspective, willingness to pay premiums and excesses also define the insurability of capital assets. In scenarios where insurers remain in the market, C-ADAPT illustrated how risk transfer could buy time in exposed locations at the expense of insurers. Thus, exposed property owners are WTP insurance companies' premiums and excesses to remain in the CHZ as long as it is financially possible for them to do so with the security of insurance cover. Notably, exposed property owners have a different risk perspective as they wish to transfer as much risk as possible to insurers. However, even without insurance, some property owners are willing to remain even if they may be forced into bankruptcy or have to delay their retirement due to diminishing asset value if a mortgage remains on the property (Long, 29 August 2017). Similarly, some property owners may use exposed capital as collateral to be leveraged against other properties and businesses, maintaining their entrenchment in the CHZ.

Outputs (Figure 6.2A and 6.3A) illustrate risk acceptance, where exposed capital does not reduce to zero in line with insurance withdrawal. Here C-ADAPT allows for exploring different risk tolerances through a WTP approach to insurance for both consumer and provider, as they are exogenous model inputs but endogenous drivers in the CLD. For example, a consumer's WTP insurer premiums and excesses were set as a constant percentage share of income at 5%. Further research, development and calibration would benefit from an approach offered by Withey, Sullivan and Lantz (2019). They utilised contingent valuation through a field survey of respondents in the Halifax Regional Municipality to define what the public is WTP for storm protection with or without climate change. By utilising public engagement in Scenario Planning, it is possible to calibrate C-ADAPT further and define thresholds and costs that reframe a community's perception of future risk. Thus, public participation in exploring scenarios is key to its success (Ramirez & Wilkinson, 2016).

### 6.2.2 Weighing up the benefits of coastal living

The behaviour of households in the CHZ is their tolerance of risk balanced against the perceived benefits of coastal living (Bin et al., 2008), whether accessibility, coastal views, ecosystem services or recreation. Taking on risk is understandable when coastal hazard risk is low and the reward of having proximity to the coastal environment is high. However, results illustrate that coastal hazards increase flood damage costs (Figure 6.1B) and alter property markets (Figure 6.2B). Coastal erosion and inundation physically impact structures and erode property values, followed by reducing residents' quality of life and peace of mind (Geis, 2000; Tonkin and Taylor, 2019). C-ADAPT included these impacts through hedonic pricing (Appendix 3) and, therefore, linked amenity value to property value and wealth. C-ADAPT is set up so that as wealth declines, so too in time will amenity value as households generate a negative perception of their economic situation, which is linked to place. However, environmental satisfaction can outweigh the risk and reduced property value in the long term (Bin et al., 2008). This was the case in Haumoana, Hawke's Bay, where vulnerable residents were offered buyouts in the 1970s, and most refused (Tonkin and Taylor, 2019). Further research is required to quantify the stakeholder rationale to live with risk beyond hedonic pricing to include other forms of contingent valuation.

The results also provide insights into the role of property values in driving property investment behaviour, which shows a disparity with published flood analyses for the study area. Smith (2019) stated that flood events change price expectations in the property market, which scale downward for those vulnerable to inundation while scaling up for those at the coast with no risk. This scaling is evident in Figure 6.2 by the diverging baseline scenarios for capital exposure. Simultaneously, the amenity value of coastal living has resulted in high property prices in New Zealand that do not yet account for risk (Smith, 2019). Increasing property prices occurred across all Hawke's Bay CHZ for 2018-2019 (OneRoof, 2019). These increasing capital values in vulnerable suburbs is contrary to a hedonic study by Daniel et al. (2009) that suggested an increase in flood risk by 1% p.a. resulted in the sales price of flood-prone properties decreasing by 0.6%. Similarly, Walsh et al. (2019) illustrated a 19% decrease in house price for unprotected homes in the 0-2 foot SLR zone. Jin et al. (2015) found a 0.18% reduction in property value given an erosion rate of 1 $m^{a-1}$ through hedonic analysis. These reports also illustrate the range of the response in the property market.

Thus, current prices in Hawke's Bay appear to reflect the benefits of coastal living rather than coastal hazard risk. A similar finding to house prices not reflecting risk was reported by Filippova et al. (2020). Broadly speaking, there is a negative relationship between the distance to the ocean and property value (Jin et al., 2015). However, with new knowledge of the coastal risk, results indicate that a change from the dynamic equilibrium for the exposed capital market occurs under RCP8.5 late in the modelled period.

Finally, coupling Scenario Planning and System Dynamics makes it possible to investigate non-market amenity values for different communities and hazard exposure. Quantification of the amenity value produced a weak relationship between property value and coastal proximity due to modest capital investment at this coast. The weak result in Figure 6.2 and dynamic equilibrium overshoot, which leads to market collapse, could be explained by the council's long-term knowledge of coastal hazards in the area and the wider community (Komar, 2010; Tonkin and Taylor, 2019). However, this is not necessarily the case for other societies with significant coastal capital investments, which maintain increasing prices in the face of increasing hazards (Bolstad, 2016). Therefore, coastal communities will have different valuations based on behavioural biases, bounded rationality and SLR beliefs (Bernstein et al., 2019).

System Dynamics modelling is beneficial here as it allows for implementing time lags that provide the system with a delayed behaviour born out of system structure (Meadows, 1989). A five-year lag was installed on both WTP insurance and willingness to accept loss (WTAL) in the Socio-Economic Module to delay community behaviour and install community bias. C-ADAPT introduces these lags to illustrate the medium-term (20-40 years) enjoyment (amenity value) of the CHZ with bounded rationality by prolonging the trend, as shown in Figure 6.2C and Figure 6.3A. However, long-term (40+ years) behavioural reframing of stakeholder perception can provide alternative opportunities to maintain amenity values through a managed retreat from coastal hazards in a timely fashion.

## 6.3 Summary

This study has demonstrated that Scenario Planning in System Dynamics is a practical approach to understanding and quantifying the long-term and evolving risks posed by coastal hazards under climate change. The method provides a basis, through integrated assessment modelling, to quantify the direct socio-economic impacts of inundation on households when government intervention is not forthcoming. Once these influential behavioural drivers are known, it becomes possible to define the medium-term dynamic equilibrium of the baseline scenario, any overshoot, or any collapse of the local-scale property and insurance markets due to coastal hazards. Planning-informed socio-economic impact analysis such as this can then lead to future reductions in risk and exposure through interventions, as planning is more effective when the long-term costs and risks are known (Longworth, 2017).

Results illustrate that economic impacts from coastal hazards go beyond the simplistic vulnerability of capital and land assets shown in Figure 6.1 due to medium-term behavioural drivers in the economic system responding *ad hoc* to long-term changes in the environmental system. Significantly, results indicate that the current trajectory of increasing capital valuations at the coast may be relatively short-lived, as shown in Figure 6.2B, where the ROI turns negative by 2030 (worst-case baseline) or 2047 (mid-range baseline). In the future, an increased understanding of the risk associated with SLR and storms will drive higher risk-based insurance premiums and excesses. Eventually, insurance market withdrawal drives vulnerable capital valuations downward, as represented by the property market return on investment in Figure 6.2B. Modelling these actions has revealed critical tolerance thresholds for both insurance providers and consumers. The resulting behaviour leads to consumers withdrawing from the insurance market earlier (2027) than insurers (2029) under the mid-range baseline and insure scenarios which are driven by household income. Where insurers remain longer in the market, they withdraw earlier (2025) than consumers (2027) under the worst-case and worst-case insure scenarios where the risk from coastal hazards is greater. The criteria for managing probabilistic risk through AEPs and identifying critical tolerance thresholds through stochastic flood events were fundamental for households to plan for their future, which was captured effectively through integrating Scenario Planning and System Dynamics in C-ADAPT.

Finally, traditional economic analysis cannot always rationalise future non-market social behaviours such as coastal amenity value. This chapter has bridged this gap through behavioural delays in System Dynamics by adding lags to WTP and WTAL to reproduce the short-term bounded rationality of stakeholders. Scenario Planning justified incorporating behaviour in the modelling. Results suggest that vulnerable communities are willing to accept risk and short-term loss to gain amenity value. Figure 6.2C illustrates this point as amenity value is somewhat maintained even without insurance, as shown in Figure 6.3A. However, property occupation may only be a medium-term activity as flood-related losses and inundation reduce capital wealth and coastal environment use. Without government intervention, households are left with devaluing, or stranded capital assets under mid-range and worst-case scenarios as sea levels rise and storms increase until abandonment becomes inevitable.

# 7. The economic implications of intervention

Chapter 7 expands the modelling undertaken in Chapter 6 to incorporate defensive mitigation and financial adaptation scenarios. Here C-ADAPT integrates the input modules with MERIT to discover the regional economic impacts of coastal hazards and the implications for the managed retreat scenarios. The results asses any benefits of managed retreat and coastal defence. Therefore, Chapter 7 continues to explore the research question: What are the socio-economic implications of managed retreat to impacted communities and economic actors through time? It also investigates the research question: What managed retreat scenarios generate a beneficial regional economic impact across sectors and over time?

## 7.1 C-ADAPT outputs for regional-scale impacts

The results of C-ADAPT are evaluated under five topics: 1) risk, 2) direct losses and disruption, 3) households, 4) industries, and 5) government. They represent aggregation at the regional scale, except for direct damages and losses at the local CHZ scale. Damages, losses and disruptions represent one indicative stochastic simulation per scenario to illustrate stochastic flood events. The results are presented for the mean statistics of 100 Latin Hypercube simulations after IAM testing. Note the no-SLR scenario does not feature here as a comparison, and only RCP4.5 and RCP8.5 climate scenarios are used for ease of interpretation. All monetary values are expressed in nominal 2007 New Zealand dollar terms.

### 7.1.1 Coastal risk

The dynamic risk profile in Figure 7.1 sets the scene for MERIT integration to C-ADAPT by applying risk quantification developed in the Risk Assessment Module and utilises dynamic feedback as the scenarios unfold. The risk remains under the baseline scenarios, and risk mitigation under the defence scenarios is only temporary as sea levels rise beyond the modelling period. Thus, baseline scenarios (1 and 2) exhibit reinforcing feedback due to the multiplication of an increasing AEP and the increasing value of exposed capital, as illustrated by the accelerating risk in Figure 7.1. As expected, the managed retreat scenarios reduce the coastal risk when compared to the baseline for the worst-case scenarios by 41.5% for bonds (7) and 35.2% for rates (8) and flatten the trajectory for the mid-range scenarios while reducing risk compared to the baseline by 25.4% for bonds (5) and 33.3% for rates (6) over the period. However, as these results are mean stochastic simulations, residual risk remains for many simulations as managed retreat is not completed by 2050. Therefore, expect further losses. Coastal defence proves to be an effective implementation to reduce the risk below the mid-range baseline by

39.9% (3) and the worst-case baseline by 4.2% (4). The residual risk here is considered the uncertainty in the timing, frequency and magnitude of climatic events.

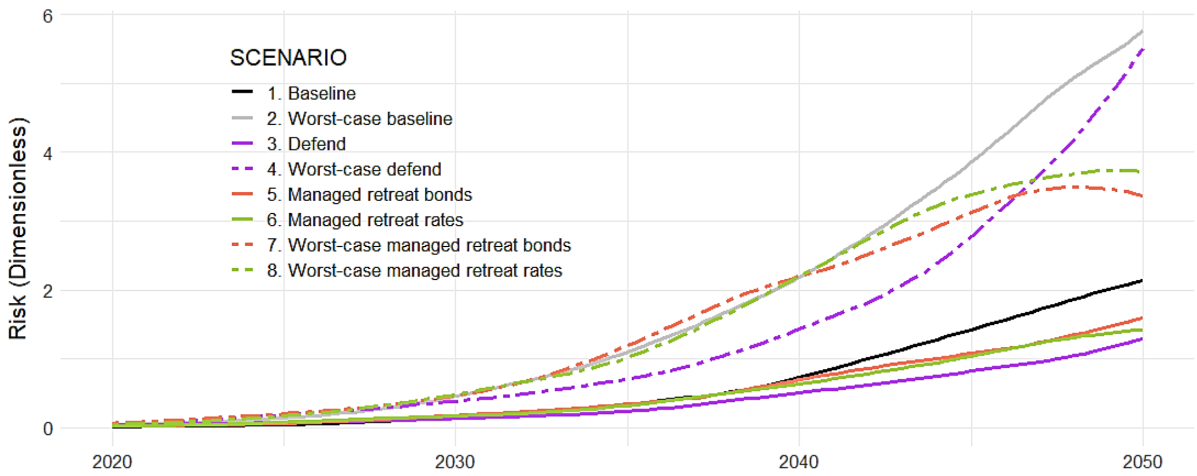



**Figure 7.1** Coastal hazard risk as the dimensionless product of the likelihood and consequence classified by scenario. Compared with the baseline, managed retreat scenarios reduce risk under the worst-case climate scenarios (2, 4, 7 and 8 for RCP8.5). Whereas, under mid-range climate scenarios (1, 3, 5 and 6 for RCP4.5), the trajectory is only beginning to change against the baseline. Defence scenarios reduce risk compared to the baseline but are not as effective as the managed retreat scenarios under the worst-case scenario. Note that the colours are sequenced to reflect the scenarios from module to output.

### 7.1.2 Direct losses and disruption

Flood events in the CHZ directly damage built capital, inundate the land and reduce business operability and infrastructure service provision (Table 7.1). It is evident in Table 7.1 from the damage reduction (light blue), return to full operability (light green) and minimised infrastructure disruption (light orange) that the defence scenario is the best option. However, as illustrated in Figure 7.2, deriving the AEL, which includes loss of economic land and damages, the selection of an ideal scenario to follow is not abundantly clear. Although, what is evident by the end of the period is that the managed retreat scenarios reduce the AEL below the baseline scenarios by 71.7% (mid-range rates scenario), 12.5% (mid-range bonds), 84.2% (worst-case rates), and 65% (worst-case bonds scenario).

Overall, the frequency and magnitude of damages reduce after 2040 under worst-case bonds, rates and defence scenarios. Under the mid-range scenarios, the damages, business inoperability and infrastructure disruption remain throughout the period. However, they reduce under the worst-case bonds and rates scenarios. Damages are reduced over the model period from NZ$$_{2007}$112.8M to NZ$$_{2007}$482.7M by the managed retreat scenarios compared with the baselines. Table 7.1 describes how inoperability and infrastructure disruption has no impact by 2040 under both the bonds and rates worst-case scenarios. Whereas the worst-case baseline scenario still has seven stochastic events that disrupt the infrastructure level of service, reducing it by up to 16% during events. Operability and infrastructure are still reduced after 2040 by 5% to 16% during events under all scenarios except the defence scenarios. When comparing bonds and rates, bonds perform slightly better than rates under the mid-range scenario, whereas rates perform better under the worst-case scenario. Fortunately, the frequency and magnitude of disruptions to business operability and infrastructure also reduce medium-term with interventions.

***Table 7.1 Stochastic simulations of built capital damage (A), disruption to business operability (B) and level of infrastructure service (C) in the CHZ***

| **A) Damages (NZ$$_{2007}$M)** | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Time** | **Measure** | **Mid-range baseline** | **Worst-case baseline** | **Defence** | **Worst-case defence** | **Bonds** | **Worst-case bonds** | **Rates** | **Worst-case rates** |
| 2020-2030 | Mean | 26.637 | 9.77 | 14.829 | 17.37 | 25.968 | 16.953 | 18.207 | 23.574 |
| | Frequency | 3 | 4 | 4 | 6 | 4 | 10 | 4 | 7 |
| | TOTAL | 79.912 | 39.082 | 59.316 | 104.221 | 103.874 | 186.49 | 72.83 | 165.023 |
| 2030-2040 | Mean | 24.025 | 35.352 | 32.208 | 0 | 6.859 | 23.956 | 36.848 | 22.854 |
| | Frequency | 6 | 7 | 6 | 0 | 1 | 5 | 2 | 3 |
| | TOTAL | 144.153 | 247.468 | 193.25 | 0 | 6.859 | 119.781 | 73.697 | 68.564 |
| 2040-2050 | Mean | 46.862 | 60.343 | 0 | 0 | 37.349 | 0 | 39.894 | 0 |
| | Frequency | 4 | 8 | 0 | 0 | 2 | 0 | 3 | 0 |
| | TOTAL | 187.451 | 482.746 | 0 | 0 | 74.698 | 0 | 119.684 | 0 |
| **B) Operability (%)** | | | | | | | | | |
| 2020-2030 | Median | 0.95 | 0.968 | 0.95 | 0.95 | 0.95 | 0.95 | 0.968 | 0.95 |
| | Frequency | 3 | 2 | 3 | 5 | 4 | 9 | 2 | 6 |
| 2030-2040 | Median | 0.95 | 0.834 | 0.95 | 1 | 1 | 0.96 | 0.834 | 0.95 |
| | Frequency | 4 | 7 | 4 | | | 5 | 7 | 3 |
| 2040-2050 | Median | 0.892 | 0.844 | 1 | 1 | 0.95 | 1 | 0.844 | 1 |
| | Frequency | 4 | 7 | | | | | 7 | |
| **TOTAL (Frequency)** | | **11** | **16** | **7** | **5** | **4** | **14** | **16** | **9** |
| **C) Infrastructure Disruption (%)** | | | | | | | | | |
| 2020-2030 | Median | 0.863 | 0.854 | 0.863 | 0.863 | 0.863 | 0.863 | 0.863 | 0.863 |
| | Frequency | 3 | 2 | 3 | 5 | 4 | 9 | 3 | 7 |
| 2030-2040 | Median | 0.863 | 0.826 | 0.863 | 1 | 1 | 0.861 | 0.863 | 0.864 |
| | Frequency | 4 | 7 | 6 | | | 6 | 4 | 3 |
| 2040-2050 | Median | 0.844 | 0.837 | 1 | 1 | 0.863 | 1 | 0.844 | 1 |
| | Frequency | 4 | 7 | | | 2 | | 4 | |
| **TOTAL (Frequency)** | | **11** | **16** | **9** | **5** | **6** | **15** | **11** | **10** |

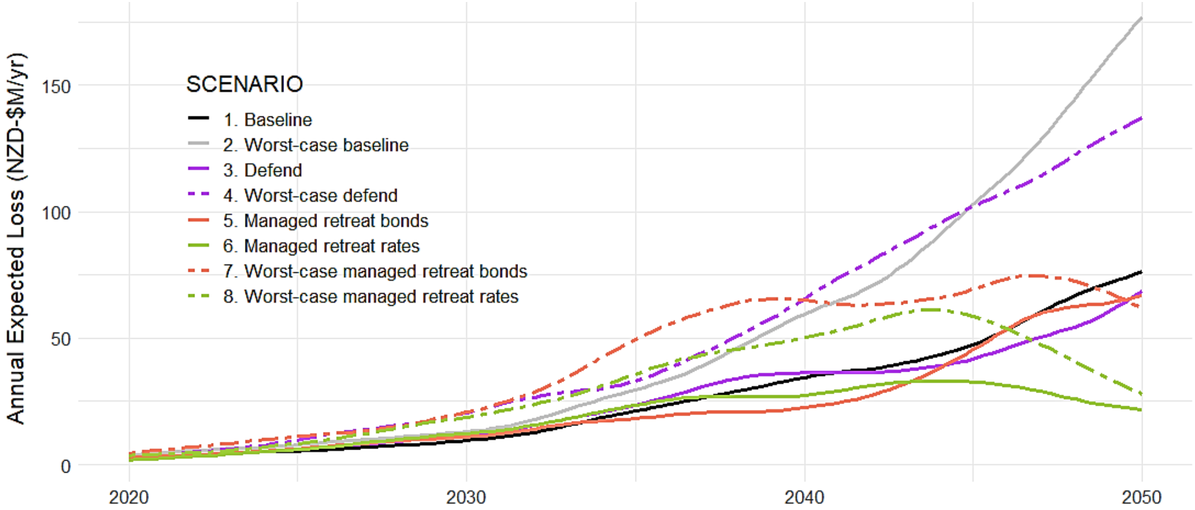



**Figure 7.2** The Annual Expected Loss (AEL) of built capital and land. All intervention scenarios have an AEL lower than the baseline under mid-range climate conditions by the end of the period. Whereas only managed retreat scenarios reduce AEL under the worst-case conditions.

### 7.1.3 Regional economic impacts on households

The economic impacts have been summarised for households in the region by two key aggregates of MERIT—the Real Household Consumption Rate (Figure 7.3) and the Unemployment Rate (Figure 7.4).

The household consumption rate determines the proportion of residual household income used for consumption versus savings based on the real interest rate (Smith, McDonald, et al., 2016). All scenarios for the household consumption rate show a general decreasing trend with a slight plateau late in the modelling period illustrating a propensity to save rather than consume (Figure 7.3). It is lowest for managed retreat under the worst-case rates scenario and highest for the worst-case bonds scenario. A possible explanation for the rates scenario is that household consumption drops as the property rates tax influences household income and savings. In contrast, managed retreat finance for bonds comes from outside the region, stimulating regional household consumption. Therefore, by the end of the period, regional household consumption under the mid-range bonds scenario is 0.5% greater than the mid-range rates scenario and 0.3% greater under the worst-case scenario.

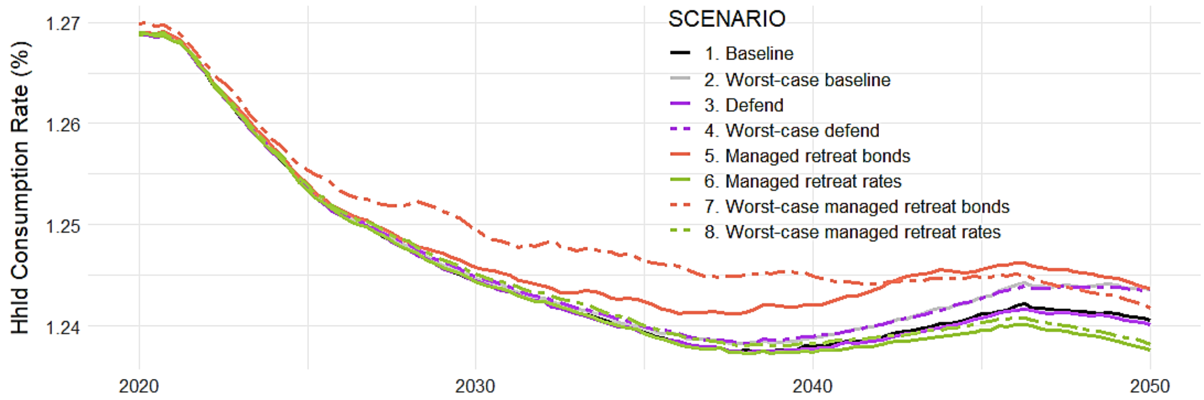



**Figure 7.3** Simulation results for the Real Household Consumption Rate. Household consumption decreases throughout the period, with the bonds scenarios having less effect overall when compared to the baseline and rates scenarios. Coastal defence scenarios do not differ much from the baselines.

Conversely, the unemployment rate stabilised for all scenarios over the period (Figure 7.4). Bonds interventions initially increase the unemployment rate and then reduce it. Diversion of investment funds from industries to government savings creates the worst-case bonds oscillation as funds are stored in bonds short-term, which increases unemployment. Over the longer term, unemployment is lower with bonds than the other scenarios as funds are released. By the end of the period, the regional unemployment rate under the mid-range bonds scenario is 1.8% lower than the mid-range rates scenario and 0.9% lower under the worst-case scenario.

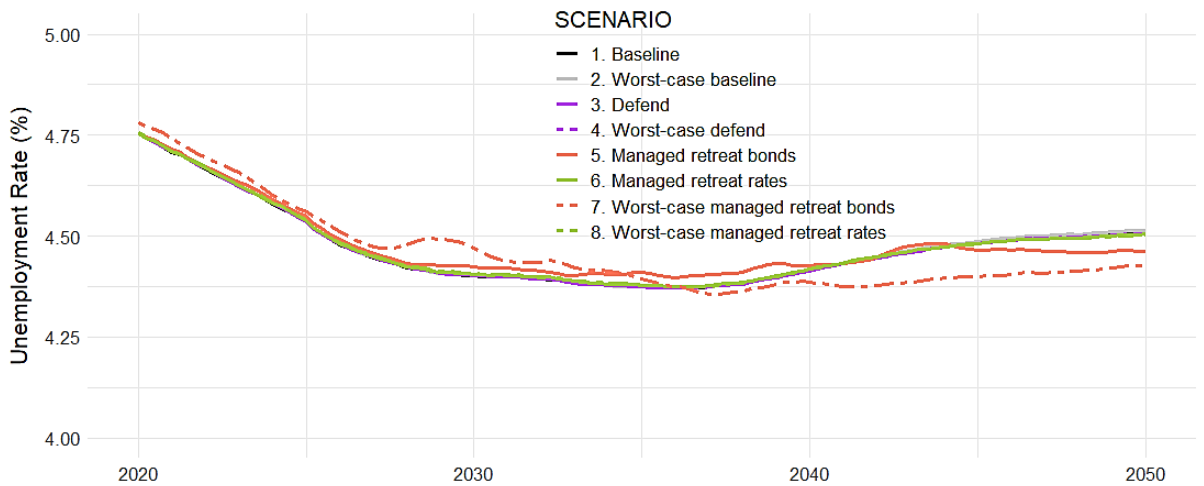



**Figure 7.4** Simulation results for the Unemployment Rate. Unemployment remains relatively stable throughout most scenarios except for bonds, as illustrated by the obscuring of results. For the bonds scenarios, it fluctuates as investment capital migrates in and out of the regional economy. The worst-case bonds scenario initially increases the unemployment rate, followed by a medium-term drop.

### 7.1.4 Regional economic impacts on industries

To better understand the complex aggregation of regional Total Value Added (TVA), MERIT outputs divide into Industry Value Added (IVA) for primary, manufacturing and service sectors. Figure 7.5 shows TVA, and Figure 7.6 shows the various IVA for particular industries of interest in real terms.

The TVA for the region increases for the period under all scenarios. The scenarios diverge slightly over time, with the rates (for both mid-range and worst-case) and bonds (only worst-case) scenarios coming out on top. The scenario divergence by 2050 shows an increase in TVA by 2.91% mid-range rates scenario, 8.27% worst-case rates scenario, 0.22% mid-range bonds scenario, 4.31% worst-case bonds scenario, 0.30% mid-range defence scenario and 1.19% worst-case defence scenario over their respective baselines. Therefore a managed retreat, and to a lesser degree defending the coast, has a positive effect on the regional economy's TVA.

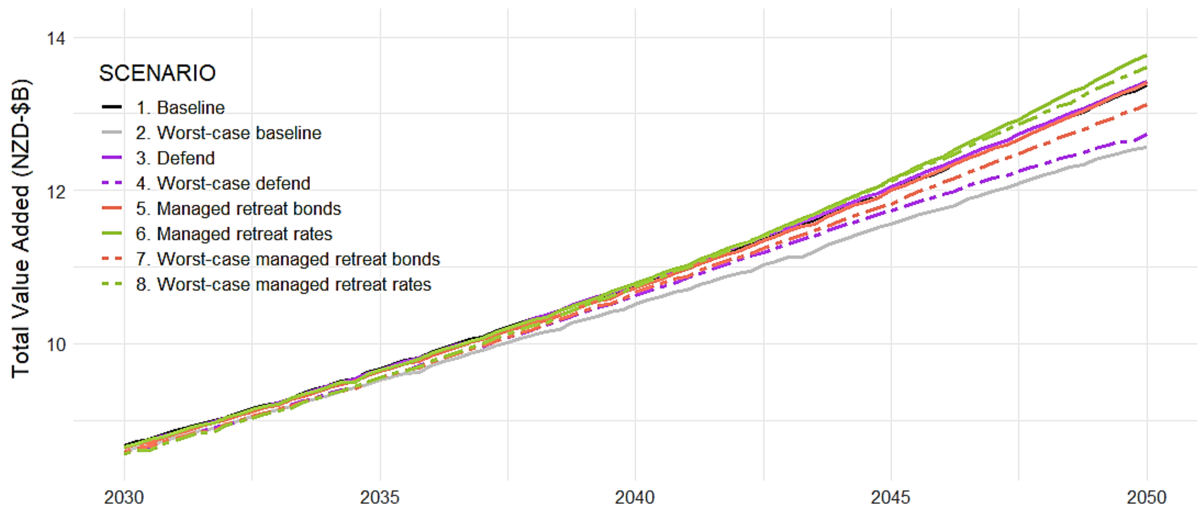



**Figure 7.5** Simulation results for the Regional Total Value Added (TVA). The managed retreat interventions stimulate regional output more than the baseline or defence scenarios, with the best results for the rates scenarios.

The regional IVA for primary production (livestock, dairy, fish, grain, forestry and mining without horticulture and fruit growing) illustrates different results across the scenarios than in other industries (Figure 7.6A). Primary production is reduced under the managed retreat scenarios as the economy reallocates capital investment to other industries offering a higher return despite resource constraints. By 2050, the rates scenarios fall below the baseline by 2.2% (mid-range) and 2.1% (worst-case). Similarly, the bonds scenarios are 1% below the baselines for the mid-range and worst-case scenarios. Alternatively, the worst-case defence scenario is more favourable than the baseline by 4.8% by 2050 for primary production as land is preserved. It comes in even by the end of the period under the mid-range scenario.

Wood and paper manufacturing increases across all scenarios (Figure 7.6B). As expected, timber is a useful commodity, and interventions enhance manufacturing, as construction requires this resource. Rates scenarios outperform baselines to 2050 by 2.2% (mid-range) and 5.7% (worst-case). In comparison, the bonds scenario performs well under the worst-case (4% greater than the baseline) but underperforms in the mid-range scenario against baselines (0.3% greater). Defence scenarios hover around the baseline’s dynamic equilibrium. Therefore, wood and paper manufacturing industries perform best under the managed retreat scenarios.

Construction industry results are depicted in Figure 7.6C. As expected, managed retreat scenarios increase construction, especially under the rates scenarios where the managed retreat sees a long and gradual relocation. By 2050, the rates scenarios exceed the baselines by 7.1% under the mid-range scenario and 16.5% under the worst-case scenario. At the same time, bonds exceed the baseline for the worst-case scenario (6%) but mirror the baseline for the mid-range scenarios. The bonds scenarios lag behind the rates scenarios by 9.7% (worst-case) and 6.8% (mid-range). Defence scenarios perform relatively well against the baselines, but the worst-case defence scenario plateaus as construction wanes by 2050.

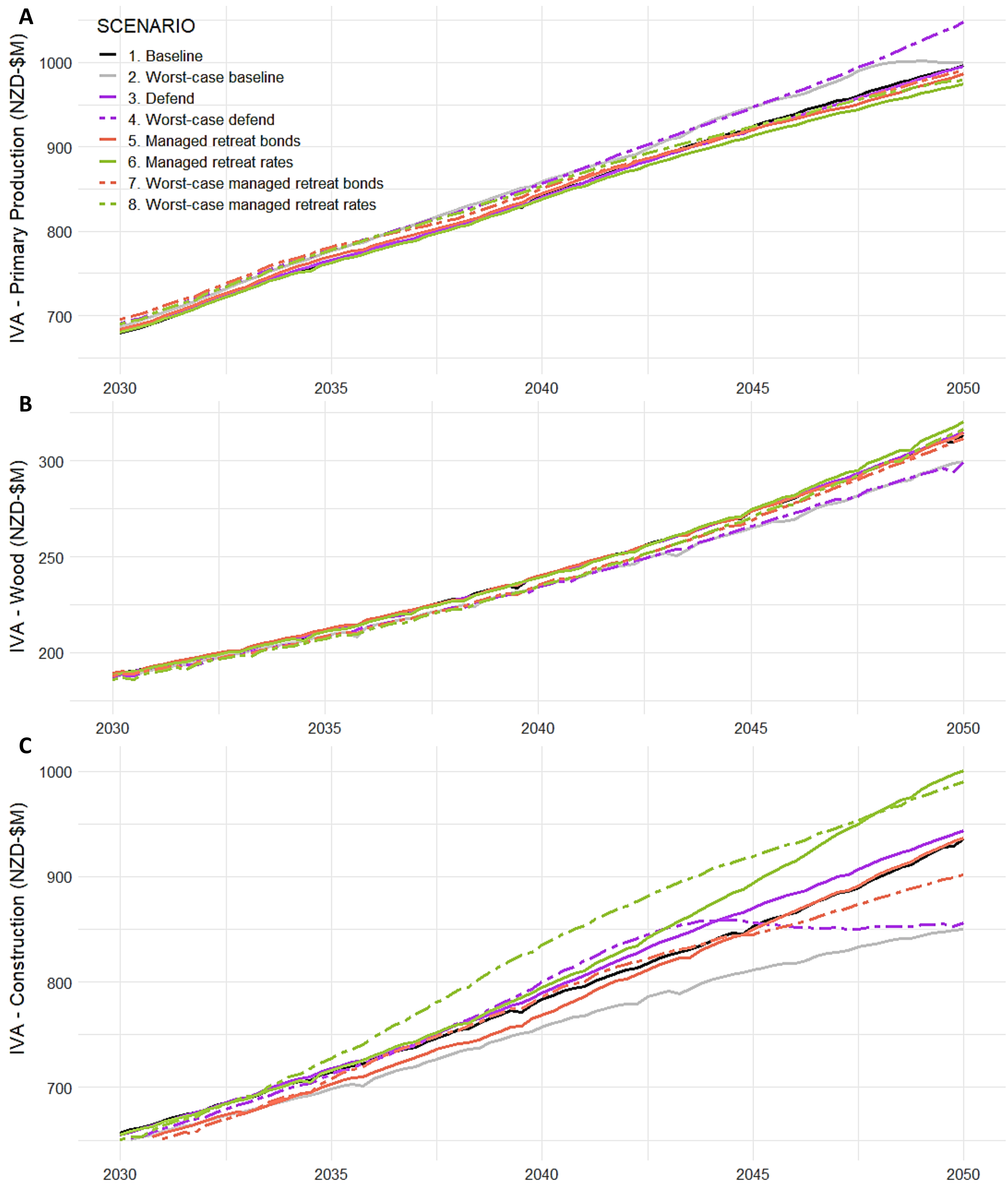



**Figure 7.6** Simulation results for the Regional Industry Value Added (IVA) illustrating one standout industry per sector. A) Primary production is slightly worse off under managed retreat scenarios when compared with the baselines. The worst-case defence scenario enables a better return. B) Wood and paper manufacturing illustrates a steady increase under all scenarios. The worst-case baseline and worst-case defence perform poorly. C) Construction ramps up under the managed retreat scenarios, particularly for the rates scenarios. The worst-case defence starts to plateau toward the end of the period but performs relatively well under mid-range conditions.

### 7.1.5 Regional economic impacts on government

Central and local government consumption is shown in Figure 7.7. Both show an increase in consumption through to 2050 due to a general trend of increasing population, production, income, taxes and government spending. However, a steeper curve gradient occurs due to the replacement of damaged and lost infrastructure by government tiers. When comparing local government against the central government managed retreat scenarios, proportionally, local government consumption is much higher than that of the central government. Figure 7.7 shows that at the peak of managed retreat funding, the bonds scenario is 6.3% in 2039 (worst-case) and 4.5% in 2050 (mid-range) greater than the baseline consumption for central government. Whereas the rates scenario is 36.2% in 2043 (worst-case) and 31.4% in 2049 (mid-range) greater than the baseline consumption for local government. Thus, rates have a more significant effect on the local government's ledger than bonds have on the central government's ledger. The impact of bonds versus rates aligns with comments from expert workshops, where a managed retreat is expected to affect the local government's balance sheet more significantly than the central government's reserves.

Concerning the defence scenarios for local government consumption, C-ADAPT shows the intricate functioning of how the environment and the economy act as a complex system. The difference in defence spending almost converges over the 100 simulations when the Pandora cell (with a total cost of NZ$$_{2007}$39.23M) is driven by inundation triggers. Therefore, one can assume that the climate trajectory over the short term has little influence over the timing of defence scenarios. The peak defence cost to local government occurs in 2038, 15.5% above baseline local government expenditure under the worst-case scenario and 13.8% above the baseline for the mid-range scenario.

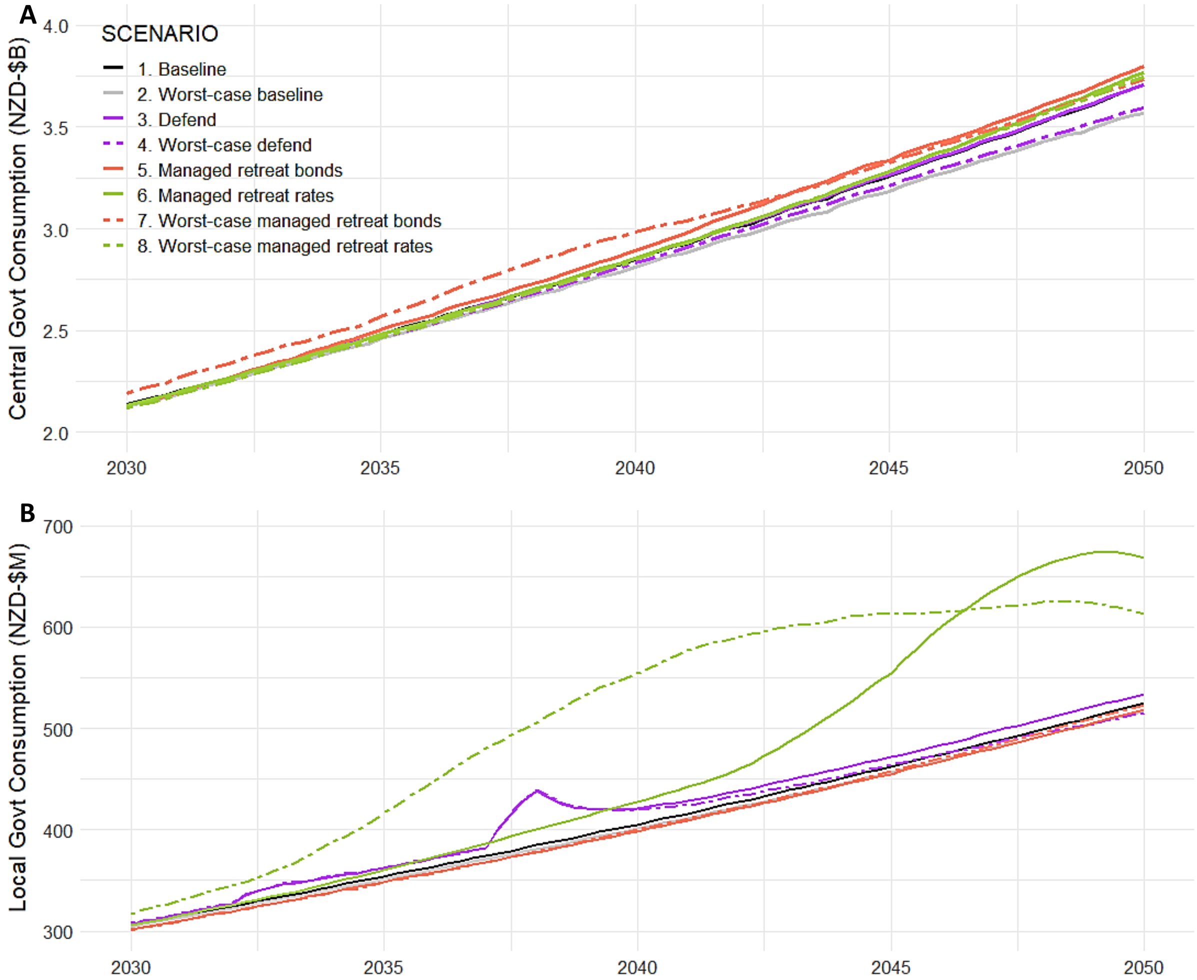



**Figure 7.7** Simulation results for Central Government Consumption (A) and Local Government Consumption (B). All scenarios increase due to local and central governments replacing damaged and lost infrastructure and population growth. Rates scenarios illustrate more significant increases in local governments' consumption compared to central government's consumption through bond scenarios. Defence scenarios appear to almost converge over the 100 simulations.

## 7.2 Implications for regional-scale impacts

Some interesting economic impacts emerge when analysing future baseline and adaptation scenarios to manage coastal hazards with a changing climate. First, capital risk management under the managed retreat scenarios, for example, reduce, if not eliminate, risk by enabling communities to become more resilient before they experience significant compounding losses (Figure 7.1). Second, property rates scenarios appear to outperform climate bonds for loss minimisation (Figure 7.2), primary industries and construction (Figure 7.6A and 7.6C). In comparison, bonds perform better for household consumption (Figure 7.3), medium-term employment (Figure 7.4) and government consumption (Figure 7.7). However, rates scenarios carry great financial responsibility for the local government to maintain equitable service provision and an operating surplus (Figure 7.7B). In contrast, the cost of a managed retreat under bonds has a negligible impact on central government proportionally (Figure

7.7A), and therefore any unforeseen costs or uncertainty would have less effect. Third, contrary to any managed retreat, defence scenarios are the most helpful scenario to mitigate short-term losses and disruption (Table 7.1). However, they can lead to spatial risk transfer for unprotected coastlines and intergenerational risk transfer when managed retreat is inevitable as 'holding the line' is no longer possible due to encroaching hydrostatic pressure or erosion. Nonetheless, a managed retreat positively affects the regional economy's productive output, as shown by the TVA (Figure 7.5).

### 7.2.1 Diverging community risk

This research aims to reveal scenarios that might lead to beneficial economic impacts of managed retreat on households, industries and government and, in turn, enable the development of resilient communities. Risk assessments have traditionally focused on exposure and vulnerability, disregarding opportunities for betterment or neglecting a community's adaptive capacities (Sajjad & Chan, 2019). Therefore, it is pertinent that we assess each scenario's risk level to inform decision-makers of resilient futures that reduce risk. In this study, the risk is a function of the likelihood of an event occurring (AEP) multiplied by the consequence (Australian Geomechanics Society, 2000). The consequence is measured by the total estimated asset (capital and land) loss. By modelling the relationship between these variables across the baseline, mitigation (coastal defence) and adaptation (managed retreat) scenarios, one can discover scenarios that deliver resilience to coastal hazards. This approach is similar to the risk-resilience-sustainability nexus described by Sajjad and Chan (2019) to replace traditional risk assessment.

Considering the first research question, both managed retreat scenarios effectively build socio-economic resilience to coastal communities' risk over the medium-term (20-30 years), as shown by the reduction in risk Figure 7.1. In comparison, defence scenarios are an appropriate short-term (1-20 years) fix unless structures are incapable of withstanding the extreme end of storm magnitude. Figure 7.1 illustrates this where the gains from coastal defence are minimal by the end of the period under the worst-case scenarios. However, one must deconstruct this general risk finding to discover the economic disparities and distributional impacts for businesses, households, and government. The following sections disaggregate the impacts of the scenarios by disruption, damages and loss, households, industries and government to address the research question on the economic implications of a managed retreat.

### 7.2.2 Disruption and loss

C-ADAPT shows that infrastructure disruption is a significant short-term threat posed by coastal hazards that leads to a fall in business operability and community resilience (Table 7.1). However, network redundancy also installs resilience against disruption (Zorn, 2017a) and infrastructure substitution (Vugrin et al., 2015), which requires further investigation. Conversely, the level of infrastructure service is also directly influenced by the interdependency of infrastructure (Zorn, 2017a).

Infrastructure is a system-of-systems where all components are inextricably interconnected by geography and physical, logical and cyber networks (Zorn, 2017a). Interconnectivity can lead to unintended or hidden consequences, which may only reveal themselves after passing critical thresholds. Interdependent infrastructure outages are a subset of business inoperability. However, they can cover a broader spatial domain where critical network nodes are disrupted, which may have a more significant impact than the inundation event itself. Spatial amplification is indeed the case for Hawke's Bay. Here, the significant infrastructure disruptions modelled were: closure of arterial roads, a state highway and the railway; reduction in the airport service (maximum 62% reduction in operability); sewage treatment plant reduction in service (max 15%); and gas supply outage (max 15%) for approximately 1-5 days (see the infrastructure outage distribution maps in Appendix 4). There was also enhanced vulnerability at the Pandora Road Bridge, given the co-location of multiple infrastructures. However, there are plans to mitigate this vulnerability by raising the bridge and its approaches to limit infrastructure flooding under the defence scenario (HBRC, 2020). See Figure 7.8 for the spatial layout of the infrastructure assets at the Pandora Road Bridge.

C-ADAPT requires more information about how industries and utility providers manage infrastructure outages through network redundancy and any costs incurred from redundancy or substitution. Accounting for these stopgap measures is essential to establish the actual cost of living with coastal hazards when compared to a more resilient managed retreat. Alongside more accurate accounting, property owners' response to changes in infrastructure service levels requires further investigation to determine when outages become unmanageable and relocation is inevitable. Fortunately, much of the critical infrastructure is set back from the coast in Hawke's Bay, which leads to only localised outages.

Long-term disruption to infrastructure services is overcome by planning for a managed asset retreat of services over coastal defence, as evidenced in Table 7.1C, where 1 (100%) represents a return to the full operational capacity of infrastructure. The latter is a short-term option that carries with it spatial and intergenerational risk transfer. Significant investments in roading, water and communication infrastructure are planned in the short to medium term for the region to account for growth (HBRC, 2016a; HBRC et al., 2017). These plans also highlight the need to build away from coastal hazards, and therefore, asset replacement in high-risk areas is not likely.

Similarly, as the AEL increases, the likelihood of CHZ occupation decreases either in an *ad hoc* fashion or by a managed retreat. What is of interest is the degree to which losses are reduced under the defence scenarios (Table 7.1A where losses fall to zero), as trigger levels lead to installing defence structures. However, losses (or further capital investment in defence) are expected beyond 2050 because coastal defence structures are predicted to only last 20-30 years (Infometrics Consulting Limited, 2017a). Therefore, managed retreat is expected after the modelled period (2050), as outlined for many exposed communities by the Coastal Hazard Strategy (HBcoast, 2017).

The reduction in losses from direct impacts, or the benefits of coastal defence or managed retreat, need to be included in decision-making and weighed against future economic costs. Reguero et al. (2020) use a similar rationale to offset the future cost of insurance and finance ecosystem-based adaptation. These include the built capital and land cost of relocation and the economic impacts on households, industries and government.

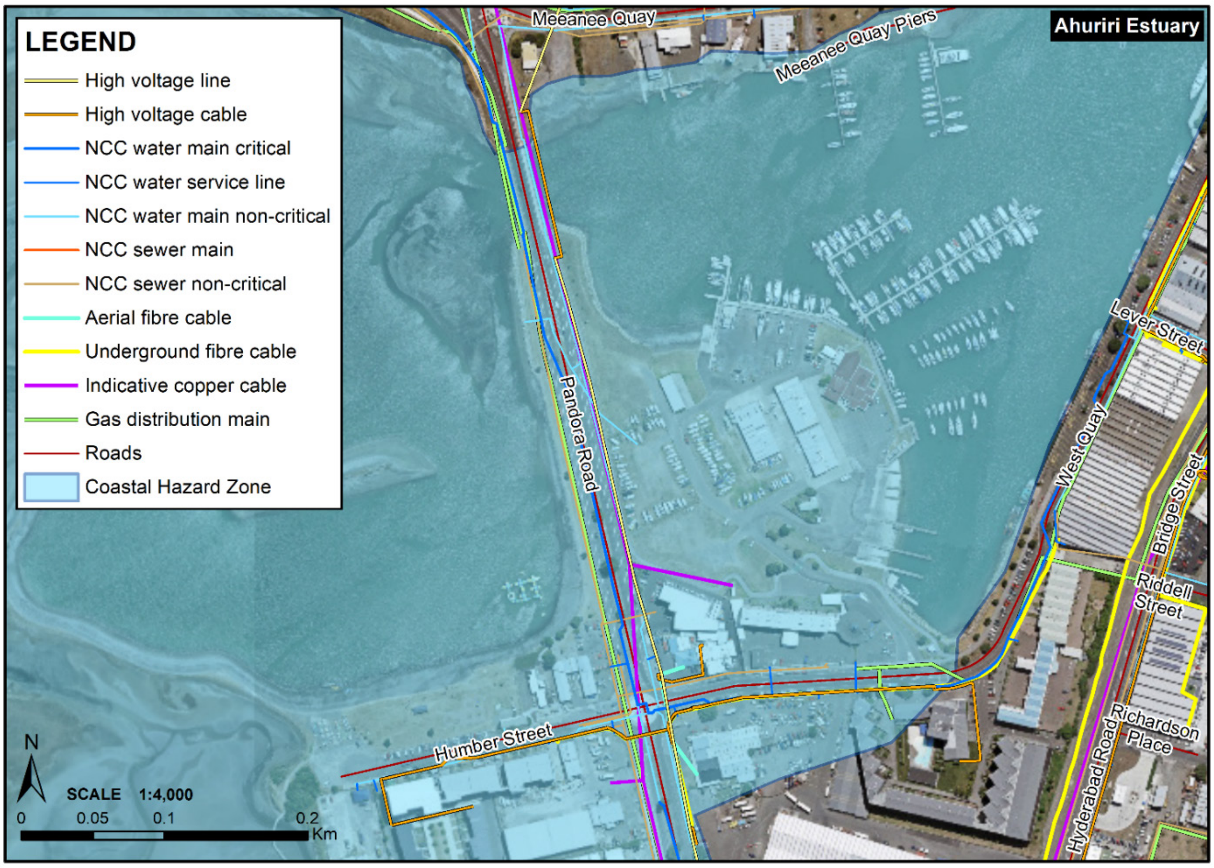



Figure 7.8 Exposed critical infrastructure at the Pandora Road Bridge in Hawke's Bay.

### 7.2.3 Scenarios for households

Real household consumption and the unemployment rate are standard indicators of household socio-economic wellbeing and economic performance more generally (Ministry for the Environment, 2019; The Economist, 2019). The volatility of these indicators is likely to come from central government monetary policy changes to inflation or interest rates (The Economist, 2019), fiscal policy changes to taxes, or globally through growth-recession Kondratieff cycles.

The bonds scenarios show that fiscal policy changes in the form of a managed retreat at the national level significantly affect regional households, as evidenced by the oscillation in the unemployment rate. Figures 7.3 and 7.4 show a positive effect on employment and consumption over the medium-term under the bonds scenarios, but this does not convert into household consumption for the worst-case rates and bonds scenarios by the end of the period, a counter-intuitive anomaly.

Regional employment increased by 1-1.5% over the 2000-2015 period (HBRC et al., 2017). This trend stalls throughout the modelling period (Figure 7.4) and reverses by the end. However, clean-up, rebuild, or a managed retreat generates jobs, household income and, in turn, household consumption. Whether these jobs are enough to offset ones lost from impacted industries and foregone investment will depend on the national-level macro-economic conditions at the time.

An interesting result for the household sector is the change in the system's behaviour (regime shift) after 2035 (See Figures 7.3 and 7.4). Further investigation of this behaviour was investigated in MERIT, and it was uncovered that the change in the stability of real household consumption and the unemployment rate is partially due to reduced spending favouring savings and the burden of imposed taxes. Bess and Ambargis (2011) discovered that diminished spending could occur due to an initial change in economic activity, such as economic 'leakages' in the form of taxes, savings or imports, resulting in less new spending that disrupts the circular flow of economic activity within an economy. In MERIT, this stems from a minor decrease in factor payments to labour (household income) at the national scale, which results from a slight decrease in the price of capital given favourable interest rates for capital investment at the expense of labour investment. Therefore, the regime shift may be created by compounding changes to the supply of built capital as floods regenerate built capital stocks. Lamperti et al. (2018) outlined this type of climate-driven process, where aggregation of agent-level climate change shocks lead to the emergence of tipping points in economic growth.

Finally, New Zealanders hold much of their wealth (~39%) in property (StatsNZ, 2018a) and leverage this for other investments, e.g. second homes, rentals, businesses, etc. Collateral associated with these leveraged investments will also be at risk. This is likely to be a significant concern to banks and insurers (Feridun & Gungor, 2020). C-ADAPT does not acknowledge the exposure of collateral assets due to the granular detail required. Thus, the extent of leveraging of assets undertaken in New Zealand needs further investigation. Similarly, investment patterns change with climate change as investments exhibit unequal risk profiles (Mercer, 2019). Dynamic investment patterns could have significant unknown flow-on effects such as reduced community investment in local business or changes to New Zealand's balance of payments from increased offshore lending. Further modelling of investment scenarios is required here.

### 7.2.4 Scenarios for industries

TVA and IVA for Hawke's Bay increase throughout the period, illustrating a growing economy with significant population growth. However, manufacturing sectors illustrate minimal growth during the calibration period (2007-2018) but are later buoyed with higher increases resulting from managed retreat scenarios. This initial stagnant growth is part of a broader industrial change in New Zealand as service industries, rather than the primary sector and manufacturing, generate industry value. In 1972, primary production made up 12% of GDP, goods-producing industries 35% and service industries 52% (StatsNZ, 2019b). By 2018, primary production was at 7%, goods-producing 19% and service industries at 65% (StatsNZ, 2019b). A switch back to manufacturing would greatly benefit Hawke's Bay through the added stimulation of managed retreat activities.

TVA at the national scale also increases – a finding similar to that of Patterson et al. (2006), who utilised a dynamic input-output approach quite different to MERIT. However, this research and Patterson et al. (2006) do not investigate the effects of climate change on the rest of the world or global-scale economic impacts and their influence on New Zealand. Such an inquiry is beyond the scope of this thesis that primarily seeks to examine the local and regional scales.

Nonetheless, TVA nationally compares unfavourably with that of OECD projections. Randers (2012) estimates through System Dynamics that GDP for OECD countries (excluding the U.S.) peaks around 2030 at $US\$_{2012}$25.5 Trillion before overshooting the dynamic equilibrium. Randers (2012) predicts that growth declines with population and stagnant productivity of service industries. However, Randers' results differ here due to the falling global population and global resource constraints. Further research on these higher-order impacts is required at the regional and national scale to assess the economic impacts of climate change collectively.

### 7.2.5 Scenarios for government

Government consumption can be regarded as either beneficial or burdensome, depending on one's political perspective or exposure to flooding (Radio New Zealand, 2020). It stands to reason that if households and firms hold exposed capital to floods, the more accepting they would be to government-funded mitigation or adaptation strategies (Mitchell, 24 July 2017). However, the converse is true for property owners on high ground and renters who may not be willing to pay for the managed retreat of distant communities or millionaires' holiday homes (Radio New Zealand, 2020). In such situations, the bonds scenarios would be a more palatable approach (as shown in Figure 7.7A). The burden is shared across a larger population and would reduce Hawke's Bay property owners' costs. A broad survey of society's WTP for a managed retreat would benefit government decision-making.

Finally, an increasing government deficit characterises high government consumption as savings are foregone to fuel investment (MIT, 1998). Thus Figure 7.7 illustrates a managed retreat for Hawke's Bay having minimal effect on the central government under the bonds scenarios. In contrast, the rates scenarios could drive a significant local government deficit to the detriment of the public provision of services in the region. Therefore future trade-offs may exist for local government consumption under the rates scenarios, which will require detailed economic analyses, robust long-term planning and ratepayers amenable to rate rises.

## 7.3 Summary

Economic modelling in this chapter has revealed some interesting economic impacts associated with future scenarios for managed retreat under a changing climate. Compared to baseline scenarios, managed retreat scenarios reduce risk by between 25% and 42% by 2050. Similarly, under managed retreat, capital losses, inoperability and infrastructure disruption are reduced when compared with baseline scenarios enabling communities to adapt to areas that are more resilient before they experience compounding disruption and loss late in the model period.

The rates scenario excelled in producing much better outcomes for TVA, where it was 2.9% ($NZ\$_{2007}$388M) above the mid-range baseline scenario and 8.3% ($NZ\$_{2007}$1.047B) above the worst-case baseline scenario. However, local government consumption increases by 36.2% in 2043 (worst-case) and 31.4% in 2049 (mid-range) over the baseline, which may create fiscal constraints for councils. Alternatively, at the peak of managed retreat funding by central government, the bonds scenario is 6.3% in 2039 (worst-case) and 4.5% in 2050 (mid-range) greater than the baseline. Although TVA only increases by 0.22% (mid-range) and 4.31% (worst-case) for the bonds scenarios. Nonetheless, the bonds scenario was more effective at increasing regional household consumption (0.5% greater than the mid-range rates scenario and 0.3% greater than rates under the worst-case scenario) and unemployment (1.8% lower than the mid-range rates scenario, and 0.9% lower under the worst-case scenario).

The defence scenarios are the most helpful to mitigate short-term losses and disruption, as Table 7.1 shows that damages, loss of operability and infrastructure disruption are mitigated by 2030 (worst-case) and 2040 (mid-range). Although coastal defence only increased economic output (TVA) by 0.3 to 1.2%. Thus, one could state that managed retreat stimulates the economy more than installing coastal defences or doing nothing. Coastal defence can also lead to spatial risk transfer for unprotected coastline sections and intergenerational risk transfer for an eventual managed retreat when 'holding the line' is no longer possible. These are considered well-known facts, yet quantifying them through economic modelling allows one to analyse scenarios and compare new policy implementations such as managed retreat alongside baseline scenarios quantitatively and objectively.

A key finding of this chapter is that property rates provide a better financial mechanism than climate bonds for loss minimisation (worst-case only), business operability (worst-case only), infrastructure disruption (worst-case only), wood manufacturing and construction. Loss minimisation resulted from modelling the behaviour of exposed communities, who were expected to shoulder a significant proportion of the cost through targeted rates and reframing the value society placed on the exposed properties. Therefore, even with the increased property tax (NZ$_{2007}$300 p.a. approximately), industries benefit more under the rates scenarios than the bonds scenarios. In comparison, bonds perform better for household consumption, long-term employment, primary production and government consumption. Therefore, households benefit more under the bonds scenarios. The external stimulus from central government increased household consumption but maintained an inflated property market for longer, and in turn, the AEL remained relatively high when compared to the rates scenarios (12.5% for the mid-range bonds scenario vs 71.7% for the mid-range rates scenario below the baseline and 65% for the worst-case bonds scenario vs 84.2% for the worst-case rates scenario below the baseline). Here accountability for risk through System Dynamics modelling influenced this outcome.

Conversely, rates scenarios carry greater financial responsibility for the local government to maintain equitable service provision and an operating surplus. However, such responsibility gives local government more autonomy over the direction of its communities and land use planning more generally. In contrast, the cost of a managed retreat under bonds scenarios has a smaller impact proportionally on the central government. Therefore, any unforeseen costs or uncertainty would have less effect.

# 8. Evaluation of scenarios through DAPP

Chapter 8 brings the preceding model results together in an analytical framework to assess the overall economic impact of the scenarios. It explores the research question: How can System Dynamics, Scenario Planning, RDM, and DAPP contribute to a coordinated approach to managed retreat for coastal adaptation? In addressing this question, the chapter uses C-ADAPT to evaluate the scenarios through System Dynamics, RDM and DAPP to define plausible futures through a least-regret matrix called PYRDM. The intention of providing this matrix is to develop a tool to weigh up disparate datasets from economic analysis on coastal management interventions and build adaptation pathways for communities and governments.

Adaptation pathways are governed by a set of rules, or signals, to decide when a pathway should be activated (Kwakkel et al., 2015). Within the IAM, these rules for triggering adaptation were explicitly set by Scenario Planning in System Dynamics through repeated exceedance of the TWL or exceedance of the AEP. However, natural variability, or noise within models, can obfuscate these signals, leading to ambiguous signposts on which to base adaptation decisions (Kwakkel et al., 2015). Here calibration, validation and sensitivity analysis are fundamental to developing clear trends and signals for DAPP. However, when utilising System Dynamics and RDM, the purpose is not intended to produce an exact point estimate (Bosomworth et al., 2017; Ramm et al., 2018). Instead, an indicative period for adaptation tipping points is sought by modellers in developing DAPP (Haasnoot et al., 2013).

In C-ADAPT, an indicative transition period for raising capital and spending on managed retreat was developed through probabilistic modelling by utilising RDM in System Dynamics is visible back in Figure 5.3. The transition periods modelled were developed in System Dynamics through Scenario Planning and RDM by two complex system lags in C-ADAPT: first, a three-year lag in the procurement of available funds; and second, a one-year lag in the allocation of regional funds. In turn, C-ADAPT behaviour creates an adaptation pathway of over 20 years for the worst-case scenario and beyond 30 years for the mid-range scenarios. Thus the DAPP modelled here is generally consistent with managed retreat intervention timeframes indicated in other work (Turner et al., 2007).

RDM here utilised the mean of 100 simulations per scenario to reduce uncertainty around the timing of these trigger and tipping points. One hundred random simulations are at the lower end for RDM described by Lempert (2013) but are nonetheless reliable to summarise plausible futures once model stability is achieved. Increasing the number of simulations beyond this becomes computationally problematic due to output size.

## 8.1 C-ADAPT outputs for pathways

The pathway results are expressed in two ways: 1) the contrasting performance of scenarios across all timesteps, and 2) the contrasting performance of each scenario for each timestep, or DAPP. As mentioned in Chapter 5, there are many outputs or key aggregates in C-ADAPT on which to base decisions. Thus, a selection of outputs that best represented different sectors of the economy (HHLD, IND, GOVT), parts of the system (state, impact, response) and variable type (stock or flow) were identified. The next step was to take the key aggregates from the RDM analysis in System Dynamics and convert them to a common scale for comparison through the PYRDM matrix. Table 8.1 shows the boolean selection for each variable's results and the corresponding value. Here the variable outputs are computed on a scale of 0 - 4 (0 being the best and 4 being the worst). The exceptions are AEL and TVA, which have been given a greater weighting of 0 - 8 due to their significant influence on managerial decisions (see IPCC, 2012; McDonald & McDonald, 2018). For more detail, Appendix 8 shows the resulting matrix of PYRDM once the least-regret computations have been performed for each scenario and timestep.

***Table 8.1 Input variables and output boolean selection used for PYRDM assessment***

| Key Aggregate | Input | | | | Output |
|---|---|---|---|---|---|
| **Annual Expected Loss (NZD)** | < | 25M | | | 0 |
| | >= | 25M | < | 50M | 2 |
| | >= | 50M | < | 75M | 4 |
| | >= | 75M | < | 100M | 6 |
| | >= | 100M | | | 8 |
| **Property Premium (NZD)** | >= | 0 | < | 1000 | 4 |
| | >= | 1000 | < | 2000 | 0 |
| | >= | 2000 | < | 3000 | 1 |
| | >= | 3000 | < | 5000 | 2 |
| | > | 5000 | | | 3 |
| **Household Consumption Rate (%)** | < | 1.24 | | | 4 |
| | >= | 1.24 | < | 1.245 | 3 |
| | >= | 1.245 | < | 1.25 | 2 |
| | >= | 1.25 | < | 1.255 | 1 |
| | >= | 1.255 | | | 0 |
| **Unemployment Rate (%)** | < | 0.044 | | | 0 |
| | >= | 0.044 | < | 0.045 | 1 |
| | >= | 0.045 | < | 0.046 | 2 |
| | >= | 0.046 | < | 0.048 | 3 |
| | >= | 0.048 | | | 4 |
| **Central Government Consumption (NZD)** | < | 1400M | | | 4 |
| | >= | 1400M | < | 1800 | 3 |
| | >= | 1800M | < | 2000 | 2 |

| | | | | | |
|---|---|---|---|---|---|
| | >= | 2000M | < | 2200 | 1 |
| | >= | 2200M | | | 0 |
| **Local Government Consumption (NZD)** | < | 200M | | | 4 |
| | >= | 200M | < | 250 | 1 |
| | >= | 250M | < | 300 | 2 |
| | >= | 300M | < | 350 | 3 |
| | >= | 350M | | | 0 |
| **Total Value Added (NZD)** | < | 8B | | | 8 |
| | >= | 8B | < | 9.5B | 6 |
| | >= | 9.5B | < | 11B | 4 |
| | >= | 11B | < | 12.5B | 2 |
| | >= | 12.5B | | | 0 |
| **Total Actual Production (NZD)** | < | 24B | | | 4 |
| | >= | 24B | < | 28B | 3 |
| | >= | 28B | < | 32B | 2 |
| | >= | 32B | < | 36B | 1 |
| | >= | 36B | | | 0 |
| **Pinvestcc (%) - Investment composite commodity consumption price** | <= | 1.05 | | | 0 |
| | >= | 1.05 | < | 1.2 | 1 |
| | >= | 1.2 | < | 1.3 | 2 |
| | >= | 1.3 | < | 1.4 | 3 |
| | >= | 1.4 | | | 4 |
| **Land use Ratio (%)** | < | 0.5 | | | 4 |
| | >= | 0.5 | < | 1 | 3 |
| | >= | 1 | < | 1.5 | 2 |
| | >= | 1.5 | < | 2 | 1 |
| | >= | 2 | | | 0 |

### 8.1.1 The robust scenario of least-regret

Comparing scenarios across all timesteps provides an overview of DAPP performance between 2020 and 2050, illustrated in Figure 8.1 and annotated in Table 8.2. Enhancing climate change effects in C-ADAPT increases regret, leading to the scenario with no-SLR (1) having the least-regret or minimum negative impact (minimum regret) compared with the robust option over the period. Generally, the mid-range (RCP4.5) scenarios (2, 4, 6 and 7) offer pathways that minimise regret more so than the worst-case (RCP8.5) scenarios (3, 5, 8 and 9). Bonds scenarios are an exception to this rule, where the mean (green triangles) and the median (orange lines) are the same for both climate scenarios, as shown in Figure 8.1. The scenario analyses across all timesteps show that the managed retreat rates scenario has the lowest economic impact compared to bonds, defence or maintaining the status quo (Figure 8.1). Another observation from Figure 8.1 is the lack of success of the defence scenario over the baseline, as indicated by the mean and median. It indicates that coastal defence is not a viable medium-term option, as minimum regret is similar to doing nothing. On the other hand, under a more extreme climate, the minimum regret from coastal defence measures is the greatest (Table 8.2).

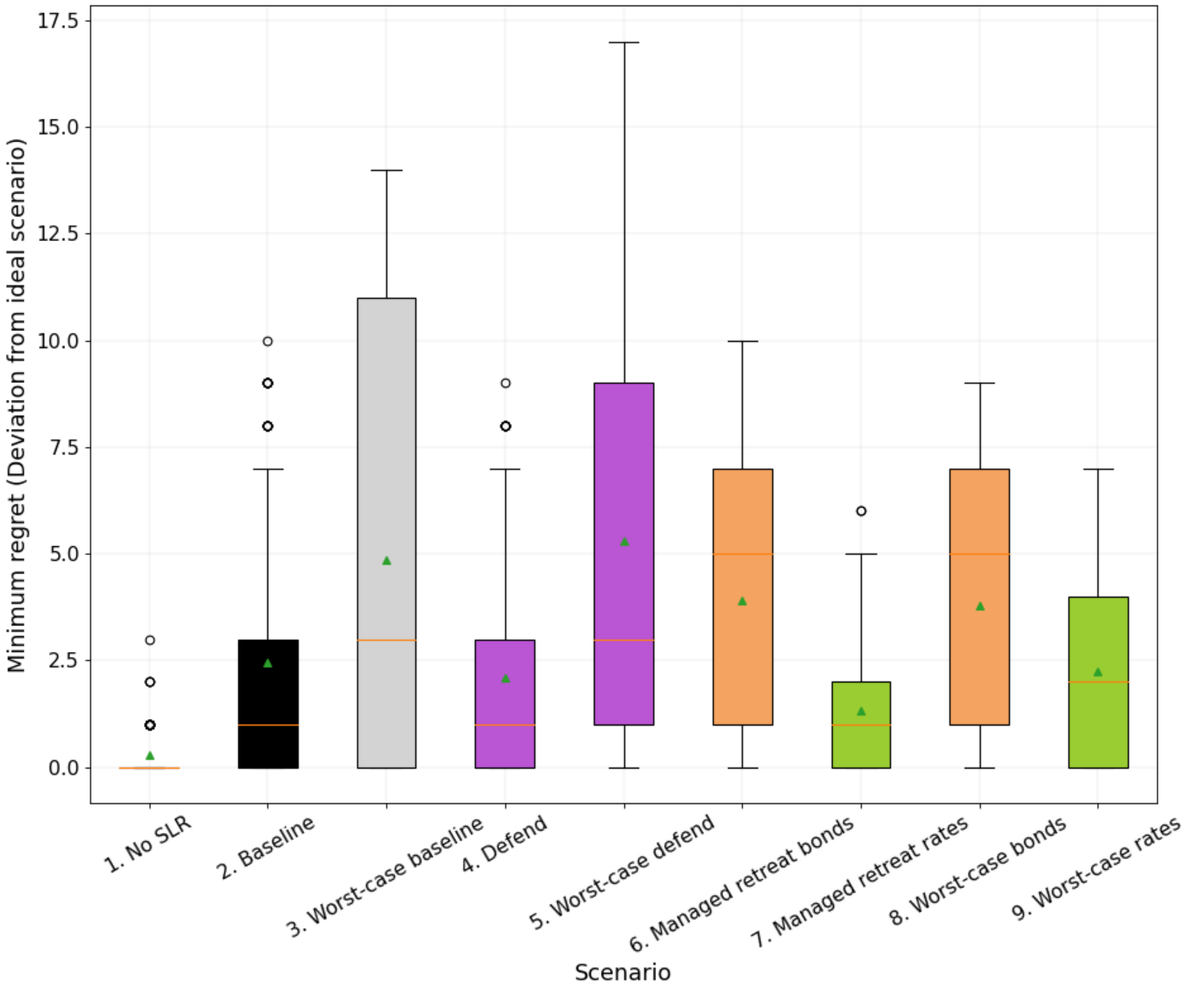



**Figure 8.1** Boxplot of minimum regret for scenarios across all timesteps. As expected, scenarios with reduced climate change such as no-SLR (RCP0) and mid-range (RCP4.5) represented by (1, 2, 4, 6 and 7), are better off than the worst-case (RCP8.5) scenarios (3, 5, 8 and 9). Note that the colours are sequenced to reflect the scenarios from module to outputs.

***Table 8.2*** ***Scenario rank across all timesteps***

| Scenario | Rank |
|---|---|
| 1. No SLR | 0 |
| 2. Baseline | 4 |
| 3. Worst-case baseline | 7 |
| 4. Defend | 2 |
| 5. Worst-case defend | 8 |
| 6. Managed retreat bonds | 6 |
| 7. Managed retreat rates | 1 |
| 8. Worst-case managed retreat bonds | 5 |
| 9. Worst-case managed retreat rates | 3 |

### 8.1.2 A timeframe to minimise regret

When analysing quarterly model outputs, a novel pattern emerges in DAPP as scenarios are compared against one another at each timestep. A general trend is evident in Figure 8.2, where interventions and baselines diverge around 2033 as C-ADAPT triggers activate the various interventions. At this point, it also becomes clear that without climate change, the no-SLR scenario minimises regret more than the other scenarios where it is predominantly reduced to zero. Meanwhile, the coastal defence scenario is highly dependent on the climate trajectory and therefore performs similar to the baseline for mid-range scenarios (±2) but produces more regret (>2) than the worst-case baseline after 2046.

For the managed retreat bonds and rates worst-case scenarios, the AEP (Figure 6.1) triggers investments and taxes between 1.2% (2020) and 1.4% (2025). The implementation of managed retreat occurs between 2035-2046 under the worst-case scenario (Figure 5.3), with the realisation of the benefits occurring around 2045 (Figure 8.3B). In contrast, governments introduce investment bonds and property taxes between 2025 and 2030 for mid-range managed retreat scenarios, with full implementation occurring beyond the analysis window. Here, not all adaptation tipping points are realised under the mid-range scenarios and modelling out to 2060 or 2070 would prove beneficial, as the baseline scenario prevails long into the modelling period.

Between 2033 and 2043, adaptation interventions through managed retreat scenarios are less desirable than the baseline scenarios. The lack of desirability is because, within this range, the costs of financing managed retreat fall on communities, industries, and governments without fully realising the financial benefits of managed retreat. Beyond 2043, the managed retreat scenarios are implemented and, therefore, reduce regret more than the baseline scenarios, particularly for the worst-case and rates scenarios. Therefore, to analyse the economic impacts of managed retreat, society cannot view the upfront costs as an inhibitor of implementation (approximately 2030 to 2040) but take a medium-term view of the distant benefits rewarded to future communities and generations (approximately after 2040). Thus society must weigh up the interdecadal costs and benefits at the inception of managed retreat and in turn intergenerational equity.

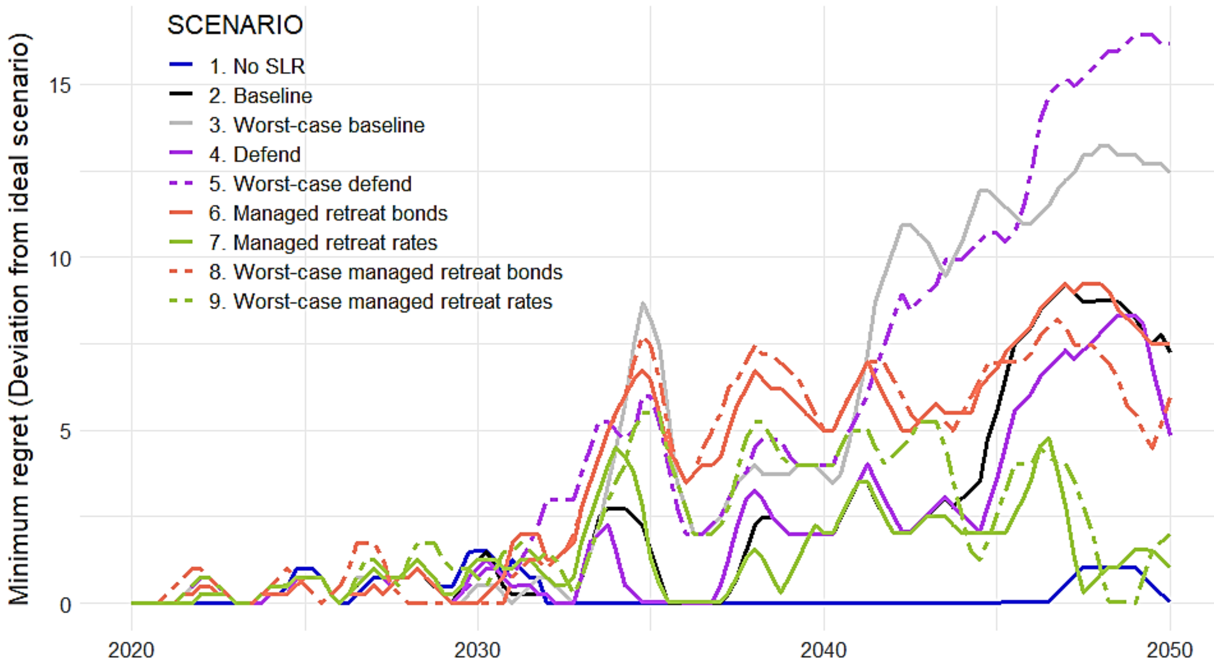



**Figure 8.2** All DAPP scenarios by timestep. Minimum regret increases over time, moving away from the no-SLR scenario as interventions and climate change ramp up. Significant divergence in regret occurs between the mid-range (RCP4.5) scenarios and the worst-case (RCP8.5) scenarios by the end of the modelling period. The managed retreat rates scenarios offer the minimum regret by the end when excluding the no-SLR scenario. A Simple Moving Average of one year is applied to the quarterly interval dataset to smooth out the graph.

Breaking down DAPP by climate scenario, differing pathways emerge. Under the mid-range climate change scenarios, the baselines, rates and defence are similar until around 2044, as shown in Figure 8.3A. The bonds scenario performs particularly poorly until 2045 when it equals the baseline scenario as financing managed retreat begins. The usefulness of the coastal defence scenario late in the period (1 to 2.5 below the baseline scenario) illustrates its economic viability under this climate scenario.

Under the worst-case scenarios, as shown in Figure 8.3B, the benefit of managed retreat starts to emerge after 2041. RDM defined the managed retreat implementation as shown in Chapter 5 in Figure 5.3, which illustrates the indicative timing of managed retreat for each scenario. Therefore, financing managed retreat begins around 2030 for the worst-case scenarios, with completion around 2041 for the worst-case bonds scenario and 2046 for the worst-case rates scenario. Therefore, Figure 8.3B illustrates the DAPP transition period for the various scenarios, where economic gains accrue over the medium-term. An interesting observation is visible around 2033–2035, where a tipping point emerges as the DAPP diverge from the no-SLR scenario. Similarly, a second tipping point occurs around 2041, where the managed retreat scenarios significantly diverge from the baseline and defence scenarios.

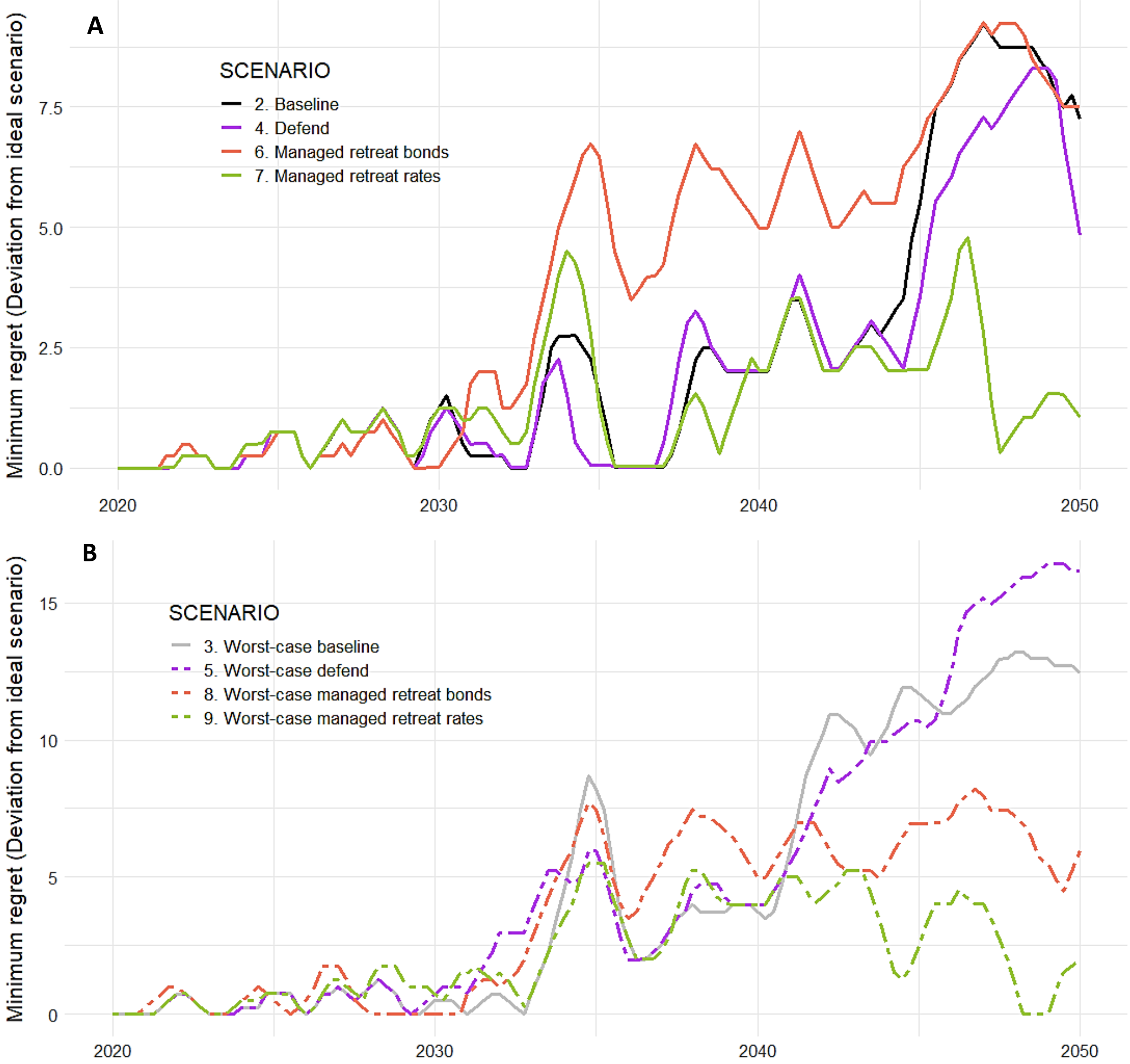



**Figure 8.3** DAPP scenarios by timestep and climate trajectory. The minimum regret under mid-range climate conditions (RCP4.5) is visible in (A), and under the worst-case climate conditions (RCP8.5) is visible in (B). Divergent scenarios become clear in (B) after 2040 as the full implementation of managed retreat occurs from costs to implementation. Whereas in (A), much of the cost of managed retreat occurs (especially for the bond scenario) with minimal implementation (except for the rates scenario). The defence scenarios tend to be useful under the mid-range climate but not under the worst-case trajectory. A Simple Moving Average of one year is applied to the quarterly interval dataset to smooth out the time series.

## 8.2 Defining DAPP for managed retreat

The following discussion is divided into four parts to understand these results better and explain how the diverging DAPP came about. The first part interrogates how the timeframe for implementing interventions by governments affects the scenarios and, in turn, DAPP. The second part examines the evolution and migration of capital supply in and out of the regional economy, disrupting its stability. Third, the role played by Scenario Planning and RDM to produce DAPP is analysed through an evolutionary economic lens, given the economic impact analysis illustrated in earlier chapters. Finally, the last section reflects on where C-ADAPT deviates from the classical DAPP approach and coastal planning more generally.

The no-SLR scenario has shown that the avoidance of climate change provides the best outcome for society. Yet adaptation is inevitable due to climate change, and when this occurs, intervening through managed retreat provides better outcomes (in terms of minimum regret) than doing nothing, as outlined by comparing the results of managed retreat with the baseline and defence scenarios (see Figure 8.3). However, managed retreat through the bonds scenario under the mid-range climate showed little difference to the baseline scenario (±1) by 2050. Although as the economy evolves, the timing of interventions, migrating capital supply, and positive feedback from environment-economy linkages in C-ADAPT interact to enhance or reduce any economic benefits measurable by the various DAPP in Figure 8.2. Therefore, the use of economic impacts in DAPP illustrates the value of planning in a staged manner to measure the success of government interventions such as managed retreat for comparison by communities.

### 8.2.1 Developing a timeframe for implementation

Deriving a timeframe for implementation through a DAPP process with RDM and System Dynamics is a suitable approach to examining future economic impacts. Boston (2017) claims that the implementation of costs is distantly followed by the realisation of benefits, leading to intergenerational cost transfer. Alternatively, in the case of managed retreat through rates illustrated here, current generations predominantly pay property taxes for the welfare of future generations, particularly under the mid-range (RCP4.5) scenarios. However, the mid-range rates scenario leads to the realisation of benefits happening sooner by reducing the time between taxing and funding, thereby reducing the economic impacts of climate change compared with the baseline. However, a significant burden falls on exposed communities, local businesses and local government. Conversely, bonds scenarios are slightly different as the benefactor of investment sees a return within years. Still, the implementation of managed retreat by central government is distant, leading to greater minimum regret between 2031 and 2045, as illustrated in Figure 8.3A.

System Dynamics and RDM were useful in developing DAPP as they enabled the exploration of thresholds and tipping points (AEPs, TWLs, erosion rates, insurability), driving behaviour and implementation in C-ADAPT. A similar approach was undertaken by Ramm et al. (2018), who utilised the strength of RDM to reduce uncertainty for coastal DAPP in a GIS platform. This research conducted sensitivity analyses (Appendix 7) to reduce uncertainty and define an implementation timeframe that was the least disruptive to the regional economy, as shown in Figures 8.2 and 8.3. This led to model feedback in System Dynamics and RDM outputs altering the scenarios. For example, the capacity to tax the population through rates was spread over an extended timeframe of 15 years, with a managed retreat implemented within two years of initial taxation and government expenditure over 17 years. Alternatively, under the bonds scenario, climate bonds are generated over ten years, with a managed retreat implemented within three years of initial bond release and government expenditure over ten years. Thus, the extended timeframe seems the most helpful approach, as shown by the rates scenarios.

### 8.2.2 Migrating capital supply

Implementing funding mechanisms for managed retreat affects capital supply, which can have higher-order impacts on the regional economy. Of note in C-ADAPT is that the composite capital supply (a combination of built capital supply, composite natural capital supply and the Constant Elasticity of Substitution function in MERIT (see Smith, McDonald, et al., 2016)) is sensitive to the timing of bonds scenarios, as significant capital diverts offshore to raise more capital for managed retreat. Constrained composite capital supply stifles aggregate investment regionally. When the timing between the initiation of the bonds and the expenditure on managed retreat is too long, the composite capital supply overshoots the dynamic equilibrium, leading to collapse.

This redistribution of investment funds away from local development toward global capital markets also significantly reduces regional TVA, which is a process evident in C-ADAPT and supported by the World Bank (2016). The DAPP for bonds scenarios sees a shift of available capital away from communities until it has breached specific triggers for implementing managed retreat. Therefore, bonds scenarios illustrate more regret than the baselines during the transition period. Although, if the transition period is short, society would be better off under the bonds scenario than the baseline.

Alternatively, developing a bonds scenario whereby significant proportions of capital remain in the regional economy would promote regional development. This is because domestic capital markets have an essential role in mobilising private capital to finance domestic development (International Finance Corporation, 2016). Yet, foreign and domestic diversification of capital investments helps reduce financial risk and enables investment success (International Finance Corporation, 2016). The Scenario Planning modelled bonds purely on the best ROI possible at conception, which has turned into a somewhat turbulent market given the global pandemic.

### 8.2.3 Assessment of DAPP through RDM

Integrating DAPP and RDM is helpful to support the development of master plans and future resource requirements (Ramm et al., 2018) ahead of any implementation. As stated by Callaway (2014), the robust scenario is the one scenario that performs best across a range of climate scenarios, a metric observable in Table 8.2. Overall, DAPP analysis through PYRDM illustrates that the rates scenarios perform well across both climate scenarios, as shown in Figure 8.3, given the setup in C-ADAPT. In contrast, the bonds scenarios illustrate little benefit over the mid-range baseline but outperform the worst-case scenario over the long term with regard to minimising regret. Conversely, the defence scenarios illustrate a high sensitivity to climate trajectory, meaning a pathway switch is required somewhere between the mid-range and worst-case scenarios.

Kwakkel et al. (2015) argue that adaptation pathways can potentially reduce costs to society. C-ADAPT assess the various economic impacts (costs or benefits) by using PYRDM to evaluate pathways of least-regret. Here the results are consistent with the assertion that over the economic medium term, developing adaptation pathways can minimise regret or the cost to society. This is particularly apparent for rates scenarios regardless of climate scenario. Figure 8.3 illustrates this point after 2043. RDM in System Dynamics defined the economic impacts, and under the rates scenario, this dictated that rates be diffused over a large area and over a longer time. Alternatively, household income and the household consumption rate suffer from an unaffordable tax. Similarly, Scenario Planning input from experts influenced C-ADAPT to reduce the proportion of tax falling on households and more falling on enterprises. It also constrained the relocation process to a steady pace to meet local government's capacity. Therefore, by assessing the scenarios through economic impact analysis, DAPP and RDM on a System Dynamics platform, an effective and coordinated approach to managed retreat between governments and communities can manifest.

Finally, the bonds scenarios are well placed to distribute the burden of managed retreat over the larger national population and acquire the financial security offered by the central government. The introduction of weighting indicators in the PYRDM matrix would be beneficial here to enhance the understanding of the impacts on central government and local government. Weightings provide indicators with safer choices in the decision-making process, although they are prone to subjectivity (Giannakidou et al., 2019). Further research could employ a series of focus groups with communities and institutions to construct indicator weightings and decipher the value society places on each metric.

### 8.2.4 Reflections on implementing DAPP for managed retreat

The DAPP presented in this chapter differs from the approach taken by Haasnoot et al. (2013). The main difference is that under their scenarios, 'transfer stations' exist where adaptation plans change pathways over long timeframes given specific triggers. As mentioned in earlier chapters, Evolutionary Economics requires a level of pathway dependency for residential or industrial change, as described by Foster and Hölzl (2004). Therefore, shifting pathways is not necessarily possible for managed retreat given land and capital constraints, and thus realising a fully implemented DAPP alongside Evolutionary Economics is not entirely possible without methodological compromise. However, the defence scenarios could implement divergent pathways toward managed retreat, as described by Haasnoot et al. (2013), given the result for minimum regret late in the modelling period between the worst-case baseline scenario and the defence scenario shown in Figure 8.3B. A possible switch to managed retreat is feasible around 2040-2060.

Further research would benefit from analysing scenarios with combinations of coastal defence, rates and bonds over a more prolonged period of 100 years to line up with the direction of the NZCPS 2010 (New Zealand Government), the Ministry for the Environment (2017) and research by Haasnoot et al. (2013). Combinations would involve an integrated all-of-government approach alongside analysing changes in equity for communities through Scenario Planning. The simplified modelling here explicitly states the distributional impacts in Table 5.2, which would become indistinct under scenario combinations. Therefore, it is feasible to adopt aspects of the methodology offered by Haasnoot et al. (2013) for adaptative pathways and utilise RDM for trigger and tipping points in System Dynamics to enable changes to pathways. It is important to note that the accuracy and stability of forward-looking models such as MERIT becomes increasingly unreliable over longer timeframes – as deep uncertainty creeps in (Smith, McDonald, et al., 2016). Thus, alignment with research on the physical science of SLR and increasing storminess, which project out to 100 years or beyond, will probably require simplification of the structural complexity in MERIT (i.e. aggregation of economic industries) to produce credible results.

## 8.3 Summary

Developing a DAPP framework based on RDM can enhance the likelihood of society realising successful long-term planning options. Not only is it possible to evaluate the overall success of adaptation pathways over time, but it can also uncover trigger points for financial planning and tipping points for the implementation of any intervention. Thus C-ADAPT through PYRDM illustrates the strengths and weaknesses of different approaches and timeframes over which decisions can and should be made to protect communities. Here Scenario Planning, economic impact modelling, System Dynamics and RDM enabled the development of DAPP. Scenarios that lead to medium-term regret minimisation can then be adopted. The DAPP here illustrates that the rates scenarios minimise regret more than other intervention measures or doing nothing at all when one ignores the apparent benefit of a world without climate change, as shown by the no-SLR scenario. However, modelling over longer time frames, alternative capital investment scenarios, the weighting of indicators or analysing combinations of implementation options would be useful extensions to increase the robustness of modelling futures.

Rates scenarios provided the minimum regret across the indicators as it was apparent that community accountability for risk and the realisation of benefits soon after the implementation of costs promoted continued regional development. RDM in System Dynamics defined the economic impacts, and under the rates scenario, this dictated that rates be diffused over a large area and over a longer time. Without diffusing rates, households suffer from an unaffordable property tax. Similarly, Scenario Planning influenced C-ADAPT to reduce the proportion of tax falling on households by directing it to enterprises. It also constrained managed retreat to a steady pace to meet the local government's capacity. Therefore, by assessing the scenarios through economic impact analysis, System Dynamics and RDM, an effective DAPP toward managed retreat was able to manifest.

# 9. Synthesis

This final chapter provides a broad synthesis of the thesis and evaluates its contribution to knowledge. It discusses the research contribution of economic modelling for coastal management by addressing the four research questions posed and then outlines avenues for future research.

## 9.1 Contribution of the research to explore coastal management decision making through economic impact modelling

This thesis developed a method to assess the economic impacts of planned local-scale pathways toward managed retreat for at-risk communities and provided insights into strategies that may support the successful implementation of large-scale managed retreat. Significantly, the method developed was novel, as it applied the quasi Computational General Equilibrium Model MERIT to the new IAM 'C-ADAPT' to integrate the environment and economic systems through coastal hazards. MERIT was adapted to research coastal management decision making by creating C-ADAPT as a tool that harnesses System Dynamics, Scenario Planning, RDM and DAPP for analysing economic impacts. C-ADAPT includes exogenous input modules, such as direct and indirect impacts of floods, risk assessment, local-scale insurance and coastal property market behaviour, infrastructure outages and interdependencies, land use planning, coastal defence costs, local government rating taxes and central government climate bonds to finance managed retreat, which fall outside its regular operation. Significantly, this approach enabled the evaluation of management futures by not only assessing the medium-term local economic impacts of coastal hazards but also assessing the flow-on regional-scale economic impacts. It then applied robust scenarios for a large-scale managed retreat by utilising local and central government resources.

A strength of this approach was that C-ADAPT's foundations in Evolutionary Economics and System Dynamics enable dynamic feedbacks and counter-intuitive aspects of system evolution to be identified that are not currently available in neo-classical and macro-economic approaches (Rezny & Bureš, 2018). C-ADAPT is more aligned with Feedback Economics, an emerging research field that interrogates economic problems with systems thinking and a feedback perspective (Cavana et al., 2021). Taking this approach facilitated an improved understanding of the economic impacts of a) when society does nothing and communities endure coastal flooding and inundation or relocate away from coastal hazards in an *ad hoc* way, and b) implementing financial and land use planning opportunities for communities to relocate through a staged process of retreat managed by the government. The thesis posed two main research questions and two secondary questions. The contributions to knowledge associated with each of these are summarised below.

## What are the socio-economic implications of managed retreat for impacted communities and economic actors through time?

Evaluating the socio-economic impacts of managed retreat on communities and economic actors required developing scenarios using the tools of Scenario Planning, System Dynamics and RDM. The baseline (status quo / do nothing) scenario was developed as a reference to compare changes over time in different scenarios. Again, the scenarios are 1) the baseline, 2) coastal defence structures, 3) managed retreat funding through climate bonds, and 4) managed retreat funding through property rating taxes. All were assessed under two or three divergent climate futures. Results showed that managed retreat reduces the direct economic impacts to aggregated regional capital, such as physical damage (by 60% for mid-range bonds, 35% for mid-range rates and 100%, or the elimination of damages, for the bonds and rates worst-case scenarios by the end of the analysis period of 2050). Inoperability and infrastructure disruption are also eliminated for the worst-case rates and bonds scenarios by 2050, the end of the modelled period. However, managed retreat comes at a financial cost of approximately NZ$$_{2007}$2.4Bn, which depending on which scenario is adopted, has distributional inequities between and within sectors (e.g. governments, households or industries).

The strength of C-ADAPT is that it facilitates analyses of the benefits and drawbacks of managed retreat in different sectors. Households and industries benefit from managed retreat primarily through risk reduction (Figure 7.1) and the ongoing provision of affordable insurance policies through risk transfer to insurance companies as they relocate away from coastal hazards. The managed retreat scenarios improve risk exposure when compared to the baseline for the worst-case scenarios by 41.5% for bonds and 35.2% for rates and reduce the trend in the dynamic equilibrium for the mid-range scenarios by 25.4% for bonds and 33.3% for rates over the period.

Where households remain at risk of coastal hazards, insurers may refuse to cover the cost of exposed assets when the AEP exceeds 2%, which was defined during expert workshops. The modelling then determined through RDM that insurers withdraw from the market in 2025 (worst-case) or 2029 (mid-range; see Figure 6.3). Thus, the risk of coastal occupation transfers back to the property owners leaving them to cover the total cost of future damage and loss, a situation known as 'partial retreat' (Daalder, 2 December 2020). Households also benefit from resilient longer-term community planning associated with managed retreat that identifies critical tolerance thresholds for planning and action when nuisance flood events become too frequent. For example, C-ADAPT was set up to execute change when nuisance flooding occurred three times (defined from expert input) to properties, erosion was within 7 m of buildings ("Mahanga E Tu Inc v Hawkes Bay Regional Council," 2014) or when the AEP exceeded 2% between 2007 and 2050. Such informal planning implementations currently used for coastal management should not be under-estimated given the long periods over which adaptation to coastal hazards usually occurs and the multiple governance structures operating over the adaptation period.

Resilient planning for communities should also maintain coastal amenity values to facilitate adaptation (Freudenberg et al., 2016). Once amenity values are known, they can be included in the value of managed retreat. For example, local government can allocate resources to maintain amenities (through maintaining the seaside buffer between development and MHWS) or relocate amenities (such as seaside parks, ecological habitats or fishing access) to the new development. This last point is highlighted in the Matariki Economic Development Plan as required (HBRC, 2016b). This study captured the costs of coastal amenities through hedonic pricing, and little quantification of coastal amenity values in New Zealand is currently available. The model also captured amenities through the land-use module by redirecting development taxes collected by local governments from the regional economy to fund adaptation activities, such as infrastructure relocation and the provision of new amenities under the baseline scenario. Development taxes equal NZ$$_{2007}$22.7M p.a. for the no-SLR scenario, NZ$$_{2007}$23.5M p.a. for the mid-range scenario and NZ$$_{2007}$26.5M p.a. for the worst-case scenario by the end of the period. Alternatively, property rating taxes or climate bonds, as outlined by the intervention scenarios, funded the process for maintaining or procuring areas for infrastructure and amenity.

Modelling the regional economy showed that some industries benefit from the added financial capital circulating in the local economy under managed retreat scenarios and, to a lesser degree, coastal defence scenarios. Results showed that the added financial capital allocated to managed retreat stimulates local manufacturing and construction, with positive flow-on impacts on retail and services by up to 2.7% for the worst-case rates scenario. This is a substantial amount, given that the CHZ represents only 1.5% of the regional population. Notably, most economic impact models simulating losses at the coast do not account for these significant macro-economic components of catastrophic events, such as the sudden spike in demand for construction materials and labour which causes a corresponding rise in regional prices (see Johnson et al., 2013). Often future damage estimates implicitly assume that construction costs track inflation (Johnson et al., 2013). C-ADAPT, through MERIT, was able to capture these dynamic changes in industries through elastic resource substitution.

In contrast with the manufacturing and construction sectors, C-ADAPT identified losses for primary production under the managed retreat scenarios. By the end of the modelling period, the rates scenarios were -2.2% (mid-range) and -2.1% (worst-case). In comparison, the bonds scenarios were -1% for both when compared with the baseline mid-range and worst-case scenarios for primary production. Furthermore, development taxes as mentioned above will become greater than the current NZ$$_{2017}$4.89M$^{a-1}$ (Hastings District Council, 2017a) and NZ$$_{2017}$3M$^{a-1}$ (Napier City Council) as properties relocate under the baseline scenario.

Thesis results indicate that the main socio-economic benefit of managed retreat to government is the reduction of risk for the communities for which they are responsible. In comparison with a do-nothing baseline, model results indicate that by 2040, managed retreat implemented either through bonds or rates would deliver substantial savings on the replacement of damaged infrastructure and amenities, and would return the level of infrastructure service to full capacity during flooding events (Table 7.1). In contrast, by this time, the worst-case baseline scenario modelled seven disruptive events on infrastructure between 2007 and 2050, reducing the level of service by up to 16% during these events. However, infrastructure relocation comes at a high cost. Where these costs fall on local government, acquiring land for managed retreat will be a substantial capital outlay to purchase 1796 Ha of suitable land (derived through GIS analysis of the CHZ) from the sums generated through property rates. The ability of local government to acquire land will vary depending on the area at risk relative to the total land area available for relocation to, population density and economic characteristics such as industry mobility.

Where the burden of managed retreat falls on the central government, it can afford managed retreat costs, as shown by its proportion of government consumption in Figure 7.7. At the peak of managed retreat funding, the bonds scenario is 6.3% (in 2039 worst-case) and 4.5% (in 2050 mid-range) greater than baseline central government consumption. At the same time, the rates scenario is 36.2% (in 2043 worst-case) and 31.4% (in 2049 mid-range) greater than the baseline local government consumption. Thus, rates have more impact on the local government's ledger than bonds have on the central government ledger because the costs of managed retreat in Hawke's Bay are being spread across the entire nation. Although, success at the central level will require political will and acceptance by the general population.

### What managed retreat scenarios generate a beneficial regional economic impact across sectors and over time?

This research question prompted the thesis to examine which adaptation scenarios generate a beneficial regional economic impact across sectors and over time to enable a successful managed retreat. It is important to note that the scenarios outlined in this thesis represent the local study area through Scenario Planning, and C-ADAPT was calibrated to the Hawke's Bay setting. However, despite this, the results and insights generated are applicable to other areas in New Zealand. For example, the effectiveness of local government utilising a rating approach to generate financial capital or central government bonds bringing outside economic stimulus to a region. Furthermore, the timing of scenarios determined by the climate trajectory played an important role in determining the success of scenarios, as many implementations under RCP4.5 occur beyond the analysis timeframe of 2007 to 2050. The influence of climate trajectory is a rule that is consistent with IPCC (2014b) reporting. Therefore, this research question closely examined the rates and bonds scenarios to define their utility in supporting managed retreat.

The use of property rates scenarios for managed retreat were highly effective in the PYRDM analysis of DAPP (see means and medians in Figure 8.1 and ranking in Table 8.2). Rates proved the most beneficial financial mechanism to reduce the Annual Expected Loss, regardless of climate. It also excelled in producing much better outcomes for Total Value Added, where it was 2.9% (NZ$$_{2007}$388M) above the mid-range baseline scenario and 8.3% (NZ$$_{2007}$1.05B) above the worst-case baseline scenario. Study results for Hawkes' Bay showed that for the construction industry, it resulted in growth (7.1% for the mid-range and 16.5% for the worst-case scenarios), an above-average result for the wood and paper manufacturing industry (2.2% mid-range and 5.7% worst-case), but lower returns for other primary production (-2.2% mid-range and -2.1% worst-case). The rates scenarios had little effect on the central government but significantly affected the local government's financial capacity.

Another reason for the rates scenarios being the pathways of least-regret is due to model feedback in System Dynamics. According to expert workshops and expert input undertaken during the Scenario Planning phase of the thesis, and descriptions by Mitchell and Williams (24 July 2017) of the financial capacity of local government to implement a managed retreat, it is counter-intuitive that rates should be the most successful scenario given the burden placed on local households, industries and government agencies. Yet feedback loops within the System Dynamics modelling revealed counter-intuitive behaviour where risk was apportioned to exposed capital in a beneficiary-pays manner. This led to a more conservative approach to investment in exposed capital as well as planning and implementing managed retreat over a longer period than the bonds scenarios. The rates scenarios include a longer transition period, so households and firms were not burdened with an unaffordable property rating tax over a short period but rather a manageable tax over a longer period.

The use of bonds to finance managed retreat was a less effective mechanism than rates for the successful implementation of managed retreat. Still, they perform better for certain key aggregates (key performance indicators). Indeed, model simulations showed that the bonds scenarios performed worse than the coastal defence scenario under mid-range conditions but better than defence under the worst-case conditions in the PYRDM analysis. Therefore, it provided consistent results across the climate scenarios, which according to Callaway (2014), is a goal of least-regret analyses. Nonetheless, modelling indicated that bonds benefit households by 0.3 – 0.5% by the end of the period compared to rates as investment capital for managed retreat from central government comes from outside the region, i.e. the national population. Thus, the average household in Hawke's Bay with a household income of NZ$$_{2007}$38,000 p.a. is NZ$$_{2007}$152 better off a year, which is similar to the regional rate imposed under the rates scenario of NZ$$_{2007}$150 p.a. Under bonds over the medium term, the unemployment rate by the end of the period is 1.8% lower than the mid-range rates scenario and 0.9% lower than rates under the worst-case scenario.

The bonds scenarios produced mixed results against the baseline for the industries shown in Figure 7.6. It performed above the worst-case baseline for construction by 6% (NZ$$_{2007}$51.5M) and wood and paper manufacturing by 4% (NZ$$_{2007}$12M), but below for other primary industries under both the mid-range (-1%, NZ$$_{2007}$10M) and worst-case scenarios (-1%, NZ$$_{2007}$9.4M) by the end of the period. To give this context, the total value of these industries that operate in the CHZ is NZ$$_{2007}$74.1M for construction, NZ$$_{2007}$22.4M for wood and paper manufacturing and NZ$$_{2007}$65.6M for other primary industries. The diverted investment capital away from industries to bonds proved unhelpful as it reduced industry growth until the implementation of managed retreat. Where central government is concerned in the financial management of the bonds scenarios, this had a visible impact through increasing government consumption.

Modelling showed the bonds scenarios also revealed counter-intuitive behaviour, which became apparent through the System Dynamics modelling. Expert workshops and expert input suggested that funding for managed retreat would come from outside the region. This would be more beneficial to the Hawke's Bay economy than property rates. Yet, this was not the case, given the modelled scenarios in Figure 7.6C for the construction industry. The bonds scenarios lagged behind the rates scenarios by 10% (worst-case) and 7% (mid-range). The bonds scenarios also lagged behind coastal defence until 2046, when construction through coastal defence stalls. What was not apparent in the Scenario Planning is the loss of local investment by diverting savings and investment away from New Zealand and into offshore managed funds. Capital investment across the region and the nation drops when bonds are issued, and it is not until the implementation of managed retreat that the investment returns. Thus, the timing of interventions is fundamental to capital management and, in turn, the success of this scenario. Here, bond scenarios investing in local economies could be the key to its success.

### How can System Dynamics, Scenario Planning, RDM and DAPP contribute to a coordinated approach to managed retreat for coastal adaptation?

Modelling risk and Scenario Planning to reflect resilient futures through managed retreat with community engagement is now a focus of local government in New Zealand (Local Government New Zealand, 2019). The integration of System Dynamics, Scenario Planning, RDM and DAPP provides a novel and valuable synergy to explore managed retreat, although not all components can be fully realised by integration. First, Scenario Planning provides avenues for community engagement around possible futures but lacks a quantitative platform to analyse futures. Second, RDM provides a platform for quantitative analysis of futures but cannot define localised opportunities for managed retreat. Third, DAPP provides a policy framework for assessing options over time but struggles with unknown futures and path dependency uncertainty. Fourth, System Dynamics provides the computational platform but can be at odds with the directive nature of Scenario Planning (see Featherston & Doolan, 2013) and DAPP. However, when the four combine, a synergy provides communities and stakeholders with a rigorous decision-making platform to base future outcomes while minimising regret. Such an integration to produce this synergy is not yet available in the literature. Therefore, the new method outlined in this thesis sets a baseline for integrated assessment modelling.

Macharis (2000) describes the least-regret approach as maintaining a conservative position to minimise the worst-case regret of future options. This approach to weighing up different climate futures, as outlined by Callaway (2014) and employed in PYRDM, is a useful methodology to apply this synergy. The results in Figure 8.2 and Figure 8.3 show that the PYRDM approach allows modellers to examine many possibilities relatively quickly, in this case, nine different options. However, Scenario Planning is limiting as it only seeks out three or four scenarios for a particular audience (Ramirez & Wilkinson, 2016), while RDM and DAPP can become overly cumbersome and confusing when too many futures are analysed simultaneously. Therefore, the results shown in Figure 8.2 were displayed in total and with separation by climate scenario in Figure 8.3 for more explicit visualisation.

Similarly, DAPP seeks multiple futures through pathway flexibility and transitions (Haasnoot et al., 2013) during the analysis window, which is not ideal for Scenario Planning or economic impact analysis, given the complexity and uncertainty of modelling future economic transactions. In this research, only one intervention per scenario was examined to maintain simplicity and isolate the impacts of that intervention. Therefore, combining these tools limits the benefit of each approach individually, but their integration creates opportunities for communities to test interventions with a more vigorous framework ahead of implementation.

Defining DAPP for coastal managed retreat by assessing scenarios becomes increasingly essential as complexity in systems builds over the medium term. Decision-makers require a more robust scientific inquiry to substantiate their decisions for communities with more certainty (Ministry for the Environment, 2017), a process suited to RDM and System Dynamics. Table 8.1 is an excellent example of synthesising diverse information from scientific enquiry into a standard metric to enhance decision-making. Here a simple Boolean operation from the Pandas Development Team (2014) in PYRDM allows for comparing diverse metrics over time. C-ADAPT can then provide decision-makers with added certainty by exploring diverse economic indicators of options ahead of financial decision-making and the implementation of a large-scale managed retreat. However, as mentioned in Chapter 3, van Delden (2009) argues that modelling should enhance policy practices rather than replace well-embedded ones.

### What strengths and weaknesses can an integrated systems simulation modelling approach provide when analysing future scenarios for managed retreat when faced with imperfect knowledge and uncertainty?

Traditionally, the evaluation of impacts given relevant pressures such as climate change, socio-economic developments or policy options determines the usefulness of a model (Haasnoot et al., 2014b). It should allow for the analysis of trade-offs, rank actions in order of performance to achieve objectives, support the improvement of plans, simulate long periods and provide an output of relevance to the decision-making process (Haasnoot et al., 2014b). The following section addresses the limitations of this research as well as its particular strengths.

#### *9.1.1 Uncertainty in land use planning with managed retreat*

This research shows that managed retreat offers a planning and financial pathway to enable exposed communities to adapt to climate change and build new resilient communities. However, adapting to coastal hazards will be demanding on land use as planning for relocation through managed retreat is not accounted for in the current planned future urban growth zones (see HBRC, 2016a; HBRC et al., 2017). Thus, C-ADAPT constrains land use under the baseline and defence scenarios. The finite supply (limits) and competition for land resources leads to scarcity, driving up its value (Watson, 2013). Concurrently, businesses seek to preserve productive soils over greenfield developments (HBRC et al., 2017) to maintain productivity in Hawke's Bay. It appears from the land allocations outlined by HPUDS, which constitute the baseline and defence scenarios, that there is ample future allocation for residential (particularly on zoned hillslopes) and industrial land uses (see Figure 4.1). Still, the concern is the under-supply for commercial use, infrastructure (roads and services) and public amenity. Similarly, the worst-case defence scenario was more favourable than the baseline for primary production economic output (IVA) by 4.8% as productive land is preserved over the medium term.

C-ADAPT illustrates this point when the composite capital supply (supply of built and natural capital) regularly overshot the dynamic market equilibrium, after which it collapsed to zero, suspending the simulation under the baseline worst-case scenario. In this case, the built capital supply (which includes land in this version of MERIT) is less than required to replace the lost built capital. Thus, as described by DeAngelis and Waterhouse (1987) and Hughes et al. (2017), positive feedback from coastal hazards (produced by significant stochastic effects of coastal hazards) can precipitate a threshold response, system overshoot and market collapse.

C-ADAPT indicates that early government intervention is needed under the baseline scenario to free up and supply land to meet infrastructure, amenity, ecosystem and industry requirements. Increasing land supply is needed because a sizeable amount of infrastructure land, amenity land, and ecosystem services are lost (664 Ha vulnerable to a 2065 1% AEP and a further 37 Ha by 2120). Ideally, higher-density housing, mixed-use zoning and new technological approaches to production can stall an unsustainable increase in total conversion and reduce the demand for land and any further degradation of ecosystems. Further modelling is required here.

### *9.1.2 Stability vs resilience*

Identifying outcomes for coastal communities also involves analysing the fundamental relationship between stability and resilience in systems. Understanding model instability leads to a better awareness of system resilience. The modelled system becomes less accommodating of perturbations as complexity increases. Such an issue became apparent when undertaking sensitivity analyses, where the modeller could not venture too far beyond the rational expectations of the interacting environment-economy system. Instability leads to system failure during calibration, validation and sensitivity analyses, which was the case for the model variables Flood Frequency, Insurance Premiums, WTP Threshold and ROI, where outlier values could exceed system thresholds.

Policymakers are beginning to realise that resilience is more important than stability for long-term sustainability, and special efforts are needed to face off exogenous system shocks or collapse (Rosser, 2011). Thus, stability can be described as 'equilibrium seeking' in the neo-classical economics context, whereas resilience can be described as 'dynamic equilibrium seeking' in an Evolutionary Economics context. C-ADAPT successfully operated the latter to produce resilient outcomes. Although with more complexity added to C-ADAPT, instability crept in to reduce resilience and increase the uncertainty of the results. Thus, C-ADAPT adopted a simpler form over multiple iterations to manufacture resilient outcomes under different climate scenarios.

## 9.2 Suggestions for future research

The suggestions for future research address five themes: 1) Expanding the scenarios; 2) Improving DAPP through community engagement in indicator valuation; 3) Incorporating spatially explicit models into system dynamics to reduce uncertainty; and 4) Modelling technological approaches outlined in the Matariki plan with Scenario Planning.

### 9.2.1 Expanding the scenarios

The modular approach of C-ADAPT allows coastal modellers, managers and economists with an intermediate understanding of System Dynamics to test their scenarios or cases and then iterate the IAM to produce unique DAPP for their local communities. Here, modellers can test bundles of options to minimise risk to government agencies and private partners. As mentioned earlier, bundling diverse funding or land use interventions as a scenario is also a possibility. For example, part-funding adaptation through central government bonds and part funding through local government property rates would be distributively more appealing for governments. Alternatively, combining short-term coastal defence with long-term managed retreat to buy time before relocation and utilise a mix of land use planning options. Such an approach was a preferred option for many communities in Hawke's Bay (Infometrics Consulting Limited, 2017a).

The prioritisation and scheduling of options and their implementation are also critical to minimise adverse economic impacts (Champalle et al., 2015). Here Gantt Charts can provide a useful tabular visualisation of bundled adaptation interventions as illustrated by Champalle et al. (2015). Further development of the PYRDM matrix, as shown in Figures 8.2 and 8.3, would be useful to illustrate the planning and implementation schedule for each scenario.

Similarly, expanding the scenarios would allow coastal scientists to assess alternative climate futures. Here, the mid-range baseline scenario illustrates RCP4.5, with the worst-case baseline set to RCP8.5 and a hypothetical case of no climate change (RCP0) added to illustrate the absolute change. Conversely, Allison (2020) modelled RCP8.5 for complex human-environmental systems in New Zealand and assumed it as the best representation of the current climate system. During sensitivity analyses, a hypothetical RCP10 was also tested with mixed results. It was possible to force the input modules to such a state. Still, the simulation failed mid-period when incorporated into MERIT due to a lack of composite capital supply. Here, the magnitude and frequency of losses were greater than the replacement rate. Thus, expanding the climate scenarios would be useful for future research to include RCP2.6 and RCP6 and investigate RCP10 to discover what is inhibiting composite capital supply under this scenario.

### 9.2.2 Community engagement on values

Community engagement is a necessary next step to weigh the key aggregates and define the value that society places on each metric. The modelling of DAPP in PYRDM currently runs an even weighting of key aggregates to discover DAPP with the exception of Annual Expected Loss and Total Value Added. However, each coastal community may value the importance of the variables differently. Therefore extending this research could incorporate focus groups with exposed communities to discover the weighting of values as described by Giannakidou et al. (2019). However, funding and time constraints have limited further research in this domain, given the long and deliberative process involved in community engagement. An extension of the work conducted by the Clifton to Tongoio Coastal Hazards Strategy 2120 (2017) with community involvement would be highly beneficial in determining community values as described by the key aggregates.

### 9.2.3 Adding dynamic spatial change

The modelling of dynamic spatial changes in coastal processes, land use and zoning require further investigation. For example, given varying degrees of climate change, integration with localised hydrodynamic modelling provides modellers with a suite of scenarios to enact as events exceed prescribed triggers. However, C-ADAPT lacks a spatial platform to manage the dynamic change in coastal processes and land use over time, instead measuring the total land use change over time given coastal hazards. Figure 9.1 illustrates an initial snapshot of planning land use zones and flooding hazards to illustrate the current acceptable areas for development using raster analysis in ESRI ArcGIS.

Dynamic integration of C-ADAPT with a GIS platform would enable better exploration of land use scenarios over time. Here the application of Spatial MERIT by Market Economics (2021) is beneficial, and similarly spatial dynamics models such as the Auckland, Waikato and Wellington Integrated Scenarios Explorers (McDonald et al., 2015; Rutledge et al., 2008). However, the scenarios modelled in this research were more to inform society of the economic costs and benefits of managed retreat rather than definitive changes in land use for Hawke's Bay, which is the next step in defining adaptation for these communities.

Similarly, the addition of dynamic coastal processes into the modelling is essential. Baron et al. (2015) express that based on their sensitivity analyses, morphological variability is more important than the uncertainty associated with the range of climate change scenarios in determining the width of CHZs. Projections modelled here are static predictions using passive flood mapping, which undervalues exposure (Anderson et al., 2018). Combining the author's previous research (Eaves & Doscher, 2015) to discover coastal hydrodynamics through SWAN and XBeach would be helpful here.

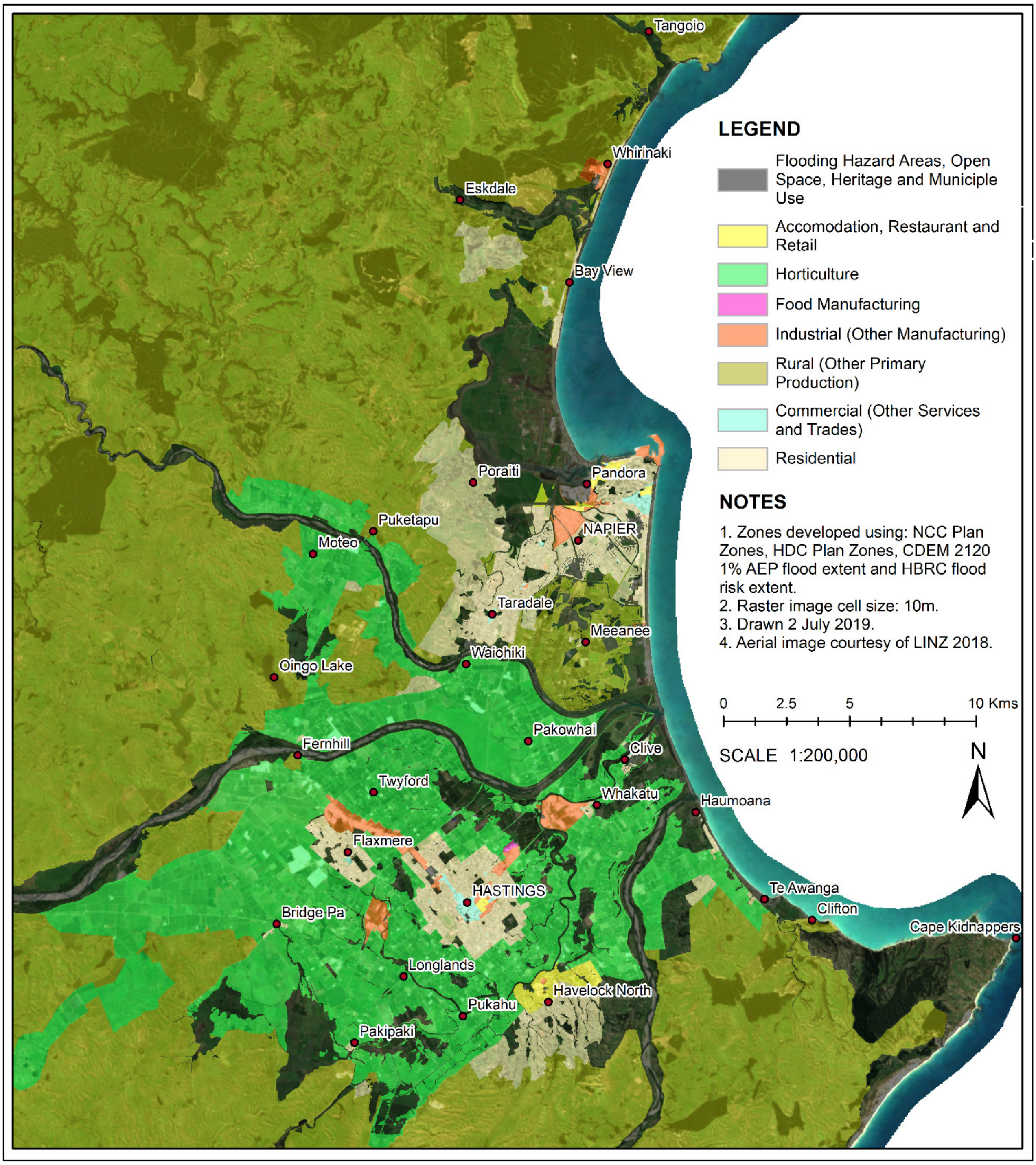



**Figure 9.1** A current snapshot of land use zones and flooding hazards illustrates acceptable areas for development in Hawke's Bay using raster analysis in ArcGIS. Black spaces represent zones already occupied or those within flood hazard zones. Lime green areas are horticultural areas to be preserved. What becomes clear is an abundance of the rural hinterland.

### 9.2.4 Scenario Planning for new technological approaches and sustainability

Finally, managed retreat seeks to enable sustainable development and, in turn, long-term resilience to nature's challenges. In addition to the results of this study, modelling alternative scenarios around technological developments and urban planning would be useful to investigate a broader range of alternative futures for a managed retreat at a local scale.

Modelling new technological approaches could result in 'strong sustainability' with no decline in natural capital due to resource substitution—thus conserving natural capital and ecosystem services by substituting natural capital for built capital or labour (Proops, 1989; Turner et al., 2001). For example, the Matariki Plan (HBRC, 2016a) seeks to improve horticultural yield per hectare through plant innovation and post-harvest technologies. Increasing total intensification through increasing yield, rather than converting natural habitats to productive areas that are subsequently lost to the sea, would be an acceptable avenue for investigation. Similarly, extending this concept to include the co-location of infrastructure and medium-density housing with endemic habitat restoration will decrease demand for natural capital and provide resilient ecological networks as they face coastal squeeze from SLR and development. Such approaches conform to the ethos of strong sustainability and Evolutionary Economics more generally.

## 9.3 Conclusion

Exposure of assets and infrastructure to multiple coastal hazards are evolving due to the slow creep of sea-level rise and increased storm intensity brought on by climate change. Policies and plans need to manage the current and future risks for coastal communities. Communities and local governments desire a standardised approach to provide consistency across New Zealand to manage these coastal hazards (Mitchell, 24 July 2017). Alongside regulatory change, central and local government's long-term strategic and integrated planning needs clarity of direction to define fair and equitable outcomes for communities, industry, and the environment to accommodate future managed retreat (Grace et al., 2018). Compensation will be needed where people are denied the ability to use or live on their land due to government decision-making (Tombs & France-Hudson, 2018).

This thesis has illustrated that large-scale managed retreat has beneficial regional level economic impacts in Hawke's Bay over the medium-term. It shows vital factors that need consideration for successful planning and implementation of managed retreat. It explores financial mechanisms that can support the adoption of this adaption strategy. The work underscores the importance of government intervention to enable funding, manage stakeholders, modify land use and purchase land for infrastructure and amenity. The key contributions of the thesis are as follows:

1. Where the local government implements customised long-term plans financed through property rating taxes, it proved to be the most robust option across all scenarios, which is counterintuitive to expert input and the financial capacity of local government. Its success was

down to an emphasis on risk minimisation by those directly or indirectly impacted, a longer implementation timeframe, and effectively increasing Total Value Added (2.9%, or NZ$_{2007}$388M above the mid-range baseline scenario and 8.3%, NZ$_{2007}$1.047B above the worst-case baseline scenario). It also outperformed all other scenarios for the industries of construction and wood and paper manufacturing.

2. Where the central government introduces climate bonds to finance managed retreat, society is generally better off than the baseline scenario of doing nothing. The use of bonds was the most helpful scenario to increase household consumption as funding primarily came from outside the region. Similarly, the unemployment rate was the lowest in this scenario.
3. Coastal defence is not a viable long-term solution as risk and loss will only increase with time. However, it is a practical short-term transitional option toward managed retreat as losses, inoperability and infrastructure outages are reduced more than the managed retreat and baseline scenarios. It also performed the best for other primary production industries as 'holding the line' maintains agricultural and pastoral land. However, it is a poor long-term option as storminess and sea-level rise become more debilitating as they exceed defence thresholds frequently while maintenance and rebuild costs increase.
4. Where large-scale managed retreat of communities is not an option, local government can lead by example by increasing and diverting development taxes toward the relocation of infrastructure and amenities through a managed retreat of their own assets. Land-use zoning for industrial and commercial land also needs to increase beyond currently planned allocations.
5. Finally, the main socio-economic benefit of managed retreat to government is the reduction of risk for the communities for which they are responsible. The central government can afford the cost of managed retreat more so than local government, as shown by the proportion of government consumption. At the peak of managed retreat funding, the bonds scenario is only 6.3% (in 2039 worst-case) and 4.5% (in 2050 mid-range) greater than the baseline for central government consumption, meaning that the implementation of the scenario will not significantly impact central government finances. In contrast, the rates scenario is 36.2% (in 2043 worst-case) and 31.4% (in 2049 mid-range) greater than the baseline for local government consumption and therefore install a financial risk on local government.

Plans and funding implementation require diligent scientific investigation of environmental systems coupled with robust analysis of the impacts on economic systems. Understanding the non-linear interactions of these complex systems enhances our knowledge of place and causes traditional decision-making to become increasingly redundant. Yet, such analyses require a framework adaptive to knowledge structures and information flows, a framework implicit in Evolutionary Economics and explicit in System Dynamics. This thesis adopts novel analyses of complex systems using Evolutionary Economics, which facilitates knowledge creation of system relationships and discovers information flows to understand behavioural drivers and provide counter-intuitive insights for coastal hazards and managed retreat. Exploring futures for managed retreat through economic impact modelling in System Dynamics and RDM can enable rigorous, long-term planning and provide insight into adaptive actions. Combining these approaches into the novel IAM C-ADAPT, which utilises the MERIT economy model, makes it possible to explore future scenarios and interventions in order to develop staged pathways, or DAPP, that enable coastal managed retreat ahead of time by examining impacts on households, industries and governments. Successful Scenario Planning can then progress into practice with stakeholders knowing the risks and benefits, resulting in the implementation of pathways that minimise regret given the uncertainty of climate change trajectory. Managed retreat can then lead to more resilient coastal communities, given their uncertain future and an evolving and dynamic environment and economy.

# References


Abel, N., Gorddard, R., Harman, B., Leitch, A., Langridge, J., Ryan, A., & Heyenga, S. (2011). Sea level rise, coastal development and planned retreat: An analytical framework, governance principles and an Australian case study. *Environmental Science & Policy*, *14*(3), 279-288. http://www.sciencedirect.com/science/article/pii/S146290111000167X

All Answers Limited. (2019). *Theory Behind Decision Making and Impact Investing*. Retrieved 4 July 2021 from https://ukdiss.com/examples/decision-making-impact-investing.php

Allen, M., Crawford, K., Théot, J., & Toscani, L. (2015). *Climate change and capital markets*. Graduate School of Stanford Business.

Allison, A. (2020). *Developing a methodology for transdisciplinary modelling of complex human-environment systems* University of Auckland]. Auckland, NZ.

Anderson, T., Fletcher, C., Barbee, M., Romine, B., Lemmo, S., & Delevaux, J. (2018). Modeling multiple sea level rise stresses reveals up to twice the land at risk compared to strictly passive flooding methods. *Scientific Reports*, *8*(1), 14484. https://doi.org/10.1038/s41598-018-32658-x

Auckland Council. (2014). *Natural Hazard Risk Communication Toolbox: Natural Hazard Risk Management Action Plan*. https://www.civildefence.govt.nz/assets/Uploads/NHRCToolbox/NHRCToolbox-Auckland-Council.pdf.

Auckland Council. (2017). *Water Quality Targeted Rate*. https://ourauckland.aucklandcouncil.govt.nz/media/19292/attachment-b-water-quality-targeted-rate.pdf

Australian Geomechanics Society. (2000). *Landslide Risk Management Concepts and Guidelines.*

Barlas, Y. (1996). Formal aspects of model validity and validation in system dynamics. *System Dynamics Review*, *12*(3), 183-210.

Barnett, J., Graham, S., Mortreux, C., Fincher, R., Waters, E., & Hurlimann, A. (2014). A local coastal adaptation pathway. *Nature Climate Change*, *4*(12), 1103-1108.

Baron, H., Ruggiero, P., Wood, N., Harris, E., Allan, J., Komar, P., & Corcoran, P. (2015). Incorporating climate change and morphological uncertainty into coastal change hazard assessments. [journal article]. *Natural Hazards*, *75*(3), 2081-2102.

Baron, H. M., Ruggiero, P., Wood, N. J., Harris, E. L., Allan, J., Komar, P. D., & Corcoran, P. (2015). Incorporating climate change and morphological uncertainty into coastal change hazard assessments. [journal article]. *Natural Hazards*, *75*(3), 2081-2102.

Barrowman, H. (2011). *Managing coastal community vulnerability: An assessment of the temporal dynamics of community vulnerability as a consequence of coastal management decision making.* University of Auckland]. Auckland.

Batten, S. (2018). *Climate change and the macro-economy: a critical review.*

Beavan, R., & Litchfield, N. (2012). *Vertical land movement around the New Zealand coastline: Implications for sea-level rise*. www.gns.cri.nz/static/pubs/2012/SR%202012-029.pdf

Bernatchez, P., & Fraser, C. (2012). Evolution of Coastal Defence Structures and Consequences for Beach Width Trends, Quebec, Canada. *Journal of Coastal Research*, *28*(6), 1550-1566. https://doi.org/10.2112/JCOASTRES-D-10-00189.1

Bernstein, A., Gustafson, M., & Lewis, R. (2019). Disaster on the horizon: The price effect of sea level rise. *Journal of Financial Economics*, *134*(2), 253-272. https://doi.org/https://doi.org/10.1016/j.jfineco.2019.03.013

Bess, R., & Ambargis, Z. (2011). Input-Output Models for Impact Analysis: Suggestions for Practitioners Using RIMS II Multipliers. The 50th Southern Regional Science Association Conference, New Orleans, Louisiana.

Bhave, A., Conway, D., Dessai, S., & Stainforth, D. (2016). Barriers and opportunities for robust decision making approaches to support climate change adaptation in the developing world. *Climate Risk Management*, *14*(Supplement C), 1-10. http://www.sciencedirect.com/science/article/pii/S2212096316300626

Bin, O., Crawford, T., Kruse, J., & Landry, C. (2008). Viewscapes and Flood Hazard: Coastal Housing Market Response to Amenities and Risk. *Land Economics*, *84*(3), 434-448. www.jstor.org/stable/27647836

Bin, O., & Kruse, J. (2005). Real Estate Market Response to Coastal Flood Hazards. In N. H. R. Center (Ed.). East Carolina University.

Bjornes, C. (2017). *A guide to representative concentration pathways.* https://www.sei-international.org/mediamanager/documents/A-guide-to-RCPs.pdf

Bodger, P., & May, D. (1992). A system dynamics energy model of New Zealand. *Technological Forecasting and Social Change*, *41*(1), 97-106. http://www.sciencedirect.com/science/article/pii/004016259290018O

Bolstad, E. (2016). *Seas Rising but Florida Keeps Building on the Coast*. Springer Nature. Retrieved 10 July 2019 from https://www.scientificamerican.com/article/seas-rising-but-florida-keeps-building-on-the-coast/

Bosello, F. (2014). The Role of Economic Modelling for Climate Change Mitigation and Adaptation Strategies. In *Routledge Handbook of the Economics of Climate Change Adaptation*. Routledge. https://doi.org/10.4324/9780203095201.ch8

Bosello, F., Nicholls, R., Richards, J., Roson, R., & Tol, R. (2012). Economic impacts of climate change in Europe: sea-level rise. *Climatic Change*, *112*(1), 63-81. https://doi.org/10.1007/s10584-011-0340-1

Bosello, F., Roson, R., & Tol, R. (2007). Economy-wide Estimates of the Implications of Climate Change: Sea Level Rise. *Environmental and Resource Economics*, *37*(3), 549-571. https://doi.org/10.1007/s10640-006-9048-5

Bosomworth, K., Leith, P., Harwood, A., & Wallis, P. J. (2017). What's the problem in adaptation pathways planning? The potential of a diagnostic problem-structuring approach. *Environmental Science & Policy*, *76*, 23-28. http://www.sciencedirect.com/science/article/pii/S1462901117300254

Boston, J. (2017). *Safeguarding the future: governing in an uncertain world.* Bridget Williams Books Limited.

Boston, J., & Lawrence, J. (2017). *The case for new climate change adaptation funding instruments.*

Boston, J., & Lawrence, J. (2018). Funding Climate Change Adaptation: the case for a new policy framework. *Policy Quarterly*, *14*(2), 40-49.

Bragen, M., & Martinez-Moyano, I. (2014). *System Dynamics Model Documentation Tool*. In (Version Java) Argonne National Laboratory. https://vensim.com/new-sdm-doc-version/

Brouwer, R., & Schaafsma, M. (2013). Modelling risk adaptation and mitigation behaviour under different climate change scenarios. *Climatic Change*, *117*(1), 11-29.

Brown, C., Seville, E., Stevenson, J., Giovanazzi, S., & Vargo, J. (2015). *Developing the business behaviours module within MERIT*. The Economics of Resilient Infrastructure Programme.

Brown, S. I., Dickson, M. E., Kench, P. S., & Bergillos, R. J. (2019). Modelling gravel barrier response to storms and sudden relative sea-level change using XBeach-G. *Marine Geology*, *410*, 164-175. https://doi.org/https://doi.org/10.1016/j.margeo.2019.01.009

Burke, M., Craxton, M., Kolstad, C. D., Onda, C., Allcott, H., Baker, E., Barrage, L., Carson, R., Gillingham, K., Graff-Zivin, J., Greenstone, M., Hallegatte, S., Hanemann, W. M., Heal, G., Hsiang, S., Jones, B., Kelly, D. L., Kopp, R., Kotchen, M., Mendelsohn, R., Meng, K., Metcalf, G., Moreno-Cruz, J., Pindyck, R., Rose, S., Rudik, I., Stock, J., & Tol, R. S. J. (2016). Climate Economics: Opportunities for advances in climate change economics. *Science*, *352*(6283), 292.

Cairns, L. (29 September 2015). Controversial coastal hazards zonings dropped. *Stuff*. https://www.stuff.co.nz/the-press/news/72501997/controversial-coastal-hazards-zonings-dropped

Callaway, J. (2014). The role of technology in adaptation. In A. Markandya, I. Galarraga, & E. Sainz de Murieta (Eds.), *Routledge Handbook of the Economics of Climate Change Adaptation*. Routledge. https://doi.org/10.4324/9780203095201

Campbell, J. (2017). *Environment commissioner tells Govt to act faster, act now.* Radio New Zealand. http://www.radionz.co.nz/national/programmes/checkpoint/audio/201850162/environment-commissioner-tells-govt-to-act-faster-act-now

Cash, D. W., & Moser, S. C. (2000). Linking global and local scales: Designing dynamic assessment and management processes. *Global Environmental Change*, *10*(2), 109-120.

Cavana, R., Dangerfield, B., Pavlov, O., Radzicki, M., & Wheat, I. (2021). *Feedback Economics: Economic Modeling with Systems Dynamics*. Springer.

Champalle, C., Ford, J., & Sherman, M. (2015). Prioritizing Climate Change Adaptations in Canadian Arctic Communities. *Sustainability*, *7*, 9268-9292. https://doi.org/10.3390/su7079268

Christchurch City Council. (2015). *Coastal hazard LIM notations to be changed.* Retrieved 13 April 2018. from https://ccc.govt.nz/news-and-events/newsline/show/957

Climate Bonds Initiative. (2019). *Climate Bonds Initiative for climate change solutions*. Retrieved 8 February 2019 from https://www.climatebonds.net/resources/overview/climate-bonds-for-beginners

CoreLogic Inc. (2018). *Insurance Premiums In 2018: Up, Up And Away.* Retrieved 19 February 2019 from https://www.corelogic.co.nz/news/insurance-premiums-2018-and-away#.XGuX17hS9hE

Costanza, R. (1989). What is ecological economics? *Ecological Economics*, *1*(1), 1-7.

Cowan, R., Fauchart, E., Foray, D., & Gunby, P. (2006). Learning from disaster. In A. Pyka & H. Hanusch (Eds.), *Applied evolutionary economics and the knowledge economy* (pp. 40-75). Edward Elgar.

Cradock-Henry, N., Blackett, P., Hall, M., Johnstone, P., Teixeira, E., & Wreford, A. (2019). *Applying adaptation pathways with Hawke's Bay primary industries*. https://www.researchgate.net/publication/339569557_Applying_adaptation_pathways_with_Hawke's_Bay_primary_industries/references

Cunniff, S., & Meyers, E. (2017). *Encouraging Investments in Coastal Conservation & Resilience.* Sage: Resilient shorelines, thriving communities.

Cutler, E., Albert, M., & White, K. (2020). Tradeoffs between beach nourishment and managed retreat: Insights from dynamic programming for climate adaptation decisions. *Environmental Modelling & Software*, *125*, 1-17. https://doi.org/10.1016/j.envsoft.2019.104603

Daalder, M. (2 December 2020). Thousands could lose insurance due to climate change. *Newsroom*. https://www.newsroom.co.nz/thousands-could-lose-insurance-due-to-climate-change

Daniel, V., Florax, R., & Rietveld, P. (2009). Flooding risk and housing values: An economic assessment of environmental hazard. *Ecological Economics*, *69*(2), 355-365. http://www.sciencedirect.com/science/article/pii/S092180090900322X

Darwin, R., & Tol, R. (2001). Estimates of the Economic Effects of Sea Level Rise. *Environmental and Resource Economics*, *19*(2), 113-129. https://doi.org/10.1023/A:1011136417375

Daysh, S. (2017). *Stage two report: Decision-making framework.* (Clifton to Tangoio coastal hazards strategy 2120, Issue. http://www.hbcoast.co.nz/resources/

de Lange, W. (2006). Coastal erosion. *The Encyclopedia of New Zealand.* https://www.teara.govt.nz/mi/coastal-erosion/print

DeAngelis, D. L., & Waterhouse, J. C. (1987). Equilibrium and Nonequilibrium Concepts in Ecological Models. *Ecological Monographs*, *57*(1), 1-21. https://doi.org/10.2307/1942636

Dellink, R., Van Der Mensbrugghe, D., & Saveync, B. (2020). Shaping Baseline Scenarios of Economic Activity with CGE Models: Introduction to the Special Issue. *Journal of Global Economic Analysis*, *5*(1), 1-27. https://jgea.org/ojs/index.php/jgea/article/viewFile/110/109

Devarajan, S., & Robinson, S. (2013). Chapter 5 - Contribution of Computable General Equilibrium Modeling to Policy Formulation in Developing Countries. In P. Dixon & D. Jorgenson (Eds.), *Handbook of Computable General Equilibrium Modeling* (Vol. 1, pp. 277-301). Elsevier. https://doi.org/https://doi.org/10.1016/B978-0-444-59568-3.00005-5

Dyckman, C., St. John, C., & London, J. (2014). Realizing managed retreat and innovation in state-level coastal management planning. *Ocean and Coastal Management*, *102*, 212-223.

Earthquake Commission NZ. (2019). *Householders' guide to EQCover*.

Eaves, A., & Doscher, C. (2015). Coastal modelling of sea level rise for the Christchurch coastal environment. *Lincoln Planning Review*, *7*(1), 3-15. https://journals.lincoln.ac.nz/index.php/LPR/article/viewFile/912/637

Eaves, A., Kench, P., McDonald, G., & Dickson, M. (2019). Balancing Sustainable Coastal Management with Development in New Zealand. In P. Khaiter & G. Erechtchoukova (Eds.), *Sustainability Perspectives: Science, Policy and Practice: A Global View of Theories, Policies and Practice in Sustainable Development*. Springer.

Ebersberger, B., & Pyka, A. (2009). The use of genetic programming in evolutionary economics. In J. Foster & W. Hölzl (Eds.), *Applied evolutionary economics and complex systems*. Edward Elgar.

Featherston, C., & Doolan, M. (2013). *Using System Dynamics to Inform Scenario Planning: A Case Study* The 31st International Conference of the System Dynamics Society, Cambridge, Massachusetts.

Feridun, M., & Gungor, H. (2020). Climate-Related Prudential Risks in the Banking Sector: A Review of the Emerging Regulatory and Supervisory Practices. *Sustainability*, *12*. https://doi.org/10.3390/su12135325

Filippova, O. (2009). The influence of submarkets on water view house price premiums in New Zealand. *International Journal of Housing Markets and Analysis*, *2*(1), 91-105.

Filippova, O., Nguyen, C., Noy, I., & Rehm, M. (2020). Who Cares? Future Sea Level Rise and House Prices. *Land Economics*, *96*(2), 207-224. https://doi.org/http://le.uwpress.org/content/by/year

Fitzharris, B. (2007). How vulnerable is New Zealand to the impacts of climate change? *New Zealand Geographer*, *63*(3), 160-168. http://dx.doi.org/10.1111/j.1745-7939.2007.00119.x

Fleming, D., Noy, I., Pástor-Paz, J., & Owen, S. (2018). *Public insurance and climate change (part one): Past trends in weather-related insurance in New Zealand.* Motu Economic and Public Policy Research.

Fleming, Z. (24 October 2017). Checkpoint In *'This is going to set a precedent' - council applying to evict homeowners.* http://www.radionz.co.nz/national/programmes/checkpoint/audio/201851000/this-is-going-to-set-a-precedent-council-applying-to-evict-homeowners

Ford, A. (2010). *Modeling the environment.* (2nd ed.. ed.). Island Press.

Foreworld Developments Ltd v Napier City Council, Judge Kenderdine (Environment Court 1998).

Forrester, J. (1961). *Industrial dynamics.* M.I.T. Press 1961.

Forrester, J. (1971). Counterintuitive behaviour of social systems. *Theoretical Decision-making*, *2*(2), 109-140.

Forrester, J. (1982). Global modelling revisited. *Futures*, *14*(2), 95-110. http://www.sciencedirect.com/science/article/pii/0016328782900830

Forzieri, G., Feyen, L., Russo, S., Vousdoukas, M., Alfieri, L., Outten, S., Migliavacca, M., Bianchi, A., Rojas, R., & Cid, A. (2016). Multi-hazard assessment in Europe under climate change. *Climatic Change*, *137*(1), 105-119. http://dx.doi.org/10.1007/s10584-016-1661-x

Foster, J., & Hölzl, W. (2004). *Applied evolutionary economics and complex systems.* Edward Elgar Pub. 2004.

Foudi, S., & Nuria, O. (2014). Flood risk management: Assessment for prevention with hydro-economic approaches. In A. Markandya, I. Galarraga, & E. Sainz de Murieta (Eds.), *Routledge handbook of the economics of climate change adaptation.* Routledge.

Frame, B., & Reisinger, A. (2016). *Exploring Options for New Zealand under Different Global Climates. Synthesis Report RA5. Climate Changes, Impacts and Implications (CCII) for New Zealand to 2100.* http://ccii.org.nz/wp-content/uploads/2017/02/RA5-Synthesis-report.pdf

Frame, B., Taylor, R., & Delaney, K. (2005). *Work in Progress: Four futures for New Zealand*.

Franzke, C., & Torello, H. (2020). Risk of extreme high fatalities due to weather and climate hazards and its connection to large-scale climate variability. *Climatic Change*, *162*(2), 507-525. https://doi.org/10.1007/s10584-020-02825-z

Freudenberg, R., Ellis, C., Tolkoff, L., & Brawley, D. (2016). *Buy-in for buyouts: The case for managed retreat from flood zones.*

Geis, D. (2000). By design: The disaster resistant and quality of life community. *Natural Hazards Review*, *1*(3), 151-160.

Georgescu-Roegen, N. (1971). *The Entropy Law and the Economic Process.* Harvard University.

Giannakidou, C., Diakoulaki, D., & Memos, C. (2019). Implementing a Flood Vulnerability Index in urban coastal areas with industrial activity [journal article]. *Natural Hazards*, *97*(1), 99-120. https://doi.org/10.1007/s11069-019-03629-w

Gibbs, M. (2015). Coastal climate risk and adaptation studies: The importance of understanding different classes of problem. *Ocean & Coastal Management*, *103*(C), 9-13. http://www.sciencedirect.com/science/article/pii/S0964569114003421

Goel, A. L. (1985). Software Reliability Models: Assumptions, Limitations, and Applicability. *Software Engineering, IEEE Transactions on*, *11*(12), 1411-1423.

Gong, M., Lempert, R., Parker, A., Mayer, L., Fischbach, J., Sisco, M., Mao, Z., Krantz, D., & Kunreuther, H. (2017). Testing the scenario hypothesis: An experimental comparison of scenarios and forecasts for decision support in a complex decision environment. *Environmental Modelling & Software*, *91*, 135-155. http://www.sciencedirect.com/science/article/pii/S1364815216305060

Gorddard, R., Wise, R., Alexander, K., Langston, A., Leitch, A., Dunlop, M., Ryan, A., & Langridge, J. (2012). *Striking the balance: Coastal development and ecosystem values.* (National research flagships climate adaptation, Issue.

Grace, E., France-Hudson, B., & Kilvington, M. (2018). *Managing existing uses in areas at high risk from natural hazards: an issues paper.*

Graham, S., Barnett, J., Fincher, R., Hurlimann, A., & Mortreux, C. (2014). Local values for fairer adaptation to sea-level rise: A typology of residents and their lived values in Lakes Entrance, Australia. *Global Environmental Change*, *29*, 41-52. http://www.sciencedirect.com/science/article/pii/S0959378014001411

Greenberger, M., Crenson, M., & Crissy, B. (1976). *Models in the policy process: public decision making in the computer era*. Russel Sage Foundation.

Groves, D., & Sharon, C. (2013). Planning Tool to Support Planning the Future of Coastal Louisiana. *Journal of Coastal Research*, *SI*(67), 147-161.

Haasnoot, M., Kwakkel, J., Walker, W., & Ter Maat, J. (2013). Dynamic adaptive policy pathways: A method for crafting robust decisions for a deeply uncertain world. *Global Environmental Change*, *23*(2), 485-498. http://www.sciencedirect.com/science/article/pii/S095937801200146X

Haasnoot, M., Middelkoop, H., Offermans, A., Beek, E., & Deursen, W. (2012). Exploring pathways for sustainable water management in river deltas in a changing environment. *Climatic Change*, *115*(3), 795-819.

Haasnoot, M., van Deursen, W. P. A., Guillaume, J. H. A., Kwakkel, J., van Beek, E., & Middelkoop, H. (2014a). Fit for purpose? Building and evaluating a fast, integrated model for exploring water policy pathways. *Environmental Modelling & Software*, *60*, 99-120. http://www.sciencedirect.com/science/article/pii/S1364815214001595

Haasnoot, M., van Deursen, W. P. A., Guillaume, J. H. A., Kwakkel, J. H., van Beek, E., & Middelkoop, H. (2014b). Fit for purpose? Building and evaluating a fast, integrated model for exploring water policy pathways. *Environmental Modelling & Software*, *60*, 99-120. https://doi.org/http://dx.doi.org/10.1016/j.envsoft.2014.05.020

Hall, D., & Lindsay, S. (2017). *Climate Finance Landscape for Aotearoa New Zealand: A preliminary survey.* (Prepared for the Ministry for the Environment, Issue.

Hamarat, C., Kwakkel, J., & Pruyt, E. (2013). Adaptive Robust Design under deep uncertainty. *Technological Forecasting and Social Change*, *80*(3), 408-418. http://www.sciencedirect.com/science/article/pii/S004016251200248X

Hamarat, C., Kwakkel, J., Pruyt, E., & Loonen, E. (2014). An exploratory approach for adaptive policymaking by using multi-objective robust optimzation. *Simulation Modelling Practice and Theory.*

Hannon, B., & Ruth, M. (1994). *Dynamic Modelling*. Springer-Verlag.

Hasselmann, K. (2010). Application of System Dynamics to Climate Policy Assessment. In A. Fitt, J. Norbury, H. Ockendon, & E. Wilson (Eds.), *Progress in Industrial Mathematics at ECMI 2008* (Vol. 15). Springer. https://doi.org/10.1007/978-3-642-12110-4_27

Hastings District Council. (2017a). *ANNUAL REPORT 2016/17 Great living, today and tomorrow.* https://www.hastingsdc.govt.nz/assets/Document-Library/Reports/Annual-Report/20162017-Annual-Report.pdf

Hastings District Council. (2017b). *Government Valuations 2017*.

Hastings District Council. (2020). *Business Investment; Whakangao Pakihi*. Retrieved 14 February 2020 from https://www.hastingsdc.govt.nz/services/business/business-investment/

Hawke's Bay Today. (2018). Hawke's Bay region's economic output grows. *Hawke's Bay Today*. https://www.nzherald.co.nz/the-country/news/article.cfm?c_id=16&objectid=12020171

Hayward, B. (2008). 'Nowhere far from the sea': Political challenges of coastal adaptation to climate change in New Zealand. *Political Science*, *60*(1), 47-59.

HBcoast. (2017). *Coastal Hazard Strategy 2120.* Hawke's Bay Regional Council. Retrieved 16 November 2017. from https://www.hbcoast.co.nz/

HBRC. (2014). *Hawke's Bay - New Zealand Global Climate Change & Barrier-Beach Responses*.

HBRC. (2016a). *MATARIKI: Hawke's Bay Regional Economic Development Strategy and Action Plan 2016*. Hawke's Bay Regional Council. https://www.hbrc.govt.nz/hawkes-bay/economic-development/matariki-hbreds/

HBRC. (2016b). *MATARIKI: Hawke's Bay Regional Economic Development Strategy and Action Plan 2016.* Hawke's Bay Regional Council.

HBRC. (2017a). *Hawke's Bay Civil Defence and Emergency Management Group online mapping site.* Hawke's Bay Regional Council. https://hbviewer.intramaps.co.nz/IntraMaps80/?default.html&configId=356ffec6-603c-480b-be35-564fe341f71d&project=Natural%20Hazards&module=Coastal%20Hazards

HBRC. (2017b). Hawke's Bay Civil Defence and Emergency Management Group online mapping site. In. Napier: Hawke's Bay Regional Council.

HBRC. (2018). *Ahuriri Lagoon Hydrograph at Causeway*.

HBRC. (2019). *Design of Groynes and Nourishment - Clifton to Tangoio 2120 Strategy-Stage 4 Wave, Shoreline Evolution and Gravel Barrier Response Modelling. Groynes Design and Cost estimates.*

HBRC. (2020). *Short-term concept design and costing for Pandora Unit Clifton to Tangoio 2120 Coastal Strategy - Design Work stream*.

HBRC, HDC, & NCC. (2017). *Heretaunga Plains Urban Development Strategy 2017.* Hawke's Bay Regional Council.

Heer, B., & Maußner, A. (2009). *Dynamic general equilibrium modeling computational methods and applications.* (2nd ed.). Springer.

Herd, E. (5 December 2018). *Investors welcome the New Zealand Green Investment Finance fund*

Hillebrandt, P. (1985). *Economic Theory and the Construction Industry* (3 ed.). Palgrave Macmillan.

Hino, M., Field, C., & Mach, K. (2017). Managed retreat as a response to natural hazard risk. *Nature Climate Change*, *7*, 364-370.

Hodgson, G. (1998). Evolutionary economics. In J. Davis, D. Hands, & U. Mäki (Eds.), *The handbook of economic methodology.* Edward Elgar.

Hsiang, S., Kopp, R., Jina, A., Rising, J., Delgado, M., Mohan, S., Rasmussen, D., Muir-Wood, R., Wilson, P., Oppenheimer, M., Larsen, K., & Houser, T. (2017). Estimating economic damage from climate change in the United States. *Science*, *356*(6345), 1362-1369. http://science.sciencemag.org/content/sci/356/6345/1362.full.pdf

Huffadine, L. (2018). *How climate change could send your insurance costs soaring*. Stuff. Retrieved 7 January 2018 from https://www.stuff.co.nz/environment/climate-news/98001955/how-climate-change-could-send-your-insurance-costs-soaring

Hughes, T., Barnes, M., Bellwood, D., Cinner, J., Cumming, G., Jackson, J., Kleypas, J., van de Leemput, I., Lough, J., Morrison, T., Palumbi, S., van Nes, E., & Scheffer, M. (2017). Coral reefs in the Anthropocene. *Nature*, *546*(7656), 82-90. http://dx.doi.org/10.1038/nature22901

Imura, M., & Shaw, R. (2010). Eco-community as sustainable coastal relocation in Sri Lanka. In R. Shaw & R. Krishnamurthy (Eds.), *Communities and Coastal Zone Management*.

Infometrics Consulting Limited. (2017a). *Real options analysis of strategies to manage coastal hazard risks* (Prepared for the Hawkes Bay Regional Council., Issue. https://www.hbcoast.co.nz/assets/Document-Library/Other-documents/Real-Options-Analysis-of-Strategies-to-Manage-Coastal-Hazard-Risks-Southern-Units-J-L.pdf

Infometrics Consulting Limited. (2017b). *Real options analysis of strategies to manage coastal hazard risks.* (Prepared for the Hawkes Bay Regional Council., Issue.

Initio. (2019). *5 Tips to insuring in a flood zone.* https://initio.co.nz/resources/guides/5-tips-to-insuring-in-a-flood-zone/

Insurance Council of New Zealand. (2018). *Adapting to climate change needs to be a top priority*. ICNZ. Retrieved 19 March 2018. from https://www.icnz.org.nz/media-resources/media-releases/single/item/adapting-to-climate-change-needs-to-be-a-top-priority/

Insurance Council of New Zealand. (2019a). *The cost of natural disasters in New Zealand.* Retrieved 19 February 2019. from https://www.icnz.org.nz/media-resources/natural-disasters/?L=0

Insurance Council of New Zealand. (2019b). *The real cost of natural disasters*. Retrieved 19 February 2019. from https://www.icnz.org.nz/media-resources/natural-disasters/?L=0

International Finance Corporation. (2016). *Developing domestic capital markets* (UN Issue Brief Series, Issue. https://www.un.org/esa/ffd/wp-content/uploads/2016/01/Developing-domestic-capital-markets_IFC-World-Bank-Group_IATF-Issue-Brief.pdf

IPCC. (1990). Coastal Zone Management. In J. Gilbert & P. Vellinga (Eds.), *IPCC response strategies working group 3 reports*.

IPCC. (2001). *Climate Change 2001: Impacts, Adaptation and Vulnerability* (Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change, Issue. https://library.harvard.edu/sites/default/files/static/collections/ipcc/docs/27_WGIITAR_FINAL.pdf

IPCC. (2012). *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation.* (A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change (IPCC). Issue. https://www.ipcc.ch/site/assets/uploads/2018/03/SREX_Full_Report-1.pdf

IPCC. (2014a). Adaptation planning and implementation. In IPCC Working Group II Contribution to AR (Ed.), *Climate Change 2014: Impacts, Adaptation, and Vulnerability.* Cambridge University Press.

IPCC. (2014b). *Climate change 2014: Synthesis report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* http://ar5-syr.ipcc.ch/

IPCC. (2014c). Technical Summary. In C. Field, V. Barros, D. Dokken, K. Mach, M. Mastrandrea, T. Bilir, M. Chatterjee, K. Ebi, Y. Estrada, R. Genova, B. Girma, E. Kissel, A. Levy, S. MacCracken, P. Mastrandrea, & L. White (Eds.), *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects.*

*Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (pp. 35-94.). Cambridge University Press.

IPCC. (2019). *Special Report on the Ocean and Cryosphere in a Changing Climate*. https://www.ipcc.ch/srocc/

Jevrejeva, S., Grinsted, A., & Moore, J. C. (2014). Upper limit for sea level projections by 2100. *Environmental Research Letters*, *9*(10), 104-108. http://stacks.iop.org/1748-9326/9/i=10/a=104008

Jin, D., Hoagland, P., Au, D., & Qiu, J. (2015). Shoreline change, seawalls, and coastal property values. *Ocean & Coastal Management*, *114*, 185-193. http://www.sciencedirect.com/science/article/pii/S0964569115001787

Johnson, D., Fischbach, J., & Ortiz, D. (2013). Estimating Surge-Based Flood Risk with the Coastal Louisiana Risk Assessment Model. *Journal of Coastal Research*, *67*(sp1), 109-126.

Jones, K. (19 February 2018). Council's sandbagging of a power box outside flood-hit Nelson homes a 'slap in the face'. *Nelson Mail*. https://www.stuff.co.nz/nelson-mail/news/101565582/swamped-nelson-residents-prepare-for-more-woe-as-gita-nears

Kahneman, D., & Tversky, A. (1979). Prospect Theory: An analysis of decision under risk. *Econometrica*, *47*(2), 263-291.

Kakwani, N. (1977). Applications of Lorenz Curves in Economic Analysis. *Econometrica*, *45*(3), 719-727. https://doi.org/10.2307/1911684

Kapmeier, F., & Gonçalves, P. (2018). Wasted paradise? Policies for Small Island States to manage tourism-driven growth while controlling waste generation: the case of the Maldives. *System Dynamics Review*, *34*(1-2), 172-221. https://onlinelibrary.wiley.com/doi/abs/10.1002/sdr.1607

Kartez, J., & Merrill, S. (2016). Climate Adaptation Finance Mechanisms: New Frontiers For Familiar Tools. *Journal of Ocean and Coastal Economics*, *3.*(2).

Kench, P., Ryan, E., Owen, S., Bell, R., Lawrence, J., Glavovic, B., Blackett, P., Becker, J., Schneider, P., Allis, M., Dickson, M., & Rennie, H. (2018). Co-creating Resilience Solutions to Coastal Hazards Through an Interdisciplinary Research Project in New Zealand. *Journal of Coastal Research.*, *85*(SP1), 1496-1500. https://doi.org/https://doi.org/10.2112/SI85-300.1

Keynes, J. (1936). *The General Theory of Employment, Interest and Money*. Macmillan.

King, A., & Bell, R. (2005). *Riskscape New Zealand - A Multihazard Loss Modelling Tool* (Vol. 5).

Knopman, D., & Lempert, R. (2016). *Urban Responses to Climate Change: Framework for Decisionmaking and Supporting Indicators.* https://www.rand.org/pubs/research_reports/RR1144.html

Komar, P. (2007). *Summary Report for Hawke's Bay Regional Council: The Coast of Hawke's Bay: Processes and Erosion Problems*. https://www.napier.govt.nz/assets/Documents/westshore-erosion-summary-07.pdf

Komar, P. (2009). The Oregon Coast experience: Good management but 'bad apples'. In A. Williams & A. Micallef (Eds.), *Beach management: Principles and practice*. Earthscan.

Komar, P. (2010). Shoreline evolution and management of Hawke's Bay, New Zealand: Tectonics, coastal processes and human impacts. *Journal of Coastal Research*, *26*(1), 143-156.

Komar, P. (2013). Earth's Changing Climate and Coastal Hazards: the U.S. Pacific Northwest and Hawke's Bay, New Zealand. New Zealand Coastal Society, Hokitika, New Zealand.

Komar, P., & Harris, E. (2014a). *Hawke's Bay, New Zealand: Global climate change and barrier beach responses* (Prepared for the Hawke's Bay Regional Council, Issue. Hawke's Bay Regional Council. https://www.hbcoast.co.nz/assets/Document-Library/Technical-Documents/Hawkes-Bay-Summary-Report.pdf

Komar, P., & Harris, E. (2014b). *Hawke's Bay, New Zealand: Global climate change and barrier beach responses.* (Prepared for the Hawke's Bay Regional Council, Issue. Hawke's Bay Regional Council.

Kourgialas, N., & Karatzas, G. (2011). Flood management and a GIS modelling method to assess flood-hazard areas: A case study. *Hydrological Sciences Journal*, *56*(2), 212-225. http://dx.doi.org/10.1080/02626667.2011.555836

Kucherenko, S., Albrecht, D., & Saltelli, A. (2015). *Exploring multi-dimensional spaces: A Comparison of Latin Hypercube and Quasi Monte Carlo Sampling Techniques.* Cornell University. Retrieved 30 June 2019 from https://arxiv.org/abs/1505.02350v1

Kwadijk, J., Haasnoot, M., Mulder, J., Hoogvliet, M., Jeuken, A., van der Krogt, R., van Oostrom, N., Schelfhout, H., van Velzen, E., van Waveren, H., & de Wit, M. (2010). Using adaptation tipping points to prepare for climate change and sea level rise: a case study in the Netherlands. *Wiley Interdisciplinary Reviews: Climate Change*, *1*(5), 729-740. http://dx.doi.org/10.1002/wcc.64

Kwakkel, J., Haasnoot, M., & Walker, W. (2012). Computer assisted dynamic adaptive policy design for sustainable water management in river deltas in a changing environment.

Kwakkel, J., Haasnoot, M., & Walker, W. (2015). Developing dynamic adaptive policy pathways: a computer-assisted approach for developing adaptive strategies for a deeply uncertain world. *Climatic Change*, *132*(3), 373-386.

Lamperti, F., Dosi, G., Napoletano, M., Roventini, A., & Sapio, A. (2018). Faraway, so close: Coupled climate and economic dynamics in an agent-based integrated assessment model. *Ecological Economics*, *150*, 315-339. http://www.sciencedirect.com/science/article/pii/S0921800917314623

Lang, M., Ouarda, T., & Bobée, B. (1999). Towards operational guidelines for over-threshold modeling. *Journal of Hydrology*, *225*(3–4), 103-117. http://www.sciencedirect.com/science/article/pii/S0022169499001675

Lawrence, J., Boston, J., Bell, R., Olufson, S., Kool, R., Hardcastle, M., & Stroombergen, A. (2020). Implementing Pre-Emptive Managed Retreat: Constraints and Novel Insights. *Current Climate Change Reports*. https://doi.org/doi.org/10.1007/s40641-020-00161-z

Lawrence, J., Sullivan, F., Lash, A., Ide, G., Cameron, C., & McGlinchey, L. (2013). Adapting to changing climate risk by local government in New Zealand: institutional practice barriers and enablers. *Local Environment*, *20*(3), 298-320. http://dx.doi.org/10.1080/13549839.2013.839643

Lee, J. (4 February 2018). West Coast storm: homeless residents and rubbish flowing into the sea. *The Press*. https://www.stuff.co.nz/the-press/news/west-coast/101159278/west-coast-storm-homeless-residents-and-rubbish-flowing-into-the-sea

Lempert, R. (2007). *Creating Constituencies for Long-term, Radical Change* (John Brademas Center for the Study of Congress, Issue.

Lempert, R., Kalra, N., Peyraud, S., Mao, Z., Bach, S., Tan, S., Cira, D., & Lotsch, A. (2013). *Ensuring Robust Flood Risk Management in Ho Chi Minh City.* https://doi.org/10.1596/1813-9450-6465

Lindgren, M. (2003). *Scenario planning : the link between future and strategy*. New York : Palgrave Macmillan 2003.

LINZ. (2012). *Tide level information for surveyors.* Land Information New Zealand. Retrieved 12 September 2012 from http://www.linz.govt.nz/geodetic/datums-projections-heights/vertical-datums/tidal-level-information-for-surveyors

LINZ. (2018). *Data Service.* New Zealand Government. http://data.linz.govt.nz/

Local Government New Zealand. (2019). *Vulnerable: the quantum of local government infrastructure exposed to sea level rise*.

Long, H. (29 August 2017). Where Harvey is hitting hardest, 80 percent lack flood insurance. *The Washington Post*. https://www.washingtonpost.com/news/wonk/wp/2017/08/29/where-harvey-is-hitting-hardest-four-out-offive-homeowners-lack-flood-insurance/?utm_term=.d23e9f7cf65d.

Longworth, E. (19 June 2017). *Alarm bells sounded over gaps in disaster resilience* [Interview]. Radio New Zealand. http://www.radionz.co.nz/national/programmes/ninetonoon/audio/201848001/alarm-bells-sounded-over-gaps-in-disaster-resilience

Longworth, E. (2017, 19 June 2017). *Alarm bells sounded over gaps in disaster resilience.* [Interview]. Radio New Zealand. http://www.radionz.co.nz/national/programmes/ninetonoon/audio/201848001/alarm-bells-sounded-over-gaps-in-disaster-resilience

Losada, I., & Diaz-Simal, P. (2014). Adaptation in coastal areas. In A. Markandya, I. Galarraga, & E. Sainz de Marieta (Eds.), *Routledge handbook of the economics of climate change adaptation.* Routledge.

Lyneis, J. (2000). System dynamics for market forecasting and structural analysis. *System Dynamics Review*, *16*(1), 3-25. https://doi.org/10.1002/(sici)1099-1727(200021)16:1<3::Aid-sdr183>3.0.Co;2-5

MacDonald, N. (2020). *Moving day at Matatā - the end of one family's fight against managed retreat*. Stuff Limited. Retrieved 20 February 2021 from https://www.stuff.co.nz/environment/123216408/moving-day-at-matat--the-end-of-one-familys-fight-against-managed-retreat

Macharis, C. (2000). Hybrid modeling: System dynamics combined with multi-criteria analysis. *System Dynamics Society*. http://www.systemdynamics.org/conferences/2000/PDFs/macharis.pdf

Macmillan, A. (2012). *Intervening in the trip to work: A system dynamics approach to commuting and public health.* University of Auckland]. Auckland. https://researchspace.auckland.ac.nz/bitstream/handle/2292/19500/whole.pdf

Magnusson, L., & Ottosson, J. (1997). *Evolutionary economics and path dependence.* Edward Elgar 1997.

Mahanga E Tu Inc v Hawkes Bay Regional Council, Thompson Judge, Clark Judge, Buchanan Commissioner (Environment Court 2014).

Manning, M., Lawrence, J., King, D., & Chapman, R. (2015). Dealing with changing risks: A New Zealand perspective on climate change adaptation. *Regional Environmental Change*, *15*(4), 581-594. http://dx.doi.org/10.1007/s10113-014-0673-1
Maoate-Cox, D. (14 June 2020). The House In *How the Government borrows money*. Radio New Zealand. https://www.rnz.co.nz/national/programmes/the-house/audio/2018750436/how-the-government-borrows-money
Market Economics. (2017a). *Economic impact of the 2016 Kaikoura earthquake: A report prepared for the Ministry of Transport.* (17022017). Market Economics.
Market Economics. (2017b). *Future demand for construction workers: Projections from the National Construction Occupations Model*.
Market Economics. (2021). *Spatial MERIT Model*. https://www.merit.org.nz/merit/spatial-merit-model/
Martin, H., & Fonseka, D. (01 February 2018). Sting in the tail for Auckland as passing storm is accompanied by king tide. *Stuff*. https://www.stuff.co.nz/auckland/local-news/101067611/flooding-closes-aucklands-tamaki-dr
Matrix Software. (2014). *Agile development methodology*. Retrieved 6 October 2017 from http://matrix-soft.org/agile-development-methodology/
Maven Consulting Ltd. (2017). *Cape coast area coastal hazards social impact analysis and valuation.* www.consultmaven.co.nz
McBean, G. (2017). Building Resilience. *International Innovation.* WWW.RESEARCHMEDIA.EU
McDonald, G. (2005). *Integrating economics and ecology: A systems approach to sustainability in the Auckland region.* Massey University]. Palmerston North, NZ.
McDonald, G., Buxton, R., & Fenwick, T. (5 November 2014). Modelling infrastructure interdependencies. National Lifelines Forum, Wellington.
McDonald, G., & McDonald, N. (2018). *Economy-wide Impacts of Proposed Policy Options for the TANK Catchments. Prepared for Hawke's Bay Regional Council*.
McDonald, G., van Delden, H., van den Belt, M., Thornton, M., Solomon, R., & Huser, B. (2015). *Auckland and Wellington Integrated Scenario Explorers (ISE), Technical Specifications Version 1.0*.
McDonald, N., Brown, C., & Chang-Richards, A. (2020). *RISKFLOW: A System Dynamics Model of the New Zealand Construction Indsutry. A technical report prepared for BRANZ*. https://www.resorgs.org.nz/wp-content/uploads/2020/12/RISKFLOW_Technical_Report.pdf
McDonald, N., & McDonald, G. (2020). Towards a Dynamic Equilibrium-Seeking Model of a Closed Economy. *Systems*, *8*, 42. https://doi.org/10.3390/systems8040042
McNeilly, H., & Daly, M. (4 June 2015). Flooding wreaks havoc in Dunedin. *Stuff*. https://www.stuff.co.nz/national/69063192/flooding-wreaks-havoc-in-dunedin
Meadows, D. (1989). System Dynamics meets the press. *System Dynamics Review*, *5*(1), 69-80.
Meadows, D. H., Meadows, D. L., & Behrens, J. (1972). *The Limits to growth: A report for The Club of Rome's project on the predicament of mankind.* Universe Books.
Mercer. (2019). *Investing in a Time of Climate Change*. https://www.mmc.com/content/dam/mmc-web/insights/publications/2019/apr/FINAL_Investing-in-a-Time-of-Climate-Change-2019-Full-Report.pdf
Merrill, S. (2015). Using Future Benefits to Set Conservation Priorities for Wetlands. *Journal of Ocean and Coastal Economics*, *2*(1). https://doi.org/http://dx.doi.org/10.15351/2373-8456.1013
Middleton, D. (2016). *Risk financing in local government*. Local Government New Zealand. https://www.lgnz.co.nz/assets/9190f8591f/42600-LGNZ-Risk-Financing-Guide-Final-WEB.pdf
Miller, R. (2009). *Input-output analysis foundations and extensions.* (2nd ed.). Cambridge University Press.
Mills, M., Leon, J., Saunders, M., Bell, J., Liu, Y., O'Mara, J., Lovelock, C., Mumby, P., Phinn, S., Possingham, H., Tulloch, V., Mutafoglu, K., Morrison, T., Callaghan, D., Baldock, T., Klein, C., & Hoegh-Guldberg, O. (2016). Reconciling Development and Conservation under Coastal Squeeze from Rising Sea Level: Planning for coastal squeeze. *Conservation letters*, *9*(5), 361-368. https://doi.org/10.1111/conl.12213
Milly, P., Betancourt, J., Falkenmark, M., Hirsch, R., Kundzewicz, Z., Lettenmaier, D., & Stouffer, R. (2008). Stationarity Is Dead: Whither Water Management? *Science*, *319*(5863), 573-574.
Ministry for the Environment. (2004). *Economic instruments for managing water quality in New Zealand.* https://www.mfe.govt.nz/publications/fresh-water/economic-instruments-managing-water-quality-new-zealand

Ministry for the Environment. (2017). *Coastal hazards and climate change: Guidance for local government.* New Zealand Government.
Ministry for the Environment. (2019). *Household consumption expenditure indicator update*. New Zealand Government. Retrieved 24 November 2019 from https://www.mfe.govt.nz/publications/environmental-reporting/household-consumption-expenditure-indicator-update/household
MIT. (1998). *Principles of Macroeconomics*. MIT. Retrieved 4 April 2020 from http://web.mit.edu/14.02/www/S98/ans2.html
Mitchell, C. (24 July 2017). Alive; the relentless sea is biting chunks out of a seaside town. *Stuff*. https://interactives.stuff.co.nz/2017/04/eaten-alive/
Moftakhari, H., Salvadori, G., AghaKouchak, A., Sanders, B., & Matthew, R. (2017). Compounding effects of sea level rise and fluvial flooding. *Proceedings of the National Academy of Sciences of the United States of America*, *114*(37), 9785-9790. https://doi.org/10.1073/pnas.1620325114
Moss, D. (2002). *When all else fails: Government as the ultimate risk manager.* Harvard University Press.
Moss, R., Edmonds, J., Hibbard, K., Manning, M., Rose, S., van Vuuren, D., Carter, T., Emori, S., Kainuma, M., Kram, T., Meehl, G., Mitchell, J., Nakicenovic, N., Riahi, K., Smith, S., Stouffer, R., Thomson, A., Weyant, J., & Wilbanks, T. (2010). The next generation of scenarios for climate change research and assessment. *Nature*, *463*(7282), 747-756. http://dx.doi.org/10.1038/nature08823
Mullin, M., Smith, M., & McNamara, D. (2019). Paying to save the beach: Effects of local finance decisions on coastal management. *Climatic Change*, *152*(2), 275-289. https://doi.org/10.1007/s10584-018-2191-5
Murray, C., McDonald, G., & Cronin, S. (2015). Interpreting Auckland's volcanic governance through an institutional lens. *Natural Hazards*, *75*(1), 441-464. https://doi.org/10.1007/s11069-014-1340-z
Napier City Council. *2016/17 Annual Report Summary for the period 1 July 2016 to 30 June 2017.* https://www.napier.govt.nz/assets/Document-Library/Reports/Annual-Reports/2017-11-29-AR-Summary-FINAL-with-Audit-NZ.pdf
Napier City Council. (2017a). *Ahuriri Estuary and Coastal Edge Masterplan*.
Napier City Council. (2017b). *Government Valuations 2017*.
Napier City Council. (2018). *Development and financial contributions policy.*
Napier City Council. (2020). *Economic Development*. Retrieved 14 February 2020 from https://www.napier.govt.nz/napier/business/economic-development/
Nelson, R., & Winter, S. (1982). *An evolutinoary theory of economic change.* Harvard University Press.
Civil Defence Emergency Management Act 2002.
Earthquake Commission Act 1993.
Local Government Act 2002.
New Zealand Coastal Policy Statement 2010.
Resource Management Act 1991.
Town And Country Planning Act 1953. http://www.nzlii.org/nz/legis/hist_act/tacpa19531953n91320.pdf
New Zealand Government. (10 February 2021). *RMA to be repealed and replaced* https://www.beehive.govt.nz/release/rma-be-repealed-and-replaced
New Zealand Government. (2010). *New Zealand Coastal Policy Statement 2010.*
New Zealand Government. (2017). *Coastal hazards and climate change: Guidance for local government.*
New Zealand Treasury. (2015a). *Guide to Social Cost Benefit Analysis*. https://www.treasury.govt.nz/sites/default/files/2015-07/cba-guide-jul15.pdf
New Zealand Treasury. (2015b). *New Zealand's future natural disaster insurance scheme: Proposed changes to the Earthquake Commission Act 1993.*
Nicholls, R., & Cazenave, A. (2010). Sea-Level Rise and Its Impact on Coastal Zones. *Science*, *328*(5985), 1517-1520.
NIWA. (2015). *National and regional risk exposure in low-lying coastal areas: Areal extent, population, buildings and infrastructure* (Prepared for the Parliamentary Commissioner for the Environment., Issue. https://www.pce.parliament.nz/media/1384/national-and-regional-risk-exposure-in-low-lying-coastal-areas-niwa-2015.pdf
NIWA. (2017a). *Managing and adapting to coastal erosion at Carters Beach: Prepared for West Coast Regional Council.*
NIWA. (2017b). *Riskscape Spatial Vulnerability Assessment Hawke's Bay Database*.
NIWA. (2017c). *Riskscape.* Retrieved 9 May 2017 from https://www.riskscape.org.nz/

NIWA. (2019). *Coastal Flooding Exposure Under Future Sea-level Rise for New Zealand.* NIWA.
NIWA MWH GNS and BRANZ. (2012). *Impacts of Climate Change on Urban Infrastructure and the Built Environment: Toolbox Handbook*. Retrieved 21 August 2013 from http://www.niwa.co.nz/climate/
Noy, I., & Townsend, W. (2020). Paying a Price of Climate Change: Who Pays for Managed Retreats? *Current Climate Change Reports*. https://doi.org/10.1007/s40641-020-00155-x
Nunns, P. (2019). *The causes and economic consequences of rising regional housing prices in New Zealand* (Publication Number 5. Centre for Applied Research in Economics) University of Auckland]. Auckland, NZ. https://cdn.auckland.ac.nz/assets/business/about/our-research/research-institutes-and-centres/CARE/the-causes-and-economic-consequences-of-rising-regional-housing-prices-in-new-zealand.pdf
O'Brien, K., Eriksen, S., Nygaard, L., & Schjolden, A. (2007). Why different interpretations of vulnerability matter in climate change discourses. *Climate Policy*, *7*(1), 73-88. http://www.tandfonline.com/doi/abs/10.1080/14693062.2007.9685639
Ojea, E. (2014). Ecosystem-Based Adaptation. In *Routledge Handbook of the Economics of Climate Change Adaptation*. Routledge. https://doi.org/10.4324/9780203095201.ch9
Oliver-Smith, A. (2006). *Understanding Katrina: Disasters and Forced Migration in the 21st Century*. Retrieved 20 June 2021 from https://items.ssrc.org/understanding-katrina/disasters-and-forced-migration-in-the-21st-century/
Omaha Beach Community Inc. (2017). *Information about Omaha Beach, New Zealand*. Retrieved 23 October 2017 from https://omahabeach.co.nz/about/
OneRoof. (2019). *OneRoof Property Report: Is your suburb hot or not?* https://www.oneroof.co.nz/news/oneroof-property-report-december-2019-is-your-suburb-hot-or-not-36969
Owen, S., Lawrence, J., Ryan, E., Kench, P., Bell, R., Rennie, H., Blackett, P., & Schneider, P. (2018). Anticipating staged managed retreat at the coastal margins. *Planning Quarterly*(209), 8-11.
Pacific Region Infrastructure Facility. (2017). *Guidance for coastal protection works in Pacific Island countries.*
Pandas Development Team. (2014). *pandas.DataFrame.loc*. Retrieved 12 March 2019 from https://pandas.pydata.org/pandas-docs/stable/reference/api/pandas.DataFrame.loc.html
Parker, T. (19 May 2017). Locations prone to flooding, erosion harder or pricier to get insurance in. *The New Zealand Herald*. https://www.nzherald.co.nz/personal-finance/news/article.cfm?c_id=12&objectid=11858309
Partridge, M., & Rickman, D. (2010). Computable General Equilibrium (CGE) Modelling for Regional Economic Development Analysis. *Regional Studies*, *44*(10), 1311-1328. https://doi.org/10.1080/00343400701654236
Patterson, M. G., McDonald, G., Golubiewski, N. E., Forige, V. E., & Jollands, N. A. (2006). Climate Change Impacts on Regional Development and Sustainability: An Analysis of New Zealand Regions. In M. Ruth (Ed.), *Smart Growth and Climate Change: Regional Development, Infrastructure and Adaptation*. Edward Elgar.
Peacock, W., & Ragsdale, A. (1997). Social systems, ecological networks and disasters: towards a socio-political ecology of disasters. In W. Peacock, B. Morrow, & H. Gladwin (Eds.), *Hurricane Andrew: Ethnicity, gender and the sociology of disasters* (pp. 20-35.). Routledge.
Pearce, W., Brown, B., Nerlich, B., & Koteyko, N. (2015). Communicating climate change: conduits, content, and consensus. *WIREs Climate Change*, *6*(6), 613-626. https://doi.org/https://doi.org/10.1002/wcc.366
Peart, R. (2009). *Castles in the Sand: What's happening to the New Zealand coast?* Craig Potton.
Peck, A., Neuwirth, C., & Simanovic, S. (2014). *Coupling System Dynamics with Geographic Information Systems: CCaR Project Report.* (Water Resources Research Report, Issue.
Penning-Rowsell, E., Green, C., Thompson, P., Coker, A., Tunstall, S., Richards, C., & Parker, D. (1992). *The economics of coastal management: a manual of benefit assessment techniques*. Belhaven Press.
Porter, M. (1985). *Competitive Strategy: Techniques for Analysing Industries and Companies*. Free Press.
Proops, J. (1989). Ecological economics: Rationale and problem areas. *Ecological Economics*, *1*(1), 59-76.
Pyka, A., & Hanusch, H. (2006). *Applied evolutionary economics and the knowledge economy.* Edward Elgar.
Python Software Foundation. (2017). *Python documentation*. In (Version 3.6.10) https://docs.python.org/3/
Radio New Zealand. (2020). *Hawke's Bay landowners fighting urban development*. New Zealand Government. Retrieved 13 July 2020 from https://www.rnz.co.nz/national/programmes/morningreport/audio/2018754658/hawke-s-bay-landowners-fighting-urban-development

Ramachandra, T., Geekiyanage, D., & Perera, S. (02 July 2017). *Study on the Application of Economies of Scale in the Construction Industry: The Sri Lankan Perspective.* The 6th World Construction Symposium 2017: What's New and What's Next in the Built Environment Sustainability Agenda?, Colombo, Sri Lanka.

Ramirez, R., Lang, T., & Peterson, G. (2021). Seven Sure-fire Ways to Do Scenario Planning Badly: A Guide to Poor Practice. *Long Range Planning*, *Announcements*. https://www.journals.elsevier.com/long-range-planning/announcements/seven-sure-fire-ways-to-do-scenario

Ramirez, R., & Wilkinson, A. (2016). *Strategic Reframing: The Oxford Scenario Planning Approach.* Oxford University Press.

Ramm, T., Watson, S., & White, C. (2018). Describing adaptation tipping points in coastal flood risk management. *Computers, Environment and Urban Systems*, *69*, 74-86. https://doi.org/https://doi.org/10.1016/j.compenvurbsys.2018.01.002

Randers, J. (2012). *2052 : a global forecast for the next forty years.* Chelsea Green Publishers.

Ranger, N., Reeder, T., & Lowe, J. (2013). Addressing 'deep' uncertainty over long-term climate in major infrastructure projects: Four innovations of the Thames Estuary 2100 Project. *European Journal of Decision Process*, *1*, 233-262.

Raybaut, P. (2009). *Spyder: The Scientific Python Development Environment*. In (Version 3.3.6) https://www.spyder-ide.org/

Reese, S., & Ramsay, D. (2010). *Riskscape: Flood fragility methodology.* NIWA.

Reguero, B., Beck, M., Schmid, D., Stadtmüller, D., Raepple, J., Schüssele, S., & Pfliegner, K. (2020). Financing coastal resilience by combining nature-based risk reduction with insurance. *Ecological Economics*, *169*, 106487. https://doi.org/https://doi.org/10.1016/j.ecolecon.2019.106487

Reisinger, A., Lawrence, J., Hart, G., & Chapman, D. (2015). From coping to resilience: The role of managed retreat in highly developed coastal regions of New Zealand. In B. Glavovic, M. Kelly, R. Kay, & A. Travers (Eds.), *Climate change and the coast: Building resilient communities* (pp. 285-310). CRC Press.

Rezny, L., & Bureš, V. (2018). Adding Feedbacks and Non-Linearity to the Neoclassical Growth Model: A New Realm for System Dynamics Applications. *Systems*, *6*, 8. https://doi.org/10.3390/systems6020008

Robichaux, L., Kench, P., & Owen, S. (2019). How Might Engineers Minimize the Implementation Gap in Coastal Risk Management? In *Coastal Management 2019* (pp. 619-632). https://doi.org/10.1680/cm.65147.619

Rosser, J. (1991). The dialogue between the economic and the ecological theories of evolution. *Journal of Economic Behaviour and Organisation*, *17*, 195-215.

Rosser, J. (2011). *Complex evolutionary dynamics in urban-regional and ecologic-economic systems from catastrophe to chaos and beyond.* Springer c2011.

Royal Society of New Zealand. (1973). *Limits to growth? a study*. Royal Society 1973.

Ruth, M., & Hannon, B. (1997). *Modelling dynamic economic systems.* Springer-Verlag.

Rutledge, D., Cameron, M., Elliott, S., Fenton, J., Huser, B., McBride, G., McDonald, G., O'Connor, M., Phyn, D., Poot, J., Price, R., Scrimgeour, F., Small, B., Tait, A., Van Delden, H., Wedderburn, M., & Woods, R. (2008). Choosing Regional Futures: Challenges and choices in building integrated models to support long-term regional planning in New Zealand. *Regional Science Policy and Practice*, *1*(1), 185-207. https://doi.org/10.1111/j.1757-7802.2008.00006.x

Sajjad, M., & Chan, J. (2019). Risk assessment for the sustainability of coastal communities: A preliminary study. *Science of The Total Environment*, *671*, 339-350. https://doi.org/https://doi.org/10.1016/j.scitotenv.2019.03.326

Sawalha, S., & AbdelNabi, H. (2020). Agile Software Development: Methodologies and Trends. *International Journal of Interactive Mobile Technologies*, *14*(11), 246-270. https://online-journals.org/index.php/i-jim/article/view/13269

Schneider, P., Lawrence, J., Glavovic, B., Ryan, E., & Blackett, P. (2020). A rising tide of adaptation action: Comparing two coastal regions of Aotearoa-New Zealand. *Climate Risk Management*, *30*, 100244. https://doi.org/https://doi.org/10.1016/j.crm.2020.100244

Scouler, A. (2010). *The challenges of coastal setbacks in New Zealand.* University of Otago]. Dunedin.

Secretariat of the Convention on Biological Diversity. (2009). *Connecting biodiversity and climate change mitigation and adaptation: Report of the second ad hoc technical expert group on biodiversity and climate change.*

Shand, T., Reinen-Hamill, R., Kench, P., Ivamy, M., Knook, P., & Howse, B. (2015). *Methods for probabilistic coastal erosion hazard assessment.* 22nd Australasian Coastal and Ocean Engineering Conference and the 15th

Australasian Port and Harbour Conference, Auckland, New Zealand. http://search.informit.com.au.ezproxy.auckland.ac.nz/documentSummary
Sharpe, M. (1 November 2020). Mexted finally pushes beach plan past rivals. *Dominion Post*. https://www.stuff.co.nz/dominion-post/10125241/Mexted-finally-pushes-beach-plan-past-rivals
Sharpe, M. (28 May 2019). Plan to make Napier and Hastings ratepayers pay $30 a year for defences against coastal erosion. *Stuff*. https://www.stuff.co.nz/environment/climate-news/113059841/plan-to-make-napier-and-hastings-ratepayers-pay-30-a-year-for-defences-against-coastal-erosion?fbclid=IwAR1Q6q-gAWrQMrSNVh3oHwEpA0DkfoE8vMsFHIKAuFVY7Da1EeQPdVgeXeY
Sharpe, M. (31 January 2020). Country's first fund to tackle sea-level rise in limbo after councils can't reach agreement on funding. *Stuff*. https://www.stuff.co.nz/environment/climate-news/119181674/countrys-first-fund-to-tackle-sealevel-rise-in-limbo-after-councils-cant-reach-agreement-on-funding
Silverman, B. W. (1986). *Density estimation for statistics and data analysis*. Chapman and Hall.
Simulistics Limited. (2017). *Working with submodels : Multiple-instance submodels : Special-purpose submodels*. Retrieved 8 August 2018 from https://www.simulistics.com/help/submodels/multiple/special.htm
Smith, C. (2019). *Kiwi beach properties rising in value - and defying climate change fears.* One Roof. Retrieved 7 March 2019 from https://www.oneroof.co.nz/news/beach-or-bust-how-are-coastal-properties-faring-35981
Smith, N., & McDonald, G. (2016a). *MERIT: A short overview document. Prepared for New Zealand Transport Agency.* Market Economics.
Smith, N., & McDonald, G. (2016b). *MERIT: short overview document. Prepared for New Zealand Transport Agency.*
Smith, N., McDonald, G., & Harvey, E. (2016). *Dynamic Economic Model: A technical report prepared under the Economics of Resilient Infrastructure Programme.* Market Economics.
Smith, N., Orchiston, C., Harvey, E., Kim, J., & Brown, C. (2016). *Scoping tourism dynamics post-quake: A module for MERIT prepared for QuakeCORE and NZ Transport Agency.* Market Economics.
Stam, E. (2006). A process model of location change in entrepreneurial firms: an evolutionary perspective. In A. Pyka & H. Hanusch (Eds.), *Applied Evolutionary Economics and the Knowledge Economy* (pp. 143-165). Edward Elgar.
StatsNZ. (2006). *New Zealand Standard Industry Output Categories Classification Tables.* New Zealand Government. http://archive.stats.govt.nz/browse_for_stats/industry_sectors/anzsic06-industry-classification/tables.aspx
StatsNZ. (2007). *National Accounts Input-Output Tables: year ended March 2007.* New Zealand Government. http://archive.stats.govt.nz/browse_for_stats/economic_indicators/NationalAccounts/input-output%20tables.aspx
StatsNZ. (2013a). *Hawke's Bay Region Business Directory Data: Multi-regional input-output tables.* New Zealand Government. http://archive.stats.govt.nz
StatsNZ. (2013b). *National Accounts Input-Output Tables: Year ended March 2013.* New Zealand Government. http://archive.stats.govt.nz/browse_for_stats/economic_indicators/NationalAccounts/input-output%20tables-2013.aspx
StatsNZ. (2016). *Household Expenditure Statistics: Year ended June 2016.* New Zealand Government. http://archive.stats.govt.nz/browse_for_stats/people_and_communities/Households/HouseholdExpenditureStatistics_HOTPYeJun16/Commentary.aspx
StatsNZ. (2018a). *Household net worth statistics: Year ended June 2018*. New Zealand Government. Retrieved 5 January 2021 from https://www.stats.govt.nz/information-releases/household-net-worth-statistics-year-ended-june-2018
StatsNZ. (2018b). *National Accounts (industry production and investment): Year ended March 2018* New Zealand Government. https://www.stats.govt.nz/information-releases/national-accounts-industry-production-and-investment-year-ended-march-2018
StatsNZ. (2019a). *Subnational population estimates*. New Zealand Government. Retrieved 28 May 2019 from http://nzdotstat.stats.govt.nz/wbos/Index.aspx?DataSetCode=TABLECODE7501&_ga=2.193915631.35004856.1559012559-695083271.1509656097
StatsNZ. (2019b). *Which industries contributed to New Zealand's GDP?* New Zealand Government. https://www.stats.govt.nz/experimental/which-industries-contributed-to-new-zealands-gdp
StatsNZ. (2020a). *Household income and housing-cost statistics: Year ended June 2020.* https://www.stats.govt.nz/information-releases/household-income-and-housing-cost-statistics-year-ended-june-2020

StatsNZ. (2020b). *Infoshare* New Zealand Government. http://archive.stats.govt.nz/infoshare/
StatsNZ. (2020c). *Infoshare.* New Zealand Government. http://archive.stats.govt.nz/infoshare/
StatsNZ. (2020d). *Regional Gross Domestic Product: Year ended March 2020*. https://www.stats.govt.nz/information-releases/regional-gross-domestic-product-year-ended-march-2020
StatsNZ. (2021). *Unemployment Rate*. https://www.stats.govt.nz/indicators/unemployment-rate
Stave, K. (2002). Using system dynamics to improve public participation in environmental decisions. *System Dynamics Review*, *18*(2), 139-167.
Stephenson, C. (2010). *Impacts framework for natural disasters and fire emergencies.*
Sterman, J. (2001). System dynamics modelling: Tools for learning in a complex world. *California Management Review*, *43*(4), 8.
Sterman, J. (2013). *Introduction to Systems Dynamics* MIT. https://www.youtube.com/watch?v=AnTwZVviXyY
Stern, N. (2007). *The economics of climate change : The Stern Review*. Cambridge University Press.
Stern, N., Jotzo, F., & Dobes, L. (2014). *Climate change and the world economy: A review article.* (9781781009185). http:///www.elgaronline.com/Research_Reviews/9781781009185/intro.xml
Storey, B., Noy, I., Townsend, W., Kerr, S., Salmon, R., Middleton, D., Filippova, O., & James, V. (2017). *Insurance, housing and climate adaptation: Current knowledge and future research.* (Motu Economic and Public Policy Research., Issue. https://www.motu.nz/our-research/environment-and-resources/climate-change-impacts/insurance-housing-and-climate-adaptation-current-knowledge-and-future-research/
Sugiyama, M., Nicholls, R., & Athanasios, V. (2008). *Estimating the economic cost of sea level rise.* (156). http://web.mit.edu/globalchange/www/MITJPSPGC_Rpt156.pdf
Tapley, K. (2016). *GBCNZ: Green Bond market overview*. https://www.nzgbc.org.nz/Attachment?Action=Download&Attachment_id=684
Proposed Plan Change No. 22 [NZEnvC 47], (2011).
Taylor-Hochberg, A. (2017). *Creative financing for managed retreat*. Retrieved 20 April 2019 from http://www.climigration.org/blog/2017/11/30/how-novel-financing-strategies-can-help-make-sense-of-managed-retreat
The Climate Change Commission. (2021). *Ināia tonu nei: A low emissions future for Aotearoa*. https://ccc-production-media.s3.ap-southeast-2.amazonaws.com/public/Inaia-tonu-nei-a-low-emissions-future-for-Aotearoa/Inaia-tonu-nei-a-low-emissions-future-for-Aotearoa.pdf
The Economist. (2017). *How government policy exacerbates hurricanes like Harvey*. The Economist Group Limited. Retrieved 1 September 2017 from https://www.economist.com/news/leaders/21727898-if-global-warming-were-not-enough-threat-poor-planning-and-unwise-subsidies-make-floods?
The Economist. (2019). Finding Phillips. *The Economist*, *433*(S4-S6).
The New Zealand Infrastructure Commission Te Waihanga. (2021). *He Tūāpapa ki te Ora - Infrastructure for a Better Future: Aotearoa New Zealand Infrastructure Strategy Consultation Document*. https://infracom.govt.nz/assets/Uploads/Infrastructure-Strategy-Consultation-Document-June-2021.pdf
The University of Auckland. (2017). *Auckland University Database: New Zealand house sales data.*
Thrush, S. F., Townsend, M., Hewitt, J. E., Davies, K., Lohrer, A. M., Lundquist, C., & Cartner, K. (2013). *The many uses and values of estuarine ecosystems*.
Tobin, G. (1999). Sustainability and community resilience: The holy grail of hazards planning? *Global Environmental Change Part B: Environmental Hazards*, *1*(1), 13-25. http://dx.doi.org/10.3763/ehaz.1999.0103
Tombs, B., & France-Hudson, B. (2018). Climate Change Compensation; An unavoidable discussion. *Policy Quarterly*, *14*(4), 50-58.
Tonkin and Taylor. (2016). *Hawke's Bay Coastal Strategy: Coastal Risk Assessment*. https://www.hbrc.govt.nz/assets/Document-Library/Reports/Coastal-Hazards/2016.SHAF.Risk-Assessment-Report.R5.pdf
Tonkin and Taylor. (2019). *Hawke's Bay Coastal Hazard Risk Strategy: A Case Study.* Retrieved 16 November 2019 from https://www.tonkintaylor.co.nz/projects/all-projects/case-study-hawke-s-bay-coastal-hazard-risk-strategy/
Tribbia, J., & Moser, S. C. (2008). More than information: What coastal managers need to plan for climate change. *Environmental Science & Policy*, *11*(4), 315-328. http://www.sciencedirect.com/science/article/pii/S1462901108000130

Trucano, T., Swiler, L., Igusa, T., Oberkampf, W., & Pilch, M. (2006). Calibration, validation, and sensitivity analysis: What's what. *Reliability Engineering & System Safety*, *91*(10), 1331-1357. https://doi.org/https://doi.org/10.1016/j.ress.2005.11.031

Turner, R., Bateman, I., & Adger, W. (2001). Ecological economics and coastal zone ecosystems' values: An overview. In R. Turner, I. Bateman, & W. Adger (Eds.), *Economics of coastal and water resources valuing environmental functions.* (pp. 1-43). Springer Science and Business Media.

Turner, R., Burgess, D., Hadley, D., Coombes, E., & Jackson, N. (2007). A cost–benefit appraisal of coastal managed realignment policy. *Global Environmental Change*, *17*(3), 397-407. https://doi.org/https://doi.org/10.1016/j.gloenvcha.2007.05.006

Turner, R. K. (2000). Integrating natural and socio-economic science in coastal management. *Journal of Marine Systems*, *25*(3), 447-460. http://www.sciencedirect.com/science/article/pii/S0924796300000336

van Delden, H. (2009). *Lessons learnt in the development, implementation and use of Integrated Spatial Decision Support Systems.* 18th World IMACS/MODSIM Congress, Cairns, Australia 13-17 July 2009. http://mssanz.org.au/modsim09

van den Belt, M., & Cole, A. (2014). *Ecosystem goods and services in marine protected areas.*

Van den Belt, M., McCallion, A., Wairepo, S., Hardy, D., Hale, L., & Berry, M. (2012). *Mediated modelling of coastal ecosystem services: A case study of Te Awanui Tauranga Habour*. https://www.researchgate.net/publication/271386717_Mediated_Modelling_of_Coastal_Ecosystem_Services_A_Case_Study_of_Te_Awanui_Tauranga_Harbour

van den Bergh, J. (2004). Evolutionary thinking in environmental economics: retrospect and prospect. In J. Foster & W. Hölzl (Eds.), *Applied evolutionary economics and complex systems* (pp. 239-275.). Edward Elgar.

Ventana System Inc. (2015). *Vensim. Industrial strength simulation software for improving the performance of real systems.* In https://vensim.com/

Vugrin, E., Verzi, S., Finley, D., Turnquist, M., Griffin, A., Ricci, K., & Wyte-Lake, T. (2015). Modeling Hospitals Adaptive Capacity during a Loss of Infrastructure Services. *Journal of healthcare engineering*, *6*(1), 85-120. https://doi.org/https://doi.org/10.1260/2040-2295.6.1.85

Waikato Regional Council. (2006). *Managed retreat from coastal hazards: Options for implementation.* (Environment Waikato Technical Report 2006/48, Issue.

Walsh, P., Griffiths, C., Guignet, D., & Klemick, H. (2019). Adaptation, Sea Level Rise, and Property Prices in the Chesapeake Bay Watershed [Article]. *Land Economics*, *95*(1), 19-34. http://ezproxy.auckland.ac.nz/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=bah&AN=134144852&site=ehost-live&scope=site

Watson, E. (2013). *A closer look at some of the supply and demand factors influencing residential property markets*. https://www.rbnz.govt.nz/-/media/ReserveBank/Files/Publications/Analytical%20notes/2013/an2013-11.pdf

Weissenberger, S. (2015). *Adaptation to climate change and sea level rise: the case study of coastal communities in New Brunswick, Canada.* Springer. 2015.

Weissenberger, S., & Chouinard, O. (2015). Adaptation tools and strategies. In S. Weissenberger & O. Chouinard (Eds.), *Adaptation to climate change and sea level rise: the case study of coastal communities in New Brunswick, Canada*. Springer. 2015.

Williams, A., & Micallef, A. (2009). *Beach management: principles and practice.* Earthscan.

Williamson, O. (1998). Transaction Cost Economics: How It Works; Where It is Headed. *De Economist*, *146*(1), 23-58. https://doi.org/10.1023/A:1003263908567

Wimmer, A., & Kössler, R. (2006). *Understanding change models, methodologies, and metaphors.* Palgrave Macmillan 2006.

Withey, P., Sullivan, D., & Lantz, V. (2019). Willingness to pay for protection from storm surge damages under climate change in Halifax Regional Municipality [Article]. *Journal of Environmental Management*, *241*, 44-52. https://doi.org/10.1016/j.jenvman.2019.04.007

World Meteorological Organisation. (2019). *Global Climate in 2015-2019: Climate change accelerates*. Retrieved 4 October 2019 from https://public.wmo.int/en/media/press-release/global-climate-2015-2019-climate-change-accelerates?utm_source=feedburner&utm_medium=email&utm_campaign=Feed%3A+wmo%2FapqD+%28World+Meteorological+Organization+News%29

Wreford, A., R., D., Zammit, C., Rajanayaka, C., Renwick, A., & Collins, D. (2020). *Robust Adaptation Decision-Making Under Uncertainty: Real Options Analysis for water storage* (Deep South National Science ChallengeFinal Research Report, Issue. https://deepsouthchallenge.co.nz/wp-content/uploads/2021/02/Robust-adaptation-decision-making-under-uncertainty-ROA-for-Water-Storage-Final-Report.pdf

Zeltkevic, M. (1998). *Runge-Kutta Methods*. MIT. Retrieved 21 August 2019 from http://web.mit.edu/10.001/Web/Course_Notes/Differential_Equations_Notes/node5.html

Zorn, C. (2017a). *The Interdependence and Recovery of Critical Infrastructure Networks Following Major Disruptions* The University of Auckland]. https://researchspace.auckland.ac.nz/handle/2292/37055

Zorn, C. (2017b). *The Interdependence and Recovery of Critical Infrastructure Networks Following Major Disruptions.* The University of Auckland]. Auckland, NZ.

# Appendices

## Appendix 1 Coastal defence costs

**Community pathways for coastal defence and their associated costs, as described by Infometrics Consulting Limited (2017b) and HBRC (2019, 2020).**

| DEFENCE COSTS FROM HBRC (2019, 2020): | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Area** | **Maintenance ($M $a^{-1}$)** | **Invest Cost ($M-2019)** | **Invest Cost ($M-2007)** | **Timeframe** | **Defence of shoreline* (m)** | **Linear Cost ($ $m^{-1}$)** | **Comments** |
| **Te Awanga & Haumoana** | 2.20 | 69.1 | 55.28 | Short term | 3,700 | 18,676 | Groynes. |
| **Northern Cell** | 2.88 | 7.05 | 5.64 | Short term | 1,950 | 3,615 | Gravel and sand nourishment. |
| **Clifton Unit** | 0.15 | 3.47 | 2.78 | Short term | 1,300 | 2,669 | Revetment & nourishment. Installed 2018. |
| **Pandora** | 0.05 | 49.04 | 39.23 | Short term | 2,144 | 22,873 | Stop banks, sheet pile, revetments, sailing club upgrade, road raising & stormwater. |
| **TOTAL** | **5.28** | **128.66** | **102.93** | **TOTAL** | **9,094** | | |
| **2007 inflation adjust** | 0.8 | | 0.8 | **Average cost ($/m)** | | **14,148** | |
| **TOTAL VALUE 2007** | **4.23** | | | | | | * HBRC values |

| ESTIMATED MODEL TIMEFRAME FOR THE IMPLEMENTATION OF COASTAL DEFENCE: | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Timeframe** | **Trigger level** | **Erosion rate* (m $a^{-1}$)** | **Building buffer to MHWS (m)** | **Buffer offset (m)** | **Implementation (Year)** | **Invest Cost ($M-2007)** | **Comments** |
| **Clifton Unit** | Installed | - | | | 2018 | **2.78** | |
| **Short-term Pandora Unit** | Inundation | - | | | 2030-2050 | **39.23** | Triggers when TWL > 12 m RL (MSL > 3.183 m) on two occasions. |
| **Short-term northern cell** | Erosion rate | 3 | 54 | 7 | 2033 | **5.64** | Westshore (benchmark HB13) erosion rate. |
| **Short-term southern cell** | Erosion rate | 0.65 | 21 | 7 | 2038 | **55.28** | Haumoana & Te Awanga average (benchmark HB2, HB3, HB4) erosion rate. |
| **TOTAL** | | | | | | **100.15** | * HBRC values |

# Appendix 2 Asset exposure

## 2A Total assets exposed to coastal hazards

**I. Exposed assets (NZ$2007) within the 1% AEP coastal inundation by 2065 (CDEM)**

| Industry | Land | Capital | Improvements | Infrastructure | Total | Area (Ha) | Land use share (%) |
|---|---|---|---|---|---|---|---|
| Accommodation, restaurant & retail services | 8,914,200 | 15,628,900 | 0 | 0 | 24,543,100 | 0.93 | 0.22 |
| Construction | 3,398,850 | 8,820,410 | 5,013,200 | 0 | 17,232,460 | 9.21 | 2.16 |
| Government, education & healthcare | 51,943,890 | 165,873,840 | 2,784,650 | 27,961,556 | 245,594,477 | 230.61 | 54.02 |
| Horticulture & fruit growing | 0 | 0 | 0 | 0 | 0 | 0.00 | 0.00 |
| Food product manufacturing | 672,300 | 1,859,200 | 0 | 0 | 2,531,500 | 0.37 | 0.09 |
| Other manufacturing | 9,260,310 | 56,184,360 | 0 | 0 | 65,444,670 | 4.59 | 1.08 |
| Other primary production | 3,063,450 | 5,954,420 | 0 | 0 | 9,017,870 | 101.75 | 23.84 |
| Other services & trades | 40,372,860 | 58,680,170 | 0 | 12,012,304 | 108,828,192 | 47.17 | 11.05 |
| Residential & real estate services | 4,062,850 | 207,163,020 | 7,216,850 | 0 | 218,442,720 | 32.23 | 7.55 |
| Wood & paper manufacturing | 0 | 0 | 0 | 0 | 0 | 0.00 | 0.00 |
| **TOTAL** | **121,688,710** | **520,164,320** | **15,014,700** | | **691,634,990** | **427** | **100.00** |

**II. Exposed assets (NZ$2007) within the 1% AEP coastal inundation by 2120 (CDEM)**

| Industry | Land | Capital | Improvements | Infrastructure | Total | Area (Ha) | Land use share (%) |
|---|---|---|---|---|---|---|---|
| Accommodation, restaurant & retail services | 23,909,000 | 71,770,000 | 0 | 0 | 95,679,000 | 3.57 | 0.33 |
| Construction | 17,260,000 | 50,802,000 | 6,040,000 | 0 | 74,102,000 | 20.22 | 1.85 |
| Government, education & healthcare | 85,657,000 | 326,837,000 | 3,695,000 | 59,739,0026 | 470,161,213 | 246.88 | 22.58 |
| Horticulture & fruit growing | 3,360,000 | 45,940,000 | 0 | 0 | 49,300,000 | 157.83 | 14.43 |
| Food product manufacturing | 18,001,000 | 41,290,000 | 0 | 0 | 59,291,000 | 11.98 | 1.10 |
| Other manufacturing | 47,867,000 | 232,612,000 | 0 | 0 | 280,479,000 | 28.64 | 2.62 |
| Other primary production | 6,157,984 | 59,470,000 | 0 | 0 | 65,627,984 | 357.62 | 32.70 |
| Other services & trades | 84,762,000 | 165,325,000 | 0 | 23,929,647 | 273,311,648 | 87.64 | 8.01 |
| Residential & real estate services | 101,962,500 | 886,816,000 | 18,991,000 | 0 | 1,007,769,500 | 171.51 | 15.68 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Wood & paper manufacturing | 8,260,000 | 14,090,000 | 0 | 0 | 22,350,000 | 7.63 | 0.70 |
| **TOTAL** | **397,196,484** | **1,894,952,000** | **28,726,000** | **77,196,860** | **2,398,071,344** | **1,094** | **100.00** |

**III. Regional asset value and areas from MERIT (NZ$2007)**

| Industry | Built capital | CHZ capital share (%) | Area (Ha) | CHZ area share (%) |
|---|---|---|---|---|
| Accommodation, restaurant & retail services | 2,571,340,000 | 3.72 | 235 | 1.52 |
| Construction | 15,313,500,000 | 0.48 | 647 | 3.13 |
| Government, education & healthcare | 7,912,390,000 | 5.94 | 678 | 36.41 |
| Horticulture & fruit growing | 200,694,000 | 24.56 | 38,510 | 0.41 |
| Food product manufacturing | 479,408,000 | 12.37 | 499 | 2.40 |
| Other manufacturing | 3,870,290,000 | 7.25 | 247 | 11.59 |
| Other primary production | 2,482,530,000 | 2.64 | 930,100 | 0.04 |
| Other services & trades | 14,043,600,000 | 1.95 | 1,606 | 5.46 |
| Residential & real estate services | 26,277,800,000 | 3.84 | 4,570 | 3.75 |
| Wood & paper manufacturing | 210,488,000 | 10.62 | 183 | 4.17 |
| **TOTAL** | **73,362,040,000** | | **977,275** | **0.11** |

2B Infrastructure assets exposed to coastal hazards used to derive the infrastructure above

| ROADS | Cost per km ($) | Sum of length (km) | Total value ($) |
|---|---|---|---|
| **Estimated replacement cost with a 1% AEP present inundation** | | | |
| Local roads NCC | 900,826 | 0.08 | 73,128 |
| Local roads HDC | 735,168 | 3.59 | 2,639,253 |
| State highways | 3,000,000 | 0.29 | 855,838 |
| **Total** | | | **3,568,219** |
| **Estimated replacement cost with a 1% AEP 2065 inundation** | | | |
| Local roads NCC | 900,826 | 4.97 | 4,479,835 |
| Local roads HDC | 735,168 | 6.11 | 4,491,876 |
| State highways | 3,000,000 | 4.59 | 13,779,361 |
| **Total** | | | **22,751,072** |

| COMMS | Quantity | Value | Total value ($) |
|---|---|---|---|
| **Estimated replacement cost with a 1% AEP present inundation** | | | |
| Chorus exchange cabinet | 1 | 40,000.00 | 40,000 |
| Underground fibre | 2,135 | 61.00 | 130,235 |
| Aerial fibre | 33 | 61.00 | 2,013 |
| **TOTAL** | | | **172,248** |
| **Estimated replacement cost with a 1% AEP 2065 inundation** | | | |
| Cell tower | 1 | 250,000.00 | 250,000 |
| Chorus exchange cabinet | 2 | 40,000.00 | 80,000 |
| Underground fibre | 3,023 | 61.00 | 184,403 |
| Aerial fibre | 1,120 | 61.00 | 68,320 |

| | | | |
|---|---|---|---|
| **Estimated replacement cost with a 1% AEP 2120 inundation** | | | |
| Local roads NCC | 900,826 | 7.12 | 6,409,464 |
| Local roads HDC | 735,168 | 26.93 | 19,795,026 |
| State highways | 3,000,000 | 5.76 | 17,280,494 |
| **Total** | | | **37,075,520** |

| RAIL | Cost per km ($) | Sum of length (km) | Total value ($) |
|---|---|---|---|
| **Estimated replacement cost with a 1% AEP present inundation** | | | |
| Total | 2,711,628 | 0.34 | **923,906** |
| **Estimated replacement cost with a 1% AEP 2065 inundation** | | | |
| Total | 2,711,628 | 3.31 | **8,977,441** |
| **Estimated replacement cost with a 1% AEP 2120 inundation** | | | |
| Total | 2,711,628 | 5.82 | **15,790,358** |

| WATER | Quantity | Value/m | Total value ($) |
|---|---|---|---|
| **Estimated replacement cost with a 1% AEP present inundation** | | | |
| Water pipes all types | 64 | 26.08 | 1,669 |
| **TOTAL** | | | **1,669** |
| **Estimated replacement cost with a 1% AEP 2065 inundation** | | | |
| Water pipes all types | 13,852 | 26.08 | 361,260 |
| HDC water mains | 9,045 | 298.61 | 2,700,927 |
| **TOTAL** | | | **3,062,188** |
| **Estimated replacement cost with a 1% AEP 2120 inundation** | | | |
| Water pipes all types | 29,103 | 26.08 | 28,192 |
| HDC water mains | 19,175 | 298.61 | 5,725,847 |
| **TOTAL** | | | **5,754,039** |

| | | | |
|---|---|---|---|
| **TOTAL** | | | **582,723** |
| **Estimated replacement cost with a 1% AEP 2120 inundation** | | | |
| Cell tower | 3 | 250,000.00 | 750,000 |
| Chorus exchange cabinet | 8 | 40,000.00 | 320,000 |
| Underground fibre | 4,584 | 61.00 | 279,624 |
| Aerial fibre | 3,725 | 61.00 | 227,225 |
| **TOTAL** | | | **1,576,849** |

| ELECTRICITY | Quantity | Value/m | Total value ($) |
|---|---|---|---|
| **Estimated replacement cost with a 1% AEP present inundation** | | | |
| HV Cable | 1,202 | 180.00 | 216,360 |
| HV Line | 2,907 | 180.00 | 523,260 |
| **TOTAL** | | | **739,620** |
| **Estimated replacement cost with a 1% AEP 2065 inundation** | | | |
| HV Cable | 5,032 | 180.00 | 905,760 |
| HV Line | 8,591 | 180.00 | 1,546,380 |
| **TOTAL** | | | **2,452,140** |
| **Estimated replacement cost with a 1% AEP 2120 inundation** | | | |
| HV Cable | 11,575 | 180.00 | 2,083,500 |
| HV Line | 24,883 | 180.00 | 4,478,940 |
| **TOTAL** | | | **6,562,440** |

| TOTAL FOR ALL INFRASTRUCTURE | Quantity | Value/m | Total value ($) |
|---|---|---|---|
| **Total infrastructure costs 2065** | | | **39,973,860** |

| SEWER | Quantity | Value/m | Total value ($) |
|---|---|---|---|
| **Estimated replacement cost with a 1% AEP present inundation** | | | |
| Sewer pipes all types | 494 | 49.98 | 24,690 |
| HDC Sewer main | 0 | 1,054.53 | 0 |
| **TOTAL** | | | **24,690** |
| **Estimated replacement cost with a 1% AEP 2065 inundation** | | | |
| Sewer pipes all types | 9,672 | 49.98 | 483,407 |
| HDC Sewer main | 711 | 1,054.53 | 749,771 |
| **TOTAL** | | | **1,233,177** |
| **Estimated replacement cost with a 1% AEP 2120 inundation** | | | |
| Sewer pipes all types | 24,959 | 49.98 | 1,247,451 |
| HDC Sewer main | 7,882 | 1,054.53 | 8,311,805 |
| **TOTAL** | | | **9,559,256** |

| STORMWATER | Quantity | Value/m | Total value ($) |
|---|---|---|---|
| **Estimated replacement cost with a 1% AEP present inundation** | | | |
| NCC drainage pipes | 3,700 | 115.56 | 427,572 |
| HDC drainage pipes | 1,124 | 777.06 | 873,415 |
| **TOTAL** | | | **427,572** |
| **Estimated replacement cost with a 1% AEP 2065 inundation** | | | |
| NCC drainage pipes | 7,919 | 115.56 | 915,120 |
| HDC drainage pipes | 3,070 | 777.06 | 2,385,574 |
| **TOTAL** | | | **915,120** |
| **Estimated replacement cost with a 1% AEP 2120 inundation** | | | |
| NCC drainage pipes | 16,291 | 115.56 | 1,882,588 |
| HDC drainage pipes | 9,459 | 777.06 | 7,350,211 |
| **TOTAL** | | | **7,350,211** |

| | | | |
|---|---|---|---|
| **Total infrastructure costs 2120** | | | **83,668,672** |
| **Utility services land cost 2120** | **3** | **232,077** | **696,231** |
| **Combined infrastructure costs 2065** | | | **73,737,589** |
| **Combined utility land costs 2065** | | | **6,910,670** |
| **TOTAL** | | | **80,648,259** |
| **Combined infrastructure costs 2120** | | | **161,823,198** |
| **Combined utility land costs 2120** | | | **7,644,051** |
| **TOTAL** | | | **169,467,249** |

| **Totals for industries:** | **2065** | **2120** |
|---|---|---|
| Accommodation, restaurant & retail services | | |
| Construction | | |
| Government, education & healthcare | **27,961,556** | **59,739,026** |
| Horticulture & fruit growing | | |
| Food product manufacturing | | |
| Other manufacturing | | |
| Other primary production | | |
| Other services & trades | **12,012,304** | **23,929,647** |
| Residential & real estate services | | |
| Wood & paper manufacturing | | |

# Appendix 3 Table of multi-variate regression analysis for hedonic pricing

**Coefficients [a]**

| Model | | Unstandardised Coefficients | | Standardised Coefficients | t | Sig. | 95.0% Confidence Interval for B | | Correlations | | | Collinearity Statistics | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | B | Std. Error | Beta | | | Lower Bound | Upper Bound | Zero-order | Partial | Part | Tolerance | VIF |
| 11 | (Constant) | 16013.837 | 23582.182 | | 0.679 | 0.497 | -30207.414 | 62235.088 | | | | | |
| | Capital_Va | 1.230 | 0.013 | 0.701 | 96.762 | 0.000 | 1.205 | 1.255 | 0.533 | 0.385 | 0.303 | 0.186 | 5.374 |
| | Land_Value | -1.218 | 0.023 | -0.380 | -54.126 | 0.000 | -1.262 | -1.174 | 0.341 | -0.227 | -0.169 | 0.198 | 5.048 |
| | MAS_View_S_0-4 | 44642.362 | 2342.932 | 0.140 | 19.054 | 0.000 | 40050.198 | 49234.527 | 0.363 | 0.082 | 0.060 | 0.180 | 5.556 |
| | Building_F | 987.450 | 28.226 | 0.454 | 34.984 | 0.000 | 932.128 | 1042.773 | 0.351 | 0.149 | 0.109 | 0.058 | 17.226 |
| | House_scale_0-10 | 28973.631 | 683.818 | 0.143 | 42.370 | 0.000 | 27633.342 | 30313.920 | 0.257 | 0.180 | 0.132 | 0.863 | 1.159 |
| | MAS_Landsc_1-3 | 32755.112 | 1075.048 | 0.101 | 30.469 | 0.000 | 30648.011 | 34862.213 | 0.243 | 0.130 | 0.095 | 0.897 | 1.115 |
| | Building_S | -723.773 | 29.048 | -0.315 | -24.917 | 0.000 | -780.707 | -666.839 | 0.273 | -0.107 | -0.078 | 0.061 | 16.395 |
| | NEAR_DIST | -4.052 | 0.178 | -0.077 | -22.743 | 0.000 | -4.401 | -3.703 | -0.130 | -0.098 | -0.071 | 0.843 | 1.186 |
| | MAS_View_0-3 | 41151.602 | 3436.944 | 0.088 | 11.973 | 0.000 | 34415.167 | 47888.037 | 0.348 | 0.052 | 0.037 | 0.181 | 5.529 |
| | LUD_Age | 16.689 | 1.533 | 0.040 | 10.888 | 0.000 | 13.685 | 19.694 | 0.109 | 0.047 | 0.034 | 0.737 | 1.358 |
| | Meshblock | 0.064 | 0.016 | 0.013 | 3.937 | 0.000 | 0.032 | 0.096 | -0.053 | 0.017 | 0.012 | 0.862 | 1.160 |

a. Dependent Variable: Price_infl

# Appendix 4 Kernel Density Estimates from Infrastructure outages

Note that the port and airport were not considered for distributional mapping as they are single point locations. Petrol stations were also not considered due to the ease of substitution between stations.

**Table A4 Infrastructure Kernel Density Estimates from ESRI ArcGIS® and modified for Vensim®.**

| Infrastructure | CHZ > 2km (µ) | Scaling (µ) | Grouped (µ) |
|---|---|---|---|
| **ELECTRICITY** | | | 0.300 |
| **HV cable** | 0.35 | 0.295 | |
| **HV line** | 0.364 | 0.305 | |
| **COMMUNICATIONS** | | | 0.243 |
| **Underground fibre** | 0.395 | 0.326 | |
| **Aerial fibre** | 0.173 | 0.158 | |
| **SEWER** | | | 0.230 |
| **HDC sewer mains** | 1.162 | 0.687 | |
| **NCC main sewer non-critical** | 0.002 | 0.002 | |
| **NCC main sewer line** | 0.001 | 0.001 | |
| **WATER** | | | 0.159 |
| **HDC water mains** | 0.169 | 0.155 | |
| **NCC water main non-critical** | 0.003 | 0.003 | |
| **NCC water main critical** | 0.0005 | 0.001 | |
| **STORMWATER** | | | 0.131 |
| **HDC stormwater mains** | 0.302 | 0.261 | |
| **NCC drainage pipes** | 0.002 | 0.002 | |
| **GAS** | | | 0.495 |
| **Distribution main** | 1.249 | 0.713 | |
| **Service** | 0.323 | 0.276 | |
| **ROADS** | 0.758 | 0.531 | 0.531 |
| **RAILWAY** | 0.159 | 0.147 | 0.147 |

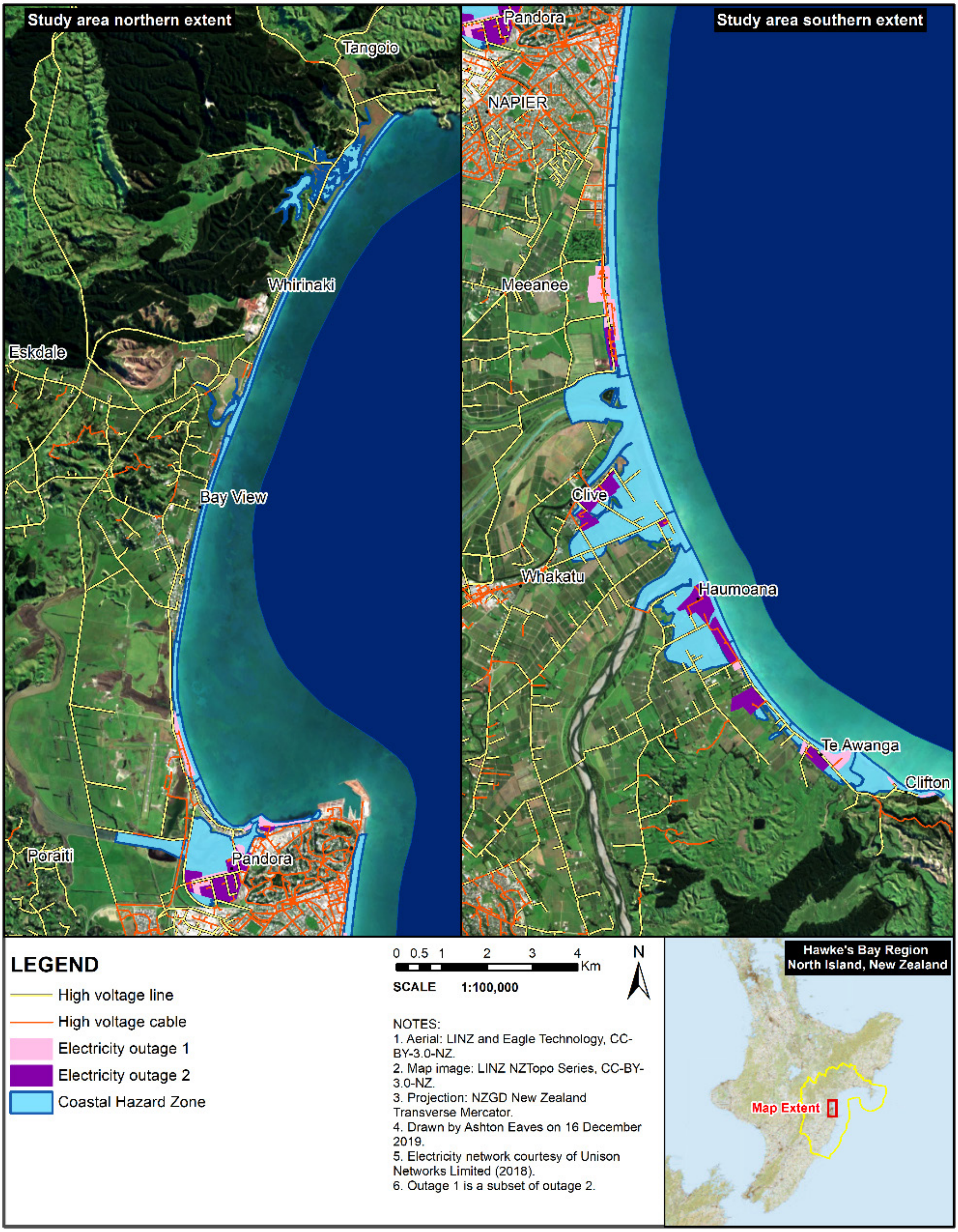



**Figure A4A** Electricity outage map.

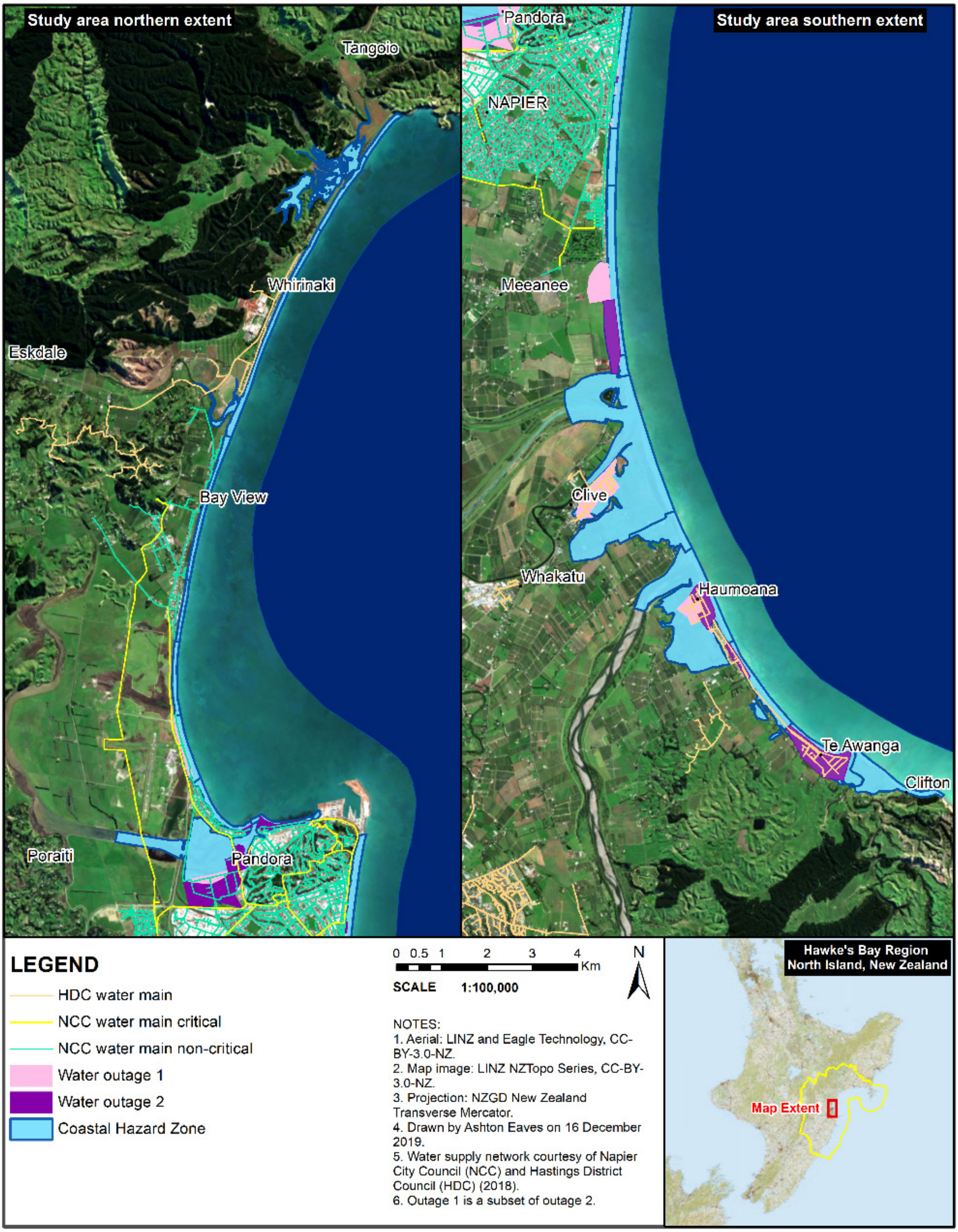



**Figure A4B** Water outage map.

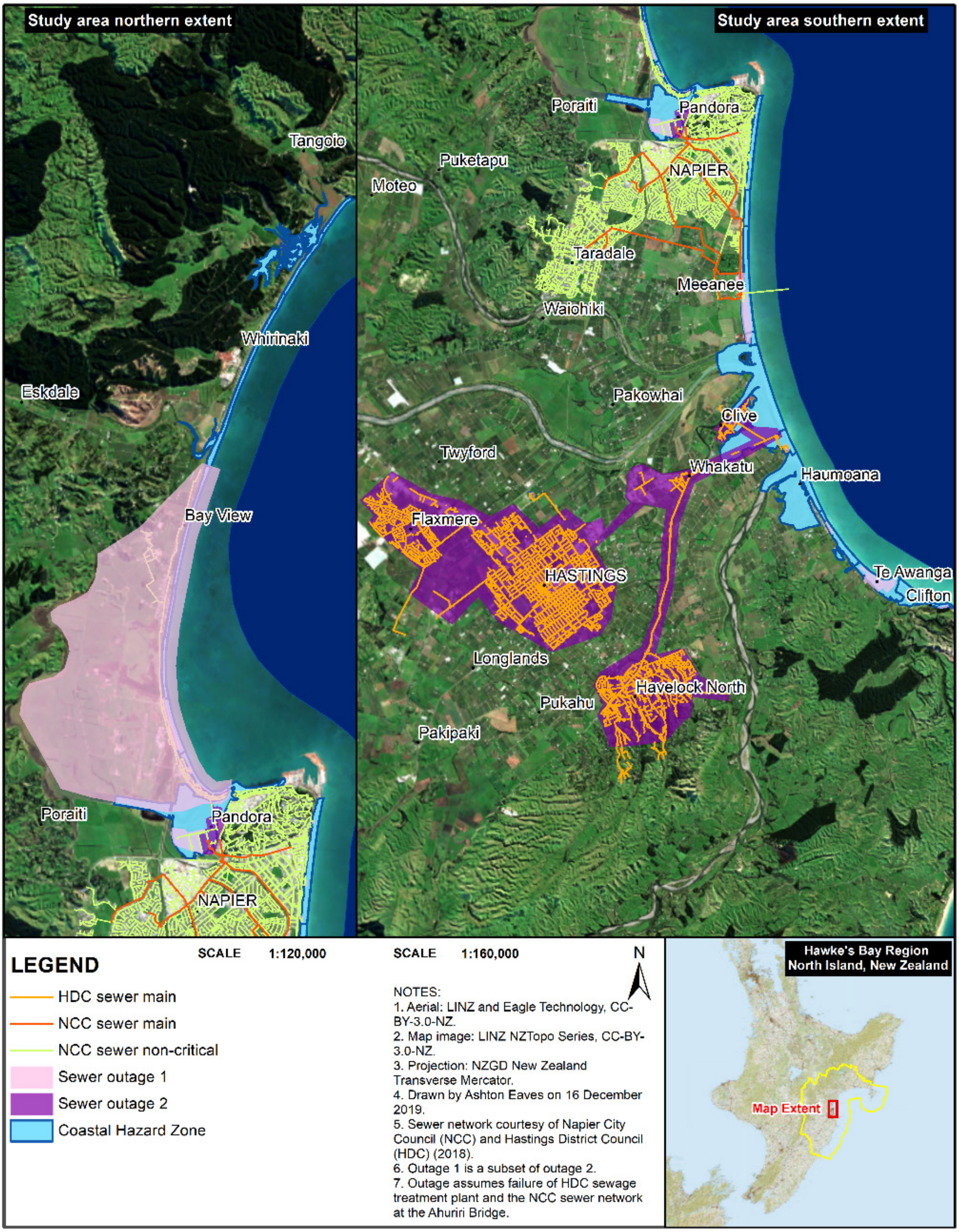



**Figure A4C** Sewer outage map.

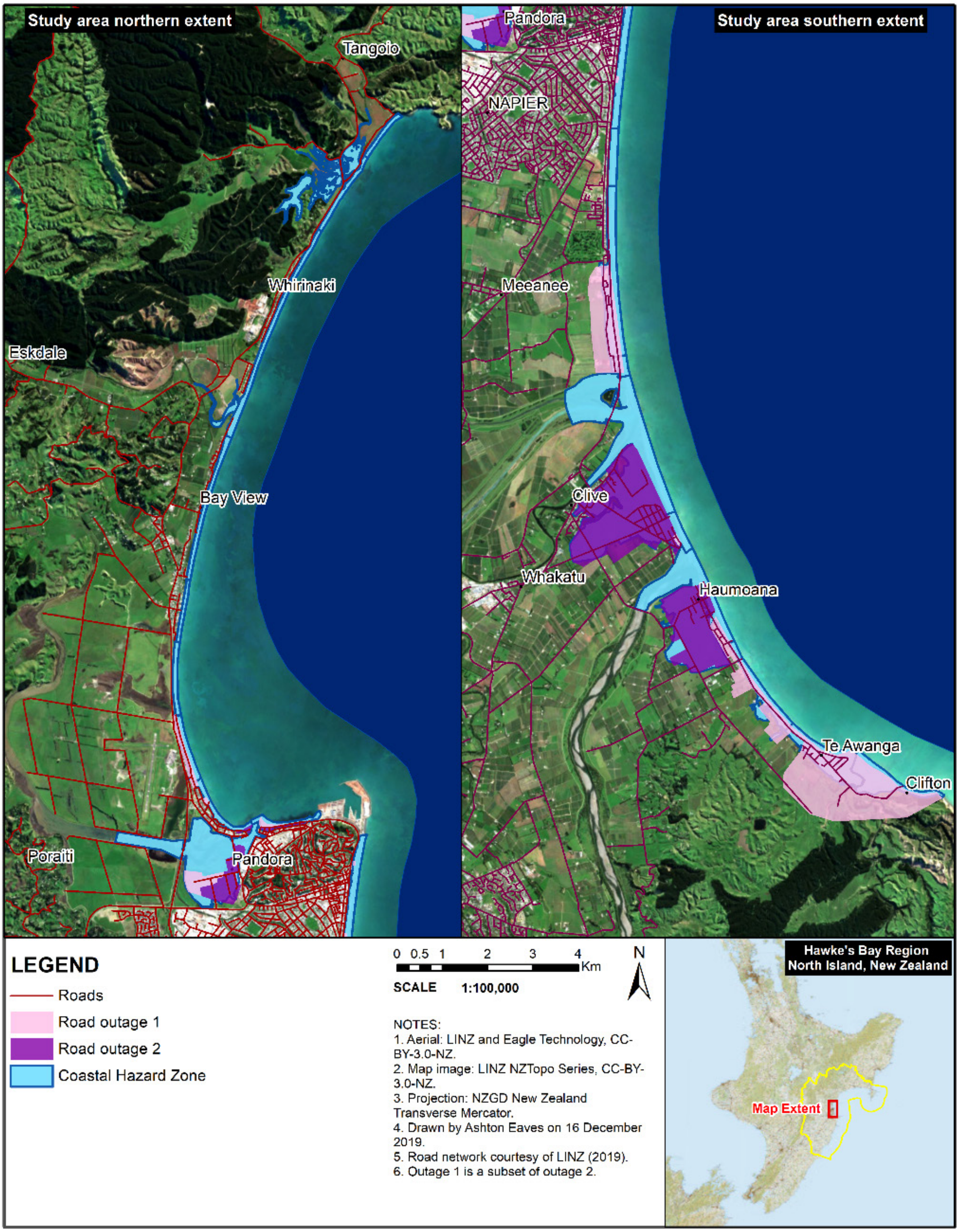



**Figure A4D** Roads outage map.

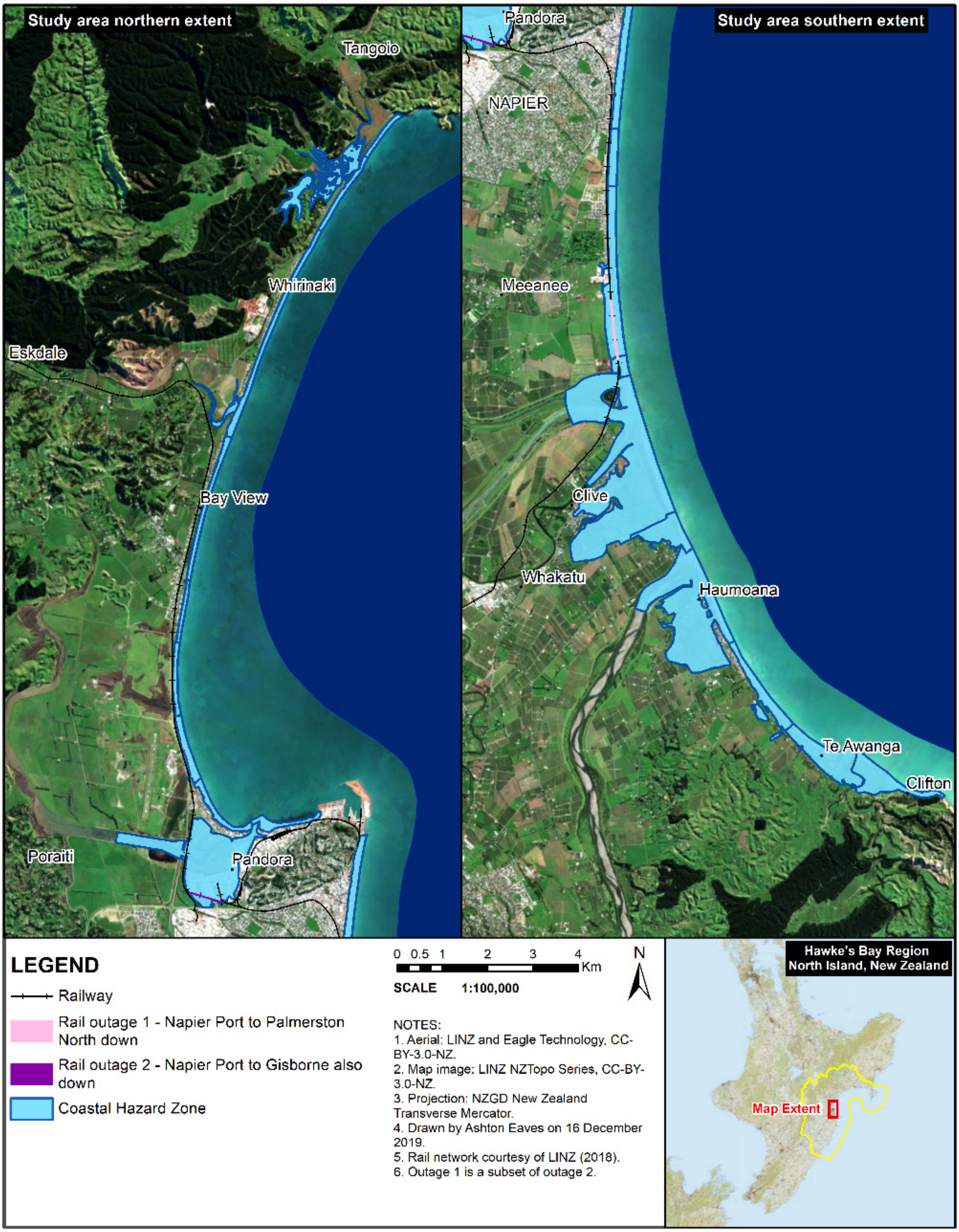



**Figure A4E** Rail outage map.

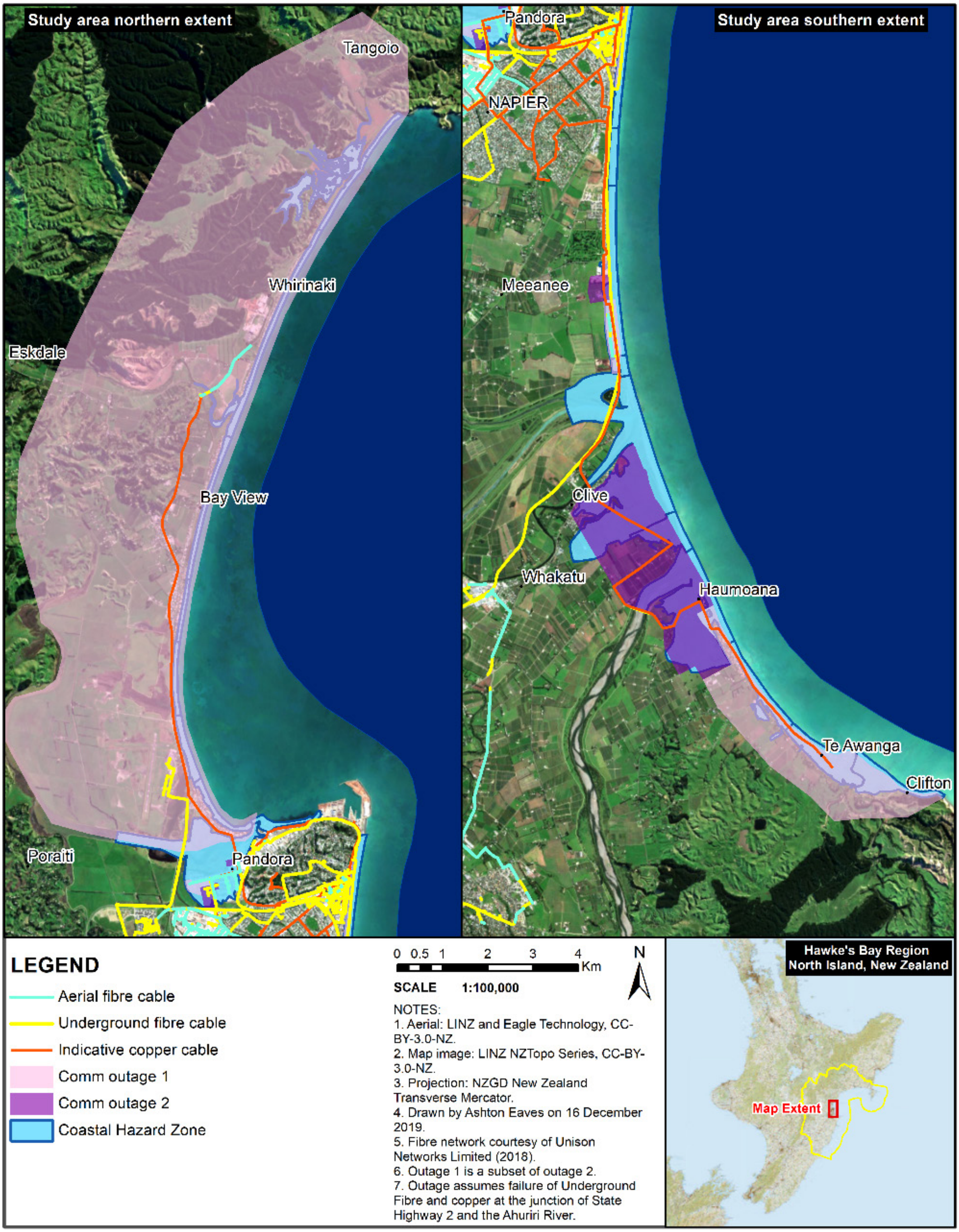



**Figure A4F** Communications outage map.

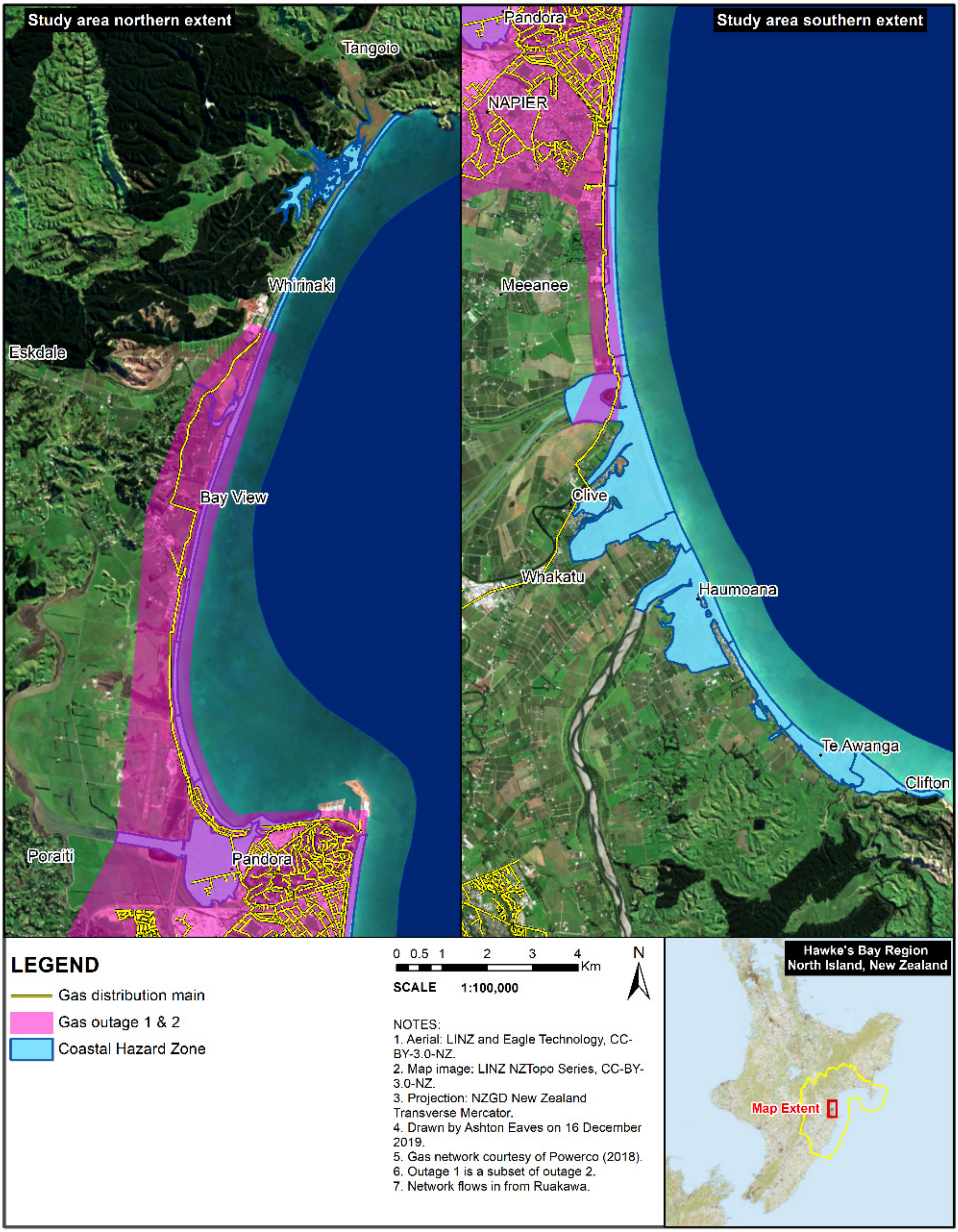



**Figure A4G** Gas outage map

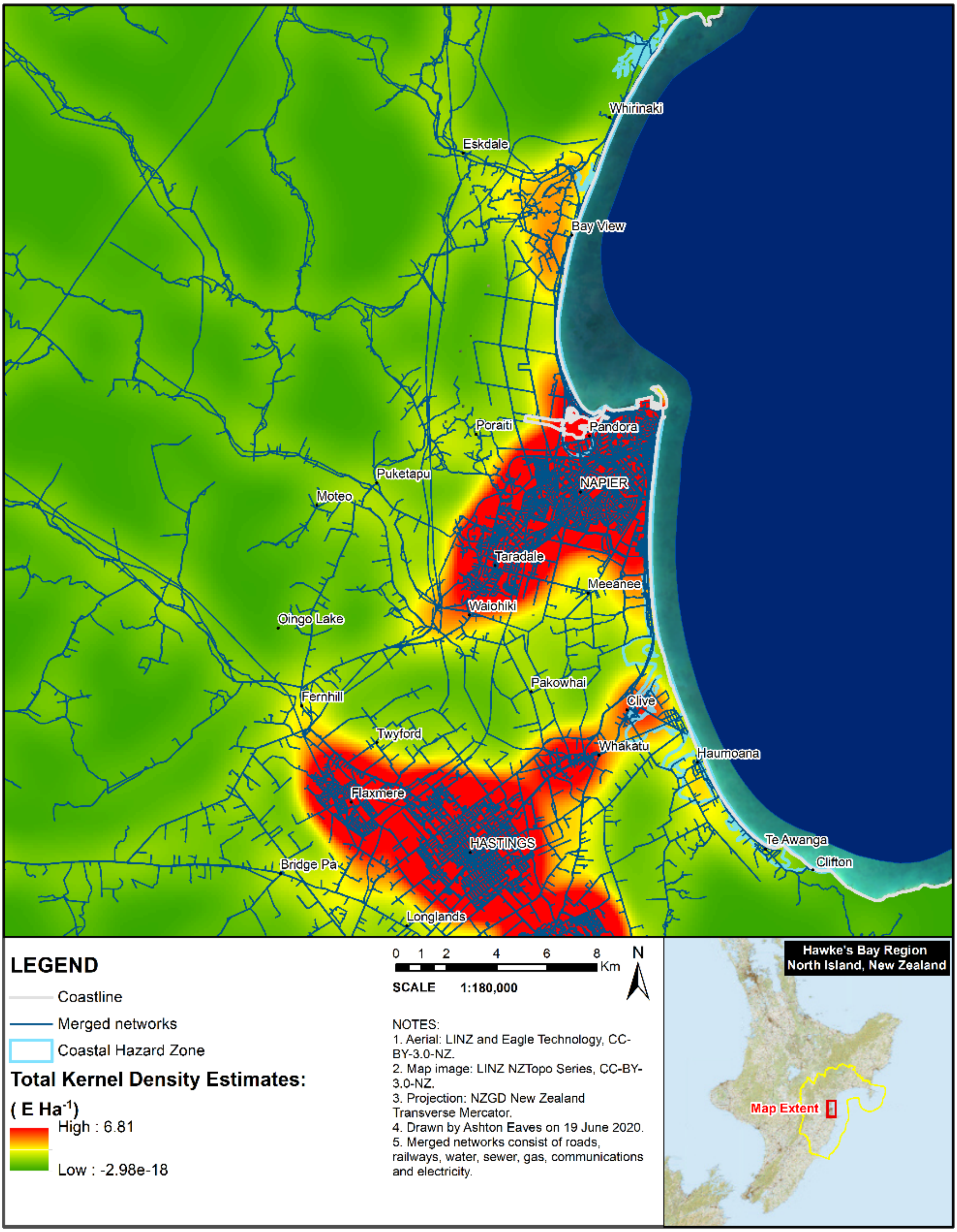



**Figure A4H** Network Total Kernel Density Estimates map

# Appendix 5 Testing

5A Table of testing undertaken for C-ADAPT.

| Test type | Conditions |
|---|---|
| **7.** Empirical direct structure tests | • Model outputs reliant on the 2009 Riskscape database were validated against 2017 local government valuations.<br>• Hydrologic inundation calibrated against Ahuriri hydrograph. Standard deviation adjusted to suit.<br>• CoreLogic (2018) estimate a year on year increase of 7% in New Zealand. The Socio-Economic Module through the Insurance variable illustrates 10%.<br>• Calculated Vulnerable Capital against the New Zealand house sales database from 1990 to 2018. Adjusted to suit the database from 2007 to 2018 of 2.6% growth for properties in the CHZ.<br>• Clean up and remediation compared to 2020 flood event.<br>• Household income and unemployment compared with actual data from 2007 through to 2018 from StatsNZ.<br>• GDP tracked against TVA for 2007 through to 2018 using modelled data and data from StatsNZ.<br>• Sectors tracked against industries for 2007 through to 2018 using modelled data and data from StatsNZ.<br>• The New Zealand Land Resource Inventory (NZLRI), the national physical land resource information database, was used for land use calibration. |
| **8.** Theoretical direct structure tests | • SLR aligns with IPCC scenarios (IPCC, 2014b).<br>• Geodetic change conforms with the MfE projections (New Zealand Government, 2017).<br>• Storm Surge, Wave Run-up, Catchment Hydrostaticity, Tide and TWL conform with measurements by Komar and the Hawke's Bay Regional Council (2014b). The 11m threshold is breached regularly before 2019.<br>• At least four flood events were recorded for Hawke's Bay by the Insurance Council of New Zealand (2019a). Claims range from NZ$1.1M to NZ$6.4M (Insurance Council of New Zealand, 2019a).<br>• Total asset replacement value was calibrated to align with the reported insurance claims from flooding of NZD 4.3M on the 3rd of June 2018 in Hawke's Bay and Gisborne (Insurance Council of New Zealand, 2019a).<br>• The initial premium is $NZ_{2007}$\$1,000 and calibrates to $NZ_{2007}$\$1,500 by 2018 to conform with Corelogic Inc (2018). During the 2016 financial year, New Zealand households, on average, spent 17.6% of their income on housing costs (mortgage or rent expenses, property rates and building-related insurance) (StatsNZ, 2016). Given that the mean regional individual income is $NZ_{2007}$\$28,000 (StatsNZ, 2020c), 5% represents a tolerable threshold percentage of capital wealth lost by households.<br>• Property rates on households and firms rationalised to income expectations from MERIT.<br>• The number of enterprises paying the general rate was compared to GDP growth from MERIT.<br>• Bonds return on investment (compound interest) is rationalised to market rates pre-covid as described by Tapley (2016).<br>• The rest of the world interest rate was rationalised with Market Economics.<br>• Interdependencies were rationalised against the New Zealand Lifelines Council (2017), and Kernel Density Estimates from the geospatial infrastructure locations.<br>• Coastal defence valuations were set out by HBRC (2019 & 2020) and compared against Infometric Consulting Limited's ROA (2017). |

<table>
<tr>
<td>9. Structure orientated behaviour tests (Note: only applied to Risk Assessment Module and Socio-Economic Module)</td>
<td>The following questions were asked of the model through Vensim® Reality Check:<br>1. Are premiums and the AEP reflected in the behavioural reframing?<br>2. Do the annual anticipated loss and insurance influence amenity value?<br>3. Does the hazard of high water levels influence premiums?<br>4. Does the integrated risk assessment reflect the changing asset and social vulnerability?<br><br>Results:<br>● 3 successes and 1 failure testing 4 Reality Check equations.<br>● The Reality Check Index as run was 4.02879e-005.<br>● Closeness score is 67.1% on 8 measurements.</td>
</tr>
<tr>
<td>10. Behaviour pattern tests</td>
<td>Behaviour pattern tests were carried out on:
<table>
<tr><td>SLR</td><td>AEP</td><td>Insurance</td><td>WTP insurance</td><td>Return period</td></tr>
<tr><td>Significant WL</td><td>Behavioural reframing</td><td>Wealth</td><td>WTAL</td><td>Market adjustment</td></tr>
<tr><td>Geodetic change</td><td>Flooded area</td><td>Exposed capital</td><td>Income</td><td>AEL</td></tr>
<tr><td>Excesses</td><td>Coastal amenity value</td><td>Premiums</td><td>Disruption</td><td>Total CHZ</td></tr>
<tr><td>Total intensification</td><td>Total new zones</td><td>Trigger count</td><td>Land balance dynamic</td><td>Compound interest</td></tr>
<tr><td>Climate bonds</td><td>Total regional bonds</td><td>Available funds</td><td>Total targeted rate</td><td>Total hhld rate</td></tr>
<tr><td>Total general rate</td><td>Retreat rates funds</td><td>Total rates tax</td><td>Total defence cost</td><td></td></tr>
</table>
</td>
</tr>
</table>

5A Reality Check testing for the Risk Assessment Module and the Socio-Economic Module.

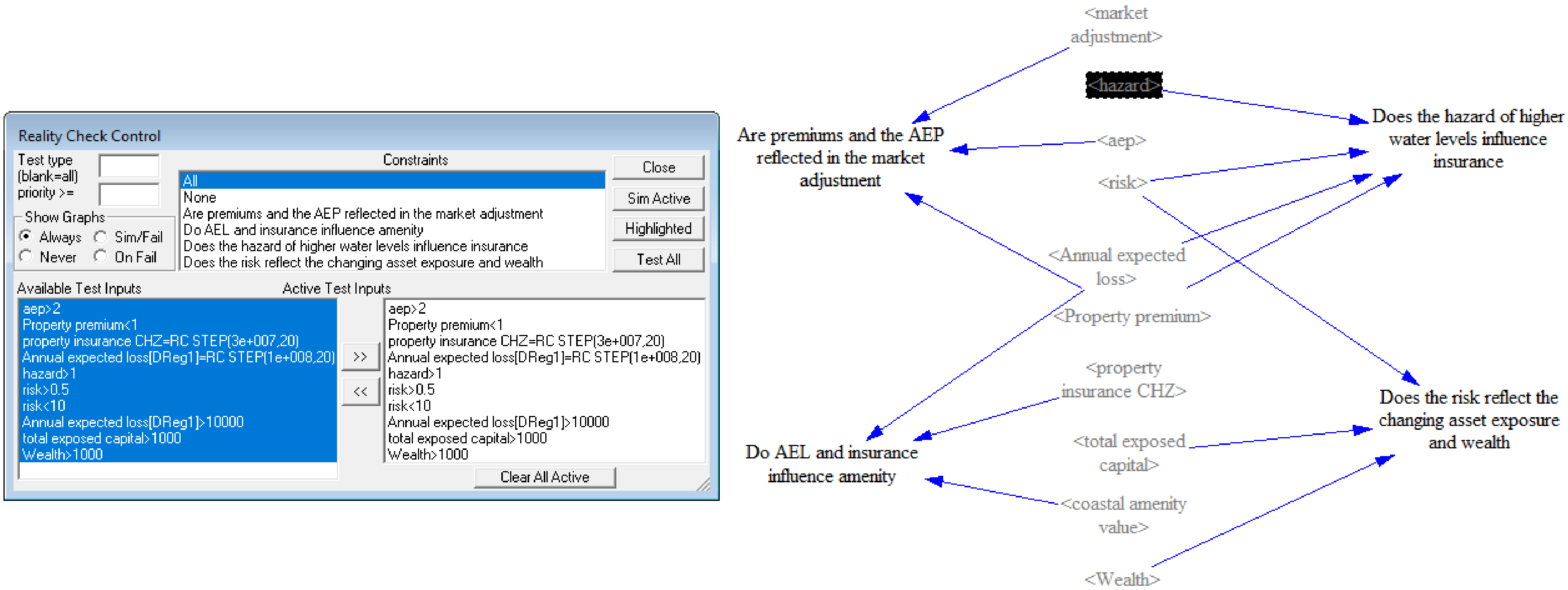



**Figure A5** Set up for the Reality Check.

# Appendix 6 Model assessment results from the SDM-doc Tool

Results for the Risk Assessment Module and the Socio-Economic Module.

## Model Assessment Results

| Model Information | Result |
|---|---|
| Total Number Of Variables | 134\|239 |
| Total Number Of State Variables | 32 (23.9%)\|72 (30.1%) |
| Total Number Of Stocks | 24 (17.9%)\|53 (22.2%) |
| Total Number Of Feedback Loops No IVV (Maximum Length: 30) [2, 18] | 50 (19\|31\|0) |
| Total Number Of Feedback Loops With IVV (Maximum Length: 30) [0, 0] | 0 (0\|0\|0) |
| Total Number Of Causal Links | 228 (134\|38\|56)\|701 (466\|78\|157) |
| Total Number of Rate-to-rate Links | 73 |
| Number Of Units Used In The Model (Basic/Combined) | 6/8 |
| Total Number Of Equations Using Macros | 0 (0.0%)\|0 (0.0%) |
| Variables With Source Information | 0 (0.0%)\|0 (0.0%) |
| Dimensionless Unit Variables | 35 (26.1%)\|35 (14.6%) |
| Variables without Predefined Min or Max Values | 130 (97.0%)\|235 (98.3%) |
| Function Sensitivity Parameters | 0 (0.0%)\|0 (0.0%) |
| Data Lookup Tables | 0 (0.0%)\|0 (0.0%) |
| Time Unit | Year |
| Initial Time | 0 |
| Final Time | 44 |
| Reported Time Interval | TIME STEP |
| Time Step | 0.005 |
| Model Is Fully Formulated | Yes |
| Model Defined Groups | No |

| Warnings | Result |
|---|---|
| Number Of Undocumented Variables | 9 (6.7%)\|18 (7.5%) |
| Equations With Embedded Data | 16 (11.9%)\|29 (12.1%) |
| Variables Not In Any View | 0 (0.0%)\|0 (0.0%) |
| Nonmonotonic Lookup Functions | 2 (1.5%)\|2 (0.8%) |
| Cascading Lookup Functions | 0 (0.0%)\|0 (0.0%) |
| Non-Zero End Sloped Lookup Functions | 5 (3.7%)\|5 (2.1%) |
| Equations With If Then Else Functions | 22 (16.4%)\|71 (29.7%) |
| Equations With Min Or Max Functions | 1 (0.7%)\|1 (0.4%) |
| Equations With Step Pulse Or Related Functions | 0 (0.0%)\|0 (0.0%) |
| Equations With Unit Errors Or Warnings | 18 (13.4%)\|29 (12.1%) |

| Potential Omissions | Result |
|---|---|
| Unused Variables | 6 (4.5%)\|17 (7.1%) |
| Supplementary Variables | 0 (0.0%)\|0 (0.0%) |
| Supplementary Variables Being Used | 0 (0.0%)\|0 (0.0%) |
| Complex Variable | 20 (14.9%)\|76 (31.8%) |
| Complex Stock | 16 (11.9%)\|36 (15.1%) |

# Appendix 7 Sensitivity analyses

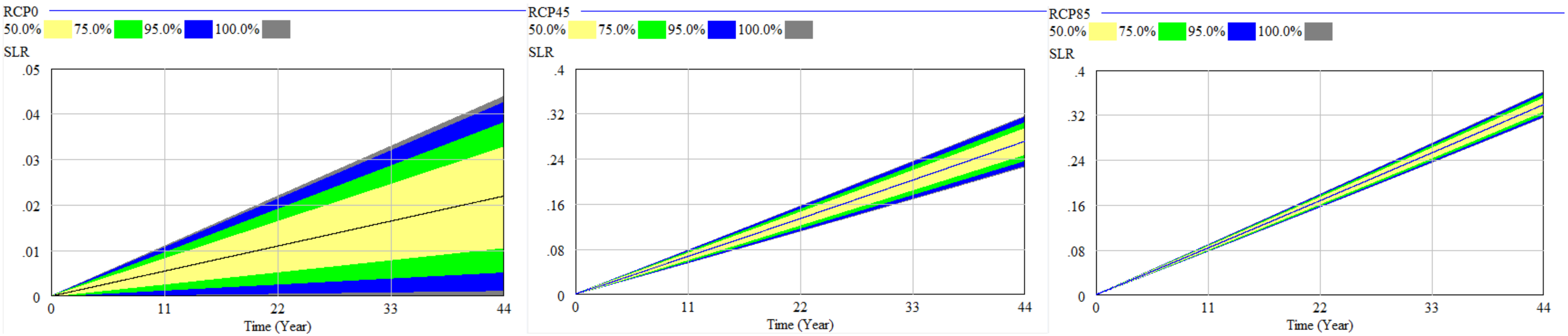
The sensitivity simulations involved 100 simulations using Latin hypercube sampling. The set-up for the Risk Assessment Module and the Socio-Economic Module is visible in Table A7, with the results of the sensitivity analyses for the key variables with their confidence intervals are also visible. Note that the black line represents the mean of all runs and the blue line the initial simulation. The sensitivity results in 7B illustrates some of the key relationships for the integration of the modules into MERIT to create C-ADAPT. Given the vast amount of results available, only a selection of RCP4.5 baseline scenario outputs and RCP8.5 scenario outputs for the rates and bonds scenarios are added.

## 7A Sensitivity results for the Risk Assessment Module and the Socio-Economic Module

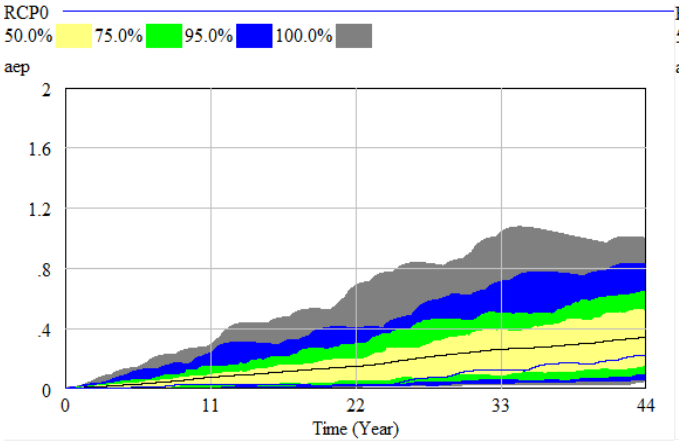
**Table 7A Sensitivity analyses set up for constants in Vensim®. Sensitivity analyses used realistic distributions for the modules.**

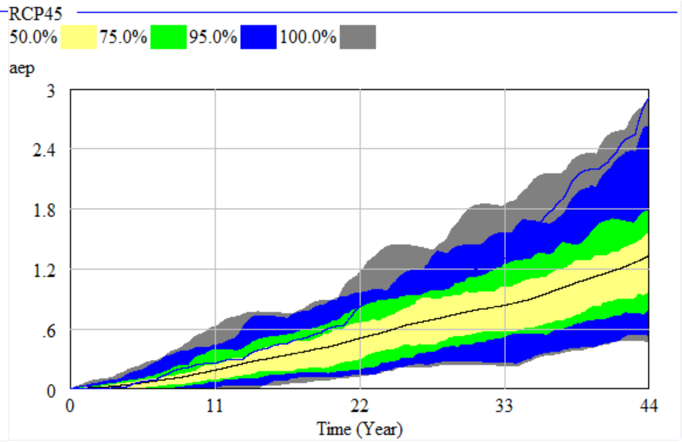
| Variable | Distribution | Range |
|---|---|---|
| NON MARKET VALUE | RANDOM UNIFORM | 0.9, 1.3 |
| INI PREMIUM | RANDOM UNIFORM | 500, 2500 |
| ROI | RANDOM UNIFORM | 0.9, 1.15 |
| ATTRITION RATE | RANDOM UNIFORM | 0.5, 1.5 |
| WTP THRESHOLD | RANDOM UNIFORM | 0.01, 0.1 |
| INITIAL EXCESS | RANDOM UNIFORM | 500, 10000 |
| FREQUENCY | RANDOM UNIFORM | 0.055, 0.068 |
| SCALE | RANDOM NORMAL | 200, 10000 |
| ICE MELT | RANDOM NORMAL | 0, 0.0011 |
| WATER DEPTH | RANDOM NORMAL | 0, 0.008 |
| INSURE THRESHOLD | RANDOM UNIFORM | 1, 7 |

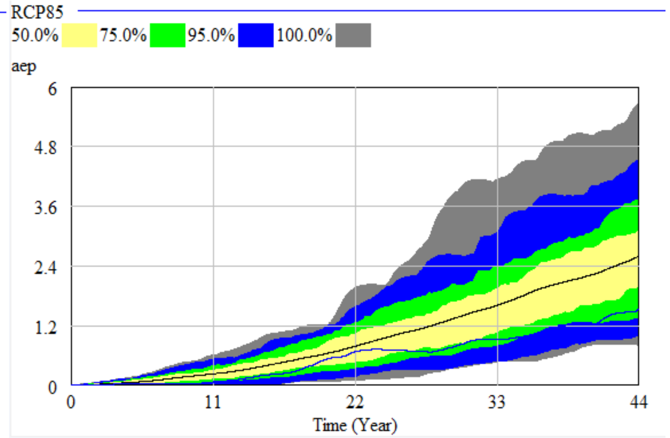
**I. Sea level rise:**



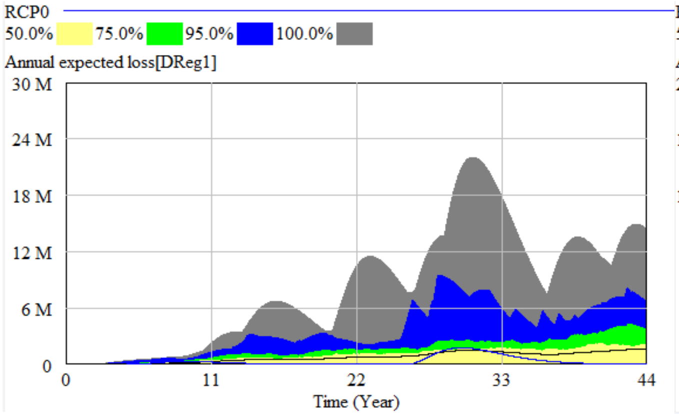
## II. Annual Exceedance Probability:

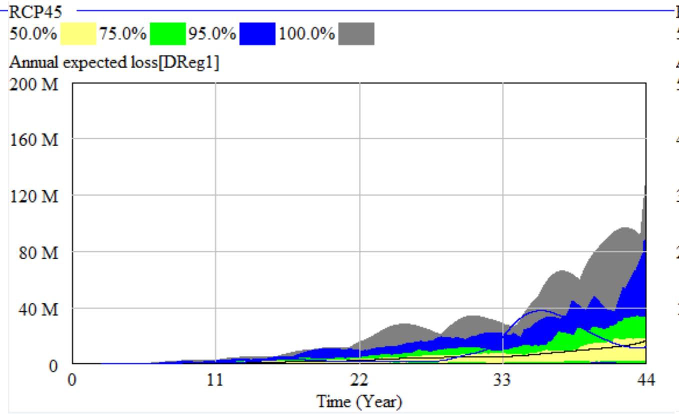


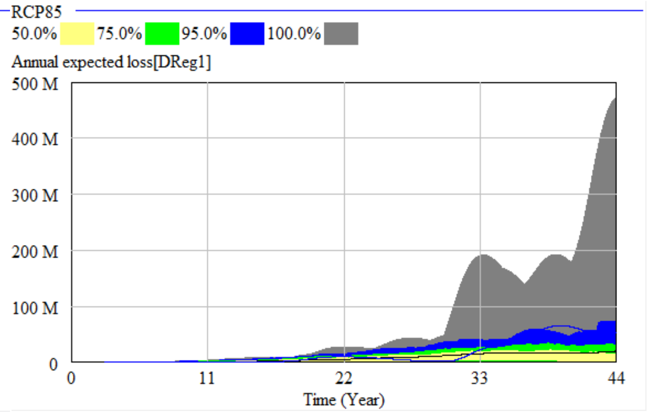



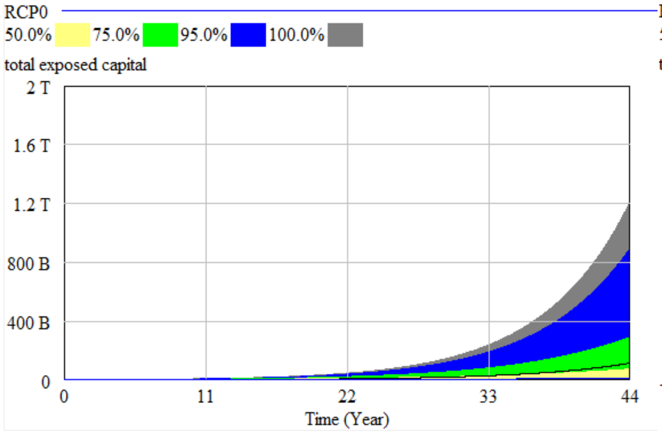

## III. Annual Expected Loss:

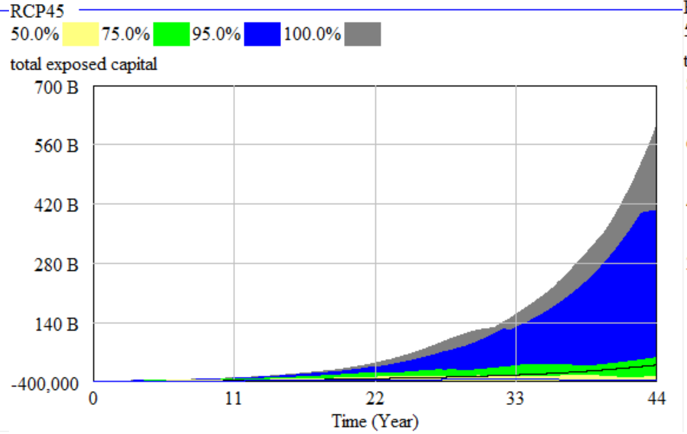


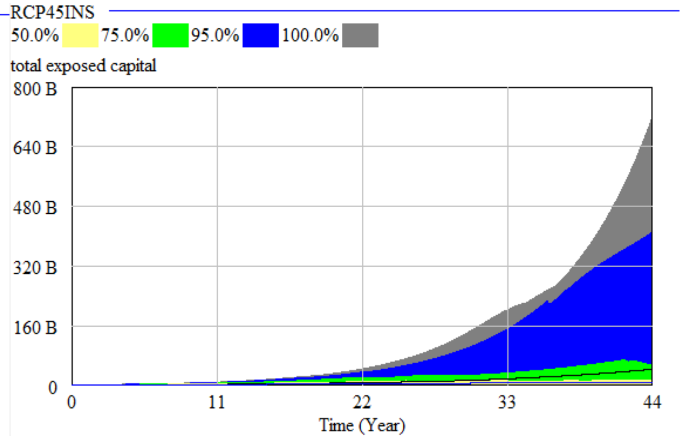



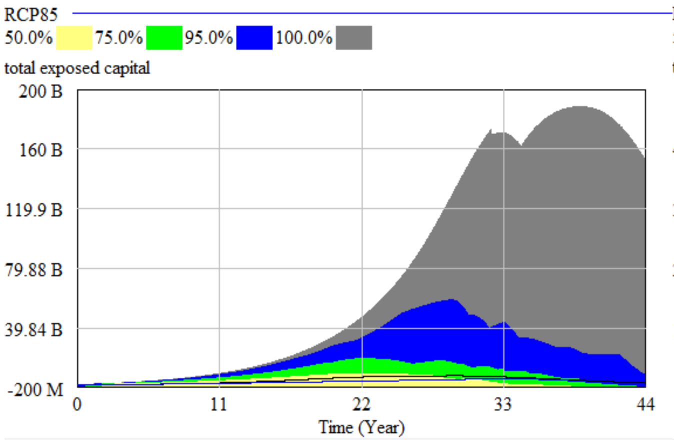



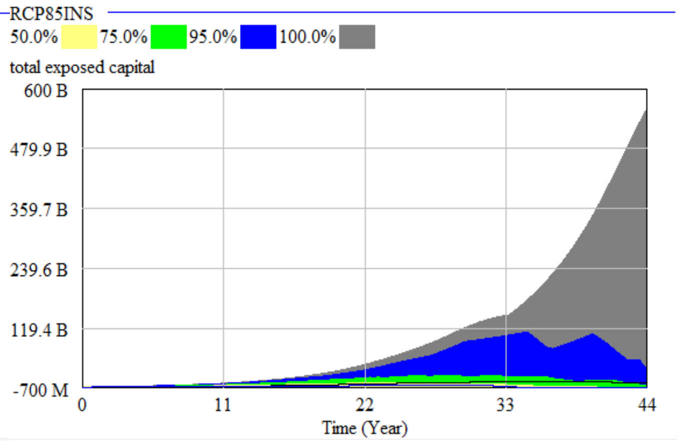
## IV. Total Exposed Capital:



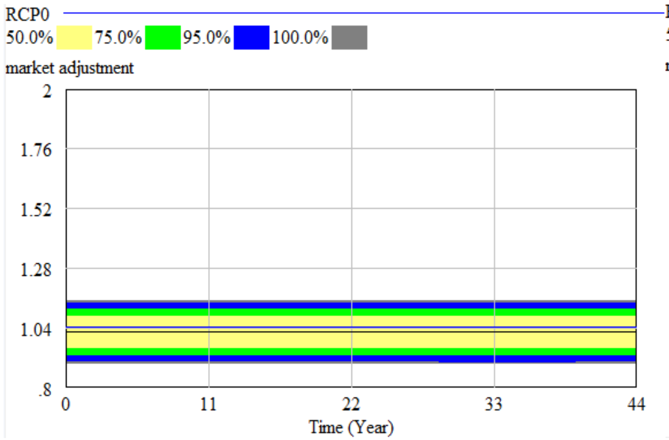



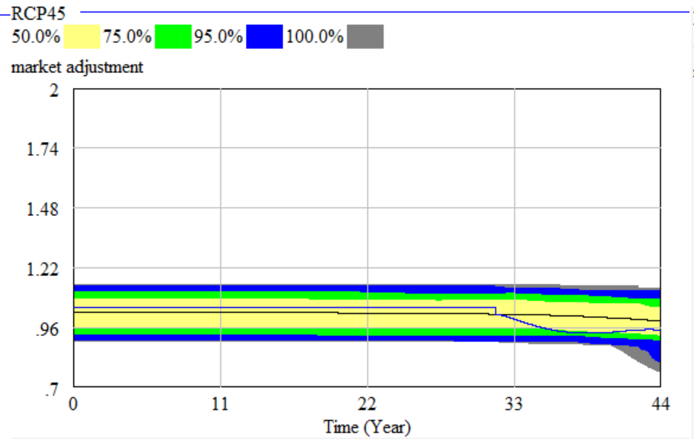



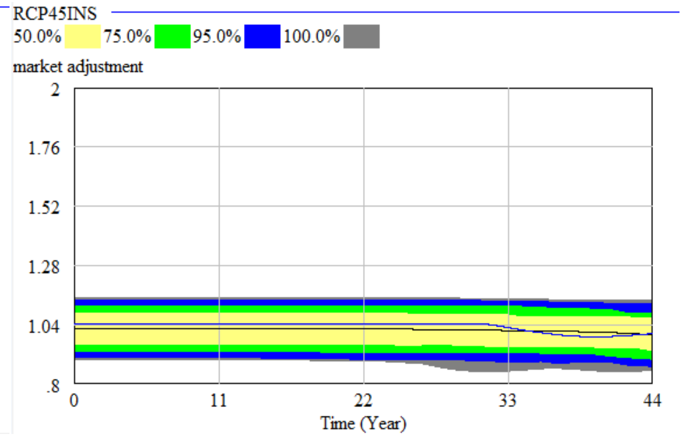



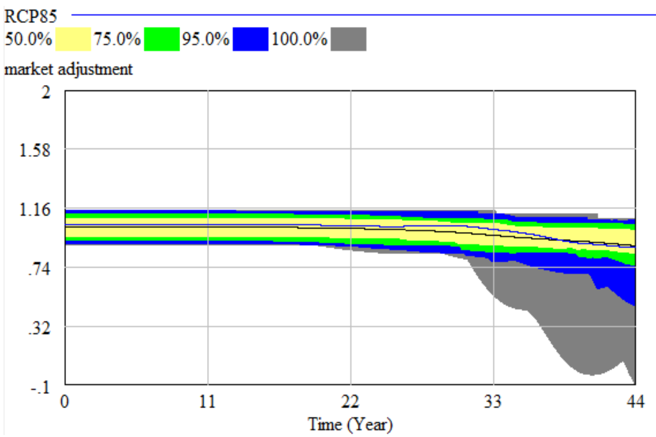



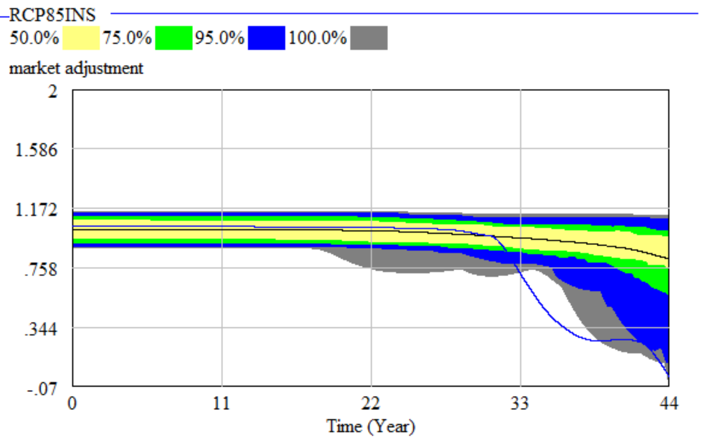
## V. Market Adjustment (Return on Investment):



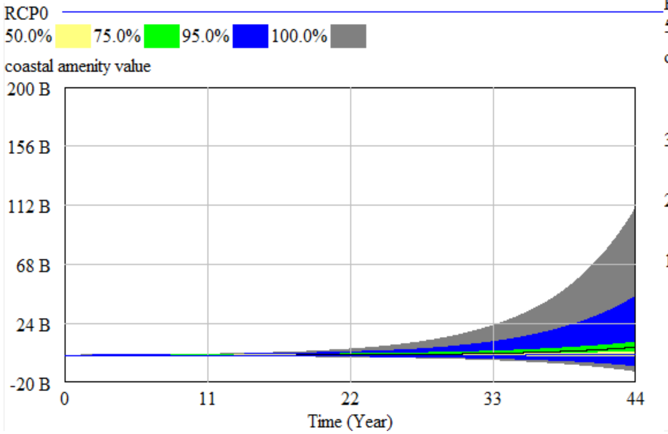



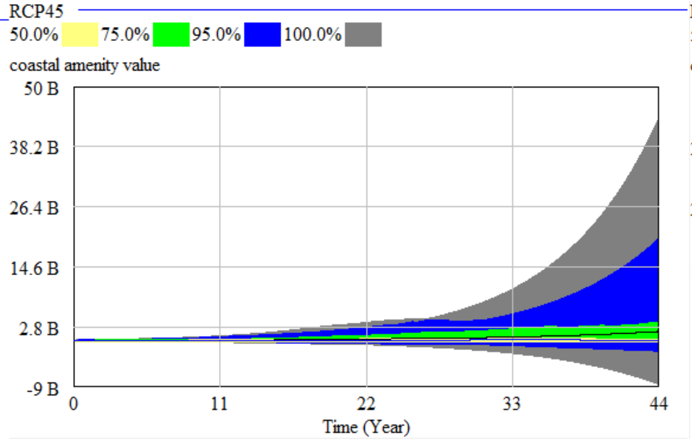



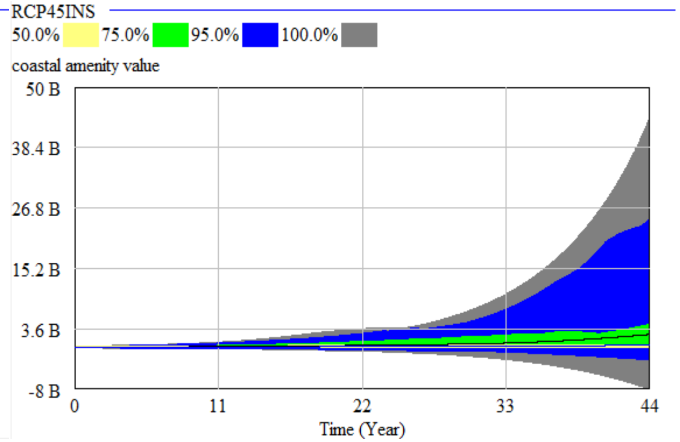



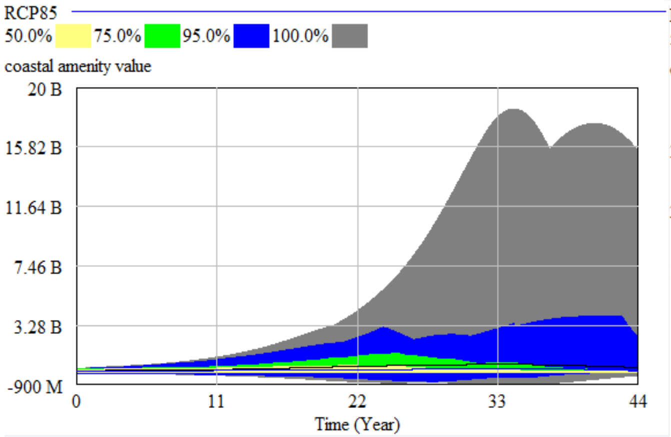



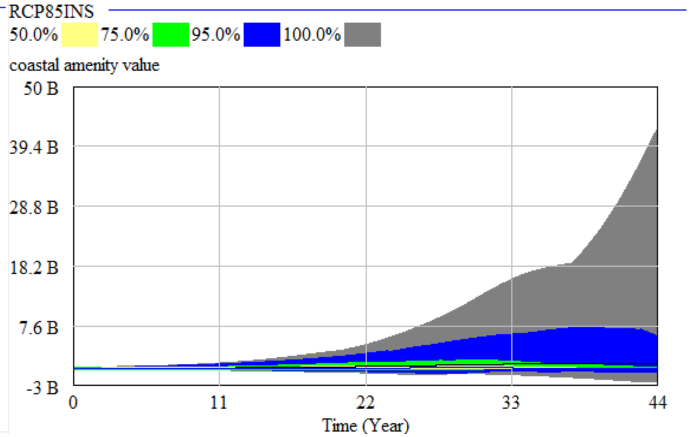
## VI. Coastal Amenity Value:



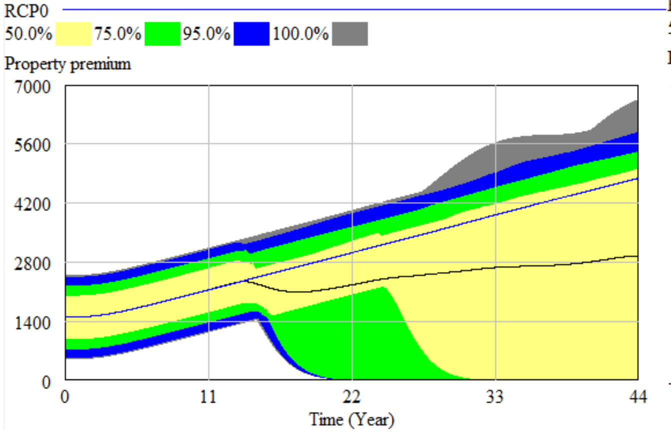



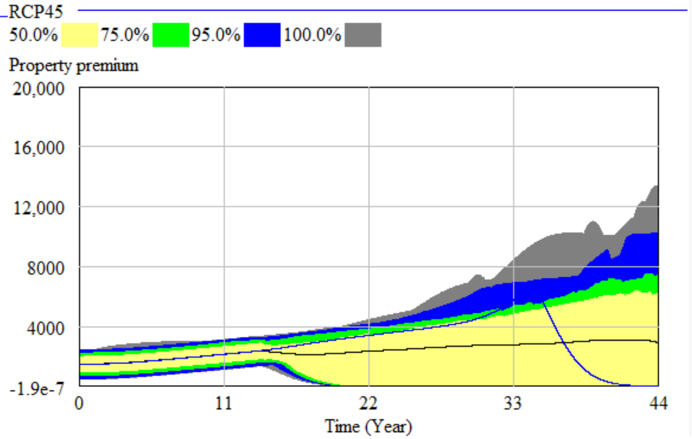



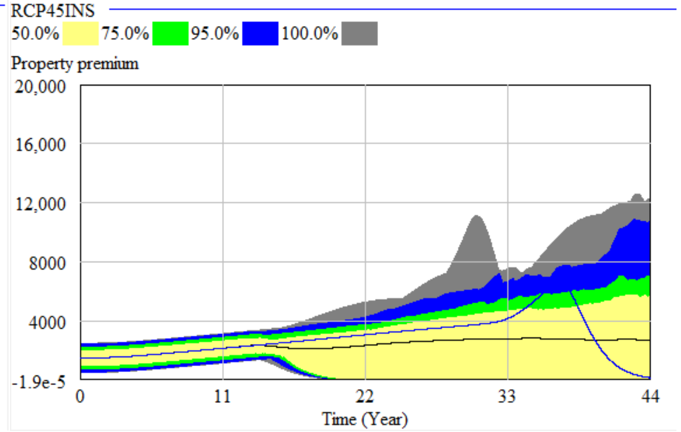



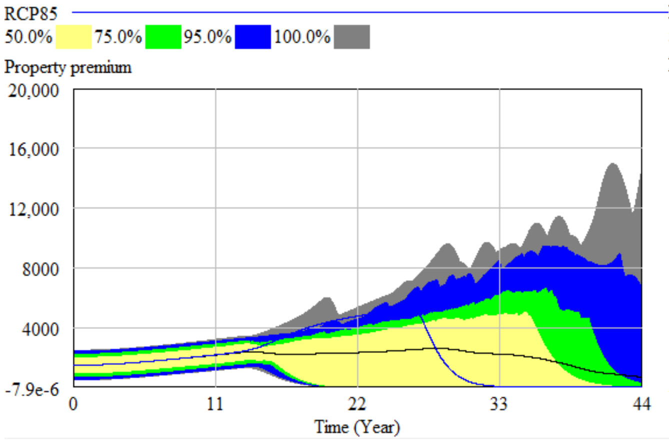



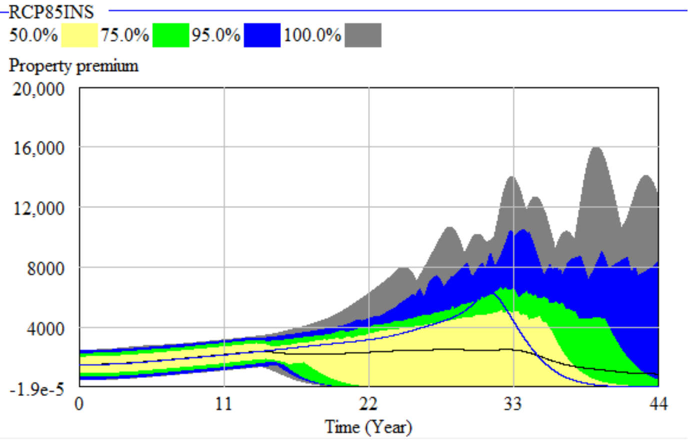
## VII. Property Premium:



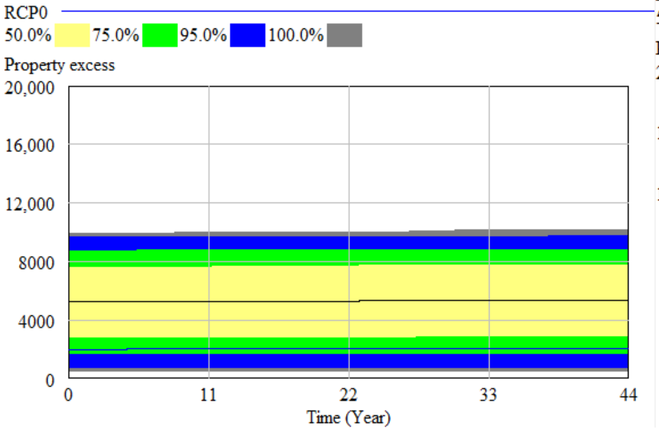



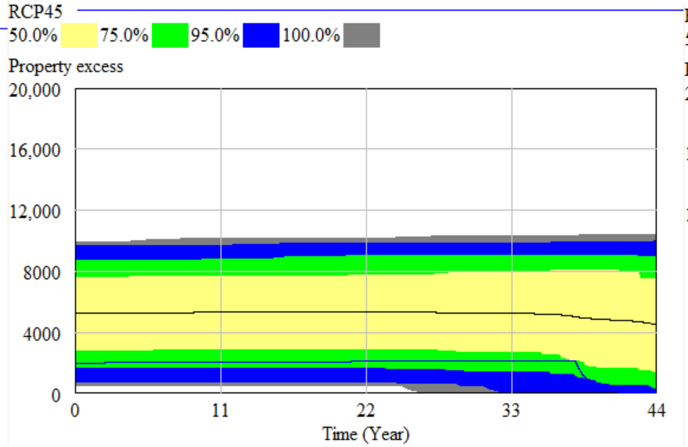



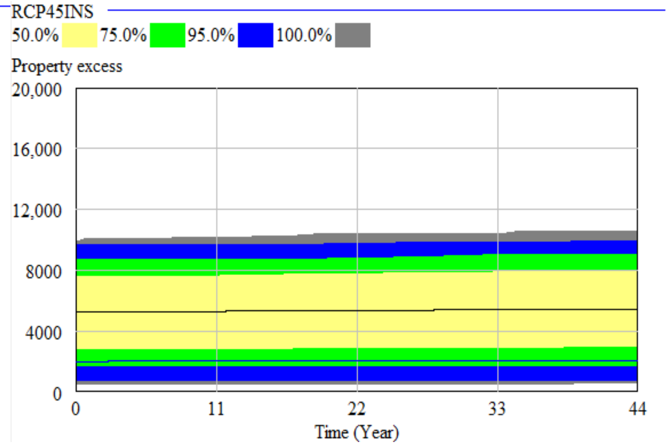



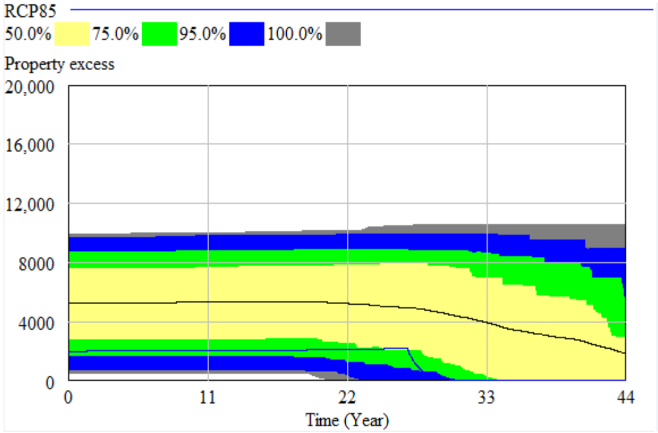



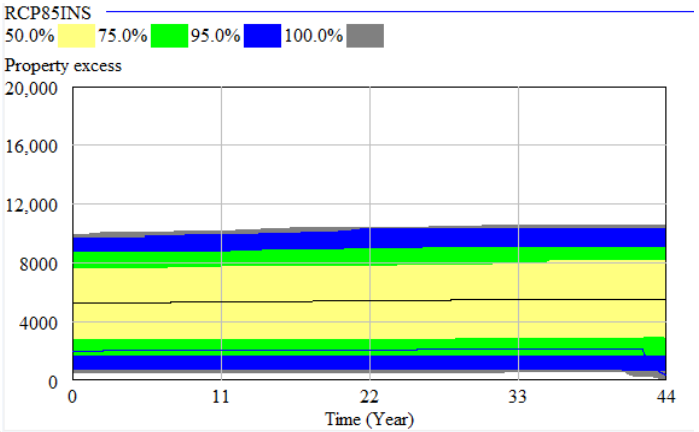
**VIII. Property Excess:**



7B Sensitivity results for MERIT integration

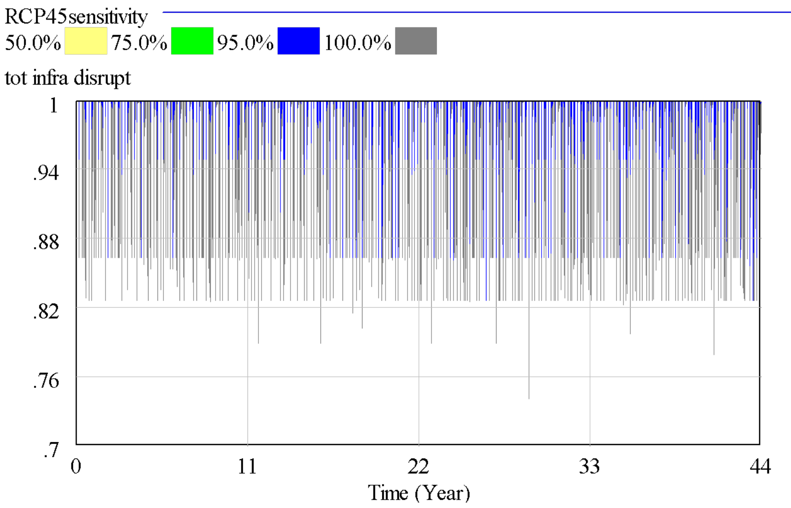
**RCP4.5**

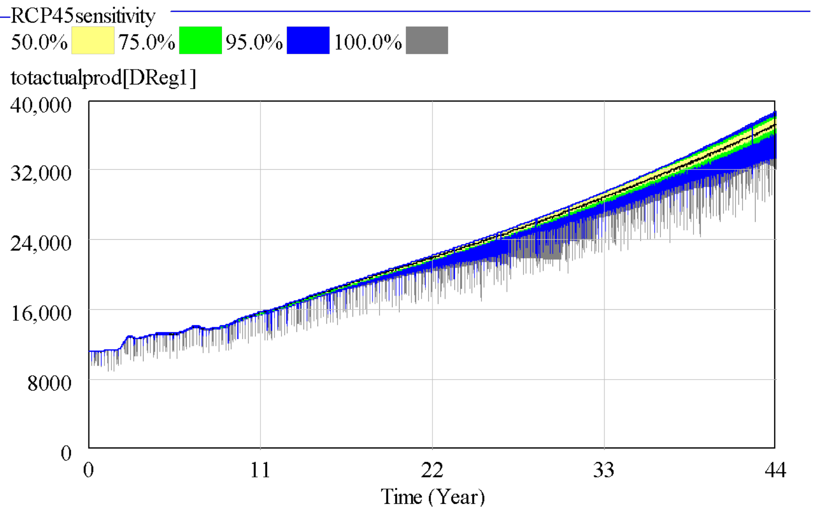
| Variable | Distribution | Range |
|---|---|---|
| FREQUENCY | RANDOM UNIFORM | 0.065, 0.067 |
| SCALE | RANDOM NORMAL | 900, 1100 |
| WATER DEPTH | RANDOM NORMAL | 0.0055, 0.0065 |

**RCP8.5**

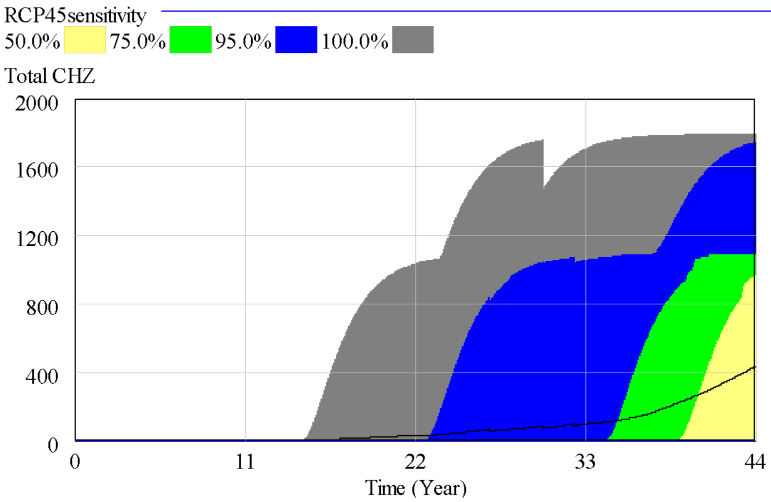
| Variable | Distribution | Range |
|---|---|---|
| FREQUENCY | RANDOM UNIFORM | 0.066, 0.068 |
| SCALE | RANDOM NORMAL | 200, 300 |
| WATER DEPTH | RANDOM NORMAL | 0.007, 0.008 |

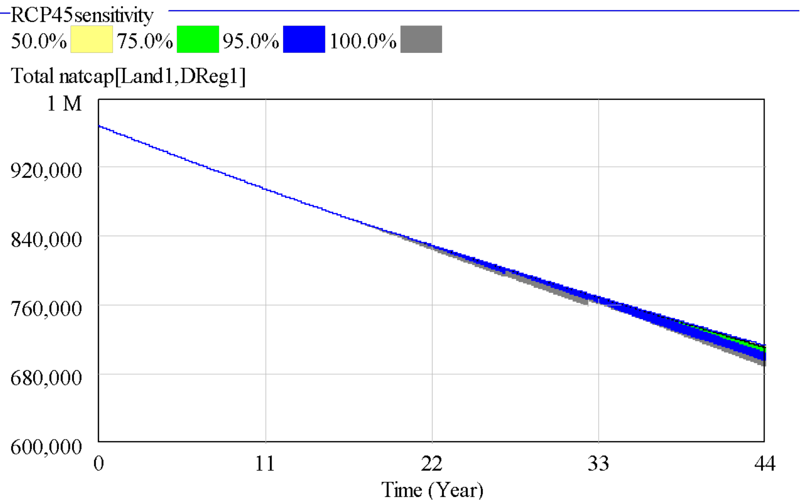
**I. The effect of infrastructure disruption on actual production (RCP4.5):**



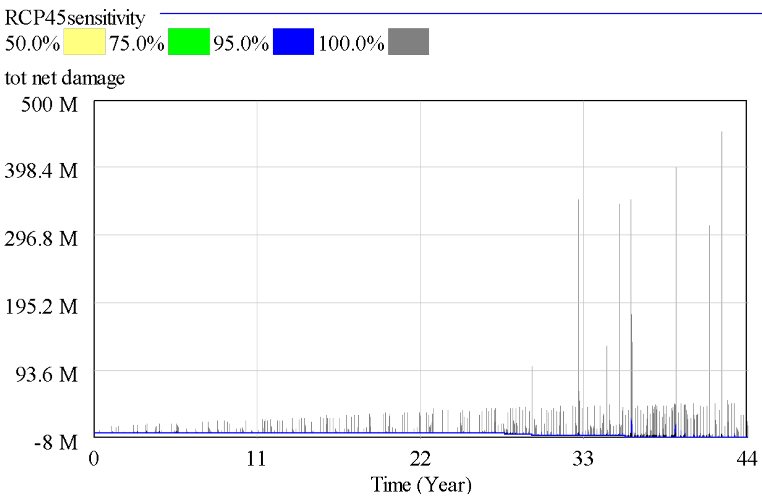



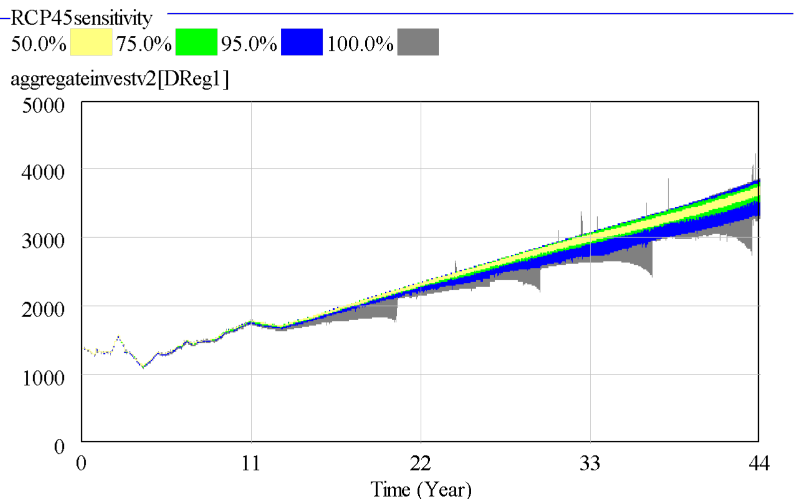
## II. The effect of CHZ land lost on natural capital (RCP4.5):



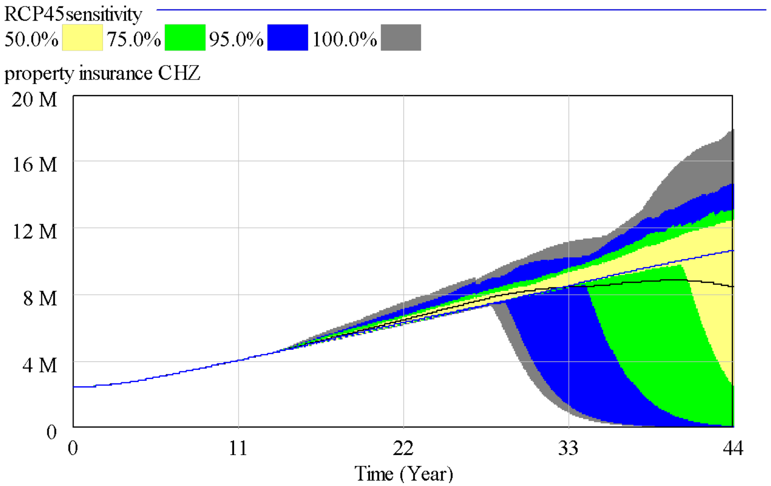



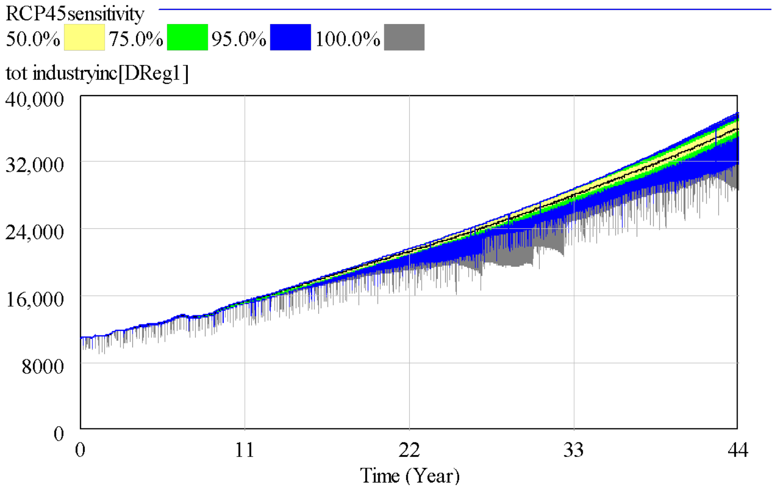

## III. The effect of damages on investment (RCP4.5):



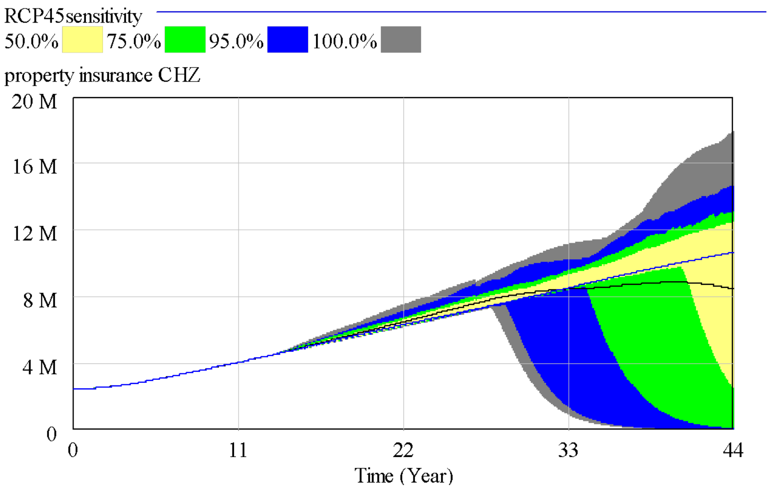



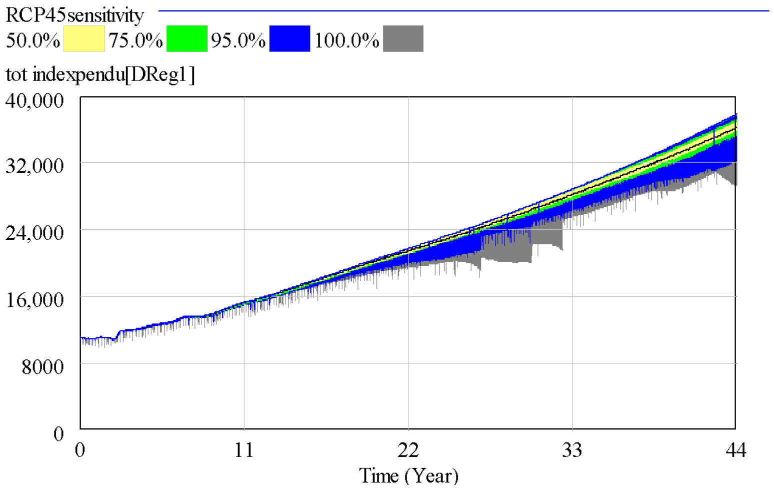
## IV. The effect of increasing insurance premiums on industry income (RCP4.5):



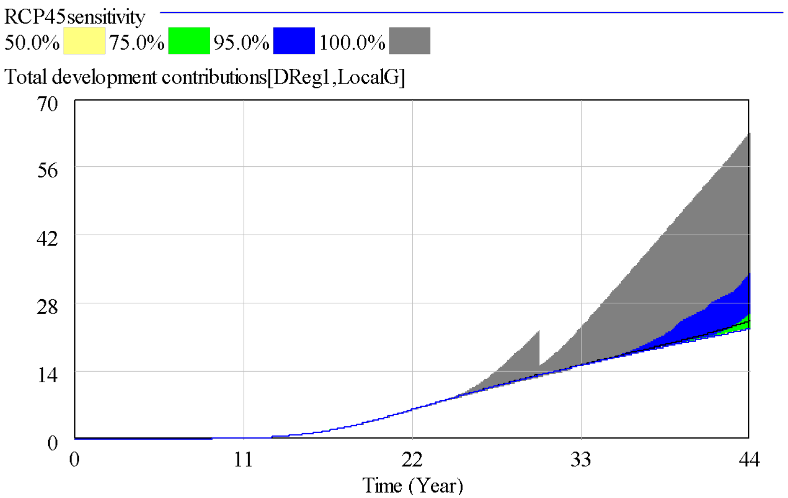



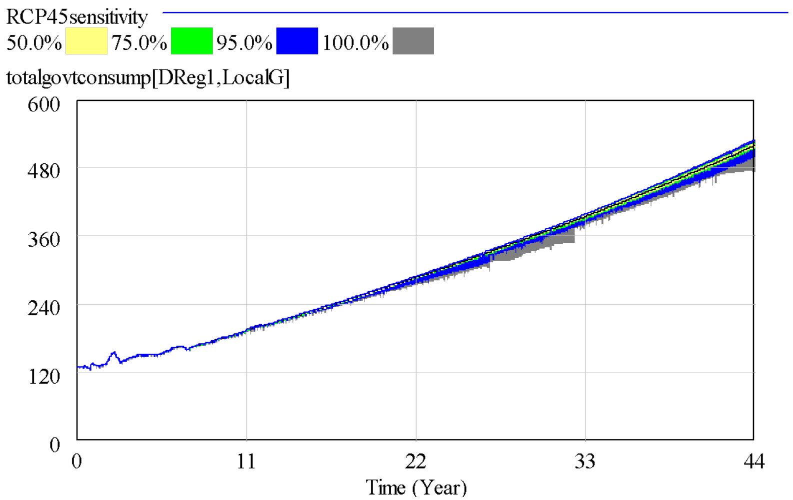

## V. The effect of increasing insurance premiums on industry expenditure (RCP4.5):



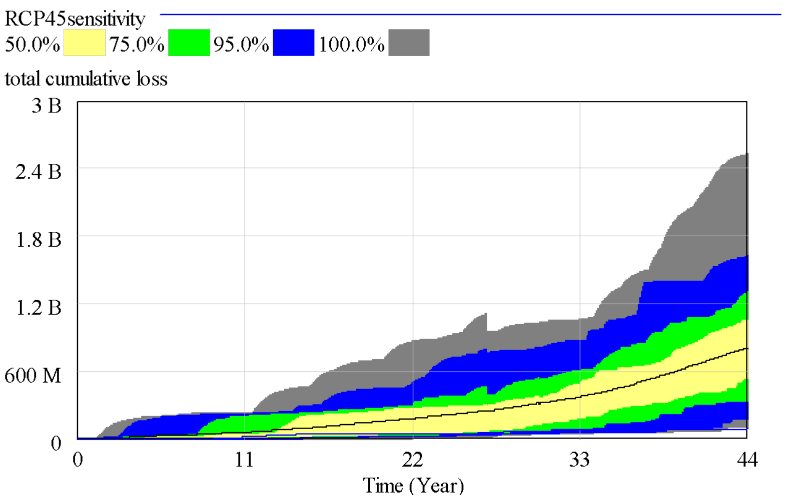



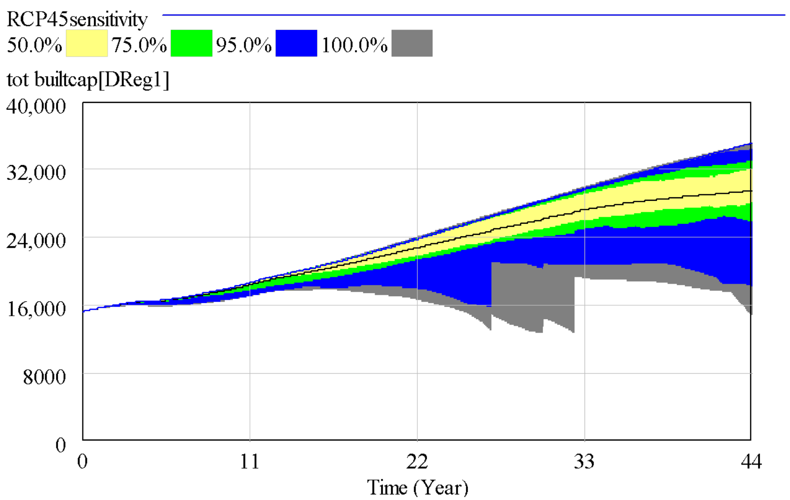
**VI. The effect of the local government development tax on total government consumption (RCP4.5):**



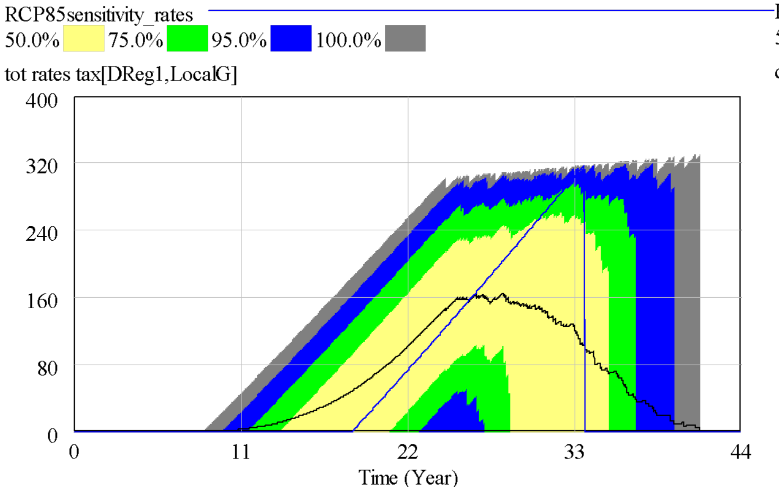



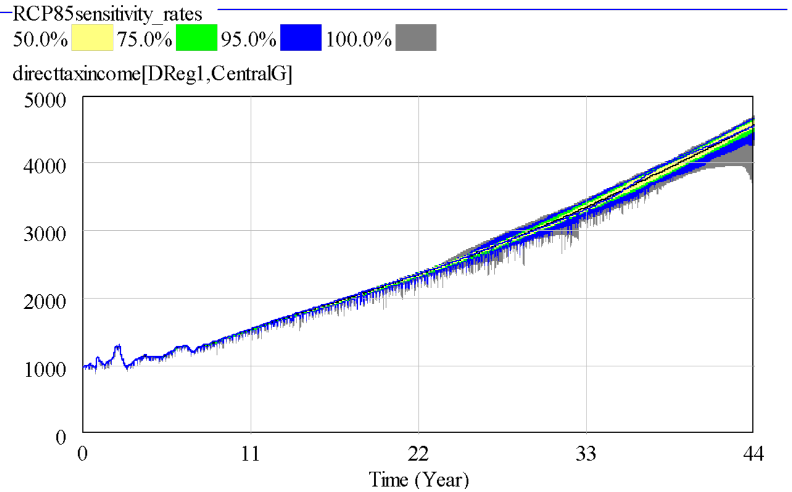

**VII. The effect of the cumulative loss of capital stock on built capital (RCP4.5):**



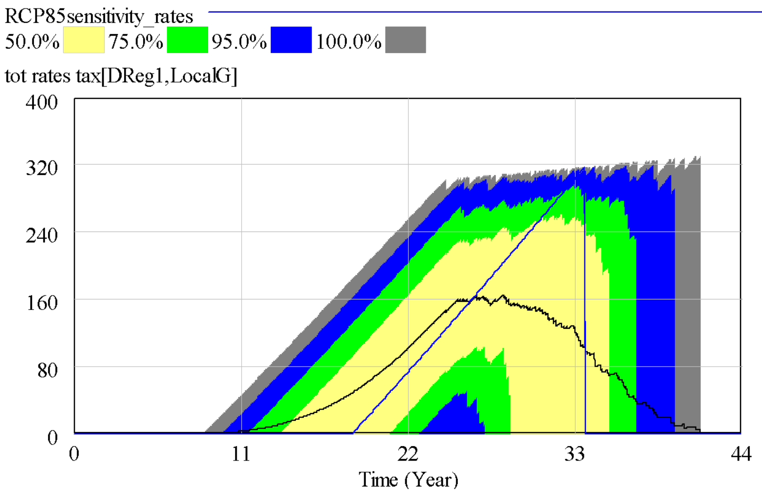



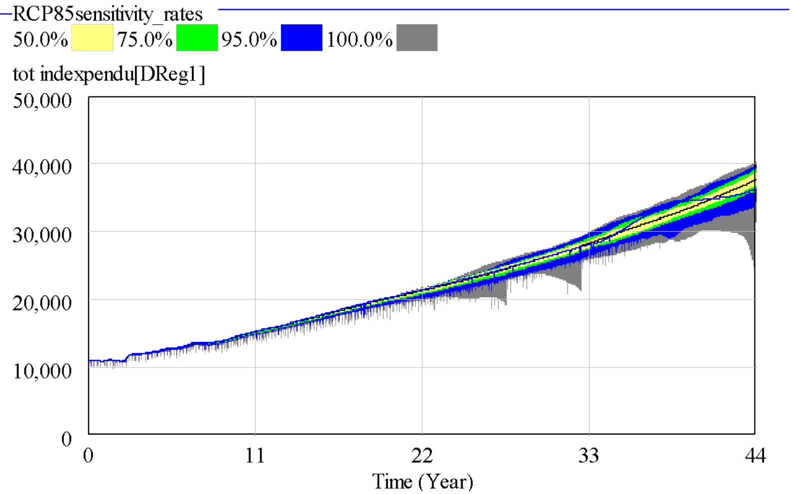
**VIII. The effect of the local government managed retreat rating tax on direct tax income (RCP8.5):**



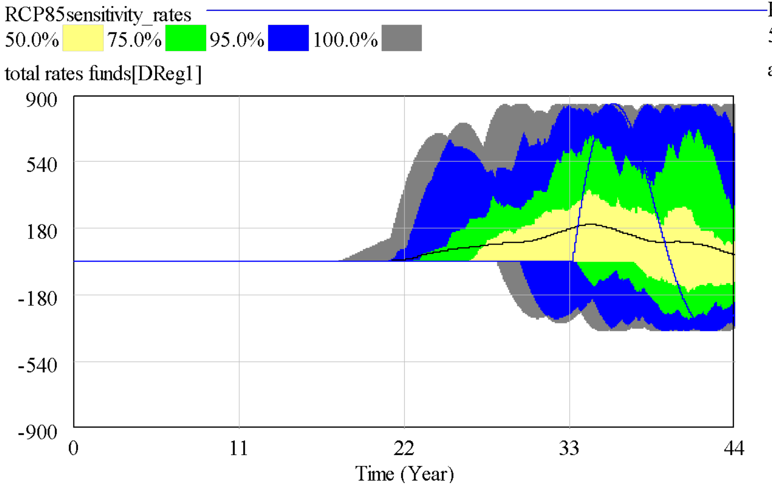



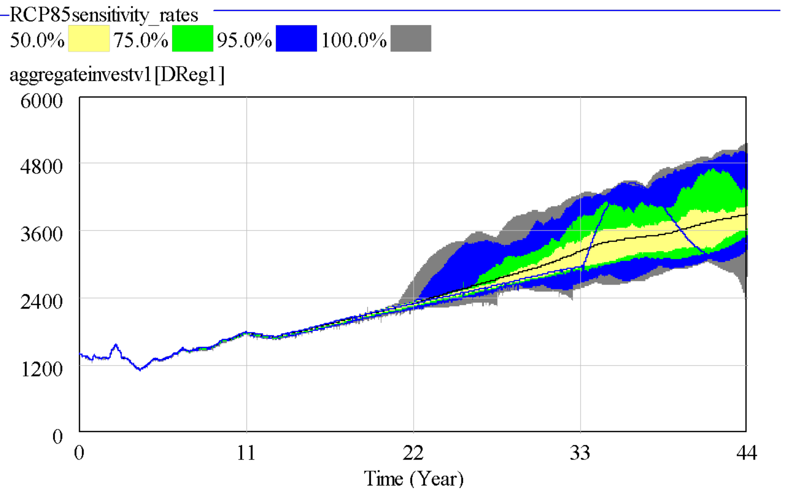

**IX. The effect of the local government managed retreat rating tax on industry expenditure (RCP8.5):**



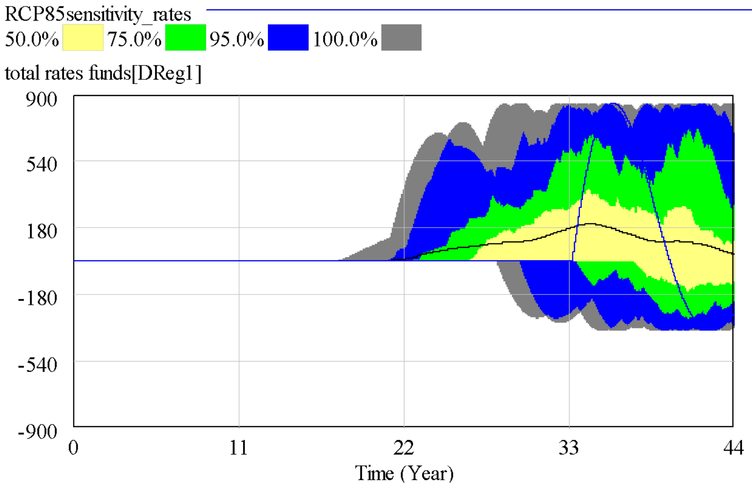



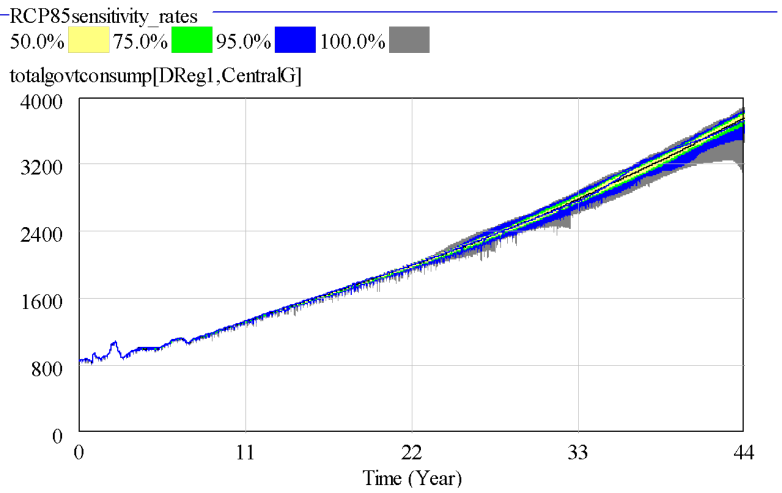
## X. The effect of local government investment through rates in new capital on aggregate investment (RCP8.5):



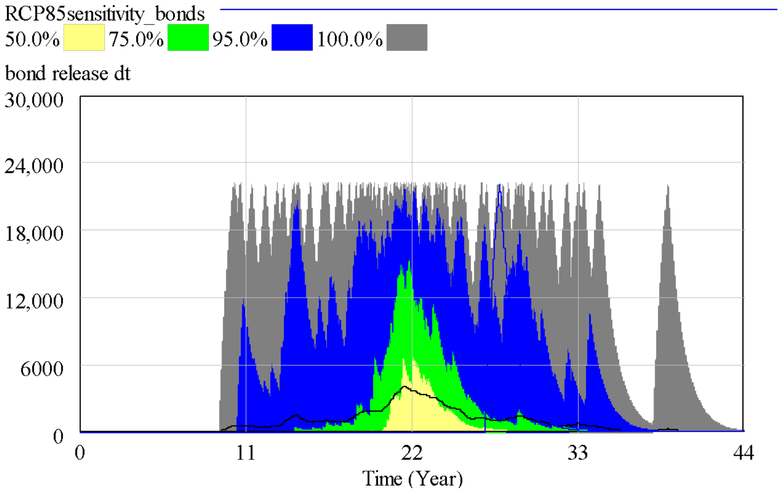



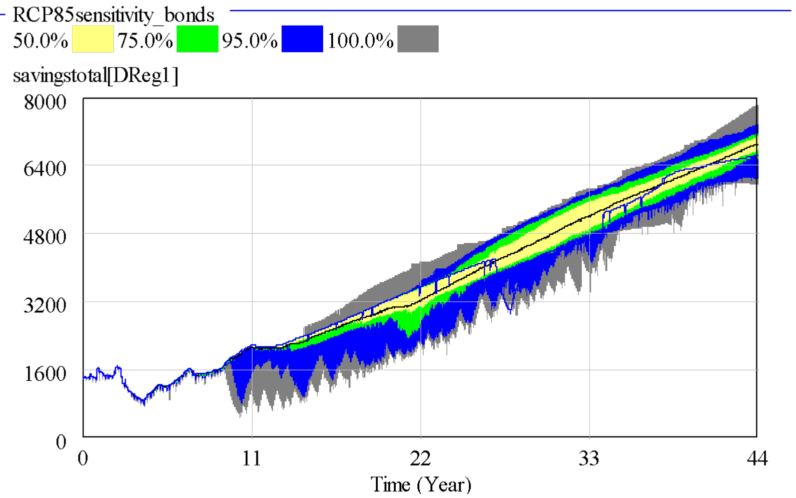

## XI. The effect of local government investment through rates in new capital on total government consumption (RCP8.5):



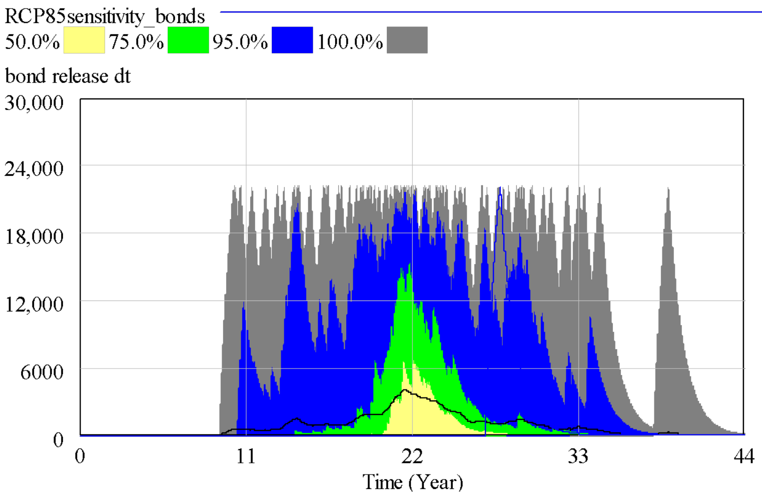



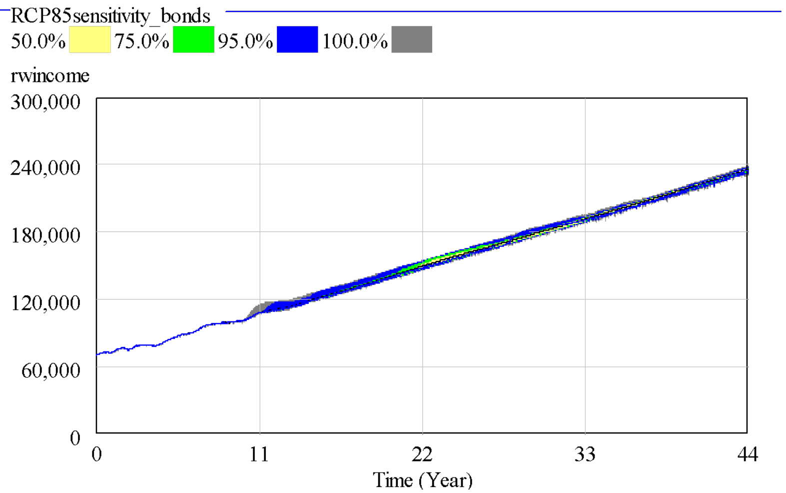
**XII. The effect of the central government bond release on total savings (RCP8.5):**



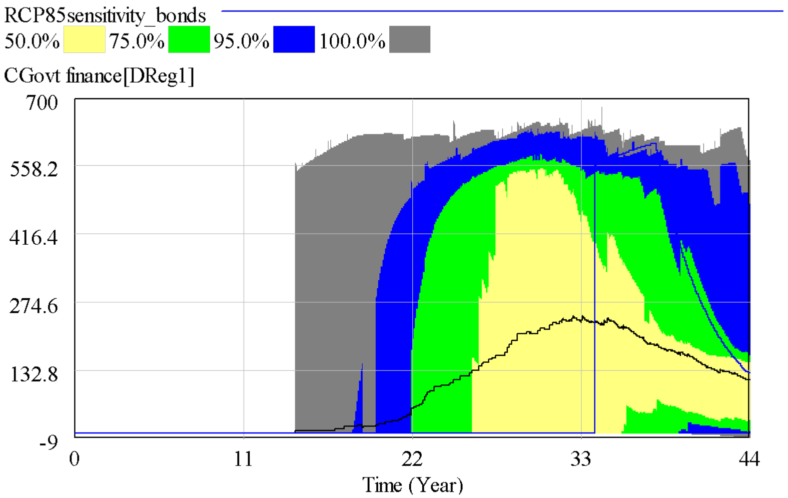



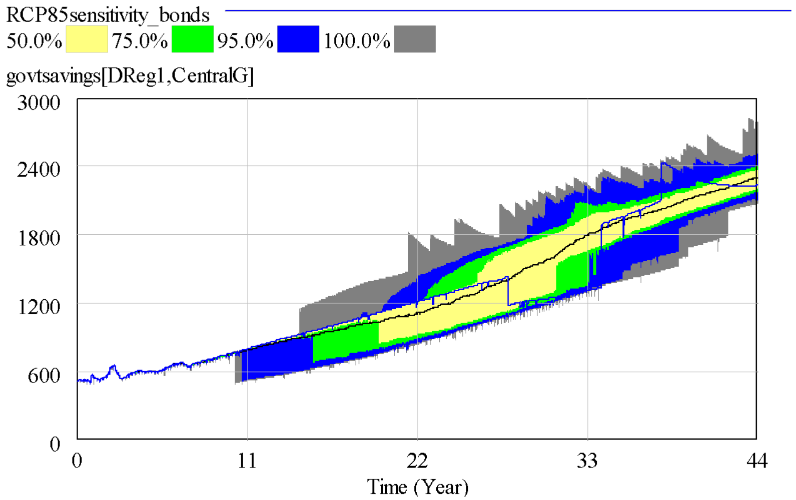

**XIII. The effect of the central government bond release on the rest of world income (RCP8.5):**



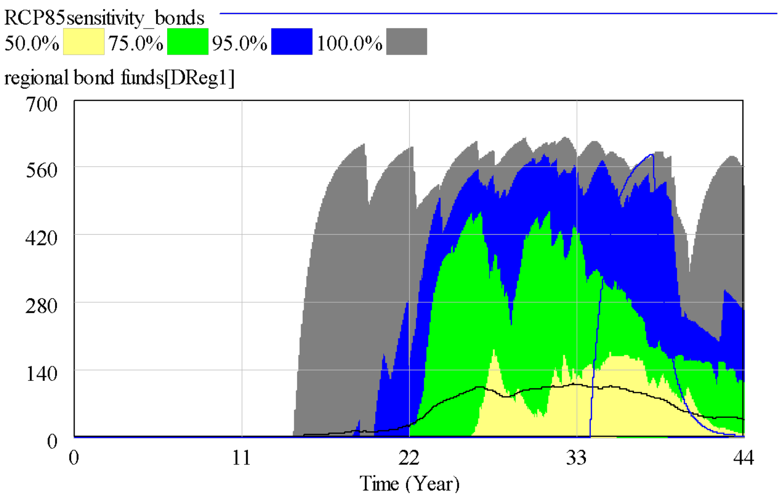



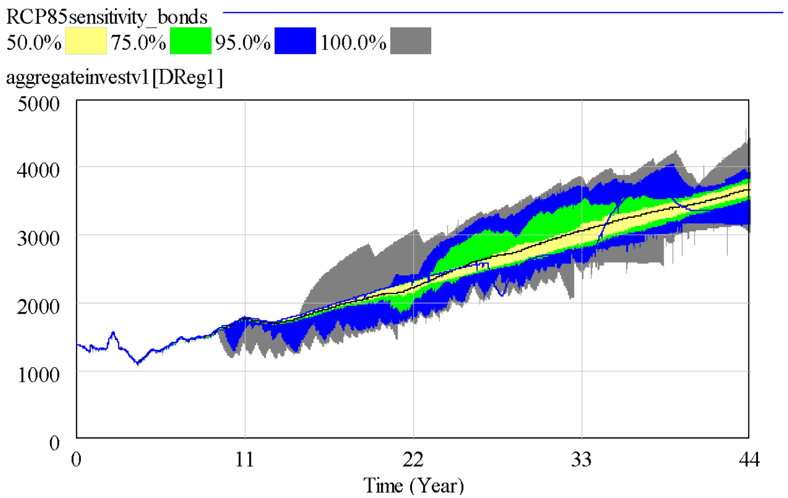
**XIV. The effect of offshore capital generation on central government savings (RCP8.5):**



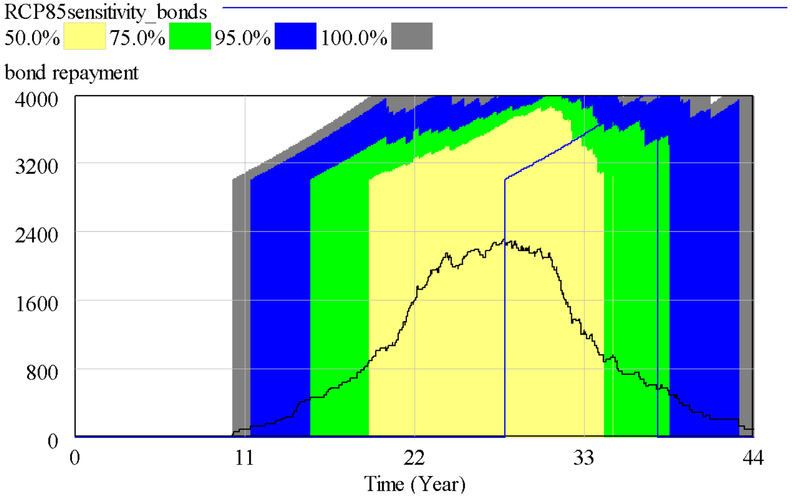



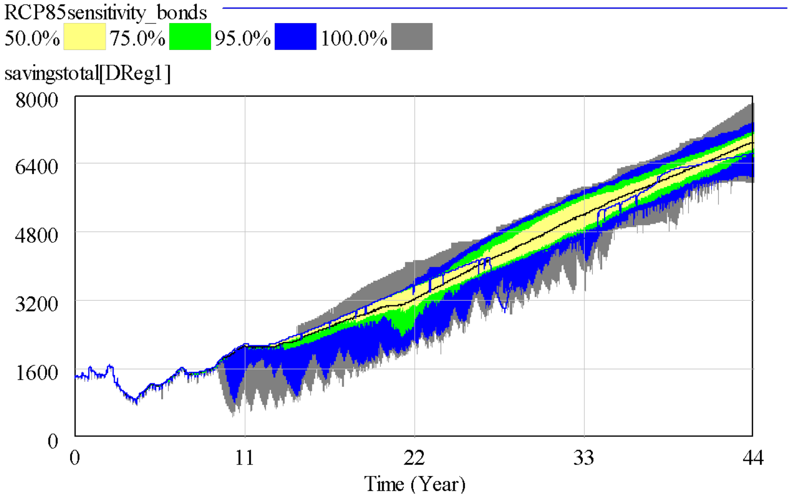

**XV. The effect of central government purchasing properties on aggregate investment (RCP8.5):**



**XVI. The effect of central government paying bonds back with interest to investors (RCP8.5):**



# Appendix 8 PYRDM output

| Time | RCP0 | RCP4.5 | RCP8.5 | RCP4.5 Defence | RCP8.5 Defence | RCP4.5 Bonds | RCP4.5 Rates | RCP8.5 Bonds | RCP8.5 Rates | sum | rank |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 2020 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2020.25 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 10 |
| 2020.5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 9 |
| 2020.75 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 8 |
| 2021 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | 17 |
| 2021.25 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | 16 |
| 2021.5 | 0 | 1 | 1 | 0 | 1 | 1 | 0 | 1 | 1 | 6 | 27 |
| 2021.75 | 0 | 0 | 1 | 0 | 1 | 0 | 0 | 1 | 1 | 4 | 24 |
| 2022 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 8 | 42 |
| 2022.25 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 7 |
| 2022.5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 6 |
| 2022.75 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 5 |
| 2023 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 4 |
| 2023.25 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 3 |
| 2023.5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2 |
| 2023.75 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 4 | 23 |
| 2024 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 8 | 41 |
| 2024.25 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | 19 |
| 2024.5 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 2 | 20 |
| 2024.75 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 0 | 2 | 16 | 56 |
| 2025 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 8 | 40 |
| 2025.25 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 12 |
| 2025.5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 |
| 2025.75 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | 18 |
| 2026 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | 13 |
| 2026.25 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 2 | 1 | 9 | 44 |
| 2026.5 | 1 | 1 | 2 | 1 | 2 | 0 | 1 | 3 | 2 | 13 | 50 |
| 2026.75 | 1 | 1 | 0 | 1 | 0 | 0 | 1 | 1 | 2 | 7 | 30 |
| 2027 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 8 | 39 |
| 2027.25 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 11 |
| 2027.5 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 8 | 37 |
| 2027.75 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 8 | 38 |
| 2028 | 1 | 1 | 2 | 2 | 2 | 1 | 2 | 0 | 3 | 14 | 52 |
| 2028.25 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 2 | 9 | 45 |
| 2028.5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 15 |
| 2028.75 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 14 |
| 2029 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 2 | 21 |
| 2029.25 | 1 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | 3 | 22 |
| 2029.5 | 2 | 2 | 0 | 1 | 1 | 0 | 1 | 0 | 1 | 8 | 36 |
| 2029.75 | 2 | 2 | 1 | 2 | 1 | 0 | 2 | 0 | 1 | 11 | 46 |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| 2030 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 0 | 0 | 6 | 26 |
| 2030.25 | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 0 | 0 | 6 | 25 |
| 2030.5 | 1 | 0 | 0 | 0 | 1 | 1 | 1 | 0 | 3 | 7 | 31 |
| 2030.75 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 0 | 3 | 7 | 29 |
| 2031 | 3 | 0 | 0 | 0 | 0 | 4 | 1 | 3 | 0 | 11 | 47 |
| 2031.25 | 0 | 1 | 1 | 1 | 3 | 2 | 2 | 1 | 1 | 12 | 49 |
| 2031.5 | 0 | 0 | 1 | 0 | 3 | 1 | 1 | 1 | 2 | 9 | 43 |
| 2031.75 | 0 | 0 | 1 | 0 | 3 | 1 | 0 | 0 | 2 | 7 | 28 |
| 2032 | 0 | 0 | 0 | 0 | 3 | 1 | 0 | 2 | 1 | 7 | 32 |
| 2032.25 | 0 | 0 | 0 | 0 | 3 | 2 | 1 | 2 | 0 | 8 | 33 |
| 2032.5 | 0 | 0 | 0 | 0 | 3 | 2 | 1 | 2 | 0 | 8 | 34 |
| 2032.75 | 0 | 0 | 0 | 0 | 3 | 2 | 1 | 2 | 0 | 8 | 35 |
| 2033 | 0 | 3 | 3 | 3 | 6 | 5 | 4 | 5 | 3 | 32 | 72 |
| 2033.25 | 0 | 3 | 3 | 4 | 6 | 5 | 4 | 5 | 3 | 33 | 74 |
| 2033.5 | 0 | 4 | 3 | 1 | 6 | 5 | 4 | 5 | 3 | 31 | 70 |
| 2033.75 | 0 | 1 | 5 | 1 | 3 | 5 | 4 | 5 | 3 | 27 | 63 |
| 2034 | 0 | 3 | 7 | 0 | 5 | 7 | 6 | 7 | 5 | 40 | 82 |
| 2034.25 | 0 | 3 | 8 | 0 | 5 | 7 | 3 | 7 | 5 | 38 | 79 |
| 2034.5 | 0 | 3 | 10 | 0 | 7 | 7 | 2 | 9 | 7 | 45 | 94 |
| 2034.75 | 0 | 0 | 10 | 0 | 7 | 6 | 0 | 8 | 5 | 36 | 75 |
| 2035 | 0 | 0 | 5 | 0 | 5 | 6 | 0 | 6 | 5 | 27 | 62 |
| 2035.25 | 0 | 0 | 5 | 0 | 2 | 3 | 0 | 3 | 5 | 18 | 58 |
| 2035.5 | 0 | 0 | 2 | 0 | 2 | 3 | 0 | 3 | 2 | 12 | 48 |
| 2035.75 | 0 | 0 | 2 | 0 | 2 | 4 | 0 | 4 | 2 | 14 | 54 |
| 2036 | 0 | 0 | 2 | 0 | 2 | 4 | 0 | 4 | 2 | 14 | 51 |
| 2036.25 | 0 | 0 | 2 | 0 | 2 | 4 | 0 | 4 | 2 | 14 | 53 |
| 2036.5 | 0 | 0 | 2 | 0 | 2 | 4 | 0 | 6 | 2 | 16 | 55 |
| 2036.75 | 0 | 0 | 3 | 0 | 3 | 4 | 0 | 6 | 2 | 18 | 57 |
| 2037 | 0 | 0 | 3 | 2 | 3 | 5 | 0 | 6 | 3 | 22 | 59 |
| 2037.25 | 0 | 1 | 4 | 3 | 4 | 7 | 1 | 7 | 4 | 31 | 71 |
| 2037.5 | 0 | 2 | 4 | 4 | 4 | 7 | 2 | 7 | 6 | 36 | 77 |
| 2037.75 | 0 | 3 | 4 | 3 | 4 | 6 | 2 | 8 | 6 | 36 | 76 |
| 2038 | 0 | 3 | 4 | 3 | 6 | 7 | 1 | 8 | 5 | 37 | 78 |
| 2038.25 | 0 | 2 | 3 | 2 | 5 | 6 | 0 | 6 | 4 | 28 | 67 |
| 2038.5 | 0 | 2 | 4 | 2 | 4 | 6 | 0 | 7 | 4 | 29 | 69 |
| 2038.75 | 0 | 2 | 4 | 2 | 4 | 6 | 0 | 7 | 4 | 29 | 68 |
| 2039 | 0 | 2 | 4 | 2 | 4 | 6 | 3 | 7 | 4 | 32 | 73 |
| 2039.25 | 0 | 2 | 4 | 2 | 4 | 5 | 2 | 5 | 4 | 28 | 66 |
| 2039.5 | 0 | 2 | 4 | 2 | 4 | 5 | 2 | 5 | 4 | 28 | 65 |
| 2039.75 | 0 | 2 | 4 | 2 | 4 | 5 | 2 | 5 | 4 | 28 | 64 |
| 2040 | 0 | 2 | 3 | 2 | 4 | 5 | 2 | 5 | 4 | 27 | 60 |
| 2040.25 | 0 | 2 | 3 | 2 | 4 | 5 | 2 | 5 | 4 | 27 | 61 |
| 2040.5 | 0 | 4 | 5 | 4 | 6 | 7 | 4 | 7 | 6 | 43 | 89 |
| 2040.75 | 0 | 4 | 8 | 4 | 6 | 7 | 4 | 7 | 6 | 46 | 96 |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 2041 | 0 | 4 | 8 | 4 | 6 | 7 | 4 | 7 | 4 | 44 | 91 |
| 2041.25 | 0 | 2 | 8 | 4 | 6 | 7 | 2 | 7 | 4 | 40 | 83 |
| 2041.5 | 0 | 2 | 11 | 2 | 9 | 5 | 2 | 7 | 4 | 42 | 87 |
| 2041.75 | 0 | 2 | 11 | 2 | 9 | 5 | 2 | 7 | 4 | 42 | 88 |
| 2042 | 0 | 2 | 11 | 2 | 9 | 5 | 2 | 5 | 5 | 41 | 86 |
| 2042.25 | 0 | 2 | 11 | 2 | 9 | 5 | 2 | 5 | 5 | 41 | 85 |
| 2042.5 | 0 | 2 | 11 | 2 | 7 | 5 | 2 | 5 | 5 | 39 | 81 |
| 2042.75 | 0 | 3 | 10 | 3 | 10 | 6 | 3 | 6 | 6 | 47 | 98 |
| 2043 | 0 | 3 | 10 | 3 | 10 | 6 | 3 | 5 | 5 | 45 | 93 |
| 2043.25 | 0 | 3 | 9 | 3 | 10 | 6 | 2 | 5 | 5 | 43 | 90 |
| 2043.5 | 0 | 3 | 9 | 3 | 10 | 4 | 2 | 5 | 2 | 38 | 80 |
| 2043.75 | 0 | 2 | 12 | 2 | 10 | 6 | 2 | 5 | 2 | 41 | 84 |
| 2044 | 0 | 4 | 12 | 2 | 10 | 6 | 2 | 7 | 1 | 44 | 92 |
| 2044.25 | 0 | 4 | 12 | 2 | 11 | 6 | 2 | 7 | 1 | 45 | 95 |
| 2044.5 | 0 | 4 | 12 | 2 | 11 | 7 | 2 | 7 | 1 | 46 | 97 |
| 2044.75 | 0 | 7 | 12 | 5 | 11 | 7 | 2 | 7 | 4 | 55 | 100 |
| 2045 | 0 | 7 | 11 | 5 | 10 | 7 | 2 | 7 | 4 | 53 | 99 |
| 2045.25 | 0 | 8 | 11 | 6 | 10 | 8 | 2 | 7 | 4 | 56 | 102 |
| 2045.5 | 0 | 8 | 11 | 6 | 12 | 8 | 4 | 7 | 4 | 60 | 106 |
| 2045.75 | 0 | 8 | 11 | 6 | 14 | 8 | 4 | 7 | 4 | 62 | 111 |
| 2046 | 0 | 8 | 11 | 6 | 14 | 8 | 4 | 8 | 4 | 63 | 113 |
| 2046.25 | 0 | 10 | 12 | 8 | 16 | 10 | 6 | 9 | 6 | 77 | 120 |
| 2046.5 | 0 | 9 | 12 | 7 | 15 | 9 | 5 | 8 | 3 | 68 | 119 |
| 2046.75 | 1 | 9 | 13 | 7 | 15 | 9 | 0 | 8 | 3 | 65 | 115 |
| 2047 | 1 | 9 | 12 | 7 | 15 | 9 | 0 | 7 | 4 | 64 | 114 |
| 2047.25 | 1 | 9 | 13 | 7 | 15 | 9 | 0 | 7 | 4 | 65 | 117 |
| 2047.5 | 1 | 8 | 14 | 8 | 16 | 10 | 1 | 8 | 0 | 66 | 118 |
| 2047.75 | 1 | 9 | 13 | 8 | 16 | 9 | 1 | 8 | 0 | 65 | 116 |
| 2048 | 1 | 9 | 13 | 8 | 16 | 9 | 1 | 6 | 0 | 63 | 112 |
| 2048.25 | 1 | 9 | 13 | 8 | 16 | 8 | 1 | 6 | 0 | 62 | 107 |
| 2048.5 | 1 | 8 | 13 | 9 | 16 | 8 | 1 | 6 | 0 | 62 | 108 |
| 2048.75 | 1 | 8 | 13 | 8 | 17 | 8 | 2 | 5 | 0 | 62 | 109 |
| 2049 | 1 | 8 | 13 | 8 | 17 | 8 | 2 | 5 | 0 | 62 | 110 |
| 2049.25 | 0 | 7 | 12 | 7 | 16 | 7 | 1 | 4 | 3 | 57 | 103 |
| 2049.5 | 0 | 7 | 13 | 4 | 16 | 7 | 1 | 4 | 3 | 55 | 101 |
| 2049.75 | 0 | 9 | 13 | 4 | 16 | 8 | 1 | 8 | 1 | 60 | 105 |
| 2050 | 0 | 6 | 12 | 4 | 17 | 8 | 1 | 8 | 1 | 57 | 104 |
| sum | 34 | 298 | 586 | 255 | 641 | 472 | 160 | 460 | 272 | | |
| rank | 0 | 4 | 7 | 2 | 8 | 6 | 1 | 5 | 3 | | |