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SPECIAL ISSUE

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Modelling economic risk to sea-level rise and storms at the coastal margin

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Abstract

We develop a methodological approach through integrated assessment using System Dynamics modelling and Scenario Planning to investigate the economic vulnerability of coastal communities to the compounding impacts of sea-level rise (SLR) and storm flooding and inundation associated with climate change. The approach uses a coastal flood risk assessment that quantifies physical drivers alongside socio-economic well-being for coastal communities to provide a methodology for managing uncertain futures through causal relationships in System Dynamics. A New Zealand case study is used to illustrate the long-term economic impacts of inaction under different SLR projections and recognise critical tolerance thresholds to help exposed property owners plan their future. Modelling scenarios using this integrated approach identified 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, and second, the decisions of households and firms to accept risk for the added value of coastal living. Model outputs suggest that the threat posed by coastal hazards drives a behavioural, socio-economic response that exceeds the initial economic exposure of capital assets. In the economic short term (1–10 years) and medium term (10–20 years), vulnerable communities accept the risk of capital loss and loss of insurability, favouring the amenity of coastal living. However, in the long term (+20 years), economic losses from repeat flooding increase risk-based insurance premiums, promote insurance withdrawal and drive negative corrections in property valuations. Unanticipated insights were obtained from the modelling, including the likely timing of tolerance thresholds, particularly the insurance withdrawal point, which is critical to insurer/consumer decision-making and community planning.

KEYWORDS

coastal risk assessment, economic impact modelling, Scenario Planning, sea-level rise, System Dynamics

1 | INTRODUCTION

Globally, climate change is unfolding with a multitude of compounding environmental hazards affecting how societies live. Sea-level rise (SLR) and the increased frequency and magnitude of coastal storms will escalate the exposure to hazards (erosion and flooding) in low-lying settlements over the next century (IPCC, 2019). The economic, environmental and social costs of these slow-onset hazards will be significant (IPCC, 2014, 2022). However, robust quantification of the risks and impacts of these hazards on coastal communities, which is necessary to support adaptation planning, is complex and methods to support this analysis are often underdeveloped. Risk assessment alone is problematic due to the inherent uncertainties embedded in climate change futures (IPCC, 2014, 2022). In contrast, economic impacts can cause positive system feedbacks that precipitate threshold shifts, cyclical effects, hysteresis or catastrophic system failure (Hughes et al., 2017). Dynamic and integrated systems approaches to economic impact modelling can potentially improve long-term coastal management decision-making (McDonald et al., 2014). Such modelling may help unravel the dynamic complexity and deep uncertainty within integrated environment-economy coastal systems (Gorddard et al., 2012). This can facilitate robust coastal risk assessment to inform society of transition paths under different future climates (Gorddard et al., 2012).

This paper utilises System Dynamics modelling and Scenario Planning through an Integrated Assessment Model (IAM) to assess how coastal hazards alter environment-economy system behaviour, which influences the decision-making of local communities. Specifically, it explores how a local economy may react under scenarios where governance interventions are not forthcoming and exposed communities continue to work and reside amid the growing spectre of increasing risk, damage and loss. Here exposed communities exhibit the economic concept known as bounded rationality, whereby perfect economic rationality does not hold (Safarzyńska et al., 2013). Modelling in System Dynamics is useful as it allows modellers to investigate system dependencies over long timeframes, stochastic shocks to the system and test policies that can lead to resilience (Forrester, 1971). Novel system behaviours are also discovered through reframing our understanding of the system with new knowledge and information from scenario simulations, what-if analyses and sensitivity analysis (Ford, 2010; Ramirez & Wilkinson, 2016). Two socio-economic drivers are central to the work described in the paper: (1) the long-term insurability of capital assets with increasing coastal risk and (2) the non-market, intangible benefit of coastal living or coastal amenity value. Once the underlying interactions of the environment-economic systems are understood, state planners, coastal managers and communities can intervene and set long-term coastal management goals.

2 | PLANNING FOR SLR AND INCREASED STORMS

Planning for coastal hazards is complex: it seeks to integrate current knowledge of the physical, social and economic system with future expectations from diverse social communities, businesses and agencies against a backdrop of a constantly changing environment. To reduce uncertainty around modelled economic futures, planners and researchers typically explore possibilities through the 'methodological pluralism' of predictions, forecasts and scenarios (McDonald et al., 2014). Predictions and forecasts produce results for a broad audience that are often based on algorithms grounded in historical analyses of bounded variable interactions (Ramirez & Wilkinson, 2016). Such algorithms have been the dominant approach to managing environmental risk (Ramirez & Wilkinson, 2016). However, this approach 'lacks a complexity of thinking or variety' (Ramirez & Wilkinson, 2016, p. 18) and cannot discover emergent behaviour in systems that exhibit uncertainty (Rosser, 2011). Scenario Planning (or strategic reframing) is an alternate approach whereby plausible future worlds are compiled from expert judgement and analysed to develop consistent stories of the future when faced with decision-making under uncertainty (Gong et al., 2017). Scenarios are uncertainty based, can explore risk, and are applicable over longer intervals (Lindgren, 2003). They can assist stakeholders in understanding the potential impacts of decisions and policies across a range of possible futures (IPCC, 2021). The use of scenarios is a preferred local government approach to managing exposed assets in New Zealand (Local Government New Zealand, 2019). Scenarios do not intend to cover all possible options but concentrate on a few dominant issues of concern for a select audience (Ramirez & Wilkinson, 2016).

Baseline scenarios, status quo or reference modes are required to characterise the socio-economic system for exposed communities. We construct baseline scenarios for coastal communities at a study site in the Hawke's Bay region of New Zealand (Figure 1). Scenarios incorporate varying climate projections reported by the IPCC (2019, 2021) into an IAM to explore the direct (first-order) economic impacts on coastal communities, such as storm damage to build capital and lost natural capital to the sea. The IPCC scenarios utilise the Representative Concentration Pathway (RCP) projections with differing atmospheric CO_2 concentrations that force changes in global temperatures and sea levels (Ministry for the Environment, 2017; van Vuuren et al., 2011). They provide a useful way of evaluating the evolving scale of risk to vulnerable communities from a changing climate. Prospective mitigation and adaptation interventions can then be assessed against these scenarios.

The current approach for risk reduction in New Zealand is to notify hazardous extents and project magnitudes of flooding and inundation for 100 years (New Zealand Government, 2010). Storms are relatively well predicted, and early warning systems are well ingrained in emergency management procedures. However, this does not seem to minimise the risk to capital and land (The Press, 2022), and public and private insurance companies are required to compensate communities for losses (Eaves, 2022). In New Zealand, property owners rely on private insurers to pay for damages and losses when they are insured. At the same time, the insurance industry argues for greater use of risk-based premiums, alongside preventative measures as a precondition for insurance cover, which can act as a good incentive for raising awareness and adapting to the risks faced (Murray et al., 2015). Therefore, by default, the insurance industry becomes a key driver in reducing potential human exposure and the financial costs of disaster through market withdrawal (Murray et al., 2015). This was the case in Christchurch after devastating earthquakes, where insurance companies, alongside the central government, scientists and engineers, decided to rebuild many coastal properties of low elevation. Households in New Zealand 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 (Earthquake Commission NZ, 2019). However, where storms are concerned, EQC only covers the remediation of land or the provision of a modest nearby section where the land is uninhabitable (Earthquake Commission NZ, 2019).

3 | THE HAWKE'S BAY

The Hawke's Bay region is of interest as it exhibits vulnerable open coast barrier beaches and estuarine environments. It was selected because of its known high risk of large-scale damages and a rich scientific research base. It is particularly exposed to coastal flooding due to the proximity of capital assets to the Mean High Water Spring tide level and chronic erosion of parts of the foreshore (HBRC, 2014). Recognising the susceptibility of the coast to these hazards, the Regional Council has established identifiable coastal hazard zones (CHZs) within the study area. SLR, the increasing frequency and intensity of storms, and significant land subsidence are anticipated to exacerbate multiple local-scale coastal hazards such as storm inundation, erosion, waterway flooding and rising groundwater New Zealand-wide (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. For this study, we used the coastal inundation extent modelled by Hawke's Bay Regional Council (see HBRC, 2017, map viewer https://gis.hbrc.govt.nz/Hazards/; or the 1% Annual Exceedance Probability [AEP] projected for 2120) as the CHZ for land-use planning and economic impact assessment. The model also utilises the 2065 inundation extent to define a step change in flood exposure. The reason for using the 2120 extent is that under New Zealand legislation, land-use decision-making at the coast must take account of coastal hazards over at least 100 years (New Zealand Government, 2010). The value of capital assets in the CHZ is estimated from the 2009 Riskscape Coastal Vulnerability Assessment (Riskscape), also shown in Figure 1 (King & Bell, 2005; NIWA, 2017a, 2017b; Reese & Ramsay, 2010).[1] The Riskscape desktop GIS application combines multiple hazard information (flooding, earthquake and tsunami) in New Zealand with asset and population exposure information. The damage ratio employed here averages seven different building types, as described by Reese and Ramsay (2010). Alongside SLR, we incorporate a geodetic (subsidence) change of −0.086 m for the modelled period based on the Ministry for the Environment's projections for Hawke's Bay Regional Council (2017).

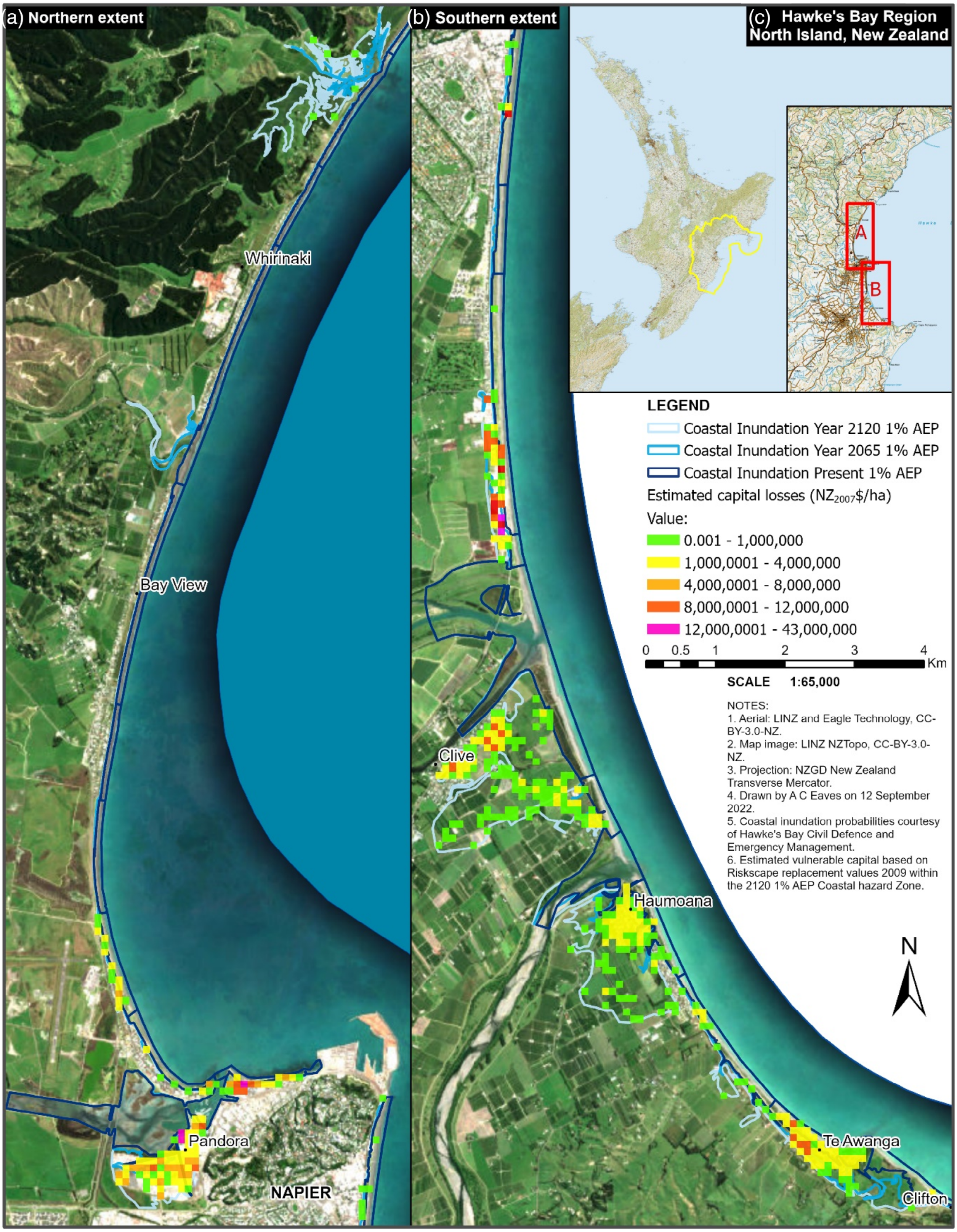

FIGURE 1 The Hawke's Bay study area showing coastal inundation probabilities and estimated capital asset losses by hectare. The Coastal Inundation Year 2120 1% polygons denote the Coastal Hazard Zone (CHZ) for calculating loss (HBRC, 2017; NIWA, 2017a, 2017b). Panel (a) shows the northern extent, Panel (b) the southern extent and Panel (c) the regional location.

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4 | METHODS

An IAM was developed to investigate the frequency and magnitude of disastrous events in Vensim® (Ventana Systems) by simulating coastal flooding and inundation on the local economy. It combines local-scale geospatial information with time-dependent hydrological and socio-economic data in this System Dynamics software package. Further input through Scenario Planning (described later) was also required for the socio-economic module (SEM) to develop consistent and anticipated futures for coastal properties.

The IAM is based on the causal loop diagram (CLD) in Figure 2. The central loop in the diagram, under the baseline scenario, is the 'Insurance loop', where communities offset coastal hazard risk by insuring against built capital damages and losses from storms that somewhat maintains their capital value. However, with SLR and increasing storminess increasingly removing built capital (buildings) and natural capital (land), property owners' wealth diminishes. The insurer's (un)willingness to pay (WTP) for foreseeable increasing damages and losses leads to their withdrawal from the insurance market (Insurer withdrawal loop) (Storey et al., 2017) which

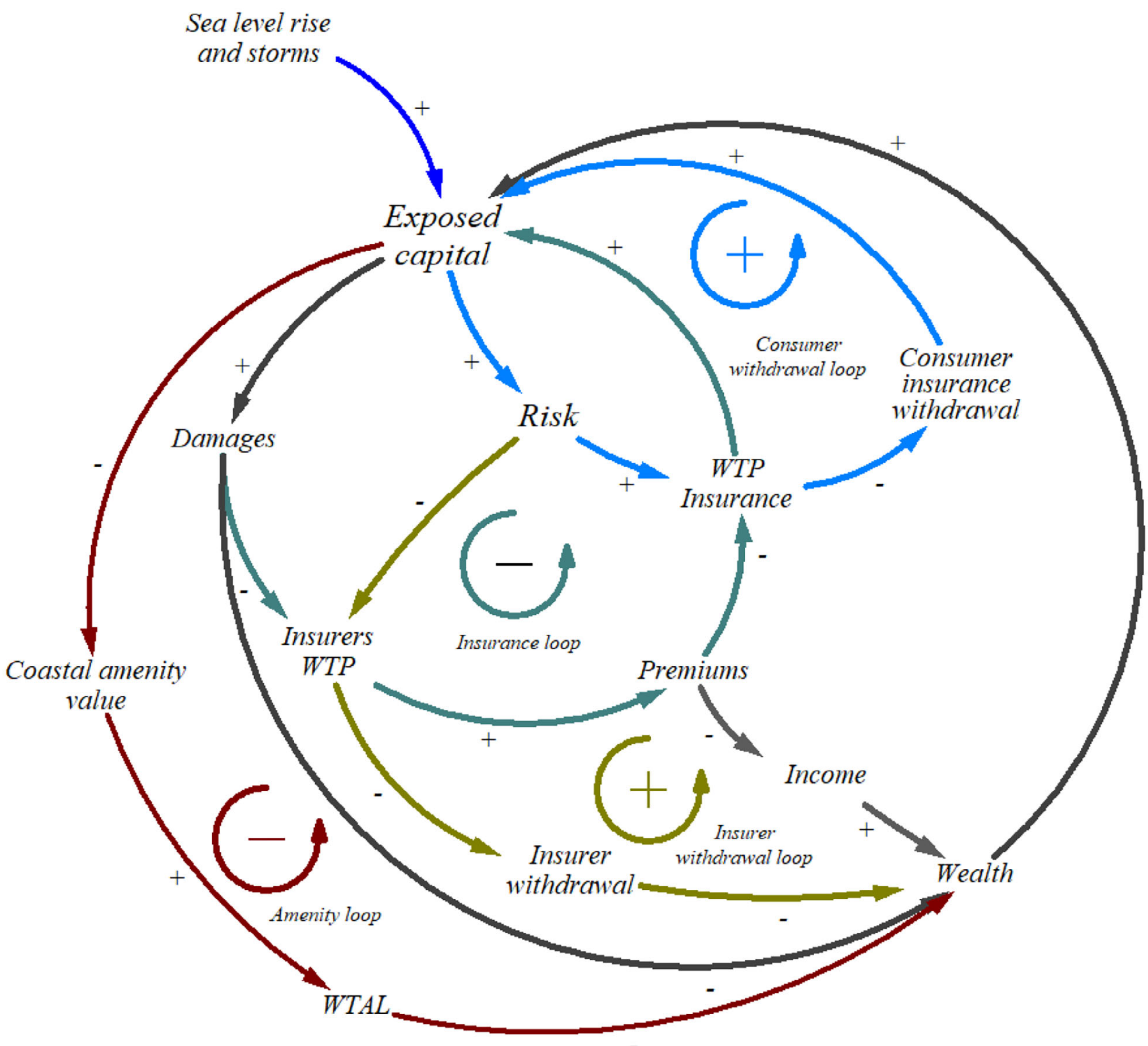

FIGURE 2 The causal loop diagram of system interactions in the Integrated Assessment Model. Under the baseline scenario, the central loop is the 'Insurance loop', where communities transfer coastal hazard risk by insuring against storm damages. Insurers' willingness to pay (WTP) for increasing damages and losses leads to their market withdrawal (Insurer withdrawal loop). Similarly, growing premiums become intolerable for consumers, leading to household market withdrawal (Consumer withdrawal loop). The 'Amenity loop' preserves capital exposure as property owners are willing to accept losses (WTAL) for coastal living benefits.

subsequently reduces the value of exposed capital. Similarly, consumers in the CHZ show unwillingness to pay an endless share of income for insurance as risk-based premiums and excesses rise. Consequently, insurance becomes intolerable; they also withdraw from the market (Consumer withdrawal loop). All outcomes fail to reduce built capital exposure to coastal hazards (as they remain in harm's way). Although, the uninsurability of stranded assets reduces the capital value from a financial perspective. Finally, exposure to hazards is accentuated by amenity value (Amenity loop) as exposed property owners are willing to accept the loss (WTAL) of capital wealth to maintain the benefits of coastal living (Bin & Kruse, 2005; Penning-Rowsell et al., 1992).

The IAM consists of two coupled modules, a risk assessment module (RAM) and an SEM. The RAM simulates hypothetical hydrological flooding under different climate scenarios to quantify asset exposure. The escalation of these hazards through time is the critical driver of system change. The changing hazard scape provides the economic system with stochastic shocks through damage and loss from increasingly higher water levels. The SEM determines the socio-economic well-being of exposed communities. It absorbs the shocks and then simulates the local property and insurance markets' response due to multiple complex economic interactions. The model runs from 2007 to 2050 with a time step is 1.8 days (*dt*) which is an applicable rate of change, balancing computational expense and requirements for model stability and accuracy in numerical integration.

4.1 | Model development

The model is briefly outlined here, with simulations, sensitivity analysis and the details on scenarios and equations (see the Technical Report) are available from https://gitlab.com/aceaves/rase_module. Note that variables in the stock-flow diagrams and equations are formatted as:

- bold are stocks;
- italics are auxiliaries;
- capitals and italics are constants.

4.1.1 | The risk assessment module

The RAM (Figure 3) combines external environmental forcing to force stochastic flooding and, in turn, exposure to economic damages and losses (see CLD in Figure 2). It aims to produce an accurate assessment of divergent variables through linear operators. Dynamic feedback is modelled through the ad hoc retreat of exposed properties following repeated inundation within the SEM module. Inundation extents, return periods, AEPs and estimated damages define hazards, risks, vulnerabilities and exposure as described by Foudi and Nuria (2014), adapted for System Dynamics as shown in Equations (1) and (2). The RAM also uses the approach of Baron et al. (2015) for assessing community exposure.

$$AEP = \left(\frac{1}{return\ period}\right) \times 1000 - 10, \quad (1)$$

where

$$return\ period = -\left(\frac{\text{Occurrence count}^2}{\text{Years on record}}\right) + 100. \quad (2)$$

Changes to the current water level were calculated using SLR trends (IPCC, 2014, 2022; Ministry for the Environment, 2017), storm surge (Komar & Harris, 2014), waves (Komar & Harris, 2014), river flooding (HBRC, 2018) and tide (LINZ, 2012) to identify significant total water levels during future storms. Land subsidence was also incorporated (Ministry for the Environment, 2017). Indicative SLR and significant total water levels that drive damages and losses are visible in Figure 4.

The global mean sea level is set to increase by an average of 0.20 m (Shared Socioeconomic Pathway—SSP2–4.5) or 0.23 (SSP5–8.5) (IPCC, 2021). Figure 4 shows that the frequency and magnitude of coastal flooding of capital assets are likely to increase by 2050, given 0.34 m SLR (high emissions baseline) or 0.27 m SLR (low emissions baseline) and increased storminess. The reason for the difference from the global mean is a regional difference and a geodetic change of −0.086 m for the model period (Beavan & Litchfield, 2012). From this hazard, the risk can be quantified.

The annual estimated loss (AEL; Equations (3) and (4)) accounts for built capital through replacement costs, stock, plant, contingent values (see NIWA, 2017a, 2017b) and loss of land. The model assumes property owners initially rebuild in situ after a disaster. Land losses are set at 1% of government land valuations for each storm event. It assumes that subsequent storms incrementally remove a share of the land area and value. 1% is the assumed inundation of the CHZ over 100 years, and therefore each storm event incrementally costs a share of the land value. There are approximately 40 significant storm events (total WL > 11.5 m) over the 44 years modelled and, therefore, account 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. However, the higher value here accounts for the clean-up or remediation costs of continued occupation.

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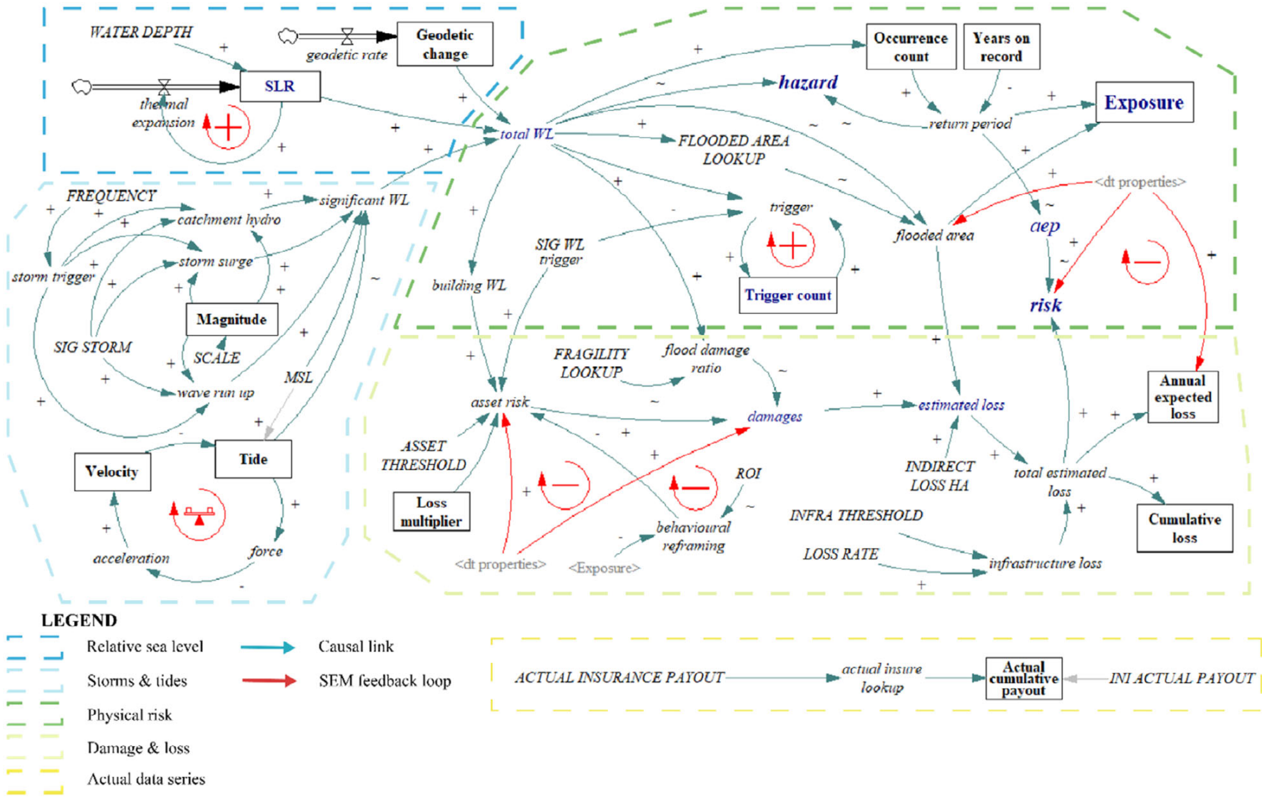

FIGURE 3 The modified stock-flow diagram for the Risk Assessment Module in Vensim. It features linear operators (causal links) to process environment-economic variables for analysis. Dynamic feedback occurs through interaction with the Socio-Economic Module through *dtproperties*, or the percentage of properties occupying the Coastal Hazard Zone. The Actual Cumulative Payout represents real-world data for comparison.

$$\begin{aligned}\frac{d}{dt}\mathbf{AEL}_{SMOOTH5} = {} & \sum total\ estimated\ loss_{IND} \\ & \times dt\ properties \times \mathbf{Time} \\ & \times CALIBRATION - \mathbf{AEL},\end{aligned} \tag{3}$$

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

where

$$\begin{aligned}estimated\ loss_{IND} = {} & \{damages + flooded\ area \\ & \times INDIRECT\ LOSS\ PER\ HA\}.\end{aligned} \tag{4}$$

4.1.2 | The socio-economic module

The SEM simulates the community's ability to accommodate exposure through economic system feedback (see CLD in Figure 2). It captures behaviour that emerges when communities face complex dynamic feedbacks present within an economy (Figure 5). Feedbacks occur as households, businesses, and markets re-evaluate behaviour with increasing coastal risk and storm damage (see Equation (5) for exposed capital and Equation (6) for market adjustment where ROI represents Return On Investment). The SEM provides insights into the value society places on coastal property amenity and risk-based insurance. The module defines stakeholder decision-making in response to evolving risks and losses from the RAM through feedback loops and behavioural delays. The module analyses the wealth, income, exposed capital, coastal amenity value and insurability. Data on exposed capital are from Riskscape (NIWA, 2017a), StatsNZ (2020), property sales (The University of Auckland, 2017), capital vulnerability assessments (NIWA, 2019) and government property valuations (Hastings District Council, 2017; Napier City Council, 2017).

$$exposed\ capital(AEP)_{SMOOTH1} = \begin{cases} \mathbf{Capital\ balance} \times market\ adjustment + \mathbf{Total\ damages} \\ \quad for\ AEP < INSURE\ THRESHOLD \\ \mathbf{Capital\ balance} \times market\ adjustment - \mathbf{Total\ damages} \\ \quad for\ AEP > INSURE\ THRESHOLD \end{cases}, \tag{5}$$

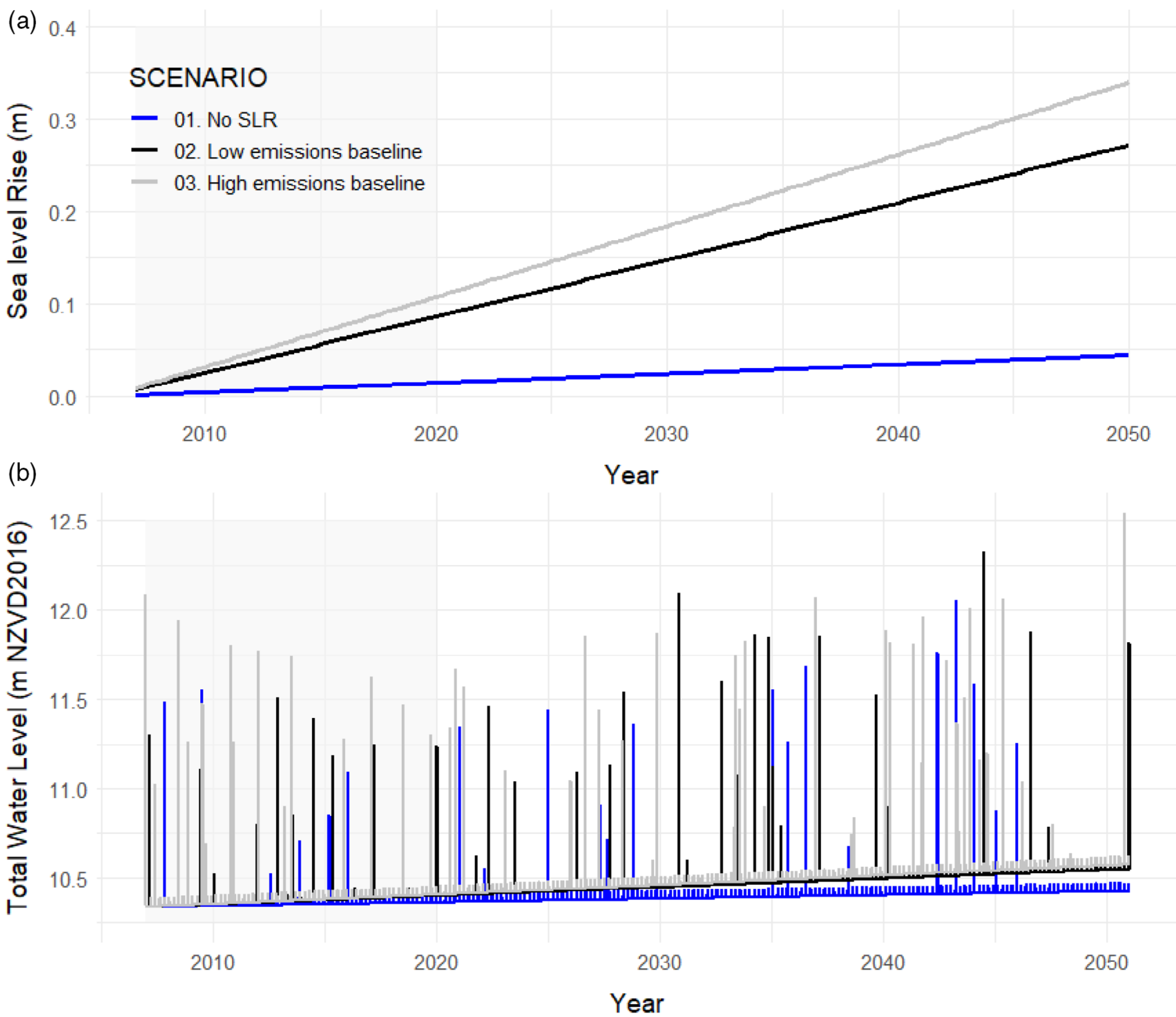

FIGURE 4 Indicative sea-level rise over 44 years from 2007 to 2050 (a) and stochastic total water levels (b) drive damages and losses to the Coastal Hazard Zone under varying climate projections. The No sea-level rise (SLR) is a hypothetical scenario without climate change, although it is still increasing due to the geodetic subsidence of the area. The grey box represents the calibration period.

where

$$\textit{market adjustment}(\textbf{Trigger count}) = \left\{ \begin{array}{c} ROI\ \textit{for}\ \textbf{Trigger count} \leq 2 \\ ROI - \left[ROI \times \left(\frac{risk}{100} \right) \right] \textit{for}\ \textbf{Trigger count} > 2 \end{array} \right\}. \tag{6}$$

The development of scenarios focussed on selected issues of concern which are for a select audience that contributes new knowledge that reframes the situation with future perspectives (Ramirez & Wilkinson, 2016). Scenarios were developed using census information, expert workshops, expert conversations, government planning documents and datasets, utility datasets, reports, industry practice and model feedback. Expert workshops were held with the Hawke's Bay Technical Advisory Group (management of coastal hazards) and the Reserve Bank of New Zealand's risk and insurance management team. Narratives around the impacts of the baseline scenario were discussed and formulated alongside likely interventions following the approach of Smith et al. (2016). Census statistical data initialised model variables such as household income and savings. Local government valuation data provided property information (parcel location and capital value) and planning documents for the environmental change. Insurance information came from expert conversations and the Insurance Council of New Zealand, while utility providers parted with asset locations and costs. Iteration and model feedback in the testing phase also design the plausibility of the scenarios as the structure must be relatively stable.

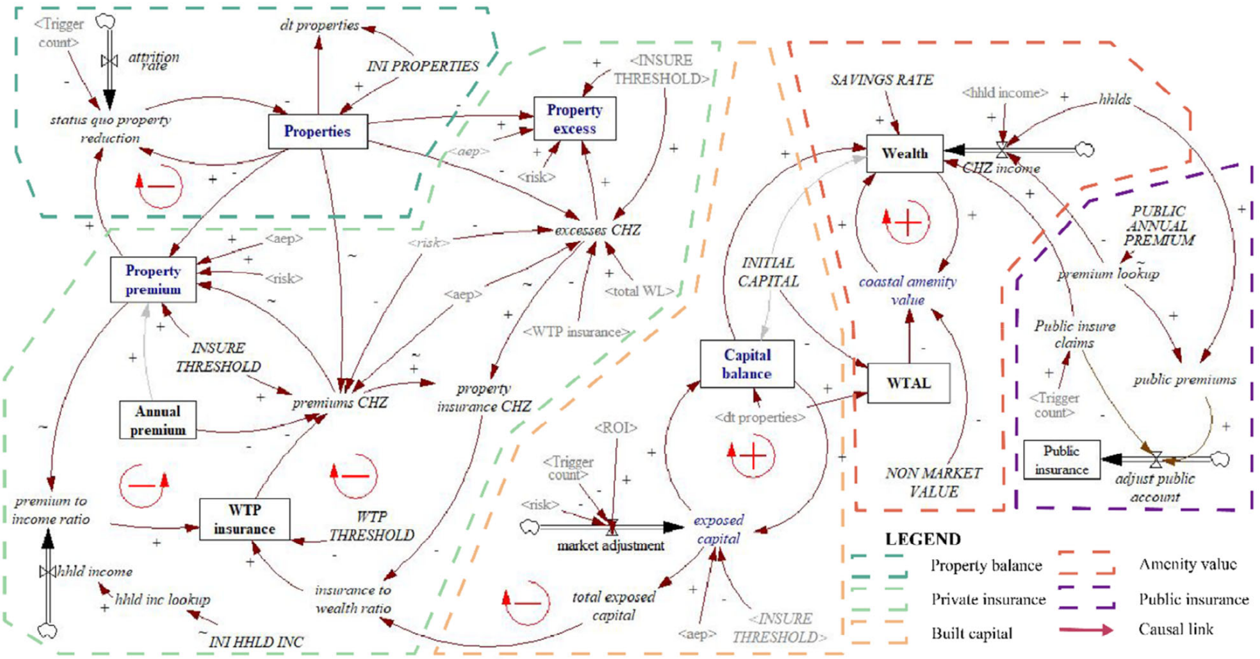

FIGURE 5 The modified stock-flow diagram of the socio-economic module in Vensim. The left-hand side operators represent insurability and properties, while the right-hand side represents capital and amenity. Extreme right is the linear operation for public insurance.

Scenarios for insurability were incorporated using expert workshops and conversations, insurance policies, census data (StatsNZ, 2020) and spatial data (LINZ, 2018) to define the premium and excess for a property in the CHZ (Equations (7) and (8)). A household's insurance tolerance threshold is set through model iteration and feedback and excesses increase with insurance claims following flood events.

$$\textbf{Property premium}(AEP)_{SMOOTH\,1} = \left\{ \begin{array}{c} 0\, for\, AEP > INSURE\ THRESHOLD \\ \left(\frac{premiums\ CHZ}{PROPERTIES} \times (1+risk)\right) for\, AEP \le 2 \\ -\textbf{Property premium} \end{array} \right\}. \quad (7)$$

Amenity values (e.g. recreation, coastal access and views, ecosystem services) were derived from a household's WTP for a service or benefit (Brouwer & Schaafsma, 2013) and a WTAL from floods (Equations (9) and (10)). Hedonic regression analyses were used to estimate monetary benefits through property market values (Ojea, 2014) which determined this non-market value (see Appendix Table A1). Thus, coastal amenity value is considered a non-market environmental service (Ministry for the Environment, 2004; van den Belt & Cole, 2014). Lags and feedback reflect the non-monetary benefits of seaside habitation and the behavioural response to capital losses and the coastal environment's reduction.

$$\begin{aligned} &\textbf{Property Premium}(t_0) = \textbf{Annual premium} \\ &\frac{d}{dt}\textbf{Property excess}(aep) = \left\{ \begin{array}{c} -\textbf{Property excess}\, for\, AEP > 2 \\ \left(\frac{excesses}{PROPERTIES} \times (1+risk)\right) for\, AEP \le 2 \end{array} \right\} \\ &\quad + \textbf{Property excess} \\ &\textbf{Property excess}(t_0) = \left\{ \begin{array}{c} 0\, for\, AEP > 2 \\ INITIAL\ EXCESS\, for\, AEP \le 2 \end{array} \right\}. \end{aligned} \quad (8)$$

$$\textit{coastal amenity value} = \mathbf{Wealth} \times \textit{NON MARKET VALUE} \times (1 + \mathbf{WTAL}) - \mathbf{Wealth}, \tag{9}$$

where

$$\begin{aligned}\mathbf{Wealth} = {} & \mathbf{Capital\ balance}_{\mathbf{IND9}} + \textit{coastal amenity value} + \textit{EQC claims} \\ & + (\textit{CHZ income} \times \textit{SAVINGS RATE}) - \mathbf{Wealth}, \\ \mathbf{Wealth}(t_0) = {} & \textit{INITIAL CAPITAL}.\end{aligned} \tag{10}$$

4.2 | The model set-up

The model is set-up with the scenarios shown in Table 1. These describe the level of environmental forcing applied under each scenario as defined by the Ministry for the Environment (2017). Insurability of assets needed further investigation to determine the general equilibrium of the insurance market. To test the insurance market, scenarios 1–3 represent the insurers' tolerance threshold to cover exposed properties (AEP <2%). Otherwise, insurers withdraw from the market. Whereas scenarios 4 and 5 represent a view where insurers remain in the market indefinitely to discover when consumers withdraw, given a lack of WTP for insurance as premiums rise. However, the property owner's tolerance threshold is their WTP up to 5% of income toward insurance or when they lose 5% of their capital wealth.

TABLE 1 Scenarios modelled.

Scenario	RCP driver	SLR (mm a^{-1})	Storm intensity increase (% a^{-1})	Storm frequency increase (% a^{-1})	Description
1	RCP0	0	0	0	**No SLR** Properties are exposed to infrequent storms and geodetic subsidence without climate change (hypothetical).
2	RCP4.5	6	0.23	1.86	**Low emissions baseline** The 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	**High emissions baseline** Property owners follow the same behaviour as (2) but are subject to higher SLR and more intense storms earlier in the period.
4	RCP4.5 Insure	6	0.23	1.86	**Low emissions insurance** Baseline scenario (2) modified so that insurers remain in the coastal property market in order to define when property owners themselves retreat.
5	RCP8.5 Insure	8	0.98	2.75	**High emissions insurance** Identical to (4) but subject to higher SLR and more intense storms.

Abbreviations: RCP, Representative Concentration Pathway; SLR, sea-level rise.

4.3 | Model testing

The IAM was assessed using Martinez-Moyano's (2012) System Dynamics evaluation framework (see Appendix Table B1). The IAM runs for 44 years (2007–2050) with calibration through to 2020. Calibration enables the refinement of time-dependent variables by adjusting model parameters to get the best match against known data and how they rationally influence the system. Testing started with 'face validity' tests (or whether the model structure and parameters make common sense) to establish logic (Ford, 2010). Testing then included: direct empirical structure, direct theoretical structure, structure-orientated behaviour, and behaviour pattern tests (Barlas, 1996) (Appendix Table A1). Iterative improvement in model function was achieved through calibration period datasets, empirical observations and expectations discussed through Scenario Planning. The calibration covered government property valuations, house sales (The University of Auckland, 2017), a local estuarine water level gauge (HBRC, 2018), NIWA (2019) risk assessments and insurance claims (Insurance Council of New Zealand, 2019). Finally, sensitivity analysis involved 100 Latin hypercube simulations per scenario using rational and random distributions of constants given simultaneous changes to multiple parameters (Kapmeier & Gonçalves, 2018). See Appendix Table C1 for the Vensim SDM-doc Tool summary and Appendix Table D1 for the sensitivity analysis.

5 | MODEL OUTPUTS

The outputs from IAM simulations indicate (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. All monetary values are nominal 2007 New Zealand dollars. Results represent the mean of 100 simulations, with the blue ribbon representing the standard error of the mean.

5.1 | The direct risks and estimated losses from future coastal hazards

The risk is defined as the likelihood and consequence of a hazard as outlined in the CDEM Act 2002 (New Zealand Government, 2002). The increasing likelihood of the hazard occurring is modelled by an increasing AEP, or the inverse of the return period (Auckland Council, 2014) (Figure 6a). The AEP remains under 2% until 2033 for the high emissions baseline scenario and 2046 for the low emissions baseline scenario. Without SLR, the AEP continues to grow in the CHZ due to tectonic subsidence and regular storms, leading to a slightly increasing trend under the No SLR scenario.

The AEL is the cost of lost land and damaged built capital in the CHZ (Figure 6b) 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 increasing and (2) the increase in the frequency of loss events. 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. 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 high emissions baseline scenario around 2041 (Figure 6b). Notably, insurance exacerbates the AEL under the high emissions insurance scenario until 2044 as risk transfer to insurers maintains living with risk without significant financial consequence to property owners.

5.2 | Behavioural response of communities

Results from the SEM in Figure 7 indicate that climate change at the coast negatively influences exposed capital, market ROI, and coastal amenity value under the high emissions baseline and, to a lesser degree, under the low emissions baseline scenarios. Whereas the hypothetical dynamic equilibrium of the market in the absence of climate change is transformed into a system of accelerating value in the capital market within exposed areas, as shown in Figure 7a. However, insurers prop up the market for exposed capital to maintain a dynamic equilibrium under the low emissions insurance scenario. Although the high emissions insurance scenario 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 high emissions scenarios and the low emissions 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 in Figure 7, signifying the initiation of a threshold as risk increases.

Results for exposed capital suggest that reinforcing feedback reduces exposed capital in the CHZ due to subsequent flood events (Figure 7a). For the low emissions baseline and the high emissions baseline scenarios, 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 Low emissions insurance scenario to reach NZ$$_{2007}$45.47B by 2050. The high emissions insurance scenario shows a significant reduction in capital exposure as storms are extensive and frequent here. It stabilises around 2040 at NZ$$_{2007}$11.39B, given the higher capital value than the high emissions baseline scenario. Without significant risk, the no-SLR scenario illustrates accelerating capital growth that reaches NZ$$_{2007}$56.66B.

The ROI for market value in the CHZ is influenced by increasing inundation and insurance costs (Figure 7b). The 'regular' positive market return of 2.4% (1.024) 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 high emissions baseline scenario around 2032 to reach −7% (0.930) by 2050. The high emissions insurance turns negative around 2030 to reach −18.9% (0.811). It turns negative by 2048 and is −0.8% (0.992) by 2050 for the low emissions baseline scenario and 2043 for the low emissions insurance scenario, which 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 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 ROI reducing at a greater rate for the insurance scenarios.

The coastal amenity value in the CHZ is highlighted in Figure 7c. Here the model is only assessing the household sector by employing subscripts; a replication of the model structure to allow for the division of elements (Ventana System Inc, 2015). It assumes that businesses 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 low emissions baseline scenario in 2028 (NZ$$_{2007}$0.3B), high emissions baseline in 2026 (NZ$$_{2007}$0.27B), and the low emissions insurance scenario in 2040 (NZ$$_{2007}$0.64B). The high emissions insurance scenario does not overshoot during the period but peaks in 2030 (NZ$$_{2007}$0.36B). Therefore, insurers remaining in the market significantly stretch 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 this scenario, given the allure of coastal living, although the uncertainty range is significant.

A fundamental driver of the socio-economic results is that insurance premiums and excesses cover the additional annual cost of CHZ living, which insurance companies impose to pool risk. Under all scenarios, the model 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 high emissions baseline and low emission baseline scenarios. Here the modelling identifies thresholds where the insurance market fails, as shown by the timing of any overshoot leading to market collapse in Table 2. The increasing cost and frequency of events undermine the capability of insurance companies to provide insurance to the CHZ for the low emissions baseline and high emissions baseline scenarios. The increasing cost and frequency lead to insurance market withdrawal when the AEP exceeds 2%, around 2026 for the high emissions baseline and 2032 for the low emissions baseline scenario (Figure 8a). If insurers remain in the market indefinitely, consumer WTP drops to zero for risk-based insurance, and they start to withdraw around 2029 for the high emissions insurance and 2033 for the low emissions insurance scenarios. When analysing the peak premium, cost drives the threshold for consumer withdrawal (as a fraction of income), whereas risk (through the AEP) drives the threshold for insurer withdrawal in the model. This leads to consumers withdrawing earlier (2027) than insurers (2029) under the low emissions baseline and low emissions insurance scenarios. In contrast, insurers withdraw earlier (2025) compared to consumers (2027) under the high emissions baseline and the high emissions insurance scenarios (Table 2).

Conversely, insurance excesses do not show significant volatility over time except for their gradual decline under the low emissions baseline and high emissions baseline scenarios (Figure 8b). Insurers start to withdraw from the 'riskier' assets in the market under the high emissions baseline around 2024 and low emissions baseline 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 insurance scenarios but dip slightly below the No SLR scenario. Insurers and consumers remain in the excess market indefinitely under the low emissions insurance, high emissions insurance 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 $NZ\$_{2007}5407$ to $NZ\$_{2007}5434$ in the absence of inflation.

6 | DISCUSSION

Combining System Dynamics with Scenario Planning is a valuable approach to analyse non-linear feedback 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 models toward an audience and outcome (Ramirez & Wilkinson, 2016).

The model 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 system 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 was 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 8a) rather than an abrupt change in the system state.

Still, modelling the low emissions baseline and high emissions baseline scenarios using this integrated approach enabled the discovery of two stand-out drivers that influence the socio-economic response of communities to coastal inundation at the local scale: first, the ongoing likelihood of risk transfer to the insurance industry (Figure 8a), and second, the decisions of households to accept risk for the added value of coastal living (Figure 7c).

6.1 | The future of risk-based insurance in coastal areas

System Dynamics enables the quantification of causal relationships and the implementation of thresholds to discover general patterns of system behaviour for the insurance market's response to coastal risk. Behaviour patterns then allow vulnerable communities and government agencies to plan futures accordingly. Here the modelling 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 insurance industry's actions and make decisions as insurers assess policies annually on a case-by-case basis, with differences occurring between insurers and locations (Parker, 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 stormwater damage (Parker, 2017).

Modelling suggests that risk-based premiums enable insurance providers to remain in the CHZ over the short-term 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 6a). However, given the extent of the study area, insurers withdrawal incrementally from the most at-risk areas, followed by a total withdrawal from the market (market collapse), as shown in Table 2 and Figure 8a.

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 alternate 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, 2017; Storey et al., 2017). However, the modelling

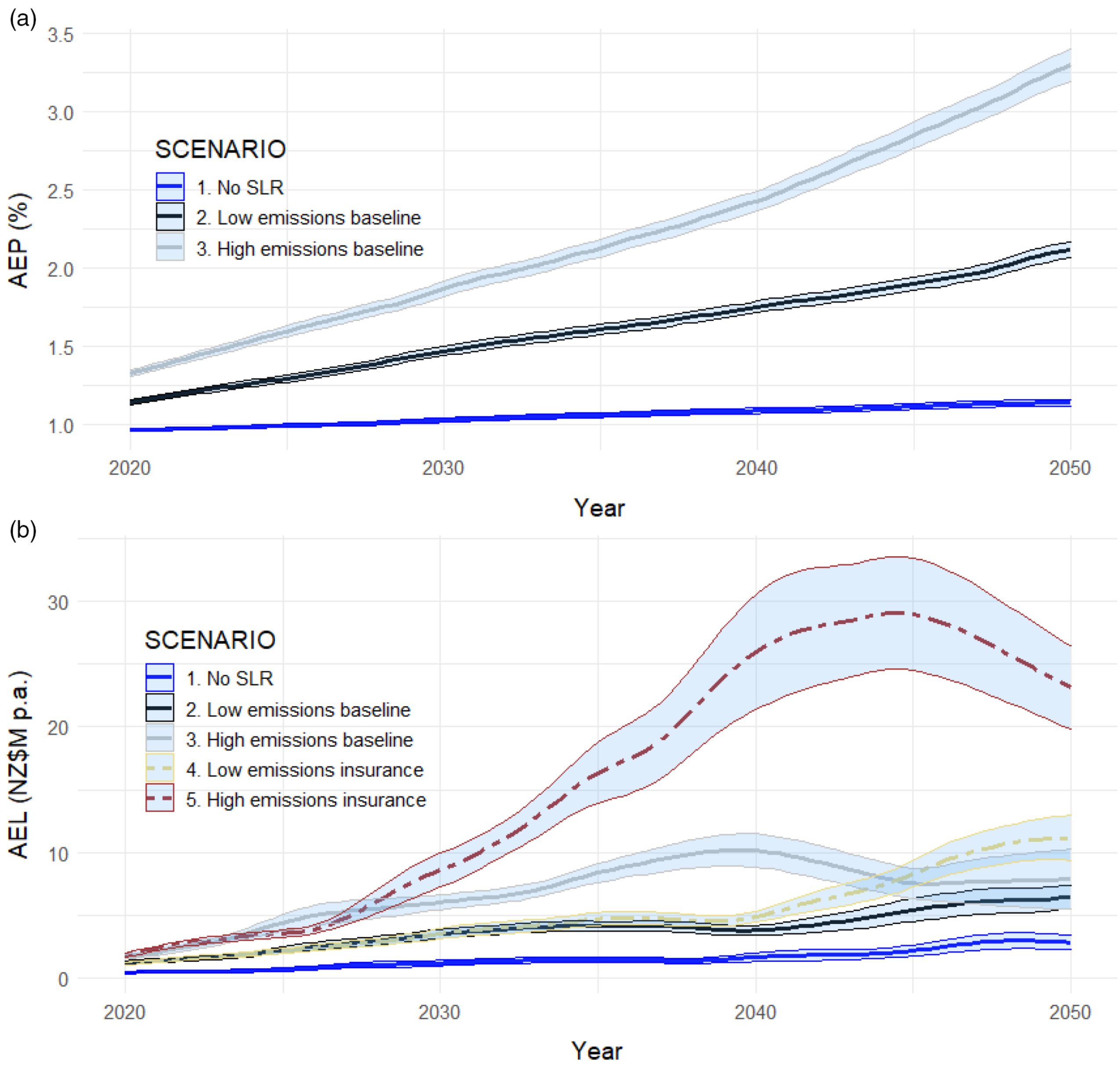

FIGURE 6 Simulation outputs for the Annual Exceedance Probability (AEP; (a)) and the Annual Expected Loss (AEL; (b)) from storms for coastal communities in Hawke's Bay. The AEP increases at different rates for each scenario. The AEL increases with the continued occupation of the Coastal Hazard Zone (CHZ) but plateaus under the high emissions baseline scenario as dynamic feedback reduces risk. Similarly, the high emissions insurance scenario peaks around 2044 at a much higher value, given the safety of insurability before it declines.

here did not achieve such high excesses because the model set-up 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, WTP premiums and excesses also define the insurability of capital assets. In scenarios where insurers remain in the market, this research 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 to do so with the security of insurance cover. Notably, exposed property owners have a different risk perspective as they wish to transfer as

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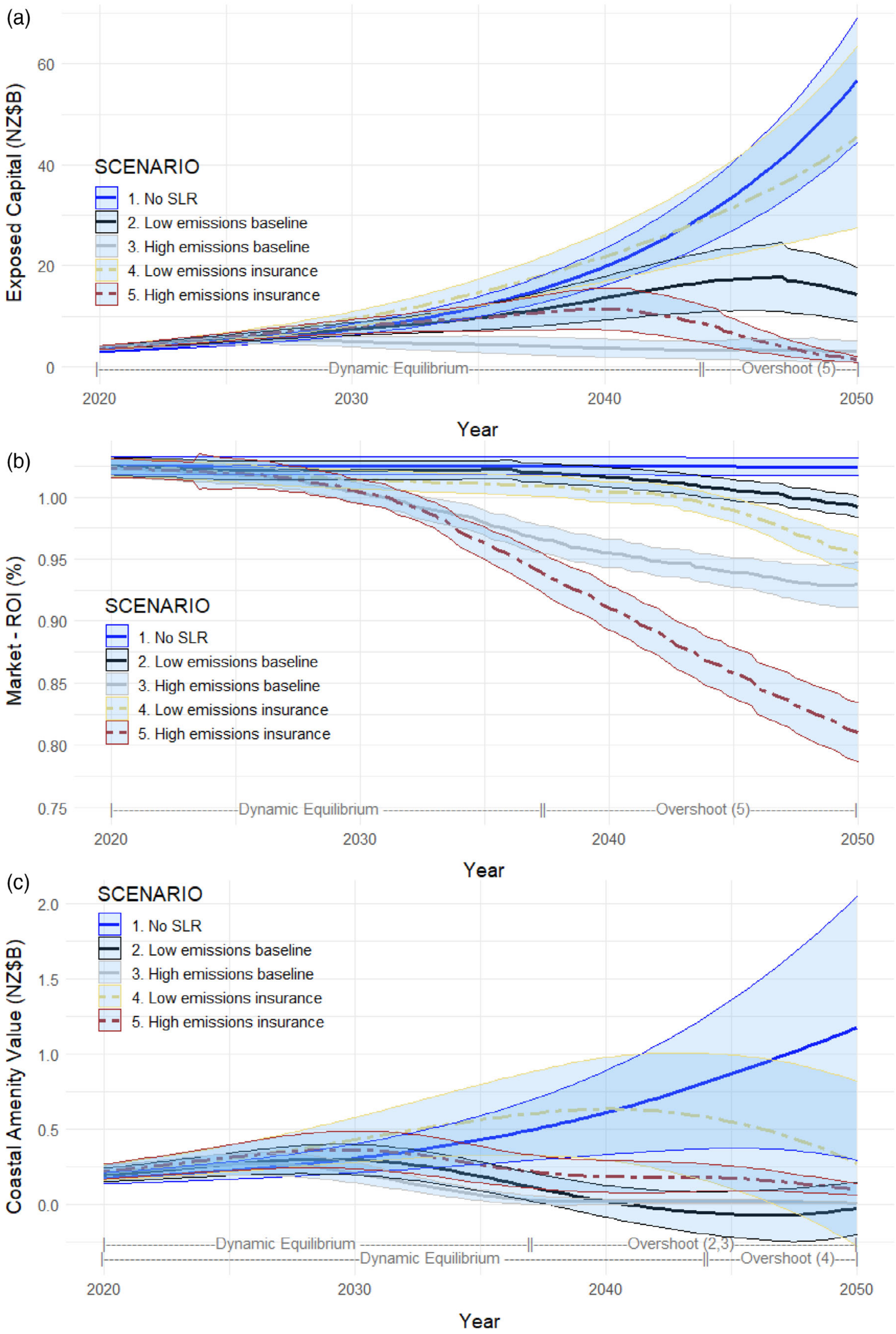

FIGURE 7 Simulation outputs for exposed capital (a), market adjustment to return on investment (ROI) (b), and coastal amenity value (c). The high emissions baseline scenario has a greater negative influence on exposed capital, ROI and coastal amenity value than the low emissions baseline and No sea-level rise (SLR) scenarios. Under enhanced insurability scenarios, households are worse off for exposed capital and ROI but are better off for amenity value.

TABLE 2 Withdrawal from the CHZ insurance market.

Scenario	Peak (year)	Peak (cost, NZ$$_{2007}$ p.a.)	Market collapse (year)
No SLR	2050	5009	–
Low emissions baseline (Insurer withdrawal)	2029	3308	2032
Low emissions insurance (Consumer withdrawal)	2027	3514	2033
High emissions baseline (Insurer withdrawal)	2025	3087	2026
High emissions insurance (Consumer withdrawal)	2027	3355	2029

Abbreviations: CHZ, Coastal Hazard Zone; SLR, sea-level rise.

much risk as possible. However, even without insurance, some property owners are willing to remain even if they may be forced into bankruptcy or delay their retirement due to diminishing asset value if a mortgage remains on the property (Long, 2017). In New Zealand, private insurance is optional, and levies paid for public insurance are tied into private premiums. After the Canterbury earthquake sequence, this situation created a moral dilemma in which the central government intervened to provide adaptation outcomes for impacted property owners in low-lying areas (Stepanova, 2018). This dilemma can be seen as undermining the integrity of insurance, signalling to property owners that the government will bail them out where properties are uninsured.

Model outputs (Figures 7a and 8a) illustrate risk acceptance, where exposed capital does not reduce to zero in line with insurance withdrawal. Here the IAM 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 by Withey et al. (2019). They used 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 using public engagement in Scenario Planning, it is possible to calibrate the modelling further and define thresholds and costs that reframe a community's perception of future risk.

6.2 | Weighing up the benefits of coastal living

The decisions of households in the CHZ are influenced by risk tolerance 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 6b) and alter property markets (Figure 7b). Coastal erosion and inundation physically impact structures and erode property values, which is followed by reducing residents' quality of life and peace of mind (Geis, 2000; Tonkin and Taylor, 2019). The model included these impacts through hedonic pricing and, therefore, linked amenity value to property value and wealth. The model set-up is 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 the 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.

The results also provide insights into the role of property values in driving property investment decisions, 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 7 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), which illustrates the high property demand manifesting in higher prices. These increasing capital values in vulnerable suburbs are 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

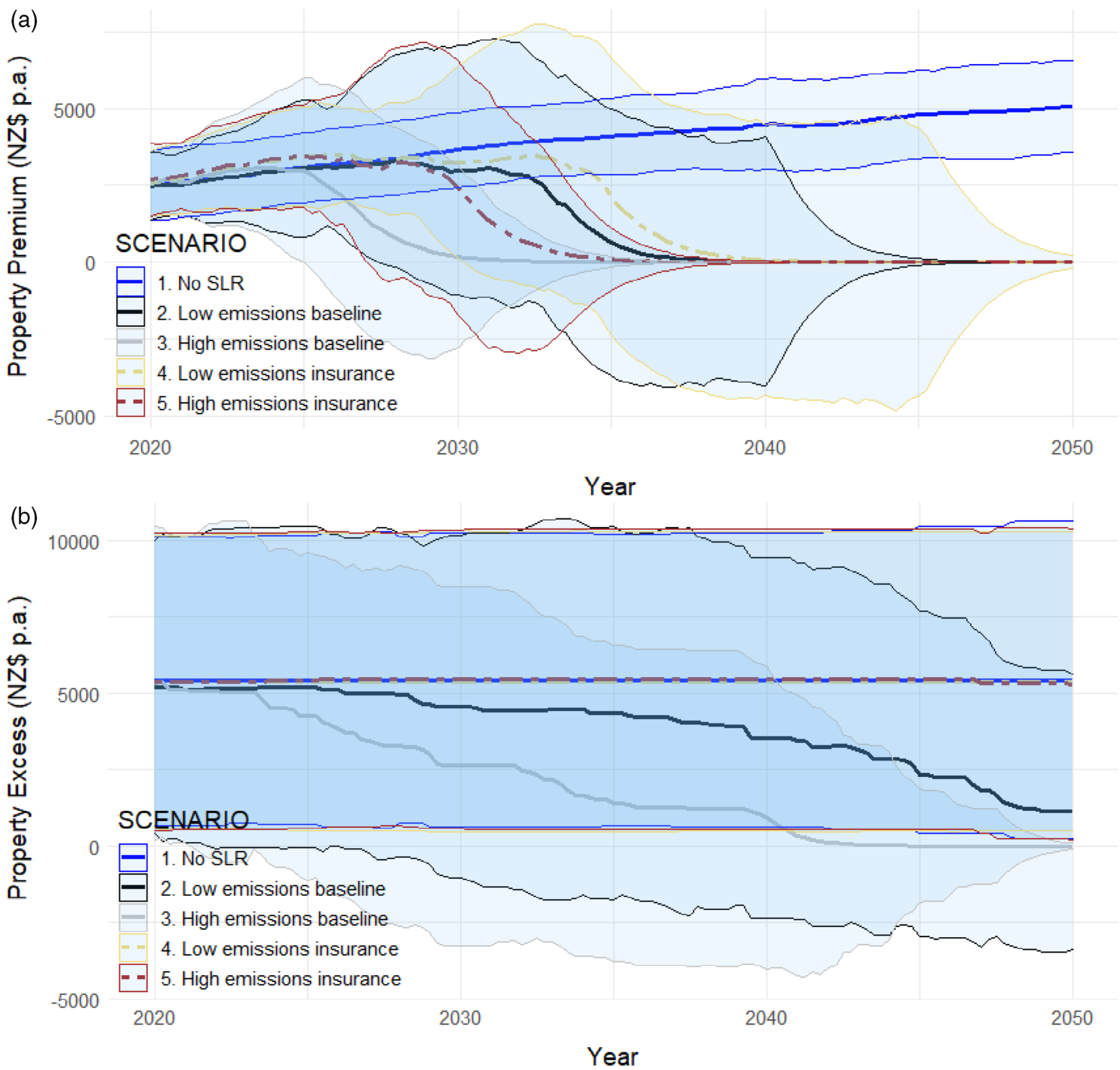

FIGURE 8 Simulation of property insurance premiums (a) and excesses (b). For premiums, insurers withdraw when the risk becomes intolerable around 2025 under the high emissions baseline scenario, and consumers withdraw when the cost becomes too great around 2027. Under the low emissions baseline scenario, consumers withdraw first around 2027, and insurers withdraw around 2029. For excesses, under the low emissions baseline and high emissions baseline scenarios, insurers incrementally withdraw from at-risk assets leading to a decline in excesses. Excesses remain reasonably stable for insurance scenarios. The error is expressed as the interquartile range for (a) and the mean for (b).

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. Thus, current prices in Hawke's Bay appear to reflect the benefits of coastal living rather than coastal hazard risk, as has been reported elsewhere by, for example, 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 the high emissions scenarios late in the modelled period. Therefore, given that the spatial distribution of impacts developed by the local government is also dynamic, modelling these impacts should be undertaken with each new spatial extent. The spatial extents here applied the 'bathtub' approach to inundation, which is acceptable for the Ahuriri estuarine environment. But further investigation is needed into future extents under hydrodynamic forcing on erosional coastlines, as outlined in Dickson et al. (2007), to define the collapse of barrier beaches in Hawke's Bay. Such a collapse would exacerbate flooding in adjacent waterways and low-lying coastal environments behind the barrier.

Coupling Scenario Planning and System Dynamics makes it possible to investigate non-market amenity values for different communities and hazard exposure. Quantifying 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 7 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).

Finally, System Dynamics modelling proved beneficial here as it allows for implementing time lags that give the system a delayed behaviour born out of system structure (Meadows, 1989). A five-year lag was installed on WTP insurance and WTAL to delay community decisions and instal community bias. It introduces these lags to illustrate the long-term economic enjoyment (amenity value) of the CHZ with bounded rationality by prolonging the trend (Figure 7c and Figure 8a).

7 | CONCLUSION

This study has demonstrated that Scenario Planning in System Dynamics is a useful approach to understand and quantify the evolving risks posed by coastal hazards with climate change. The method provides a basis, through integrated assessment modelling, to quantify the socio-economic impacts of inundation on coastal capital. Once these influential behavioural drivers of the system are known, it becomes possible to define the medium-term dynamic equilibrium of scenarios and any overshoot or collapse of the local-scale property and insurance markets due to the risk posed by 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).

Model results suggest that economic impacts from coastal hazards go beyond the simplistic vulnerability of capital and land assets because medium-term behavioural drivers in the economic system respond to long-term irreversible changes in the environmental system. Significantly, results indicate that the current trajectory of increasing capital valuations at the coast may be relatively short-lived. 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. Modelling indicates that critical tolerance thresholds exist for both insurance providers and consumers, with consumers withdrawing from the insurance market earlier (2027) than insurers (2029). Where insurers remain longer in the market, they withdraw earlier (2025) than consumers (2027) under the high emissions insurance, and low emissions insurance scenarios as their financial risk from coastal hazards is greater.

Traditional economic analysis does not adequately account for non-market social decision-making, such as appreciating coastal amenity value in the face of rising coastal inundation risk. This research has bridged this gap using Scenario Planning and by implementing behavioural delays in System Dynamics through lags to the willingness to pay and willingness to accept loss that mimic the short-term bounded rationality of stakeholders. Results suggest that vulnerable communities are willing to accept risk and minor short-term loss to gain amenity value. 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 the low emissions and high emissions scenarios as sea levels rise and storms increase until abandonment becomes inevitable.

DATA AVAILABILITY STATEMENT

My data and models are available online from Gitlab and are referenced in the article.

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ENDNOTE

[1] Note: dollars are nominal NZ$$_{2007}$. NZ$$_{2007}$ 1.00 = NZ$$_{2022}$ 1.39 and NZ$$_{2007}$ 1.00 = US$$_{2022}$ 0.44.

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APPENDIX A

TABLE A1 Table of multi-variate regression analysis for hedonic pricing. Highlighting reflects the value used in the model.

Coefficients[a]

Model		Unstandardized coefficients		Standardised coefficients			95.0% Confidence interval for B		Correlations			Collinearity statistics	
		B	Std. error	Beta	*t*	Sig.	Lower bound	Upper bound	Zero-order	Partial	Part	Tolerance	VIF
11	(Constant)	16,013.837	23,582.182		0.679	0.497	−30,207.414	62,235.088					
	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	44,642.362	2342.932	0.140	19.054	0.000	40,050.198	49,234.527	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	28,973.631	683.818	0.143	42.370	0.000	27,633.342	30,313.920	0.257	0.180	0.132	0.863	1.159
	MAS_Landsc_1–3	32,755.112	1075.048	0.101	30.469	0.000	30,648.011	34,862.213	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	41,151.602	3436.944	0.088	11.973	0.000	34,415.167	47,888.037	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 B

TABLE B1 Table of tests.

Test type	Conditions
1. Empirical direct structure tests	• Model outputs reliant on the 2009 Riskscape database were validated against 2017 local government valuations. • Hydrologic inundation calibrated against Ahuriri hydrograph. Standard deviation adjusted to suit. • CoreLogic Inc (2018) estimate a year on year increase of 7% in New Zealand. The socio-economic module through the Insurance variable illustrates 10%. • 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.
2. Theoretical direct structure tests	• SLR aligns with IPCC scenarios (IPCC, 2014). • Geodetic change conforms with the MfE projections (Ministry for the Environment, 2017). • Storm Surge, Wave Run-up, Catchment Hydrostaticity, Tide and Total Water Level conform with measurements by Komar and the Hawke's Bay Regional Council (2014). The 11 m threshold is breached regularly before 2019. • At least four flood events recorded for Hawke's Bay by the Insurance Council of New Zealand (2019). Claims range from NZD1.1M to NZD 6.4M (Insurance Council of New Zealand, 2019). • Total asset replacement value was calibrated to align with the reported insurance claims from flooding of NZD 4.3M on 3 June 2018 in Hawke's Bay and Gisborne (Insurance Council of New Zealand, 2019). • The initial premium is $\$NZ_{2007}$1000 and calibrates to $\$NZ_{2007}$1500 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, 2018), 5% represents a tolerable threshold percentage of capital wealth lost by households.
3. Structure orientated behaviour tests	The following questions were asked of the model through Vensim® Reality Check: 1. Are premiums and the AEP reflected in the behavioural reframing? 2. Do the annual anticipated loss and insurance influence amenity value? 3. Does the hazard of high water levels influence premiums? 4. Does the integrated risk assessment reflect the changing asset and social vulnerability? Results: • One success and three failures testing 4 Reality Check equations; • The Reality Check Index run is 5.15783e−005; • Closeness score is 97.6% on eight measurements.
4. Behaviour pattern tests	Behaviour pattern tests were carried out on: SLR; AEP; Insurance; WTP insurance; Return period Significant WL; Behavioural reframing; Wealth; WTAL; Market adjustment Geodetic change; Flooded area; Exposed capital; Income; Estimated loss Excesses; Coastal amenity value; Premiums

APPENDIX C

TABLE C1 Table of model assessment results from the SDM-doc Tool.

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 D: Sensitivity analysis

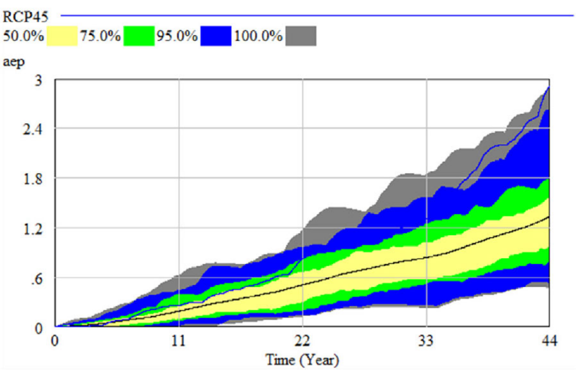
The sensitivity simulations involved 100 simulations using Latin hypercube sampling with the set-up visible in Table B1. The results of the sensitivity analysis for key variables with their confidence intervals are also visible below.

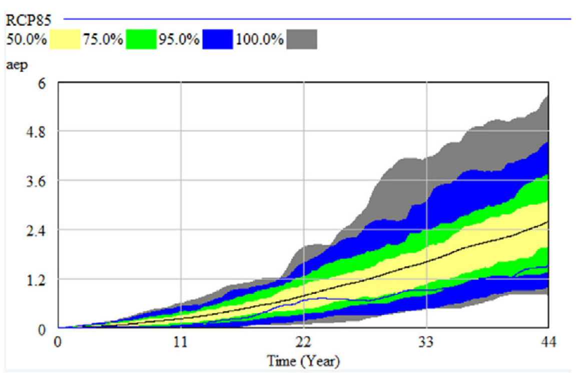
TABLE D1 Sensitivity analysis set-up for constants in Vensim®. Sensitivity analysis used realistic distributions.

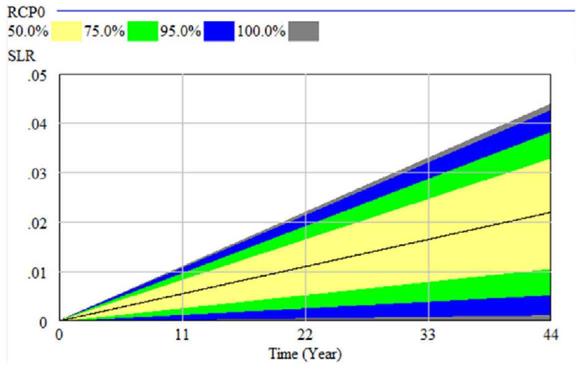
Variable	Distribution	Range
Non market value	Random uniform	0.9–1.3
INI premium	Random uniform	500–2500
ROI	Random uniform	0.9–1.15
Attrition rate	Random uniform	0.5–1.5
WTP threshold	Random uniform	0.01–0.1
Initial excess	Random uniform	500–10,000
Frequency	Random uniform	0.055–0.068
Scale	Random uniform	200–10,000
ICE melt	Random uniform	0–0.0011
Water depth	Random uniform	0–0.008
Insure threshold	Random uniform	1–7

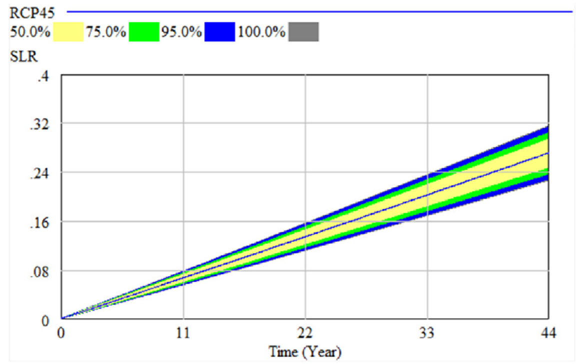
The scenarios are labelled as follows: RCP0 is the 'No SLR' scenario, RCP45 is the 'low emissions baseline' scenario and RCP85 is the 'high emissions baseline' scenario.

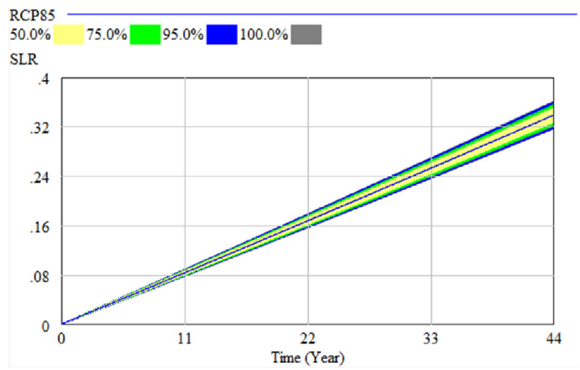
Sea-level rise:



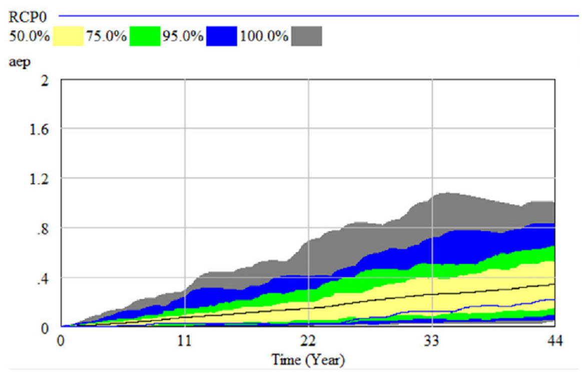








Annual Exceedance Probability:



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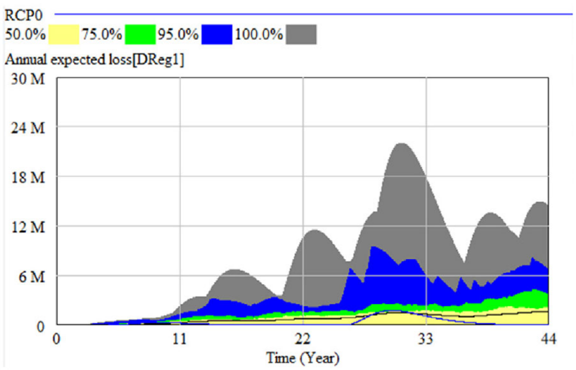
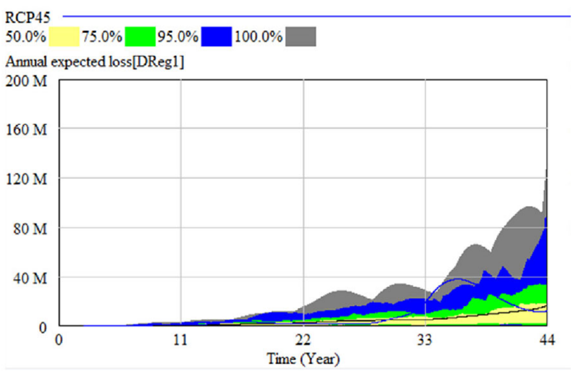
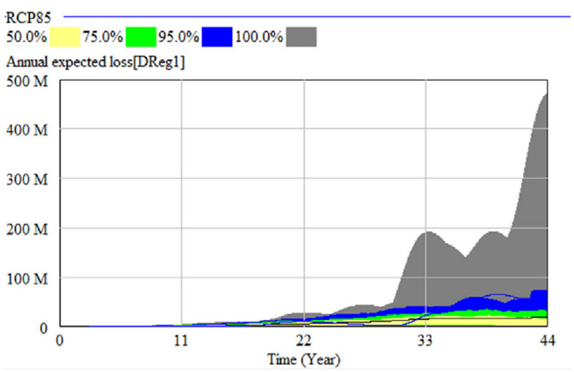
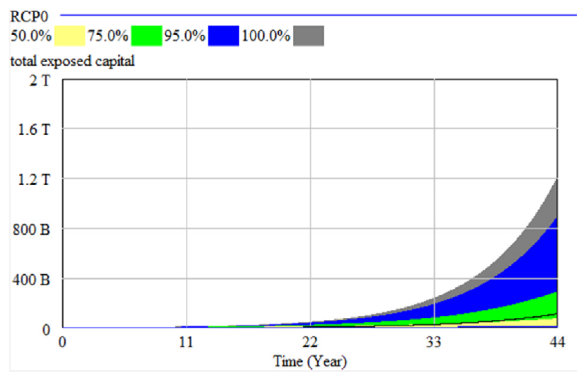
Annual Expected Loss:

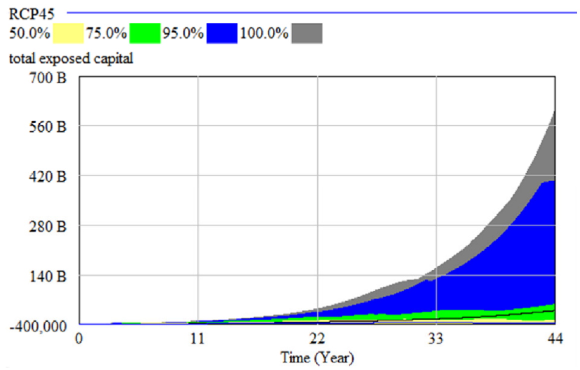


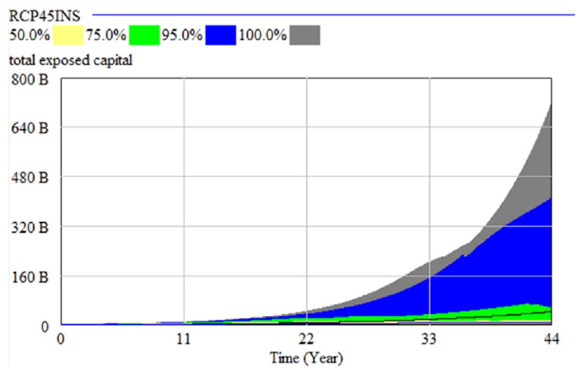


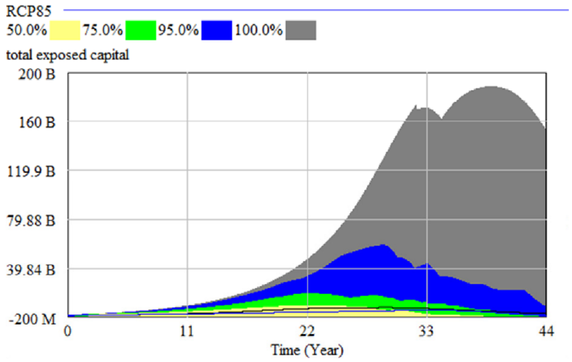


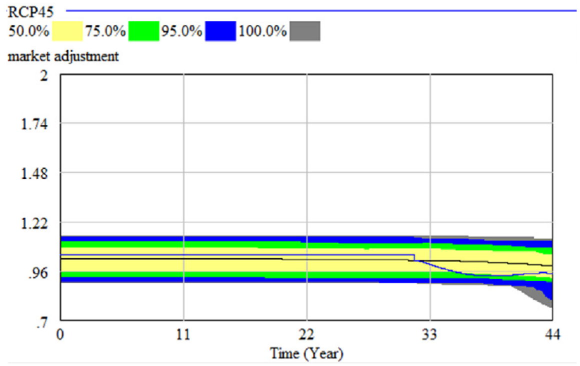
Total Exposed Capital:

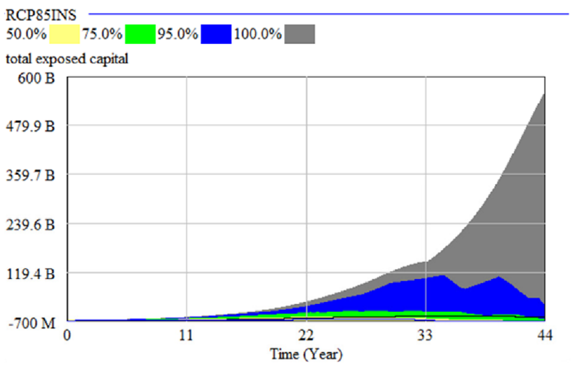


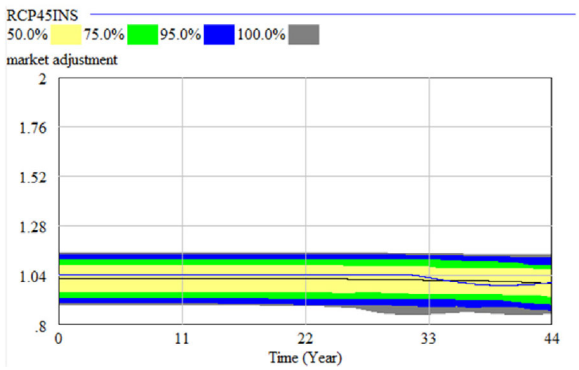




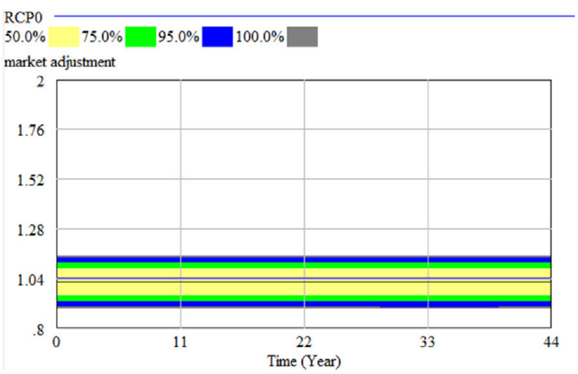


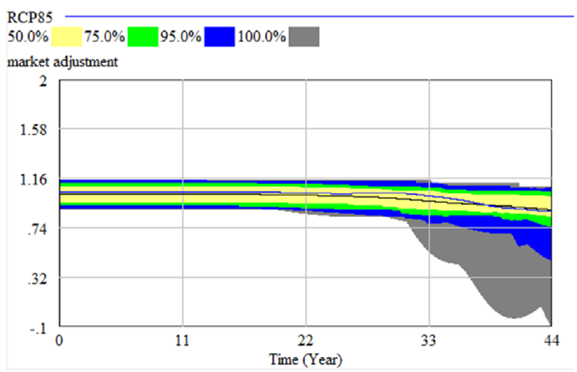


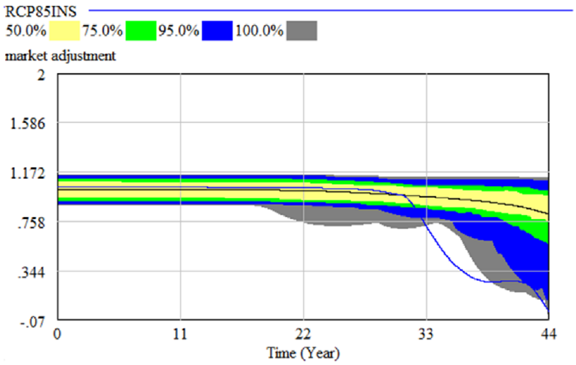


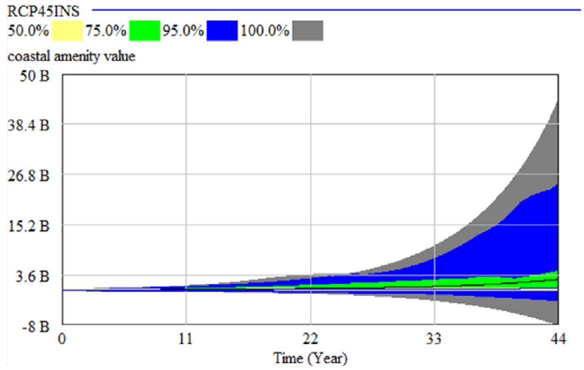


Market Adjustment (Return on Investment):

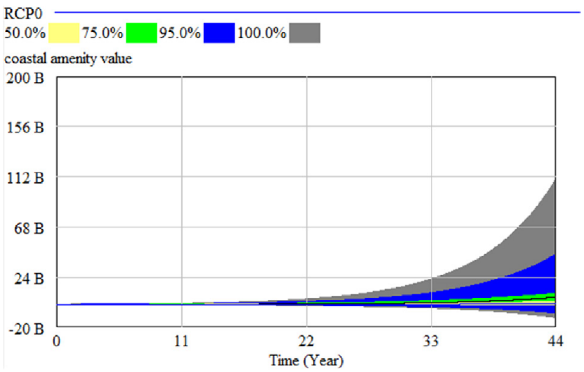


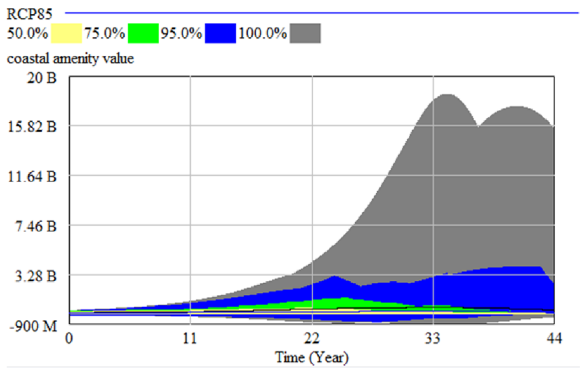


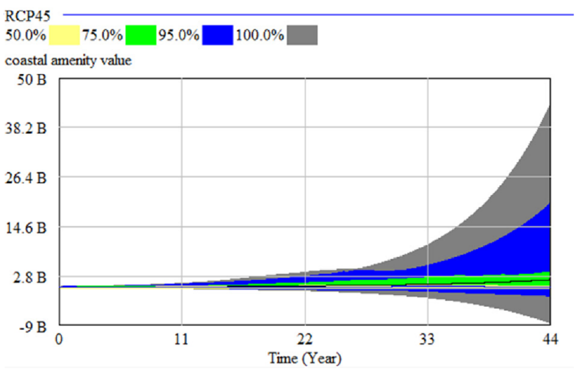


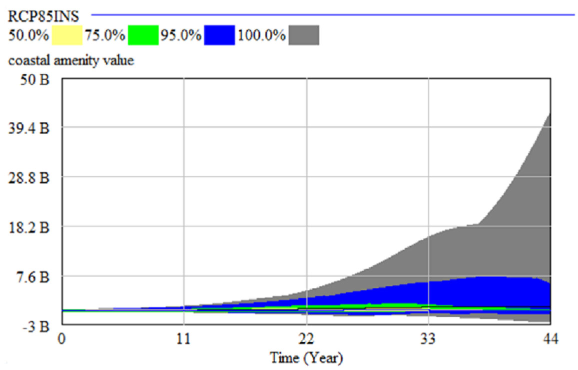


Coastal Amenity Value:

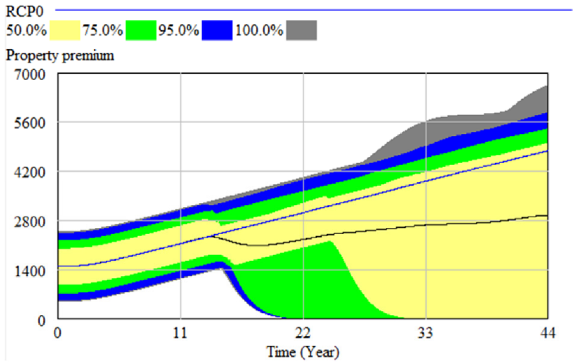


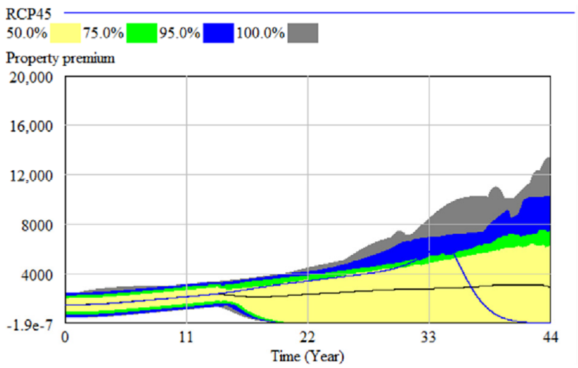


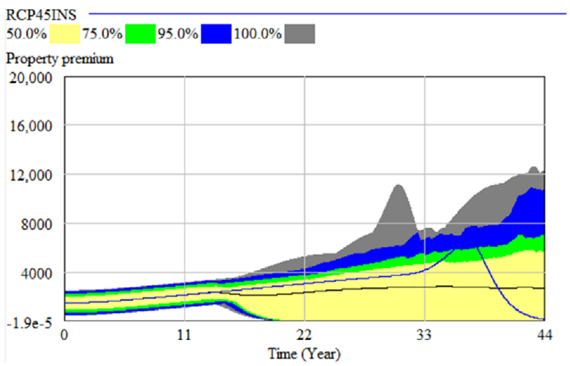


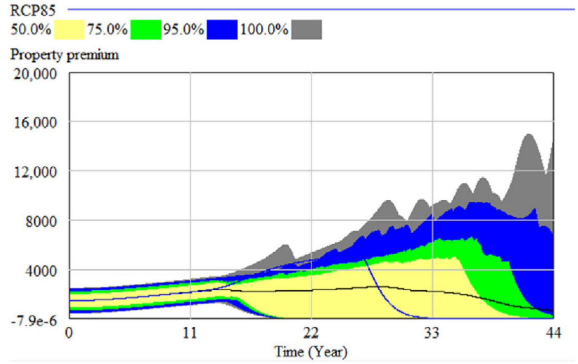


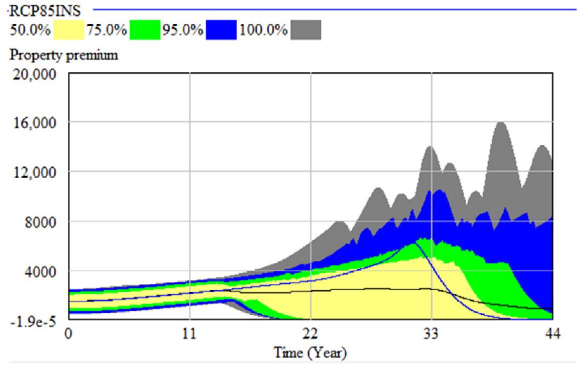
Property Premium:



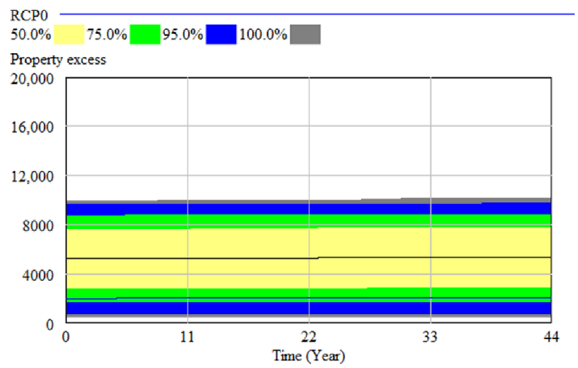








Property Excess:



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