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## Abstract

How will the increased frequency of coastal inundation events induced by sea level rise impact residential insurance premiums, and when would insurance contracts be withdrawn? We model the contribution of localised sea level rise to the increased frequency of coastal inundation events. Examining four Aotearoa New Zealand cities, we combine historical tide-gauge extremes with geo-located property data to estimate the annual expected loss from this hazard, for each property, to establish when insurance retreat is likely to occur. We find that as sea level rise changes the frequency of inundation events, 99% of properties currently within 1% AEP coastal inundation zones can expect at least partial insurance retreat within a decade (associated with less than 10cm of sea level rise). Our modelling predicts that full insurance retreat is likely within 20 – 25 years, with timing dependent on the tidal range in each location, and, more intuitively, on the property's elevation and distance from the coast.

JEL-Codes: Q540, R380.

Keywords: insurance, retreat, sea level rise, SLR, climate change.

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## 1 Introduction

Accelerating sea level rise and increasing storminess, two effects of a warming climate, mean that coastal developments are becoming increasingly exposed to more frequent and severe hazards. These include coastal inundation, erosion and shoreline recession (IPCC 2014). This problem poses a challenge for almost any low-elevation coastal settlement worldwide, including diverse locations such as Bangkok, Jakarta, Shanghai, Brisbane, New Orleans, Miami, Rio de Janeiro, and Lagos.

Residential insurance transfers risks that are of low enough probability. When the likelihood of damage increases, insurance becomes increasingly costly, until it is no longer viably supplied by commercial insurance companies. *Insurance retreat* from coastal locations is thus an inevitability once sea level rise causes insurers' insurability thresholds to be crossed.

Except for the near-term occurrence of an actual disaster, it is the loss of residential insurance that will likely be the first mechanism by which homeowners will experience material economic loss directly attributable to climate change. Since mortgages are typically conditional on insurance (especially at the time of issuance), the withdrawal of residential insurance results in an immediate drop in property values. For many households, the value of their home is larger than their net wealth, so the consequences of a decline in their property's value can have very significant consequences for their balance sheets.

Beyond the impact on individual households balance sheets through insurance's impact on property prices, however, a sound insurance sector also contributes to the financial security of individuals and firms and supports economic growth by allowing efficient risk-taking. Disaster insurance functions most effectively for society when it achieves four aims: 1) transfers the financial risk from individuals, families, and companies, to financial markets; 2) incentivises risk reduction ex-ante and speeds up recovery ex-post; 3) encourages investment in productive opportunities; and 4) protects the most vulnerable in our society from falling into poverty in the aftermath of an event (Linnerooth-Bayer et al. 2019). The permanent loss of insurance is therefore a matter of concern not only for the affected property owners but for public policy more generally. Providing advanced warning of when and where insurance retreat can be expected is the focus of this paper.

In this study we quantify annual expected-loss-based premiums for insurance against coastal inundation for residential property. We focus specifically on how these premiums change as sea level rise lifts the baseline of existing storm surges thereby increasing the probability of coastal inundation. We use data on property elevation, the replacement cost of residential homes, hazard maps of coastal areas with a one percent probability of being inundated each year, and the distribution of observed extreme sea levels from historical tide-gauge data. With these data, we model the actuarially-fair risk-based premium for this hazard at the property level and how it can be expected to change over time.

In Aotearoa New Zealand (henceforth Aotearoa), almost a third of the 1.6 million residential houses in the country are located within 1km of the coastline. In Aotearoa, as is true in many countries, insurance policies are renewed annually. With such frequency of renewal, insurance retreat can occur any year, and certainly during the term of a typical mortgage (with a median duration of 20 years in Aotearoa).

Currently in Aotearoa residential insurance covers almost all hazards. Therefore, once the expected-loss-based premium for a hazard reaches, an albeit subjective, affordability threshold, insurers begin to limit the coverage they offer to new and existing customers. We analyse these thresholds at the property level to identify where and when homeowners are most likely to experience either partial or full "insurance retreat" due to sea level rise. The term "full insurance retreat" refers to the point when insurers stop offering or renewing insurance policies because properties in that location face an escalating hazard (Storey, 2017). Before that point is reached, a "partial insurance retreat" may occur whereby insurers begin to limit the extent to which homeowners are able to transfer the risk to the insurer.

A partial retreat may include monetary caps on coverage (decreasing the sum insured), extraordinarily large hazard-specific deductibles (excesses) or the exclusion of one or more hazards (unbundling).

Our primary contribution is in explicitly quantifying how soon insurance retreat can be expected. Aotearoa provides an early case study since its particular climatic conditions when combined with its historical patterns of development, means it will experience sea level induced insurance retreat earlier. While we focus on the impact of sea level rise on insurance availability, the approach can be applied to any hazard which is escalating (i.e. becoming more frequent and severe) under climate change.

This quantification of future insurance retreat has far-reaching implications for property markets and spatial planning. Residential property owners are currently underestimating climate risk when they assume future insurance costs will reflect historical trends. As a result, coastal property markets continue to enjoy increased investment even as coastal inundation becomes more frequent. With assets continuing to accumulate at the coast, local and central governments face strong demands to build and maintain the infrastructure servicing those assets.

We conducted this forward-looking study to fill a key knowledge gap hindering better adaptation decisions. This knowledge gap is one that is unlikely to be addressed by the insurance industry itself. Since residential insurance policies are renewed each year and reinsurance contracts are typically for no more than three years, insurers have little incentive to conduct analyses of how expected losses will change in the medium and long term. Insurers also have very little interest in publicizing any likely future retreat, lest it leads to policy reactions against that (in several jurisdictions, policymakers have tried to prohibit these retreats, at least temporarily).

Insurance retreat is most predictable with sea level rise but insurance retreat is inevitable in other locations facing escalating hazards under climate change. We selected sea level rise for our first study of insurance retreat since climate science provides a high level of confidence in the *minimum* rate of change of this hazard. The projections contained in this first study are therefore conservative. Further, while projected sea levels in the second half of this century has been widely communicated, our study shows that insurance retreat occurs decades before properties are permanently inundated by sea level rise.

In section two we place the current study in the existing literature. Section three describes the data used in this study, section four the empirical methodologies deployed, and section five presents our results, section six discusses the implications of our results and section seven concludes.

## 2. Literature Review

While there is a significant body of literature on past changes to insurance premiums, the literature on future changes to insurance premiums is limited (Bouwer 2013, Pastor Paz et al. 2020, Phelan 2011). Much of the existing literature focuses on questions of consumer willingness to pay rather than insurers' willingness to supply (Booth et al. 2022, Browne et al. 2015, Dixon et al. 2017, Landry 2021). There is little expectation that insurance retreat could soon be commonplace even as governments are increasingly asked to act as the insurer of last resort when insurance supply is disrupted following major catastrophes (Binskin et al. 2020, Furukawa et al. 2020, Jarzabkowski et al. 2019, Kousky 2019, Kraehnert et al. 2021, Lucas et al. 2021, PRA 2015).

Where literature has focused on future expected losses it tends to anchor analysis on 2100 (Vousdoukas et al. 2018). While this timeframe is the foundation for physical climate projections, the time value of money makes this horizon inconsequential for near-term financial decisions relating to residential property. Bower (2013) argues that the signal on expected losses from anthropogenic climate change is likely to be lost within coinciding changes in exposure and vulnerability, at least until 2040. Our study holds exposure and vulnerability constant to demonstrate that changes in a single hazard - coastal inundation - is sufficient to trigger a contraction of insurance supply as early as 2030. Consequently, our study has relevance for pre-emptive adaptation decision-making already today.

Studies that have examined closer horizons have estimated no more than a doubling of expected losses by 2050 from river flooding (Jongman et al. 2014) or wildfire (Dixon et al. 2018) whereas our study demonstrates how sea level rise alone (in the absence of major investments in risk reduction) will result in a five-fold increase in expected losses over the same timeframe.

Loss of insurance supply has been observed following catastrophic events such as Hurricane Andrew in Florida in 1992 (McChristian 2012), Cyclone Yasi in Australia in 2011 (Ma et al. 2012) or the 2021 recent wildfires in California (Poizner 2022). To the authors' knowledge, no study has quantified the future near-term loss of insurance supply from escalating hazards under climate change.

Mean sea level in Aotearoa will rise by at least 10cm by 2040 from 2020 levels, under all four Intergovernmental Panel on Climate Change (IPCC) Representative Concentration pathways (RCPs) (MfE, 2017). In 2015, The Parliamentary Commissioner for the Environment (PCE, 2015) estimated that in some locations with 10cm of sea level rise, coastal storms that currently demonstrate a 1% Annual Exceedance Probability (AEP) are likely to reach an AEP of 4.88%.[1] This is equivalent to a storm with 1 in 100 year Annual Recurrence Interval (1:100 ARI) becoming a 1 in 20 year storm (1:20 ARI), after just 10 cm of sea level rise.

Private conservations with the insurance industry suggests that insurance retreat begins when the likelihood of an event reaches 2% AEP (1:50 ARI), and residential insurance will be

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[1] Note that the intensity of coastal storms will also increase with climate change, but we focus on the frequency change of coastal inundation from storm surges that is caused exclusively by sea level rise. The investigation of the changing frequency that is associated with increases storminess necessitates climate modelling that is not yet reliable enough for this purpose.

almost impossible to secure by the time the AEP reaches 4.88% (1:20 ARI) [Kerr et al. 2017]. Evidence from the United Kingdom suggests that insurance retreat can occur even sooner; private flood insurance has become difficult to obtain for properties that have an AEP for flooding of only 1.32% (1:75 ARI) (Surminski, 2014). This suggests that our assumptions of a partial retreat threshold at 2% AEP and a full retreat threshold at 4.88% AEP are conservative.[2]

Before a threshold for full retreat occurs, local insurers have typically engaged in partial retreats by, for example, setting high deductibles (excesses) in hazardous locations rather than increase premiums beyond a level anticipated to be publicly acceptable (Furley, 2017).[3]

## 3 Data

### 3.1 Sources and issues

This study uses modelled property data from RiskScape, elevation data from the New Zealand School of Surveying, tide gauge and coastline data from Land Information New Zealand (LINZ),-and extreme sea level extent modelling from the National Institute of Water and Atmosphere (NIWA). This section explains each of these in detail, including any limitations associated with each dataset.

### 3.11 Properties

The building asset module of RiskScape is a modelled property-level dataset that includes estimates of every building in the country, including its geographic location (as a point), floor height, floor construction, and replacement cost.[4] The available residential property dataset contains approximately 1.6 million properties in mainland Aotearoa; each property is given a unique identifier. We trim this dataset by removing those properties with a replacement cost of less than the 1st percentile value or greater than the 99th percentile values. Replacement cost data is obtained from CoreLogic's Quotable Value (QV) dataset; which is used in Aotearoa for property tax purposes. The assigned construction types are consequently used to identify replacement costs obtained from the Rawlinson's construction handbook guidelines (Rawlinsons 2013).

The dataset geo-locates each building with an approximate co-ordinate point, rather than a building outline shapefile which, when we examine them, may make marginal properties on the edge of inundation boundaries fall outside the boundary even if some of the building outline falls within. It also means the distance we measure to the coast for each property will likely be slightly higher than the true value.

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[2] In Aotearoa, a public insurer - the Earthquake Commission (EQC) - covers the first tranche of natural hazard risks for all residential property that is privately insured (with fire insurance). However, for storm events, only the *land* is covered by the EQC, and not the *dwellings* located on that land. As such, we ignore the presence of public insurance in the calculations that follow.

[3] This publicly acceptable level is most likely defined internally in each insurance company, based on subjective affordability criteria.

[4] The building asset information relates to any "permanent enclosed structure including a roof, walls and one or more level", and its various attributes were assigned based on the methods outlined in Cousins (2009), King & Bell (2009), King et al. (2009), and Lin et (2016).

### 3.12 Elevations

We use elevation information from the New Zealand School of Surveying Digital Elevation Model version 1.0 (NZSoSDEM). The NZSoSDEM models elevation at a spatial resolution of 15m and was created by the School of Surveying through interpolation of LINZ topographic vector data (topo-maps). The NZSoSDEM is a series of 30 maps whose extent correspond with the LINZ Topo250 topographic map series (Columbus et al., 2011).

The elevation data in the NZSoSDEM, while nationally consistent, has some modelling errors; for example, a few elevations are negative (we exclude these). The vertical accuracy of these data was approximated to be +/- 5m for 90% of the values). We have therefore constrained our analysis to only those properties that also fall within the 1% AEP extreme sea level extents (henceforth ESL1 zones) which was delineated based on Light Detection and Ranging (LiDAR) data. The spatial resolution in the NZSoSDEM is lower than we would have ideally liked to use for our analysis (15m), but these are the best available data at the national level.[5]

### 3.13 Tide gauges and sea levels

LINZ maintains a national database of tide stations which includes an archive of sea level data. From LINZ and the Port of Auckland, we also utilise hourly tide gauge data. We adjust for the local vertical datum difference to chart datum and for the average local sea level as described by Hannah (2015). We also remove unrealistic spikes (following the general principle described in Bell et al. (2015). We then aggregate to a daily level, using only those daily periods with all 24 hourly measurements, and then to annual, using only those with at least 350 daily measurements available. From this, we find our annual-maxima sea level series at the four ports.

Our analysis uses this annual maxima time series of sea levels at each port, beginning with the earliest available full calendar year of data. The dataset covers four Aotearoa ports: Auckland, Wellington, Lyttleton (Christchurch), and Dunedin, which are the four tide gauges with sufficient historical records to conduct Generalised Extreme Value (GEV) analysis. Table 2 provides further information on these four port tide-gauges. Figure 1 presents a simple visualisation of the annual maxima time-series data.

### 3.14 Flood inundation shapefiles

We use ESL1 zones - provided as shapefiles - developed by NIWA. These outline the horizontal extent of extreme sea levels which have a 1% AEP, which incorporate tide, storm-surge, mean sea-level anomaly and wave setup; see Paulik et al. (2019) for a detailed explanation. The modelling of ESL1 zones can only be done for the areas of the coastline

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[5] The NZSoSDEM models elevation at a stated vertical accuracy of 90% within +/-5m. There are a number of publicly available national Digital Elevation Maps (DEMs) for Aotearoa. The highest resolution (8m from LINZ) is unfortunately only recommended for cartographic visualisation. The globally available MERIT DEM from Yamazaki et al. (2017) with +/-2m vertical accuracy, is available for research purposes over Aotearoa, but only has a 90m grid resolution. Others available include the Geographx 20m or Landcare 25m resolution DEMs. The accuracy of the NZSoSDEM product was comprehensively assessed using a statistically sound selection of 3791 check points throughout the country. The comparison of results with other available country-wide DEM demonstrates an improvement in terms of quality in addition to a finer spatial resolution. We chose to use a nationally consistent product rather than the locally specific LiDAR offerings in Aotearoa, to allow for a nationally comparable methodology.

where LiDAR elevation is available. The ESL1 water heights exclude the influence of tides in estuaries and open coast wave effects. The spatial extent of the ESL1 is consequently likely to be more limited than the full extent of the coastal inundation hazard because both of these exclusions would expand the area exposed to this hazard. NIWA supplied ESL1 zones are plotted in Figure 2 (Paulik et al 2019).

### 3.15 Coastline

We use the LINZ New Zealand Coastlines dataset (LINZ 2020), which identifies the line forming the boundary between the land and sea defined by mean high water (MHW).

### 3.2 Properties exposed to coastal inundation

Based on datasets in 3.1 we carry out the following geo-processing steps for each property in Aotearoa:

- Distance to coast - we calculate the distance to the coast for each property by finding the nearest point along the New Zealand Coastline multiline shape from each property and calculating the distance between these two points in metre;
- Elevation - we approximate the elevation of each property by assigning the elevation of relevant 15m NZSoSDEM raster grid cell;
- Flood threshold height - we establish the threshold height by adding the ground elevation to the property's floor height; and
- "In zone" classification - we attach a binary variable for whether each property is "in zone", i.e. whether the coordinates associated with a property fall within an ESL1 zone.

### 3.3 Summary statistics

In creating the core sample for our analysis we only use those RiskScape properties within 1km of the coast, with all required variables available. We also trim those properties with the highest and lowest percentiles of replacement costs. Note that there are 451,903 coastal properties (within 1km of the coast). Of those 10,238 fall within the ELS1 boundaries. While Auckland is by far Aotearoa's largest city it has the smallest number of homes within the ELS1 boundaries (539 properties) reflecting comparatively fewer low-lying neighbourhoods. Christchurch, Aotearoa's second largest city, has the highest number of properties within ELS1 zones (4,850 properties) and while a greater proportion of these properties have concrete floors and so incur less damage if exposed to water, these properties also have lower median floor height and so are more likely to be exposed to flooding. Dunedin has the second highest number of properties within ESL1 zones (3,105 properties) and the oldest housing stock with almost half of ESL1 properties constructed over a century ago. The summary statistics of core variables for properties within the four cities are presented in Table 3.

## 4 Methodology

We develop a three-step algorithm. The first involves using Generalised Extreme Value (GEV) modelling to estimate the parameters of the distribution of extreme sea levels at each port, and in particular the difference in sea level required to convert a 1% AEP into a 4.88% AEP (i.e., when full insurance retreat is assumed to have occurred). The second involves modelling the approximate 1% AEP flood height at each property, and the third models the approximate required risk-based insurance premiums for this particular hazard at each location, given different sea level heights. These steps are explained in detail below.

### 4.1 Estimating distributions of extreme sea levels

The GEV method offers a statistical framework with which one can make inferences about the probability of very rare events (Embrechts et al. 1997). We utilise the GEV methodology of Coles (2001) to parameterise the distribution of extreme sea levels in the four cities (Auckland, Wellington, Christchurch/Lyttleton and Dunedin). We define annual maxima of sea levels from the four tide-gauges, where superscript $p$ denotes port city site and subscript $t$ denotes time. We define the annual maxima from the available hourly data as:

$$X_t^p = max\left(X_{1|t}^p, \dots X_{H|t}^p\right) \text{ for each } t \qquad (1)$$

The annual maximum time series at each port is developed using the methodology outlined in Stephen et al. (2020), with the addition that we require each year of observation to have a level of completion of at least 95 percent (~ at least 350 days).

The cumulative distribution of a GEV distribution is:

$$F(x; \mu, \sigma, \xi) = exp\left\{-\left[1 + \left(\frac{x-\mu}{\sigma}\right)^{-1/\xi}\right]\right\} \qquad (2)$$

where the three parameters $\mu, \sigma, \xi$ denote shape, location and scale of the distribution respectively. This allows the distribution to follow either a Gumbel, Frechet or Weibull distribution, equivalent to type I, II and III respectively when the shape parameter is equal to 0, greater than 0, or less than 0.

For each port site, we fit the resulting annual maxima to a GEV distribution using Maximum Likelihood Estimation (MLE) without a-priori assumption on the sign of the shape parameter (Embrechts 1997). These indicate which of the three distributions provides the best fit, and allow us to then generate yearly annual recurrence intervals for different return periods (and convert these to their respective annual exceedance probabilities). This conversion from annual recurrence interval (ARI) to annual exceedance probability (AEP) is performed as below:

$$AEP = 1 - exp\left(-\frac{1}{ARI}\right) \qquad (3)$$

This produces an estimate of the expected water height from the high tide elevation, per port, of a 1% AEP ESL (ESL1) event (excluding, for now, 'wave setup' heights), as well as expected water heights at the other AEP levels, by year.

### 4.2 Flood hazard modelling

For coastal flood hazard maps Paulik et al. (2019) have:

1. Estimated the mean sea-level (MSL) and mean high-water spring elevations (MHWS10; the 90th percentile of all high tides) at consistent distances around the Aotearoa coastline (see Figure 2).

2. Estimated extreme sea levels (ESL1) elevations (where ESL1 = 1.28 x MHWS10 (x 1.1 if within an estuary) + 0.34 + wave-setup, equal to 0m (estuaries) 0.5m (sheltered coasts) or 1.5m (open coasts).[6]
3. Using an 90m MERIT Digital Elevation Model (DEM) from Yamazaki et al. (2017), extrapolated an 8m finer-resolution MERIT DEM.
4. Added 3m to the coastal ESL1 values (from step 2) and spatially mapped this onto the Aotearoa version of the MERIT DEM (created in step 3) to identify coastal inundation areas for ESL1+3mSLR[7]
5. Spatially mapped the coastal ESL1 values (from step 2) onto high-resolution LiDAR elevations to identify coastal inundation areas for ESL1 extents and for ESL1+0mSLR at 10cm increments until the ESL1+3mSLR scenario (from step 4).

In the ESL1 zones of the four cities, we add the GEV-derived storm tide height to the ground elevation of each property inside the ESL1 zone (at the property's coordinate point) to estimate property-specific water heights. We take the difference between property elevation and modelled ESL1 water height as below:

$$\begin{cases} property\ elevation_i = ground\ elevation_i + floor\ height_i \\ water\ height_p = SL_p^{GEV\ 1\%AEP} + wave \\ w = water\ height\ over\ floor\ boards_i = water\ height_p - property\ elevation_i \end{cases} \tag{4}$$

where $SL_p^{GEV\ 1\%\ AEP}$ denotes a port's 1% AEP water height using the GEV analysis explained in section 4.1, and *wave* denotes wave setup and is estimated as 0.5m (following Paulik et al., 2019).

### 4.3 Insurance premium model

We model property-level (*i*) annual risk-based premiums $r_i$ produced solely from this ESL1 hazard, of properties within the ESL1 zones, based on expected annual losses as below:

$$r_i = loading \cdot d_i \cdot replacement\ cost_i \cdot AEP \tag{5}$$

where:

- $r_i$ denotes estimated risk-based premium for this hazard
- *loading* is an insurer parameter for administrative costs and a profit margin
- $d_i$ is a damage function which takes a threshold approach based on water level and flooring type (see below).

Reese & Ramsay (2010) model flood fragility curves for various building types. We follow their example, but rather than using these curves directly (which would provide a false sense of precision), we take a threshold approach summarised in Table 1.

This damage function uses the modelled RiskScape data which categorises homes into timber or concrete flooring construction only. We choose to take the approximate average damage ratio for either concrete-or-masonry homes or timber homes at the mid-point of 0-1m flood

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[6] Note here 1.28 was used by Paulik et al. (2019) as a proxy for the relationship between tidal-gauge 99th and 90th percentile heights

[7] The post process MERIT DEM was not available to this study. In its place we used the New Zealand DEM.

depths, and the approximate overall damage ratio for flood depths higher than 1m above the floorboards.

It is standard practice to assume an insurance "*loading*" of 30%; see for example, Hudson (2018). We follow this practice.

### 4.4 Exclusions

We make a number of necessary exclusions to our analysis. Most of these mean our estimates are likely to be conservative: 1) The increased severity of extreme weather events caused by climate change is not considered[8]. 2) We use a single conservative wave setup value of 0.5m. 3) This analysis does not include any deductibles (excesses) for insurance products. 4) The inundation models we use do not allow the isolation of current defences/flood mitigation measures such as sea walls, flood gates or pumps, or further investment in them.

## 5 Results

### 5.1 Influence of sea level rise on projected water heights of extreme sea levels

The GEV estimated 1% AEP extreme sea level heights are presented in Table 4 at the four ports. To identify the distribution generating the least error we apply the *likelihood ratio test* (Reiss et al. 2007) to compare the optimised GEV to a Gumbel distribution since the Gumbel distribution was used by Hunter (2015) as the basis of the analysis for the PCE (2015). Our results indicate Auckland and Wellington ports observed extreme values were best described by a Gumbel distribution whereas Christchurch and Dunedin more closely follow a Weibull distribution. For consistency with PCE (2015) we follow Hunter (2015) and apply a Gumbel distribution to all four port-cities (see Table 5).

Using this information, we estimate the sea level at different return periods. Table 6 present the difference between sea level at higher AEPs and the sea level at the 1% AEP level to identify the approximate impact of sea level rise on AEP. Figure 3 displays the curves for each port, where the x axis is the difference between the estimated sea level of the AEPs above 1% and the 1% AEP - thus, the sea level rise required to increase the frequency of the 1% AEP event to the given AEP.

Interestingly, the difference between the curves is primarily driven by the size of port tidal ranges rather than materially larger storm surge heights at different latitudes. Locations with large tidal ranges are more likely to absorb a storm surge of a given size within the existing tidal range, thereby avoiding damage from overtopping of existing high water lines. The key retreat thresholds for each port-city is presented in Table 6.

### 5.2 Insurance results

### 5.21 Estimating current risk-based premium pricing

In Table 7 we present the results from our property insurance modelling. For each specification we present the sample size, that is, the number of properties that are located within the ESL1 zones and less than 1000m from the coast. In order to perform this analysis

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[8] As opposed to the increased frequency of inundation caused by existing storms when the base sea level rises.

we require GEV results (dependent on tidal gauge data being available with a sufficiently long record).

Table 8 presents the estimated hazard specific premiums. We find that in Auckland the median annual single-hazard expected-loss-based premium (currently) would be approximately $2,000 within the current ESL1 zones. For Wellington, we find that the median would be $1,800, and for both Canterbury and Dunedin we find a median of $1,600.

It is worthwhile noting that our present day modelling of these *single-hazard* expected-loss-based premiums are several times higher than current *all-perils* insurance premiums in Aotearoa, which in 2017 were estimated to be, on average, only $1,050 per annum (Treasury, 2017). This suggests that, at this point in time, there is still substantial cross-subsidisation of low elevation coastal properties (by those at higher elevations).

### 5.32 Timing

In order to understand the timing of retreat, we compare the differences between our GEV results estimating 1% AEP water heights with 2% AEP and 4.88% AEP and compare these with expected sea level rise in Aotearoa.[9] By comparing the difference between these AEPs, we can estimate the timing of partial and full insurance retreat for exposed properties in each of the four cities we examine. Recall that "partial retreat" is when insurers begin to limit the extent to which homeowners can transfer risk to the insurer. The timing of partial and full insurance retreat for coastal homes, estimated conservatively for RCP 4.5, is shown in Figure 5.[10] Partial retreat is estimated to happen soonest in Wellington and Christchurch, starting less than a decade from today. Only slightly later are Dunedin and Auckland which see similar partial insurance retreats shortly after 2030.

Ultimately, this process of insurance retreat in the ESL1 zones will result in full retreat from all the properties therein. We estimate that this process will culminate in the 2040s with only a few years separating the first to the last city we examine. This is a troubling observation. Typically, sea level rise is discussed as a concern for property owners in the later part of this century, when the rising seas permanently inundate properties. Our analysis demonstrates that insurance retreat will happen much sooner.

## 6 Discussion

This study illustrates that insurance retreat can be expected in many locations in Aotearoa within the next two decades. Aotearoa has particular circumstances which may precipitate insurance retreat earlier: small variability in storm surges, narrow tide ranges, large coastline relative to GDP, very high insurance penetration rates, and bundled insurance. Identifying locations which face inevitable insurance retreat enables anticipatory adaptation. Our methodology has application to any location facing escalating hazards under climate change.

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[9] Expected sea level rise is taken from MfE (2017) and shown in Figure 4.

[10] We also investigated RCPs 2.6 and 8.5, finding between 2-5 years difference (at most) for either partial or full retreat.

The only intervention that permanently reduces risk from sea level rise is managed retreat however managed retreat continues to face fierce public opposition.[11] Instead, coastal communities seek public funding to remain in place.

The relatively small height differences between 1% and 4.88% AEP events in Aotearoa means that hard and soft defences (such as seawalls and dune refurbishment) could forestall insurance retreat by reducing the probability of inundation directly *from the coast*. Defences that attempt to establish a vertical barrier between the sea and residential properties, however, are unable to reduce flooding from extreme precipitation which is also expected to increase with climate change. In fact, vertical seaward barriers can exacerbate pluvial and fluvial flooding when these barriers prevent excess water from draining to the sea. While there may be some argument for investment in hard and soft structures to defend critical infrastructure, the use of barriers to hold back coastal inundation will be futile as seas continue to rise. At best these structures extend the timeframe affected properties can benefit from risk transfer through insurance.

Recognising where insurance retreat is inevitable can also help prevent maladaptive measures such as the introduction or extension of public insurance to affected locations. Offering a public subsidy on homes that face insurance retreat from private insurers underwrites continued development in hazardous locations and encourages people to remain in harm's way.

The public subsidy will also quickly become prohibitively expensive. A simple calculation is illustrative. Imagine a $1,000,000 wooden floored property in one of Wellington's ESL1 zones where the land value is $500,000 and the value of the buildings is $500,000. With just 30 centimetres of sea level rise, a 1 in 100 year flood (ARI 1:100) will become an annual event (ARI 1:1). The AEP for an annual event (ARI 1:1) is 63.21%. Therefore after just 30 centimetres of sea level rise this property will face annual expected losses of $94,818 in today's dollars[12]. 30 centimetres is expected within the next 50 years. In other words the expected-loss-based premium will increase from $1,950 today to more than a 10th of the value of the property within 50 years[13].

To avoid a partial or full insurance retreat insurers may break with their historical practice by unbundling the hazards covered in their policy offerings (and retreat only from coverage of specific hazards). This unbundling would have wide-ranging implications for the local insurance market. Without an all-hazards insurance system, it is likely that the current exceptionally high levels of residential insurance for natural hazards will be difficult to maintain (Nguyen and Noy, 2020). Further, this partial retreat will almost certainly exclude the very hazard(s) that pose the greatest threat to the property.

In Aotearoa, mortgages are often granted with repayment periods of up to 30 years but the maximum period for fixed interest rates is only 5 years. Since insurance contracts are renewed annually and insurance is a prerequisite for securing a mortgage, failing to maintain insurance can trigger a legally-defined default or at the very least result in much a higher interest rate on the mortgage. Currently, there is a general absence of compliance checks, and

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[11] How insurance retreat can inform financial innovations to support managed retreat is the subject of a separate study (Storey 2022).

[12] Annual Expected Losses = Value of structure ($500,000) x AEP (63.21%) x Damage Function (30%).

[13] Annual Expected Loss Based Premium = Annual Expected Losses x 1.3 (Insurer Loading).

banks seldom know whether the properties they mortgage remain insured beyond the time of issuance.

Concern over insurance retreat and the mismatch between annual insurance policies and long-term mortgages has already been raised by financial regulators (RBNZ, 2021). Though some jurisdictions require private insurers to notify regulators when insurance is withdrawn (Plitt & Maldonado, 2012) there is no such requirement in Aotearoa, nor is there any legal prohibition or constraint on the non-renewal of insurance policies.

Despite the significant policy issues this poses, insurers have few incentives to communicate anticipated insurance retreat. Residential insurance policies are renewed annually. This provides insurers an opportunity to regularly reassess the profitability of properties exposed to escalating hazards under climate change. As coastal inundation events become more frequent, insurers can estimate the probability of floodwaters breaching a property’s floorboards and therefore triggering an insurance claim. As this probability approaches an insurer’s retreat threshold (e.g. 5%, 2% or even 1.32% AEP) the insurer can decide whether to renew the policy for another 12 months. This allows ample time for the insurer to withdraw from properties before the expected losses on the property become unprofitable.

On the other hand, if an insurer were to give advance warning that it expects its insurance retreat threshold to be breached on particular properties, the insurer could face public appeals to subsidise those properties, potentially indefinitely, or suffer reputational damage for abandoning loyal customers in their hour of greatest need.

This study demonstrates that thousands of houses in Aotearoa will experience full insurance retreat within the next two decades. Aotearoa is exposed to storm surges, from extra-tropical cyclones and other low pressure systems, with relatively limited natural variability. This study found the height difference between extreme and frequent storm surges (e.g. 1 in 100 year and 1 in 20 year storm surges respectively) to be less than 20cm. Consequently, even a small amount of sea level rise is able to dramatically increase the probability of coastal inundation. This is compounded by Aotearoa’s pattern of development in the previous century which was concentrated near the waterways used for transportation in the late 19th and early 20th centuries. Little regard was given to the oral history of extreme events held by indigenous Māori. Failure to incorporate oral history spanning multiple centuries shortened the record used when the distance between colonial settlements and the edge of the sea was established. Consequently, the undeveloped buffer just above high tide was inadequately small to avoid the reach of infrequent coastal inundation. Residential property in Aotearoa still hugs its coasts very tightly.

## 7 Conclusion

Projected sea level rise will increase the frequency of what is now a 1% AEP coastal inundation event. Using this quantifiable relationship, and hazard frequency thresholds for insurers, we estimate that within a decade insurance companies will start shifting their offerings along Aotearoa’s coasts. Current all-hazards insurance for coastal flood-prone properties will be increasingly difficult to renew.

Given these results, we suspect that insurance retreat in Aotearoa’s most hazardous locations will be the first lever that insurance companies pull. As the volume of properties experiencing insurance retreat grows, and with it, public scrutiny of private insurers' response to physical climate risk, unbundling of all-hazards coverage is likely to follow. We expect private insurers to reduce cross-subsidisation for the most exposed properties, and to begin to dismantle the all-hazards bundling that helps ensure such high penetration rates of residential insurance in Aotearoa. Once insurers start to accurately price climate-related hazards, competitive pressures will force insurers to differentiate more between properties and across hazards. Insurers should be expected to withdraw coverage from properties and hazards where expected losses regularly exceed socially acceptable premium levels. This unbundling will also have implications for the pricing of non-climate hazards, for example, earthquake hazards. Removing ubiquitous cross-subsidisation will have ramifications for insurance pricing and insurance retreats from other hazards.

We anticipate that because of the particular characteristics of the local market, insurance retreat will soon happen in Aotearoa. This study therefore provides a preview of the insurance retreat likely to be experienced in the many locations globally facing sea level rise and escalating hazards from climate change. Our study provides additional impetus to affected communities to expedite climate adaptation decisions. It also encourages private insurers to anticipate developments of their markets under climate change, and to consider potential policy responses to insurance retreat such as increased regulation or the provision of public insurance.

In future research, we aim to investigate insurance retreat for multiple weather-related hazards. Equally important is to further examine the sensitivity of our conclusions to outlier event and tipping points (e.g, unusually strong storms or the speeding up of sea-level rise, respectively). Once these are available, future work should also incorporate inundation water's duration and speed, more accurate modelling of elevation, more precise property footprints and construction standards/materials, and storminess projections. All of these, we believe, will provide further confidence in our findings.

## Tables

| **Floor Type** | **Damage Function** | |
|---|---|---|
| | $w_i$ <=1m | $w_i$ >1m |
| **Timber** | 0.3 | 0.5 |
| **Concrete** | 0.1 | 0.5 |

**Table 1:** Damage Function by Floor Type and Water Height ($w_i$, see Eq.4)

| Datum name | Location |
|---|---|
| Auckland 1946 (AVD-46) | Port of Auckland |
| Wellington 1953 (WVD-53) | Port of Wellington |
| Lyttelton 1937 (LVD-37) | Port of Lyttelton |
| Dunedin 1958 (DVD-58) | Port of Dunedin |

**Table 2:** Local vertical datum reference with tide gauge location

| | Coastal houses in ESL1 (n) | Construction year (median) | Flooring (mean) 1=wood 2=concrete | Floor height (median) | RiskScape replacement cost (median) |
|---|---|---|---|---|---|
| **Auckland** | 539 | 1970 | 1.20 | 63 cm | $314,000 |
| **Wellington** | 1,744 | 1955 | 1.17 | 63 cm | $273,000 |
| **Christchurch** | 4,850 | 1970 | 1.65 | 40 cm | $239,000 |
| **Dunedin** | 3,105 | 1925 | 1.15 | 63 cm | $248,000 |

**Table 3:** This table presents summary statistics of our coastal residential properties located within 1% AEP extreme sea level (ESL1) zones in four cities. Replacement cost is presented in 2020 NZ$. *Note this excludes properties more than 1km from the coast.

| | **1% AEP estimated height (2019)** |
|---|---|
| **Auckland** | 3.146m |
| **Wellington** | 1.306m |
| **Christchurch** | 1.478m |
| **Dunedin** | 1.765m |

**Table 4:** Estimated 1% AEP extreme sea level (ESL1) height, from high tide (MHWS10), using a Gumbel distribution, for each of the four port-cities (rounded to 3dp)

| | **location** | **scale** | **shape** | **n** |
|---|---|---|---|---|
| **Auckland** | 2.711 | 0.095 | 0 | 97 |
| **Wellington** | 0.975 | 0.072 | 0 | 66 |
| **Christchurch** | 1.106 | 0.081 | 0 | 52 |
| **Dunedin** | 1.356 | 0.089 | 0 | 54 |

**Table 5:** Gumbel parameters for each of the four port-cities, using data up to 2019. n denotes the number of annual maxima available to estimate these parameters. Figures rounded to three decimal points.

| | **Difference 1% - 2% AEP estimated water height** | **Difference 1% - 4.88% AEP estimated water height** |
|---|---|---|
| **Auckland** | 0.066m | 0.154m |
| **Wellington** | 0.050m | 0.117m |
| **Christchurch** | 0.057m | 0.132m |
| **Dunedin** | 0.063m | 0.145m |

**Table 6:** Gumbel estimated minimum required sea level rise for a 1% AEP (1:100 ARI) extreme sea level inundation event (ESL1) to become either a 2% (1:50 ARI) or a 4.88% AEP (1:20 ARI) event, at each of the four ports (m, rounded to 3dp)

| National elevation of properties | | | | | | |
|---|---|---|---|---|---|---|
| | Total | <50cm | 50cm-1m | 1m-1.5m | 1.5m-2m | >2m |
| **All** | 1,466,330 | 10,420 | 9,340 | 10,780 | 9,960 | 1,425,830 |
| **Coastal** | 451,900 | 10,140 | 8,740 | 8,370 | 7,830 | 416,820 |

**Table 7:** Residential property counts by elevation band.
Modelled property data from RiskScape and modelled elevation data from the New Zealand School of Surveying (NZSoSDEM). Coastal subset includes only properties within 1km from the coastline. Note these modelled figures only include homes built before 2013 and are likely to be underestimates. Figures rounded to nearest 10.

| | | **Current modelled hazard specific premium** | | | **Future modelled hazard specific premium in absence of retreat** |
|---|---|---|---|---|---|
| | **N** | **Median** | **Mean** | **Std dev.** | **Median** |
| Auckland | 539 | $2,000 | 2,600 | 4,227,100 | $10,000 |
| Wellington | 1,744 | $1,800 | 1,740 | 1,623,500 | $8,700 |
| Christchurch | 4,850 | $1,600 | 2,100 | 2,996,800 | $7,600 |
| Dunedin | 3,105 | $1,600 | 1,800 | 778,800 | $7,900 |

**Table 8:** Results presented using the climbing specification for water height per property. Results presented rounded to the nearest hundred, and only for in-zone coastal properties.

# Figures

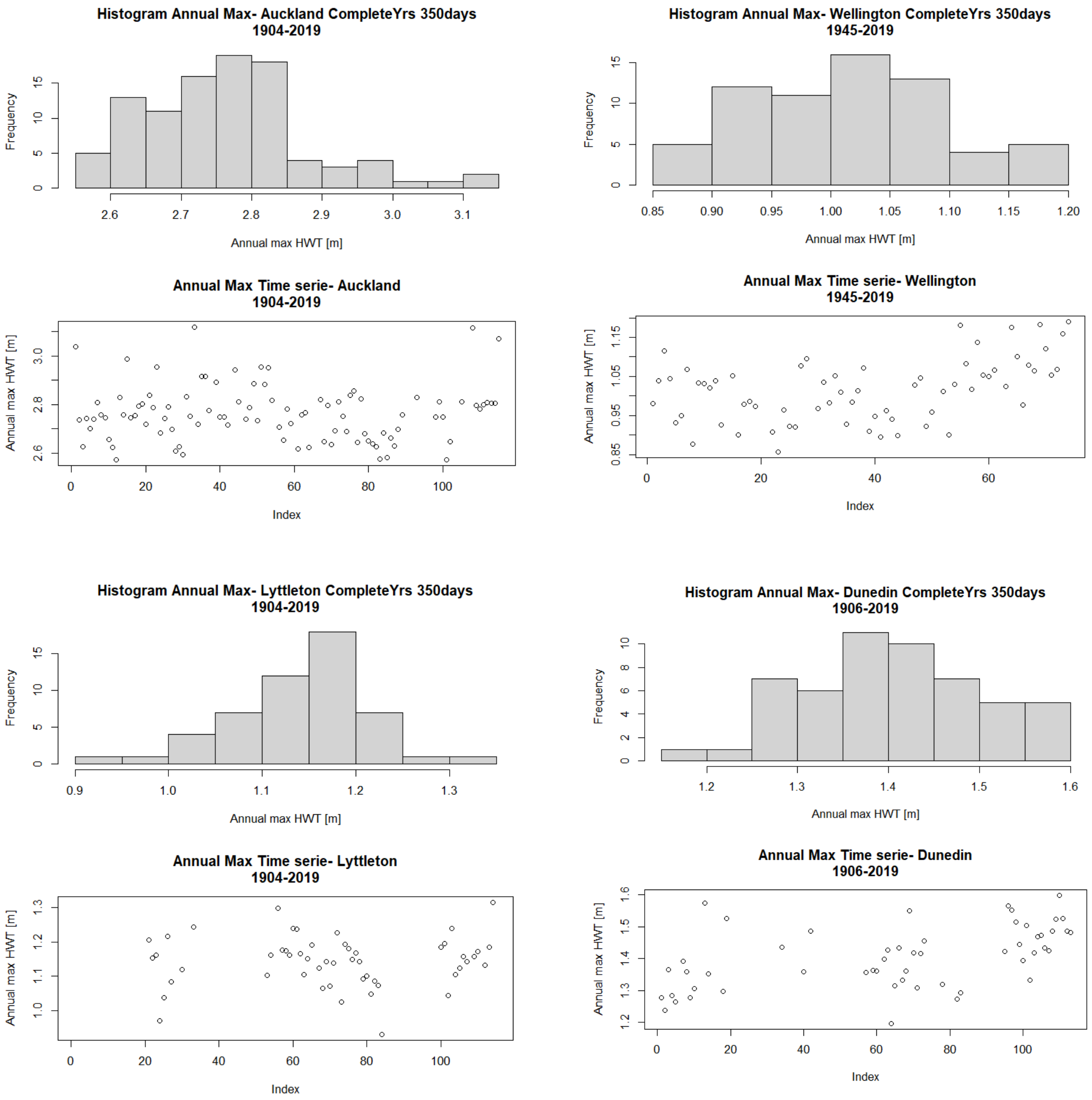

**Figure 1:** Annual post-processed maximum sea levels for the four ports.

**Figure 2:** 1% AEP Extreme Sea Level (ESL1) coastal inundation zones in four major cities Note we only analyse properties within 1km of the coast, though these maps show the original (full) ESL1 zones.

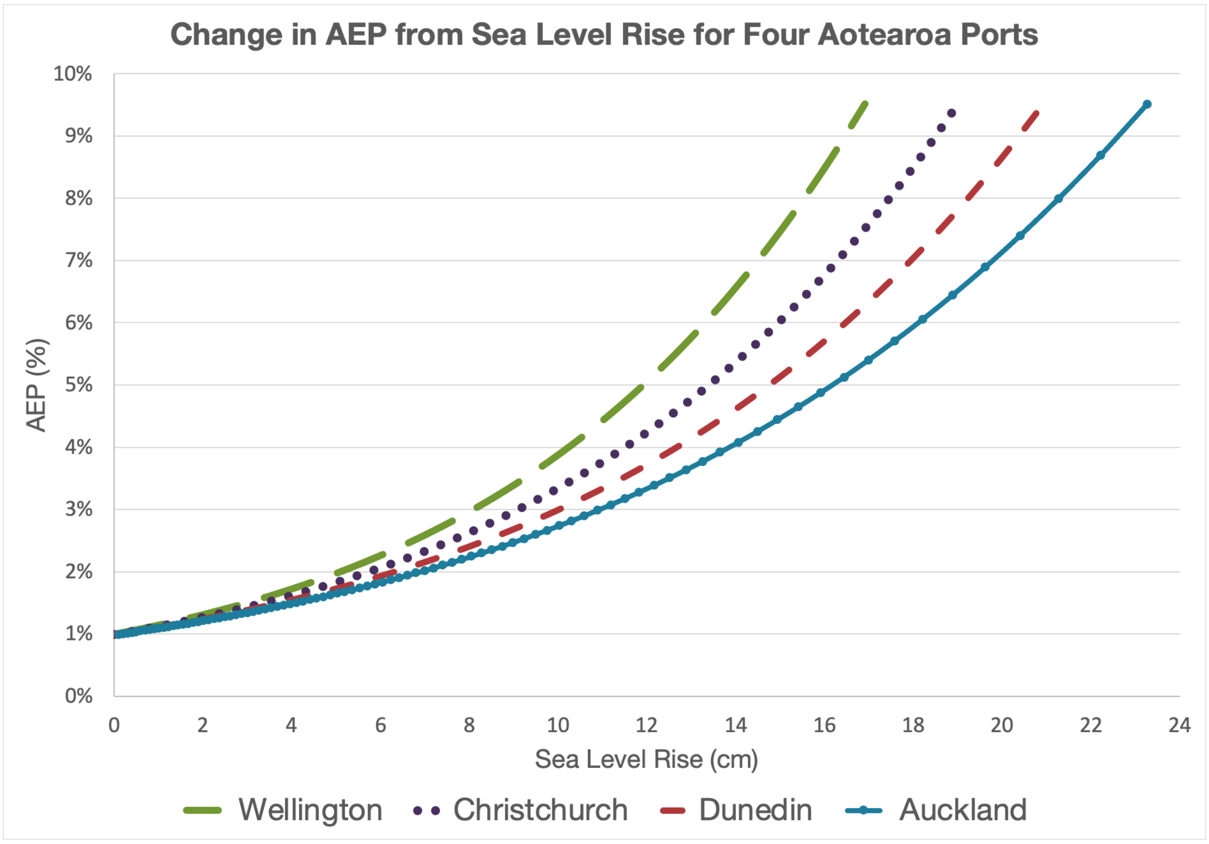

**Figure 3:** Estimated minimum impact of sea level on annual exceedance probabilities, by port .

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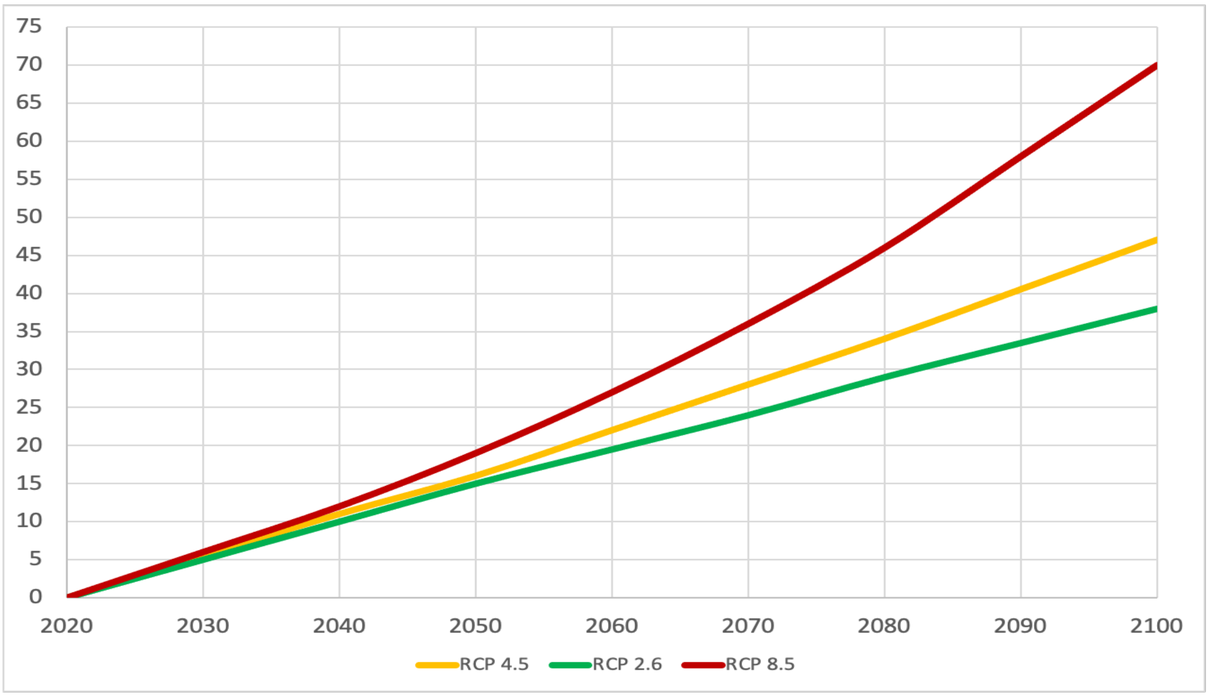

**Figure 4:** Sea level rise projections under Representative Concentration Pathways (RCPs): 2.6, 4.5 & 8.5. Author's own visualisation of data from MfE (2017)

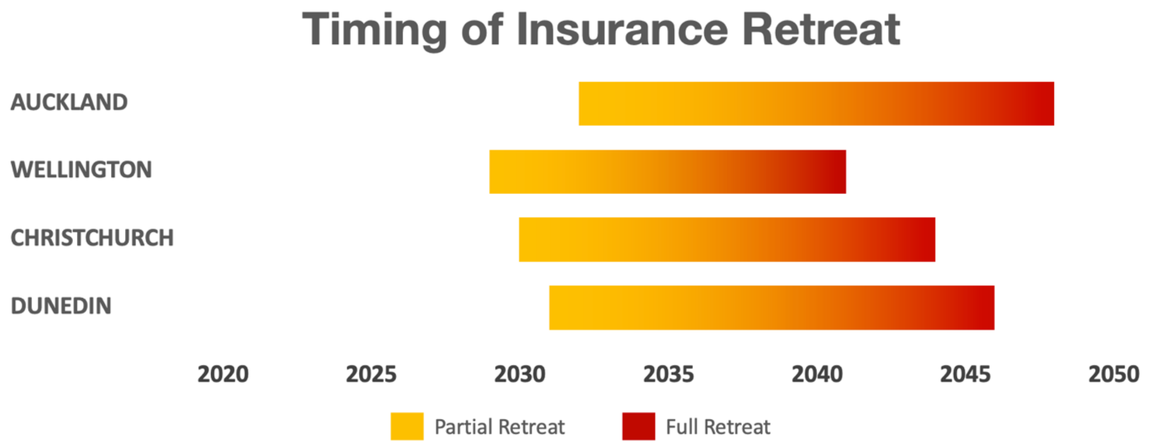

**Figure 5**: Timing of modelled insurance retreat for properties in the 1% AEP (1:100 ARI) coastal inundation zones per port-city. Note this analysis uses Sea Level Rise from RCP 4.5 (MfE, 2017), Gumbel distributions using data to 2019. Authors' own graphic.

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