Coastal Hazard and Climate-Change Risk Exposure in New Zealand: Comparing Regions and Urban Areas

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SUMMARY

Despite its hilly and mountainous terrain, New Zealand is nevertheless exposed to long-term risk from sea-level rise and coastal hazards in pockets of low-lying coastal areas where urban and peri-urban settlements are concentrated.

Over 2015, the National Institute of Water & Atmosphere (NIWA) carried out the first nationally-consistent coastal risk exposure for the Parliamentary Commissioner for the Environment in New Zealand, using available high-resolution topography, asset, population and tide information. Such an analysis has previously been hampered by access to high-resolution topography datasets (e.g., LiDAR) and disparate databases on built assets.

High-resolution GIS spatial modelling to determine the national scale coastal risk exposure was based on extracting areas of land in elevation bands above mean high water spring (MHWS) viz. 0.25, 0.5, 1, 1.5, 2, 2.5, 3 m above MHWS, from LiDAR survey data wherever available – otherwise the lower-accuracy national DEM was used (partly based on the Shuttle Radar Topography Mission). For the “risk census”, demographics and assets such as buildings, kilometers of road/rail, land-use, land parcels and other infrastructure have been enumerated for urban areas, regionally and aggregated nationally from the NZ RiskScape, NZ Statistics and Land Information NZ databases in relation to the coastal-elevation bands.

Overall in New Zealand, despite only 0.7% of the land area being below 3 m (MHWS), the normally resident population in this zone is 6.6% and the building replacement costs are 4.4% for residential buildings and 6.9% for non-residential buildings of New Zealand’s building stock, with NZ$52B (2011) potential exposure for all buildings (and NZ$19B for the 0–1.5 m elevation zone). This highlights that land area is not a reliable proxy for coastal risk exposure.

This type of national coastal “census” does not necessarily mean that these people and assets will be directly affected but it does mean they are potentially exposed to coastal hazards and sea-level rise over differing timeframes – with those on lower elevation bands much more likely to be impacted in the shorter term. More in-depth regional or local studies by councils are now required to demonstrate the actual risk for specific scenarios of coastal hazards and sea-level rise over various timeframes, to provide a more robust evidence-base for engaging with vulnerable coastal communities. The recent national study however does broadly indicate the extent of coastal risk

exposure nationally and which regions or urban areas are more at risk from coastal inundation hazards in conjunction with rising seas. It also highlighted some shortcomings in using national geo-spatial databases which can be rectified.

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1. BACKGROUND

Despite its hilly and mountainous terrain, New Zealand (NZ) is nevertheless exposed to long-term risk from sea-level rise and coastal hazards in pockets of low-lying coastal areas where urban and peri-urban coastal-holiday settlements and infrastructure are concentrated.

The national NZ Coastal Policy Statement requires land-use planning out for "at least 100 years" and to avoid redevelopment or land-use change that would increase the risk from adverse effects of coastal hazards and climate change (including tsunami) together with an objective to locate new development away from coastal areas prone to risk from climate change.

The mean level of the sea is rising globally due to climate change from a warming atmosphere. Over the past century up to present, New Zealand's average rise in mean sea level has been similar to the global-average rate – therefore future projections of global-average sea-level rise are generally applicable to NZ (Hannah & Bell, 2012). In tandem with this rise in sea level, the frequency of coastal storm inundation has increased, as evident in low-lying parts of Auckland, with the occurrence of these events set to escalate as sea-level rise accelerates (Stephens, 2015).

Planning for both coastal erosion and inundation and climate-change effects is a hotly-contested space for vulnerable communities and their councils and requires a sound evidence base built around the time-varying risk exposure.

There has been no previous national overview of the coastal risk exposure New Zealand faces nationally and regionally to coastal weather-related hazards, long-term sea-level rise (SLR) and climate change, to inform national prioritisation and provide an indicative risk exposure comparing regions and urban centres. Such an analysis has previously been hampered by NZ-wide availability of high-resolution topography datasets (e.g., LiDAR) in all coastal areas and no comprehensive national database on assets and infrastructure to complement population census data. There is now about 85% of the low-lying coast (0–3 m above mean high water spring–MHWS) which has been covered by some form of LiDAR survey, albeit with varying accuracy and point-cloud density and the RiskScape project (Schmidt et al., 2011), a joint venture between NIWA and GNS Science, has galvanised efforts to collate a national databse of buildings and some types of infrastructure.

Against this backdrop, NIWA was commissioned by New Zealand's Parliamentary Commissioner for the Environment (PCE) to provide a nationally-consistent coastal risk exposure as a first pass assessment at the national level, aggregated up from a comparison of results at the urban and regional levels (Bell et al., 2015). This underpinned the PCE's report on preparing New Zealand for rising seas (PCE, 2015).

2. METHODOLOGY FOR NATIONAL RISK EXPOSURE

2.1 Overall Approach

Inundation of lower-lying coastal areas usually occurs from a complex combination of coastal and weather processes (e.g., tides, storm surge, wave runup) modulated by climate variability from annual to inter-decadal climate cycles up to longer-term trends from climate change, particularly sea-level rise.

Assessment of the coastal inundation risk is usually undertaken for various likelihood (return-period) scenarios for the present-day situation and extended out to one or more planning timeframes, particularly for "at least 100 years" as required under the 2010 New Zealand Coastal Policy Statement. Tsunami is also a coastal inundation hazard to be considered when giving effect to the national policy statement. However, the exposure to coastal-inundation hazards also varies markedly between open coastal situations around different regions which have a high wave exposure compared with semi-enclosed embayments or inlets, and then between open coasts and more quiescent estuary, lowland river, fjord and harbour environments.

One approach would be to apply a generic storm-surge scenario across all coastal and estuarine areas of NZ, adding various increments of credible sea-level rise. However, because of the spatial variability in exposure to coastal-inundation hazards between and within regions, and the additional local, but sizeable, effect of wave runup, this study instead explores the coastal-risk exposure over a common set of land-elevation bands relative to the local mean high-water spring (MHWS).

Focusing on a stock take of residents and assets (buildings and some infrastructure types) in various coastal elevation bands, provides a first pass for the level of risk exposure nationally and a comparison between urban centres and regions. Lower elevation bands, up to 1–1.5 m above MHWS, have a higher exposure in the present and near future when compared to higher elevation bands, up to 3 m above MHWS. However higher elevation bands will be increasingly exposed to coastal hazards as sea level rises, particularly on wave-exposed coasts. The enumerated risk-exposure values presented here are only elevation based with no modulation for existing coastal defences/levees or consideration of sea-inundation volumes being able to fully spread inland over wider low-lying coastal plains during storm-tides (or small tsunami).

2.2 Digital Elevation Models (DEMs)

The national risk-exposure study was undertaken within the context that currently there is no nation-wide high-resolution digital elevation model (DEM) of NZ at sub-metre vertical accuracy. Yet, the accuracy of land-elevation datasets is paramount when discriminating combined coastal inundation and sea-level rise for elevation increments, such as 0.5 m.

While there are substantial areas of high-resolution elevation coverage across coastal areas (mainly from LiDAR surveys which typically can achieve vertical accuracies of ±0.15 m or better), there is by no means full national coverage for areas below 10 m relative to MHWS (LiDAR DEMs for approximately 15% of lower-lying coastal areas were not available). Therefore, to undertake a national appraisal of coastal risk exposure that includes all coastal plains a national coastal DEM is for now a necessity to aim for.

New Zealand's "modified enhanced" national DEM at 25 m grid spacing (referred to from here as "the national DEM"), has been modified from the enhanced DEM produced by NZ's Landcare Research (Barringer et al., 2002), generated from the Land Information NZ topographic contour data and subsequently blended by SKM (now Jacobs) with NASA global terrain 30-m-gridded data from the Shuttle Topography Radar Mission–SRTM for the KiwImage project (SKM, 2008). While improvements to the national DEM have been made, it is likely that the accuracy for coastal plains is similar (or slightly better) than the 30-m SRTM DEM, as the blended contour data was only at 20 m contour-height increments, although spot heights at a 25-m grid were also assimilated from the Landcare Research DEM. The absolute height accuracy for the national DEM for NZ is not specifically stated in the metadata, but the elevations across the relatively flat coastal plains are likely to be of the order of 3–4 m. The national DEM is relative to mean high-water (MHW) – but is also not specifically defined – a further source of uncertainty.

Light detection and ranging (LiDAR), sometimes called laser altimetry, involves a rotary-scanning laser (usually mounted under an aircraft) emitting pulses of laser light (in the near-infrared spectral band) and capturing the reflection through a sensor to measure distances to the surface. High sampling rates (e.g., typically in the range of 1 ping per 0.5–1.0 m^2 (urban areas) to 1 ping per 4–25 m^2 in rural areas) produce high-spatial resolution 3-D "point clouds", which include a mix of the 1st return reflection (e.g., off building roofs or tops of trees or vegetation) and last-return reflection off the ground surface or larger buildings.

The study had access to LiDAR DEMs or point-cloud data from 11 of the 16 regions on NZ's two main islands, as shown by the extent of surveyed coastal areas in Figure 1. The regional LiDAR data were supplied with a variety of resolutions and accuracies, and in most cases an amalgam of surveys over several years. Comparison of results from both the available LiDAR datasets and the full coverage of the national DEM, showed that approximately 15% of NZ's coastal margin 0–3 m above MHWS was not covered by available LiDAR data.

The study derived risk-exposure results using both the national DEM, for a 0–3 m coastal elevation zone only, and those areas where more-accurate LiDAR surveys were available, at accuracies typically down to 0.15 m. Where LiDAR data was available the results were enumerated for smaller elevation bands or increments of 0, 0.25, 0.5, 1, 1.5, 2, 2.5 and 3 m height above MHWS (being the zero baseline).

2.3 GIS modelling

Prior to the mapping in each region, pre-processing involved two steps:

– A study area polygon was created from approximately the +20 m elevation contour inland and to ~1 km offshore, to be used as the analysis area. This study area polygon can be described as a "window" within which the GIS looks for the intersection of the coastal land elevations with the relevant LiDAR DEM.

Figure 1: Coverage of LiDAR DEMs or point-cloud datasets across NZ used in this Project, sourced from Land Information NZ or directly with the relevant councils.

– The LiDAR DEM coverage within the "window" in each region was manually sub-divided into coastal watershed "masks" or compartments to which a particular MHWS height along the coast would apply. For this study, a MHWS-10 height was adopted for consistency around NZ, being the high tide height above which only 10% of all high tides exceed it

(Bell, 2010). The relevant MHWS-10 and mean sea level (MSL) offset, relative to the datum of the LiDAR DEM, were then added and assigned to these coastal area masks as the “zero baseline” level above the local vertical datum before applying the overlays for the various elevation bands. When using the national DEM, which is relative to a nominal MHW, no additional MSL offset was added locally.

Other than the Auckland region, where tidal MHWS-10 heights were known inside the larger estuaries (Stephens et al., 2013), elsewhere in NZ, MHWS-10 heights were generally not available inside estuaries. So the assumption was made to simply adopt the MHWS-10 height at the coastal entrance for the estuary or harbour, either from known tidal observations or from NIWA’s ocean and shelf tidal model (Walters et al., 2001).

Maps of coastal areas above the relevant MHWS-10 were created within GIS by intersecting the levels separating each elevation band with the LiDAR DEM or 3 m only for the national DEM. These intersections of the land topography were then used to create GIS polygons that map the areas where the terrain is between the lower and upper levels of the elevation band.
The GIS polygons for each elevation band, in each region where LiDAR DEMs were available, were then input to the risk-exposure analysis in GIS to enumerate assets, such as buildings, roads, rail, jetties and airports.

It became clear during the study that the GIS elevation polygons would need to be clipped to remove waterbodies such as the coast, estuaries, rivers and coastal lakes, in order to enumerate areas of land and thereby resident population (which relies on the ratio of land area in each elevation band to the total mesh block area). Accurate clipping of LiDAR polygons to waterbody shorelines proved a challenging exercise, as existing national water-land boundary datasets have been derived previously from the coarser national topographic map series at a 1:50,000 scale. There were also numerous locations where the geomorphology of the boundary of the water body had changed in the interim, particularly estuary and river mouths, which are well known for altering their geographical size and shape. Clipping of the LiDAR-derived elevation bands was therefore mostly undertaken manually using the most recent geo-referenced aerial photography.

2.4 Asset and population databases

Building, infrastructure and land assets within the coastal margin were compiled from a range of readily accessible geospatial databases. Building assets were geo-located using the national building asset inventory from RiskScape (Schmidt et al. 2011). This inventory contains structural and non-structural attribute information for over 2.1 million buildings in New Zealand, sourced primarily from QV Property Valuation datasets, enhanced by additional building attributes (e.g., construction, cladding) from work undertaken by the NZ Earthquake Commission, limited field surveys and proxy attributes such as floor level, derived in RiskScape from the age of the building (in relation to foundation styles).

For this study, attributes reported from the RiskScape inventory for buildings located in coastal areas up to 2011, included use category (e.g., residential, industrial/primary production, commercial, critical facility, community) and relevant replacement costs in NZD(2011) based on floor areas, number of storeys and use type, and a unit area construction cost (Bell et al., 2015).

Additional building identification was performed where recent georeferenced aerial photography and building footprint shapefiles were available. A vector polygon representing coastal land area up to 10 m above MHW was initially overlaid on a building point dataset from the RiskScape national building asset inventory to identify buildings either missing or to update building foot prints. Around 11,300 additional coastal buildings were added to the RiskScape inventory as vector points with RiskScape type standard use category and NZD$2011 replacement cost attribute fields assigned. Separate analyses were also undertaken by including and excluding buildings within the main Red Zone of Christchurch, where buildings are being abandoned following the 2010/2011 Canterbury earthquakes.
Infrastructure assets assessed for the study were limited to roads, railway, airports and airfields and wharves/jetties, which are accessible from national databases. Similar to buildings, a national road inventory available from RiskScape was used to locate road sections within each coastal elevation band. Road type (e.g., local, collector, arterial and motorway) and length (km) attributes could only be identified from this inventory. In addition to roads, Land Information NZ (LINZ) provides geospatial data for railways, airports, airfields and wharves at a national level. Railways and wharves were represented as vector lines while airport and airfield locations are provided as vector points.

NZ census 2013 data (5 March 2013) for the ”normally-resident” population was obtained from the Statistics NZ web site, subdivided into three main age brackets (of which only 0–65 years old and >65 years old) were used. In the census processing, NZ residents who are away from their usual address on census night are allocated back to the area where they usually live and form part of the census “usually resident” population count of that area (Stats NZ, 2014).

To obtain an estimate of the population in any census mesh block, where the elevation-band polygons only partially cover the mesh block, a pro rata of the total population of the mesh block (by linear interpolation) was calculated according to the ratio of the area of either the 0–3 m coastal elevation zone from the national DEM or LiDAR elevation-band overlay, relative to the entire area within the mesh block. This approach tended to over-estimate the normally resident population in lower-lying areas near MHWS, whereas people mostly live towards the higher end of any coastal mesh block. For this reason, results for population counts from the lower LiDAR elevation bands were aggregated into a single count for elevation ≤0.5 m above MHWS-10.

2.5 Geographic-area clipping

Final results in the form of counts of assets and residents for each elevation-band polygon were clipped to various geographic-boundaries (e.g. urban areas, territorial local authorities, regions) and aggregated nationally across NZ (Bell et al., 2015).

3. NATIONAL DEM COMPARED TO LiDAR-DEIVED RISK EXPOSURE

3.1 Land areas and assets

The clear and most obvious finding is that the present national DEM for NZ is inadequate, with insufficient accuracy, to rely on for the detailed risk-exposure analyses being attempted here in this study. While there is not yet full LiDAR survey coverage available for NZ coastal areas, the total land-cover area and population within the cumulative 0–3 m coastal zone derived from the available LiDAR DEMs is nearly double those enumerated from the national modified DEM for the same elevation range. This matches similar findings internationally comparing DEMs largely based on the SRTM e.g., Strauss & Kulp (2014) found the use of the SRTM DEM alone significantly underestimated the coastal land area likely to be exposed to sea-level rise in the US, compared to modern LiDAR elevation data (by a factor of 3 to 4).

As a result of the areal underestimation, the national DEM in NZ also substantially underestimates the risk exposure (buildings and infrastructure) by around half when compared with the available LiDAR elevation datasets for the same elevation zone (0–3 m). As an example, using the 0–3 m elevation zone for the areas where LiDAR was available there were 89,780 buildings (all types) enumerated, based on the national DEM. and 166,750 based on LiDAR (i.e., only 54% of the LiDAR count). There is an even greater underestimate for total replacement building costs of $24B (2011) compared to $52B (2011) for areas where LiDAR was available, with land area containing higher-cost commercial buildings in central business areas substantially underestimated. Hence a key finding from the study is that coastal-risk exposure assessments must be based on high-resolution and sub-metre accuracy LiDAR.

3.2 Estimates for coastal areas where LiDAR is currently unavailable

Despite the underestimates, the national DEM results can demonstrate the national relativity across all regions, including for the five regions where LiDAR was not available as shown by grey areas in Figure 2 and detailed in Bell et al. (2015).

The five regions contained ~3,900 buildings within the 0–3 m elevation zone of the national DEM, with 70% from two of the regions, and a total building replacement cost around $1.5B (2011), with nearly 60% of the costs arising from one region. Similarly in the 5 regions where LiDAR surveys were not available, the total road (all types) and railway length (224 km and 11.5 km respectively) in the 0–3 m elevation zone were 13% and 16% respectively of the national total using the national DEM alone. This establishes that the LiDAR-derived coastal-exposure analysis probably applies to around 85% of the total national exposure.

4. RESULTS: LiDAR-DEIVED COASTAL RISK EXPOSURE

4.1 Overall "national" summary

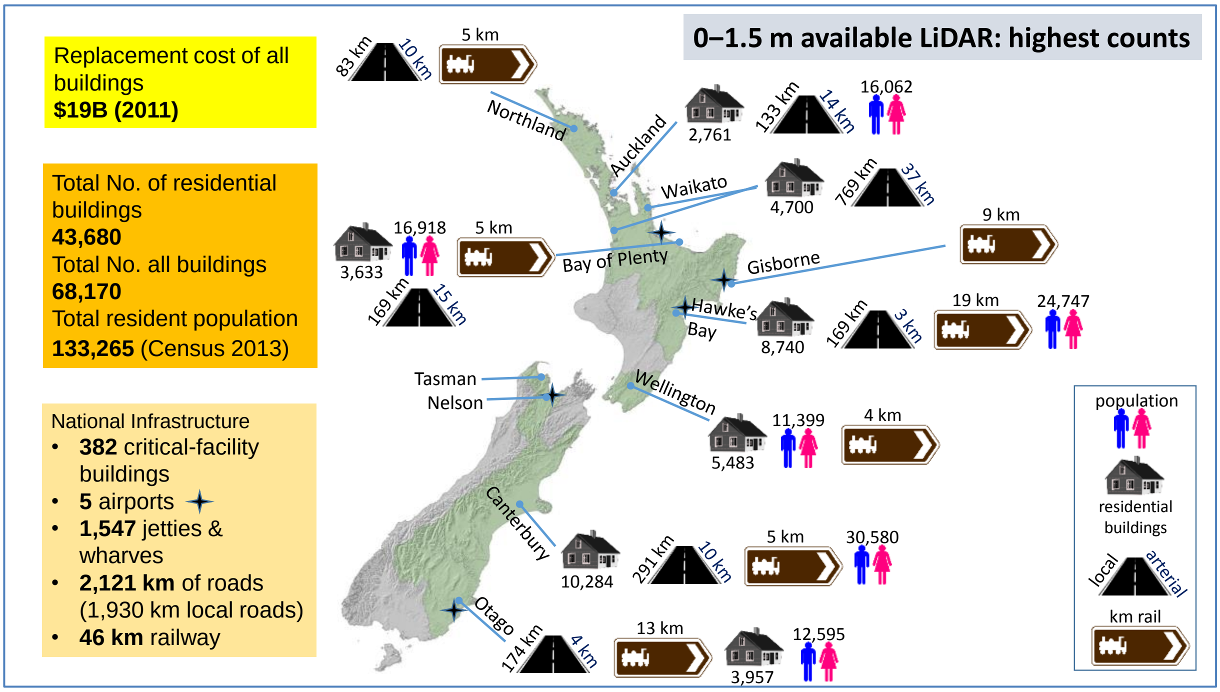
A summary of the coastal risk exposure is shown in the infographics below (Figure 2), showing entries for just the highest regional counts of assets or population (i.e., not all results shown) and a summary of national totals on the left. The "national" results, based on the analyses of available

LiDAR DEMs or point-cloud data, have been aggregated from elevation bands for the lower 0–1.5 m elevation zone and the wider 0–3 m elevation zone (MHWS-10).

The percentages of the NZ population normally resident in the 0–1.5 m and 0–3 m elevation zones (3.1% and 6.6% respectively) and the total NZ building replacement costs (1.6% and 4.4% respectively for residential and 2.5% and 6.9% for non-residential buildings) are substantially higher than the 0.5–0.7% of land-cover area of A-NZ for these same coastal elevation zones. This highlights that land area is not a reliable proxy for coastal risk exposure.

For the wider 0–3 m coastal elevation zone where LiDAR DEMs were available, the national totals are:

– normally resident population of 281,902 (2013 Census)
– nearly 294,000 land parcels (i.e., legal properties)
– total number of buildings is 166,750 with a replacement cost of $52B in 2011 $NZ
– nearly 92% of the coastal risk exposure (using building replacement costs as a measure) is derived from urbanised areas compared with rural areas
– 1,014 critical-facility or government buildings
– over 3,900 km of road, with nearly 91% designated as local roads
– 154 km of railway lines identified
– over 1500 jetty or wharf structures, and
– 7 or more airports (partially or substantially exposed) and 25 airstrips or aerodromes.



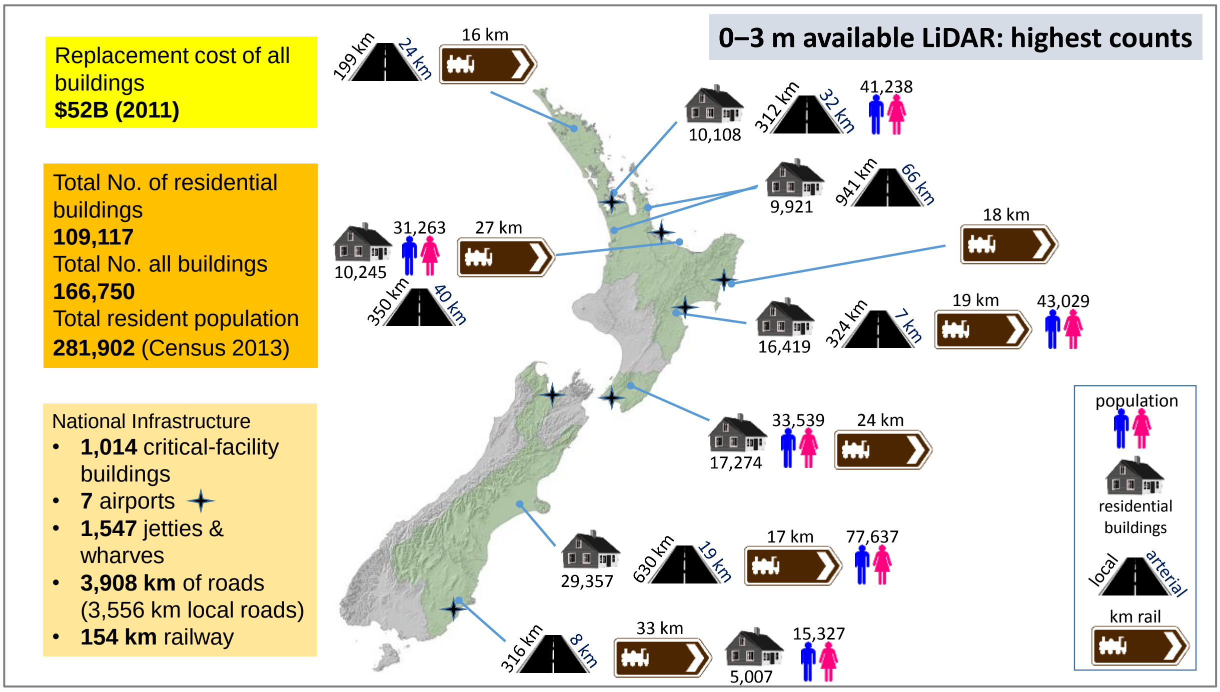


Figure 2: Summary of regions with the highest counts of assets or populations and national totals for coastal risk exposure across regions with LiDAR available (excl. grey-shaded areas) for the 0–1.5 m and 0–3 m elevation zones. Notes: Population (all ages) from 2013 Census (normally-resident); regional building counts only include residential-type buildings (from RiskScape) and excl. the Residential Red Zone in Christchurch; roads subdivided into "local" (includes local and feeder roads) and "arterial" (includes arterial and motorways), stars show airports that partially or wholly occupy the elevation zone. Replacement costs from RiskScape. based on 2011 NZ$. Critical-facility buildings include those for engineering lifelines and utilities, emergency services, government and education.

4.2 Population

Of the regions with LiDAR datasets available (see labelled regions in Figure 2), two-thirds of people resident in the more exposed 0–1.5 m coastal elevation zone, lived in either Canterbury (~23%), Hawke's Bay (~19%), Bay of Plenty (~13%) or Auckland (~12%), rising slightly to around 68% of all people who were resident in the wider 0–3 m elevation zone. For Canterbury and the Christchurch urban area, following the 2010/2011 earthquakes, there was a 36% decrease in the population of the most damaged Red Zone areas in the east of Christchurch city, with these reductions already present in the Census 2013 dataset used for this Project, but the analysis does not include any further changes following Census night.

Across any particular region, the resident population in the 0–3 m coastal zone (based on areas with available LiDAR surveys) is generally quite a small proportion at <10% of a region's population. Exceptions include Hawke's Bay (east-coast North Island), with 28% of the region's population in this low-lying zone, followed by Tasman (north-west, South Island) with 16% and Canterbury and

Nelson at 14%. Otago has a high proportion of people residing in the lower 0–1.5 m coastal elevation zone compared to the 1.5–3 m zone, due to the low-lying nature of coastal plains in Otago (including Dunedin City) adjacent to steeply rising topography. Apart from Northland and Waikato and to a lesser extent Tasman, the main concentration of populations in these low-lying elevation zones are essentially in urban areas or settlements. For example, Christchurch City makes up 96–97% of the Canterbury region population in the coastal elevation zones, and similarly Dunedin City makes up 87–89% of the Otago total.

4.3 Buildings

Canterbury and Hawke's Bay, followed by Waikato, have the most buildings of all types in the 0–1.5 m elevation zone, but the Wellington and Bay of Plenty regions join this group with the highest building counts across the wider 0–3 m elevation zone. The building count for the latter in the Wellington region is boosted by a higher proportionate number of commercial buildings (predominantly Wellington and Lower Hutt).

Canterbury, Auckland, Wellington and Hawke's Bay dominate the building replacement cost national totals, with Auckland (NZ$11B – 2011) and the Wellington region (NZ$9.8B) returning the highest regional replacement-cost totals for the 0–3 m elevation zone, which is reflected by commercial-building stock situated near the edges of their respective harbours.

Interestingly, the eventual removal of all buildings from the Christchurch Residential Red Zone following the 2010/11 earthquake sequence has reduced the city's coast-risk exposure in the in the lower 0–1.5 m elevation zone by around 31% in terms of buildings of all types, but less so for the wider 0–3 m elevation zone with a 17% reduction in building numbers.

Based on results for buildings from the incremental elevation bands (0.25, 0.5, 1, 1.5, … 3 m above MHWS-10) where LiDAR surveys were available, three different elevation profiles of coastal risk exposure were revealed:

- highest proportion of risk exposure for a region in the lowest-lying elevation band (0-0.25 m) occurs in Waikato and Otago regions
- a rapid increase in risk exposure occurs at elevations between 0.5–1 to 1.5–2 m (majority of regions)
- a steady increase in risk exposure up to the 3 m upper limit assessed e.g., Auckland and especially Gisborne.

The highest numbers of all types of buildings identified for urban areas nationally in the 0–3 m elevation zone are dominated by Christchurch City – excluding the Red Zone (45,833 – up from 15,556 for the 0–1.5 m zone), Napier (25,046 up from 14,207 for 0–1.5 m) and Lower Hutt (10,199 up from 4,635 for 0–1.5 m). Together, the 5 urban areas of Christchurch (excluding the Red Zone), Central Auckland Zone, Napier, Wellington and Lower Hutt, account for ~NZ$28B in building replacement costs or nearly 60% of the total replacement cost across all urban areas in NZ (NZ$47.6B) for the 0–3 m elevation zone where LiDAR DEMs were available. Results indicate that nearly 92% of the coastal risk exposure (using building replacement costs as a risk-exposure measure) in NZ is derived from urbanised areas compared with rural areas.

4.4 Infrastructure

All regions with LiDAR coverage contain a range of road types located within both the 0–1.5 m and 0–3 m coastal elevation zones, although the regional and national totals for road length are dominated by “local” roads and streets (91% of the total for all types). The total length of all types of road is highest in the Waikato for both aggregated coastal zones, with just over 800 km and 1,000 km respectively, followed by Canterbury.

Nationally there are around 192 km of arterial roads within the 0–3 m coastal elevation zone, with the most extensive networks located in Waikato, Bay of Plenty and Northland. Expressway or motorway networks located within the four major urban areas all contain segments within both the 0–1.5 m and 0–3 m elevation zones. For motorways, Auckland’s State Highway network occupies the greatest extent in each of these cumulative elevation zones with 5 km and 18 km respectively, although upgrades are underway to raise some of the causeway sections.

Nationally, railway-track length triples between 0–1.5 m and 0–3 m elevation zones from 46 km to 154 km. Otago has the most extensive railway track in both elevation zones with 13 km and nearly 33 km respectively. Railway networks associated with major ports in the Bay of Plenty (27 km) and Wellington (24 km) means these regions also contain relatively extensive track networks in the 0–3 m elevation zone.

A total of seven airports were identified as being totally or partially within the 0–3 m elevation zone for areas with LiDAR datasets available. A number of airfields and aerodromes (25) are also located in the 0–3 m elevation zone from the LiDAR analysis, which are predominantly in regions with relatively large areas of primary production land or coastal resorts such as Waikato.

Nationally, there are over 1,500 jetty and wharf structures, with a combined length of 100 km around the NZ coast adjacent to the low-lying areas that were delineated in the 0–3 m national modified DEM (not repeated for the LiDAR analysis). The highest number of coastal maritime structures are in Otago and Auckland (61% of the national total), with both regions together accounting for 57% of the total cumulative length, with Auckland having the highest cumulative length of structures at nearly 30 km. Northland has the third highest count for jetties and wharves.

5. CRITICAL RECOMMENDATIONS TO IMPROVE A NATIONAL COASTAL-RISK ASSESSMENT

To enable a true national appraisal of coastal-risk exposure to coastal hazards and sea-level rise, including consideration of high-magnitude low-frequency tsunami inundation events, all coastal-plain areas with elevations below 15 m throughout NZ should be covered by high-resolution LiDAR surveys. This data should then be processed to produce bare-earth DEMs, which if processed to standard protocols and rectified to a common vertical datum, could be coalesced into a national high-resolution coastal DEM for New Zealand. Similar coverage for river flood plains upstream would be a useful seamless adjunct to a high-resolution national coastal DEM, as floodplains usually transition into a coastal plain or river mouth at the coast. Land Information NZ is now proceeding with a national project to collate and produce a high-resolution national DEM and is developing procurement specifications and protocols for purchasers of LiDAR surveys to enable national consistency in LiDAR surveys and processing (B. Johns & G. Blick, pers. com., LINZ).

An adjunct recommendation is the development of an accurate and high-resolution present-day shoreline (or water-land boundary) for coastlines, estuaries, wetlands, rivers and lakes and converted to GIS polygons, along with associated MHWS tide levels for the entire New Zealand coastline. The existing GIS resources, such as the NZ Coastlines, NZ Lake and the NZ River Polygons available on the Land Information NZ Data Service, have insufficient accuracy for clipping land elevation bands in higher-resolution LiDAR DEMs to remove water bodies or wetland areas. Such high-resolution land-water boundary polygons would also need to be regularly updated to track geomorphic and anthropogenic changes in coastal land-water boundaries, which will change more frequently as sea level rises. Further tide data is needed inside estuaries, tidal creeks and lowland rivers to establish improved MHWS tide baselines.

Finally, the ongoing use of various local vertical datum's (13 regional ones in use) and chart datum's (for nearshore bathymetry) around NZ is a hinderance to undertaking nationally-consistent risk assessments (adds step jumps in MSL offsets) and similarly for establishing a high-resolution national coastal and riverplain DEM. Land Information NZ will be recommending that future LiDAR surveys use the national NZ Vertical Datum (2009), or upcoming revisions, derived directly from ellipsoid heights, as part of proposed survey-procurement protocols (B. Johns & G. Blick, pers. com., LINZ).

6. NEXT STEPS

The results presented from this study provide a first pass assessment quantifying what is exposed regionally and aggregated nationally for the coastal margin of NZ by enumerating assets and residents in low coastal-elevation bands.

More detailed testing and assessment of appropriate coastal-hazard and climate-change scenarios on LiDAR DEMs should be (or have already been) undertaken at the regional or local scale by the relevant local-government agencies to derive a more accurate risk profile to inform their priority responses to managing coastal development under the NZ Coastal Policy Statement 2010 and the Resource Management Act 1991 and providing an evidence-base to assist with community engagement. Already, flowing from this study, vulnerable low-lying communities like South Dunedin (ground-water and surface flooding), are being engaged through dialogue with the council around the future adaptation responses, and additional infrastructure agencies have requested further targeted coastal risk-exposure assessments to assist with prioritization of future adaptation measures.

Land Information NZ is embarking on national projects for assembling a more accurate national DEM, based on LiDAR or other high-resolution elevation data and procurement specifications for purchasers of LiDAR surveys.

REFERENCES

Barringer, J.R.F.; Pairman, D.; McNeill, S.J. (2002). Development of the high-resolution Digital Elevation Model for New Zealand. Landcare Research Contract Report LC0101/170 prepared for the NZ Foundation for Research Science & Technology, July 2002: 31 p. https://lris.scinfo.org.nz/document/213-dem_accuracy/download/

Bell, R.G. (2010). Tidal exceedances, storm tides and the effect of sea-level rise. Proceedings of 17th Congress of the Asia and Pacific Division of the IAHR, Auckland, 21-24 February 2010.

Bell, R.G.; Paulik, R.; Wadhwa, S. (2015). National and regional risk-exposure in low-lying coastal areas: Areal extent, population, buildings and infrastructure. NIWA Client Report HAM2015-006 prepared for the Parliamentary Commissioner for the Environment. October, 270 p. http://www.pce.parliament.nz/publications/preparing-new-zealand-for-rising-seas-certainty-and-uncertainty

Hannah, J.; Bell, R.G. (2012). Regional sea level trends in New Zealand. *Journal of Geophysical Research–Oceans 117*, C01004: doi:10.1029/2011JC007591

Parliamentary Commissioner for the Environment (2015). Preparing New Zealand for rising seas: Certainty and uncertainty. 92 p. http://www.pce.parliament.nz/publications/preparing-new-zealand-for-rising-seas-certainty-and-uncertainty

Schmidt, J.; Matcham, I.; Reese, S.; King, A.; Bell, R.; Henderson, R.; Smart, G.; Cousins, J.; Smith, W.; Heron, D. (2011). Quantitative multi-risk analysis for natural hazards: a framework for multi-risk modelling. *Natural Hazards 58(3)*: 1169–1192. doi: 10.1007/s11069-011-9721-z

SKM (2008). KiwImage technical analysis. SKM Memo by Richard Lemon to the NZ Defence Force for the KiwImage Project. 17 October 2008.

Stats NZ (2014). *2013 Census data user guide*. Publication prepared by Statistics NZ: 27 p.

Stephens, S.; Wadhwa, S.; Gorman, R.; Goodhue, N.; Pritchard, M.; Ovenden, R.; Reeve, G. (2013). Coastal inundation by storm tides and waves in the Auckland Region. *NIWA Client Report* HAM2013-059 to Auckland Council. http://www.aucklandcouncil.govt.nz/EN/planspoliciesprojects/plansstrategies/unitaryplan/Documents/Section32report/Appendices/Appendix%203.28.7.pdf

Stephens, S.A. (2015). The effect of sea-level rise on the frequency of extreme sea levels in New Zealand. NIWA Consultancy Report HAM2015-090, prepared for the Parliamentary Commissioner for the Environment: 52 p. http://www.pce.parliament.nz/publications/preparing-new-zealand-for-rising-seas-certainty-and-uncertainty

Strauss, B.; Kulp, S. (2014). New analysis shows global exposure to sea-level rise. *Research Report by Climate Central*, USA. http://www.climatecentral.org/news/new-analysis-global-exposure-to-sea-level-rise-flooding-18066

Walters, R.A.; Goring, D.G.; Bell, R.G. (2001). Ocean tides around New Zealand. *New Zealand Journal of Marine and Freshwater Research 35*: 567–579.

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