An Assessment of Vulnerability to Climate Change in Auckland

Mario Andres Fernandez and Nancy E. Golubiewski

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Climate Change Risk Assessment series 2019

Climate Change Risk Assessment 2019

As communities across the world set out to plan for climate change mitigation and adaptation, they first seek to understand how climate change will affect their city, region, or country.

The Climate Change Risk Assessment (CCRA) has been produced by Auckland Council's Research and Evaluation Unit (RIMU) in support of the Auckland Climate Action Plan (ACAP) at the request of the Chief Sustainability Office. Its aim is to provide information about the risk and vulnerabilities the Auckland region may face under a changing climate regime, which is already underway. In 2018, national climate change projections were scaled-down to produce a more specific picture of their likely effects within the Auckland region. Based on this, CCRA adopted the Intergovernmental Panel on Climate Change's (IPCC) representative concentration pathway (RCP) 8.5 ("business as usual") scenario as its guiding projection, given the lack of evidence of any meaningful and sustained decreases in emissions that would shift to other projection pathways.

The eight reports in the CCRA consider various components of key risks – that is, hazard, exposure, and vulnerability – across sectors and systems of interest: people (heat vulnerability, climate change and air quality), society (social vulnerability and flooding), and natural environment (terrestrial and marine ecosystems), as well sea level rise at regional and local scales. A summary report has also been produced.

Titles in the Climate Change Risk Assessment series:

An assessment of vulnerability to climate change in Auckland
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Boyle, J., N. E. Golubiewski, K. Balderston and C. Hu (2019)

Summary: *Climate change risks in Auckland*
Auckland Council (2019). Prepared by Arup for Auckland Council

Executive summary

Vulnerability to climate change entails the degree to which geophysical, biological, and socio-economic systems are susceptible to, and unable to cope with, adverse impacts of climate change (Houghton, 1996). Vulnerability assessments to climate change have become grounds for environmental and climate change policy as they inform the allocation of priorities for funding and intervention; facilitate comparisons between geographic units; assist the development of adaptation options (Brenkert and Malone, 2005; Füssel and Klein, 2006; Ibarrarán, Malone and Brenkert, 2009); and promote a culture of resilience.

This report carries out a vulnerability assessment taking Auckland as a case study. As Auckland has varying geographic, socio-economic and climatic patterns, an assessment at the local level could assist decision-makers to better identify exposed assets and communities at greater risks of climate change impacts as well as to explore mechanisms for developing resilience.

The assessment is based on the construction of two indices: the impact index (II; representing exposure and sensitivity) and the adaptive capacity index (ACI), for which a number of socio-economic, demographic and climatic variables are selected. Census area units (CAU) are the level of analysis. The assessment entails a relative comparison (ranking) of CAUs in terms of the vulnerability indices. Vulnerability hotspots are defined as those CAUs suffering high climate change impact and having low adaptive capacity. It is found that the hotspots locate to the south of the Auckland isthmus and in western Auckland and are characterised by relatively high rates of one-parent households, lower average household income, higher housing stress (greater income allocated to rent payments); low shares of house ownership and high deprivation index; and low proportions of cropland, grassland or forest.

This report contributes to the understanding of the drivers of vulnerability in Auckland as well as their spatial variation across the region.

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1.0 Introduction

Auckland is expected to face major impacts from climate change over the coming decades. In a business-as-usual scenario, extreme weather events (such as heat waves, heavy rainfall and droughts) are likely to increase in frequency and severity. Temperature could increase by 0.8°C in 2040 and the number of hot days (days > 25°C) are projected to triple by 2100 (Pearce *et al.*, 2018).

Vulnerability to climate change, and its manifestations, entails the degree to which geophysical, biological, and socio-economic systems are susceptible to, and unable to cope with, adverse impacts of climate change (Houghton, 1996). Vulnerability assessments seek to improve the understanding of the drivers of vulnerability and their social and economic implications (Brooks, Adger, and Kelly 2005), as well as their spatial variation at local scales (Fernandez, Bucaram, and Renteria 2015). The assessments have become grounds for environmental and climate change policy as they inform the allocation of priorities for funding and intervention (Preston, Yuen and Westaway, 2011); facilitate comparisons between geographic units; assist the development of adaptation options (Brenkert and Malone, 2005; Füssel and Klein, 2006; Ibarrarán, Malone and Brenkert, 2009); and promote a culture of resilience (Birkmann and Birkmann 2006).

Vulnerability assessments summarise the complexity of the causes and consequences of climate change, as well as their associated risks. The assessments often require the selection, weighting, and aggregation of the likely sources of vulnerability, represented through quantitative indicators, which are used to construct vulnerability indices. The constructed indices are then used to rank geographic units so that it is possible to identify climate change vulnerability hotspots.

A previous assessment in New Zealand shows that a number of socio-economic and climatic indicators may be used to identify vulnerability profiles at a refined spatial resolution (Fernandez, Bucaram, and Renteria 2017). Nonetheless, that assessment is exploratory as it is based on climatic forecasts of a coarse resolution; since the drivers of vulnerability may be locally-variable and unevenly distributed, it may not capture particular variations of forecasted effects of climate change. As the Auckland region has varying geographic, socio-economic and climatic patterns that influence climate change vulnerability, an assessment at local level could be of benefit to policy-makers.

There is an extensive literature about vulnerability assessments. Lung et al., (2013) develop an indicators-based assessment for the European Union that quantifies potential regional changes in weather-related hazards. Their results show a trend towards increasing impact from heat stress, forest fire risk and flood risk for most parts of Europe; due to low adaptive capacity, regions in eastern and southern Europe are identified as hotspots. Binita, Shepherd, and Gaither (2015) develop a vulnerability index that captures both longer-term changes in precipitation and temperature as well as episodic events such as floods, heat waves and droughts. Their constructed index also includes socio-demographic variables indicating the population's ability to withstand or cope with climate change. They found that income and other economic assets cannot fully offset or mitigate the risk posed by a changing climate because both wealthy and poor population groups living in coastal areas are similarly exposed to flood risks.

Bucaram, Fernández, and Renteria (2016) and Fernandez, Bucaram, and Renteria (2015) incorporate spatial and temporal patterns of climatic and socio-economic variables to construct vulnerability indices in Ecuador and Uruguay. The indices are constructed based on the statistical behaviour of the indicators, capturing the multi-dimensionality of vulnerability. Machado and Ratick (2017) explore vulnerability to flooding in the eastern United States and find that different assumptions on the assessment model result in quite differing outcomes (e.g., risk and adaptation strategies). Their findings imply that transparent and careful selection of indicators, as well as their aggregation, is critical for the construction of the vulnerability indices.

Tapia *et al*., (2017) assess urban vulnerability to heatwaves, droughts and floods in 571 European cities. They find that the factors driving vulnerability are unevenly distributed, which results in complex spatial patterns in the distribution of vulnerability. Thus, local or fine-grained assessments should be conducted to advance the understanding of urban risks to climate change, as a contribution to adaptation planning.

This report carries out an assessment of vulnerability to climate change in Auckland. A number of socio-economic, demographic and climatic indicators are selected based both on the literature and data availability. As vulnerability varies in space and time and arises out of specific social and ecological processes (Barnett, Lambert and Fry, 2008), the indicators here are tied to local-scale variation across Auckland. Those indicators represent the three components of climate change vulnerability: exposure, sensitivity and adaptive capacity (Pachauri and Reisinger, 2007). The indicators for exposure and sensitivity are combined to construct an impact index (II). The adaptive capacity index (ACI) is constructed to represent the response of communities to future threats, based on the existing socio-economic conditions and circumstances (Eriksen and Kelly, 2007). These two indices are then used to identify the vulnerability hotspots. The spatial resolution of the assessment is at Census

Area Units (CAU) as an approximation to Auckland suburbs (Statistics New Zealand, 2016).

It is found that the hotspots locate to the south of the Auckland isthmus and in western Auckland. The hotspots are characterised by CAUs having households whose incomes and housing ownership ratios are lower than in the rest of Auckland. Households in the hotspots spend 36.7 per cent of their income on rent, which is higher than in the rest of Auckland, 30.3 per cent. The unemployment rate, the share of one-parent households, age dependency ratio and the deprivation index are also higher in the hotspots. Hotspots show low road density and fewer environmental resources reflected as low shares of CAU land on crops, grass and forest. The hotspots also show higher index values for the number of hot days, and total precipitation change, and slight differences on the index values for mean temperature and wind speed.

In addition, compensation between adaptive capacity and impact indicators occurs across Auckland as several CAUs with relatively high exposure (greater II score) are not identified as hotspots, arguably because of greater adaptive capacity (greater ACI score).

This report is structured as follows. Section 2 describes the assessment approach, the selection of the indicators and the construction of the vulnerability indices. Section 3 presents and discusses the results. Section 4 concludes. Appendix A takes a closer and descriptive look of the spatial patterns of vulnerability in each local board. Appendix B contains a statistical analysis to characterise the vulnerability hotspots.

2.0 Assessment approach

This report carries out a vulnerability assessment based on indices calculated for each CAU in Auckland. This section describes the rationale for the selection of indicators and the assessment approach.

2.1 Indicators for exposure, sensitivity and adaptive capacity

Vulnerability is defined as the degree to which geophysical, biological, and socio-economic systems are susceptible to, and unable to cope with, adverse impacts of climate change (Houghton, 1996). Vulnerability is separated into its three components (Adger, Arnell, and Tompkins 2005; Hartmann, Tank, and Rusticucci 2013; Houghton 1996):

1. Exposure: the condition of disadvantage due to the position or location of a subject, object or system at risk).
2. Sensitivity: the ability of a subject, object or system to meet a climatic threat and receive a possible impact due to the occurrence of an adverse weather event).
3. Adaptive capacity: the ability of a system, community or society exposed to climatic hazards to cope with, absorb, and recover from the effects of an adverse weather event effectively and in a timely manner, considering the preservation and restoration of its essential basic structures and functions.

Since vulnerability entails multiple stressors corresponding to the socio-economic, physical and geographic properties of the population's environment (O'Brien *et al.*, 2004; Tol and Yohe, 2007), and the assessments seek to characterise how climate change impacts are manifested and responded to, then a number of indicators are selected to represent the multidimensionality of that characterisation (Malone and Engle, 2011) (Table 1).

The selection of the indicators relies on the attributes of concern for any vulnerability assessment: the integrity of human lives (Lung *et al.*, 2013), resilience of communities, and the role of ecosystem services on shaping vulnerability. In practice, the rationale for using indicators is to represent in quantitative form any qualitative aspect of the vulnerability components. To do so, in this assessment two indices are constructed (Fernandez, Bucaram, and Renteria 2017; Ibarrarán, Malone, and Brenkert 2009). The sensitivity and exposure indicators are combined to construct an impact index (II). The adaptive capacity index (ACI) is constructed to represent the response of communities to future threats, based on the existing socio-economic conditions and circumstances (Eriksen and Kelly, 2007). Each indicator and its function is described below (see Table 1), descriptive statistics are presented in Table 2. The conceptual relationship between each indicator and vulnerability is described in the fourth column of Table 1. For example, when a exposure or sensitivity indicator is high (↑), vulnerability is high (↑); similarly, when adaptive capacity to respond is high (↑), vulnerability is low (↓) (Brenkert and Malone, 2005; Ibarrarán, Malone and Brenkert, 2009).

Exposure to climate change effects are represented by the number of dry and hot days, the number of days with heavy rainfall and total precipitation change, mean wind speeds, mean temperature, relative humidity, and exposure to coastal inundation risk (Füssel, 2010). Data were sourced from Auckland-specific climate change projections and correspond to a business as usual (RCP 8.5) scenario for 2040 [1] (Pearce *et al.*, 2018).

Sensitivity is represented by indicators of local socio-economic structure and land-use patterns. First, the NZ Deprivation Index summarises access to communication, education or transport and is scaled to have a mean of 1000 index points and a standard deviation of 100 index points (see Atkinson, Salmond and Crampton, 2014). The index provides a deprivation score for each meshblock[2] in New Zealand. The index is averaged across meshblocks to get an estimate for each Auckland CAU. Second, the unemployment rate, the percentage of one-parent households, and an age dependency ratio[3] are used to represent dependency rates. Third, road density (the length of road per square kilometre of populated area) (Fernandez, Bucaram and Renteria, 2015), and the ratio of populated or developed areas relative to CAU area (to represent the degree of intrusion of human activity into the natural landscape) are used to capture the effects of development and infrastructure (Schelhaas *et al.*, 2010).

Adaptive capacity is closely linked to the concept of social vulnerability, the characteristics of an individual or group that influences their capacity to anticipate,

[1] A Representative Concentration Pathway (RCP) is a greenhouse gas concentration trajectory that describes different climate futures, all of which are considered possible depending on how much greenhouse gases are emitted in the years to come. The four RCPs (RCP2.6, RCP4.5, RCP6, and RCP8.5) are labelled after a possible range of radiative forcing values in the year 2100 relative to pre-industrial values (Meinshausen et al., 2011)

[2] A meshblock is the smallest geographic unit for which statistical data is collected (Statistics NZ 2015)

[3] Defined as the ratio of population under 15 and over 65 years of age to the population between 19 and 64 years of age. A high ratio implies that economically active individuals have others to support, suggesting limited resources for adaptation (Fernandez, Bucaram, and Renteria 2017; Ibarrarán, Malone, and Brenkert 2009; Brenkert and Malone 2005)

cope with, resist and recover from a physical hazard (Blaikie *et al.*, 2004; Otto *et al.*, 2017). The index is constructed based on the following indicators: average household income, share of CAU land on cropland (annual and perennial), grassland (low and high-producing and with woody biomass) and forested land (natural and planted).

Average household income by CAU represents access to financial and material resources, and markets, which may be used as buffers against climatic risk (Ibarrarán, Malone and Brenkert, 2009). A wide range of skills or economic assets, allowing higher returns in market activities, is an important factor for households and communities to achieve income diversification and increase resilience to climate change hazards (Anderson and Woodrow, 1991; Stigter, 1995; Dercon and Krishnan, 1996; Eriksen and Kelly, 2007).

Data on land cover come from the LUCAS NZ land use map for 2012. In developing countries, agriculture and primary sectors are usually associated with “subsistence” or “smallholder” farmers, where socio-economic, demographic, and policy characteristics limit the capacity to adapt to climatic changes (Morton 2007; Fernandez, Bucaram, and Renteria 2015). In contrast, New Zealand agriculture and primary sectors are export-orientated and characterised by high levels of development and technology adoption, which along with the availability of knowledge, information, and macroeconomic stability, support and facilitate far greater resilience to climate change at the local and national levels (Challinor *et al.*, 2007). Arguably, higher shares of land in agricultural production is also likely to generate higher food self-sufficiency and nutritional security, and thus higher adaptive capacity (Maiti *et al.*, 2017). Therefore, adaptive capacity in this report is represented as the share of CAU land on cropland and grassland.

Furthermore, ecosystems and their associated services increase adaptive capacity of communities, assuming adequate maintenance and enhancement through sustainable use (Adger *et al.*, 2005; Vignola *et al.*, 2009). Thus, linkages between ecosystems and communities can help to reduce vulnerability and enhance resilience of these linked systems to climate change, particularly in coastal areas (Adger *et al.*, 2005). Whether or not those linkages between biodiversity, ecosystem services, and communities are yet fully understood (Ma 2005; Schröter *et al.*, 2005), biodiversity is argued worth protecting in its own right as vulnerability depends on the ability of ecosystems and society to cope with the impacts (Schröter *et al.*, 2005; Lindner *et al.*, 2010). Therefore, adaptive capacity is also represented by the share of CAU land covered by forests (Schelhaas *et al.*, 2010).

Table 1: Indicators used to measure vulnerability components

Index	Indicators	Functional relationship
Exposure	Coastal inundation – 50 years return 1 metre sea level rise	Vulnerability ↑ as indicator ↑
	Dry days < 1 mm	Vulnerability ↑ as indicator ↑
	Total precipitation percentage change	Vulnerability ↑ as indicator ↑
	Heavy rainfall days > 25 mm	Vulnerability ↑ as indicator ↑
	Hot days > 25	Vulnerability ↑ as indicator ↑
	Mean temperature	Vulnerability ↑ as indicator ↑
	Mean wind speed	Vulnerability ↑ as indicator ↑
	Relative humidity	Vulnerability ↑ as indicator ↑
Sensitivity	Deprivation Index	Vulnerability ↑ as deprivation index ↑
	Unemployment rate*	Vulnerability ↑ as unemployment ↑
	Ratio of population under 15 and over 65 to 19-64 *	Vulnerability ↑ as rate of dependency ↑
	Percentage of populated area relative to CAU area	Vulnerability ↓ as % populated area ↑
	Percentage of one-parent households*	Vulnerability ↑ as % of one-parent households ↑
	Road density (Ratio of km of road per km^2 of populated area)	Vulnerability ↓ as ratio ↑
Adaptive Capacity	Average household income*	Vulnerability ↓ as income ↑
	Housing stress (ratio of rent payments to household income)*	Vulnerability ↑ as housing stress ↑
	Percentage of population that are owner-occupiers of house*	Vulnerability ↓ as % owning house ↑
	Percentage of area in cropland**	Vulnerability ↓ as % on crops production ↑
	Percentage of area in grassland**	Vulnerability ↓ as % on grass production ↑
	Percentage of area in forest **	Vulnerability ↓ as % of forest cover ↑

Note: *Data at CAU level, extracted from Census 2013. ** Data extracted from LUCAS NZ land use map 2012. Climatic (exposure) data extracted from Pearce *et al.,* (2017)

Table 2: Descriptive statistics of selected indicators

	Mean	Standard deviation	Min	P25	Median	P75	Max
Deprivation Index	994	87	884	929	964	1034	1337
Unemployment rate	5%	2%	1%	3%	4%	6%	13%
Ratio of population under 15 and over 65 to 19 and 64	50%	13%	5%	44%	49%	56%	129%
Percentage of populated area relative to CAU area	0.682	0.363	0.000	0.472	0.853	0.997	1.000
Percentage of one-parent households	11%	6%	1%	6%	9%	13%	31%
Average household income ($)*	75,922	10,955	36,550	68,214	76,382	83,857	111,083
Housing stress (ratio of rent payments to household income)	31%	11%	1%	29%	34%	38%	57%
Percentage of population that are owner-occupiers of house	45%	14%	3%	35%	46%	56%	71%
Percentage of area in cropland	16%	16%	0%	5%	11%	24%	66%
Percentage of area in grassland	45%	30%	0%	16%	54%	70%	99%
Percentage of area in forest	11%	14%	0%	2%	6%	14%	91%
Road density (Ratio of km of road per km^2 of populated area)	0.930	0.468	0.001	0.672	0.987	0.987	3.380

Note: *household income calculated from grouped data available online from Stats NZ. Publicly available Stats NZ data only reports frequency data, for the category of income above 100 thousand an upper limit of 110 thousand is assumed to calculate the descriptive statistics and to keep the model tractable. Data updated for 2018 figures.

2.2 Weighting, aggregation and identification of vulnerability hotspots

To construct the vulnerability indices (II, ACI), and to ensure meaningful comparisons, the assessment normalises the indicators between zero and one. Let X_{id} denote the i^{th} indicator in the d^{th} CAU ($i = 1,2, \ldots ,20;\ d = 1,2, \ldots ,420$). Each indicator, y_{id}, is normalised by re-scaling such that $y_{id} = \frac{X_{id} - Min_d X_{id}}{Max_d X_{id} - Min_d X_{id}}$ if the indicator is assumed to be positively associated to vulnerability, or $y_{id} = \frac{Max_d X_{id} - X_{id}}{Max_d X_{id} - Min_d X_{id}}$ otherwise.

Normalisation allows that relative increases in the normalised indicators drive equivalent increases in the corresponding composite index, and thus avoiding any bias favouring those indicators with greatest absolute magnitude, variation or score (Mazziotta and Pareto, 2017).

The normalised indicators (correspondent to II or ACI) are combined through a geometric product function (Fernandez, Bucaram, and Renteria 2017, Tol and Yohe 2007; Lung *et al.*, 2013) specified as follows: $y_d^{II} = \prod_{i \in P} w_i y_{id}$ and $y_d^{ACI} = \prod_{i \in A} w_i y_{id}$, where P is the subset of indicators representing exposure and sensitivity, and A representing adaptive capacity; w_i is the weight of each indicator, where $0 < w_i < 1$ and $\sum_i w_i = 1$. The assessment assumes weights are equal for all indicators (number of indicators: 20, weight = 1/20=0.05) (Lung *et al.*, 2013)

This combination approach does not require strong assumptions about whether a deficit in one indicator may be compensated by a surplus in another (the degree of substitution or compensation among indicators). For example, whether exposure to sea-level rise can be offset by a high level of income or built infrastructure (Hinkel, 2011; Mazziotta and Pareto, 2017). Hence, the geometric product function is a compromise solution between a linear aggregation (where full compensation between indicators is allowed) and a non-compensatory logic (where vulnerability is determined solely by the weakest of its adaptive capacity determinants) (Munda and Nardo, 2005; Tol and Yohe, 2007).

The constructed indices (II and ACI) are classified into five vulnerability categories according to quintiles (0-20%, 20-40%, 40-60%, 60-80%, 80-100%) (see Table 3). These categories represent relative impacts between Auckland CAUs. Similar to Lung *et al.*, (2013), vulnerability hotspots are identified as those CAUs with either very high or high impact and very low or low adaptive capacity.

3.0 Results

3.1 Identification of vulnerability hotspots

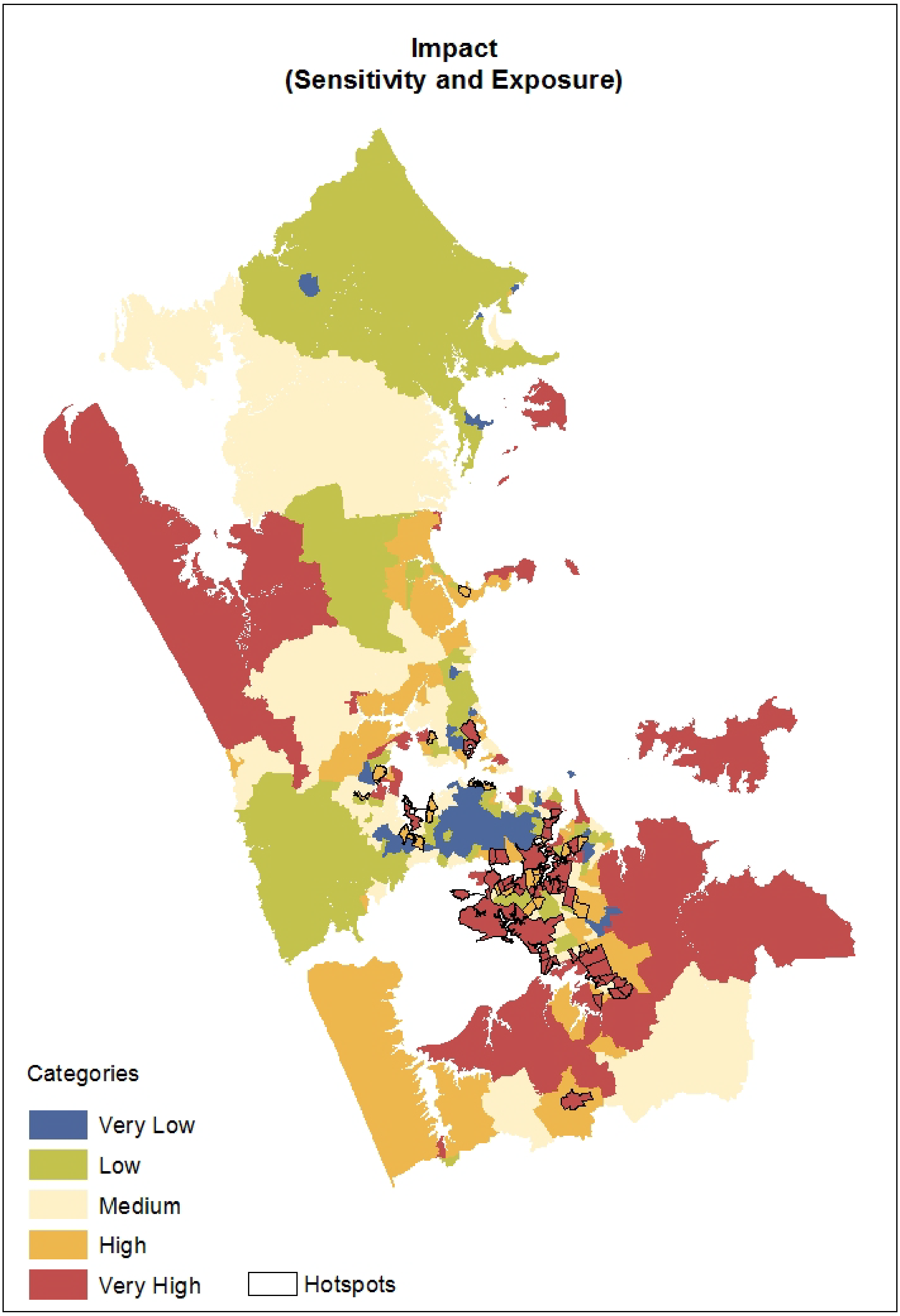
This section describes the II and ACI scores across CAUs (Table 3 and Figure 1), the spatial distribution of scores, and vulnerability categories (Figure 1) (more details by local board in Appendix A), and provides a characterisation of the hotspots (more details in Appendix B). Developing this information is important in identifying priority areas for vulnerability reduction efforts (Machado and Ratick, 2017).

As described in Section 2.2, the scores of the constructed indices (II and ACI) are classified into five vulnerability categories by quintiles (0-20%, 20-40%, 40-60%, 60-80%, 80-100%) (Table 3). A score in II approaching 0 means in relative terms the CAU is not affected by the climate change impacts, likewise a score of 0 in the ACI index means that the CAU may not have adequate capabilities to cope with climate change impacts. Vulnerability hotspots are those CAUs with high or very high II, and low or very low ACI. These hotspots (Figures 1 and 2), locate to the south of Auckland isthmus and a few in western Auckland. In total, 64 vulnerability hotspots are identified, about 15 per cent of Auckland CAUs.

Table 3: Descriptive statistics of vulnerability indices

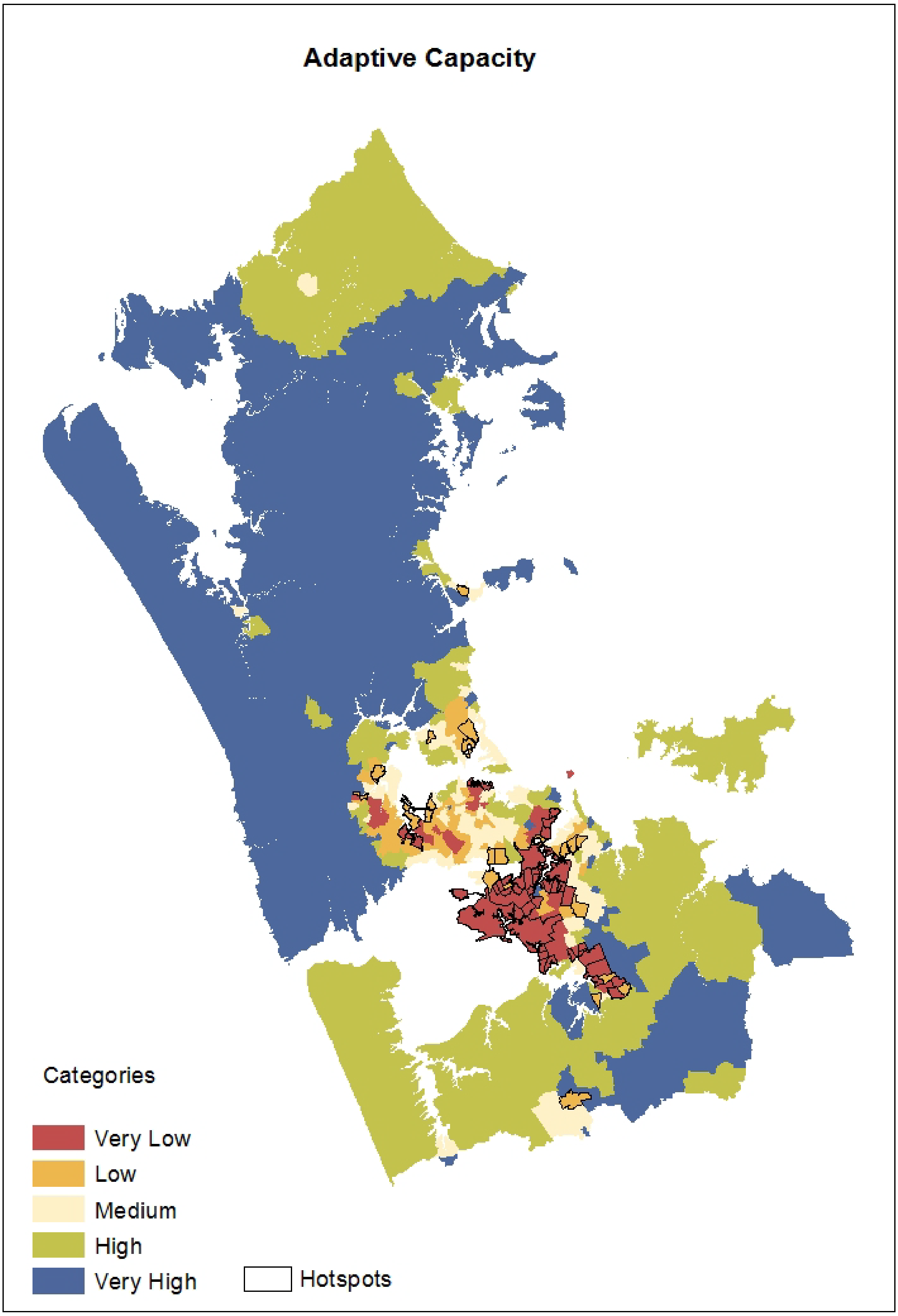
	II	ACI
Mean	0.232	0.61
Median	0.227	0.64
Standard Deviation	0.074	0.174
Min	0	0
P20	0.165	0.462
P40	0.211	0.598
P60	0.243	0.682
P80	0.288	0.759
Max	0.473	0.926
Impact Index (Exposure and sensitivity) – categories		
Very low impact	0 - 0.165	
Low impact	0.165 - 0.211	
Medium impact	0.211 - 0.243	
High impact	0.243 - 0.288	
Very high impact	0.288 - 0.473	
Adaptive Capacity Index – categories		
Very low adaptive capacity	0 - 0.462	
Low ACI adaptive capacity	0.462 - 0.598	
Medium ACI adaptive capacity	0.598 - 0.682	
High ACI adaptive capacity	0.682 - 0.759	
Very high ACI adaptive capacity	0.759 - 1	

Figure 1: Vulnerability assessment and hotspots – Auckland



Note: Categories represent the score quintiles. Hotspots are those CAUs with high or very high II, and low or very low ACI

Figure 2: Vulnerability assessment and hotspots – Auckland



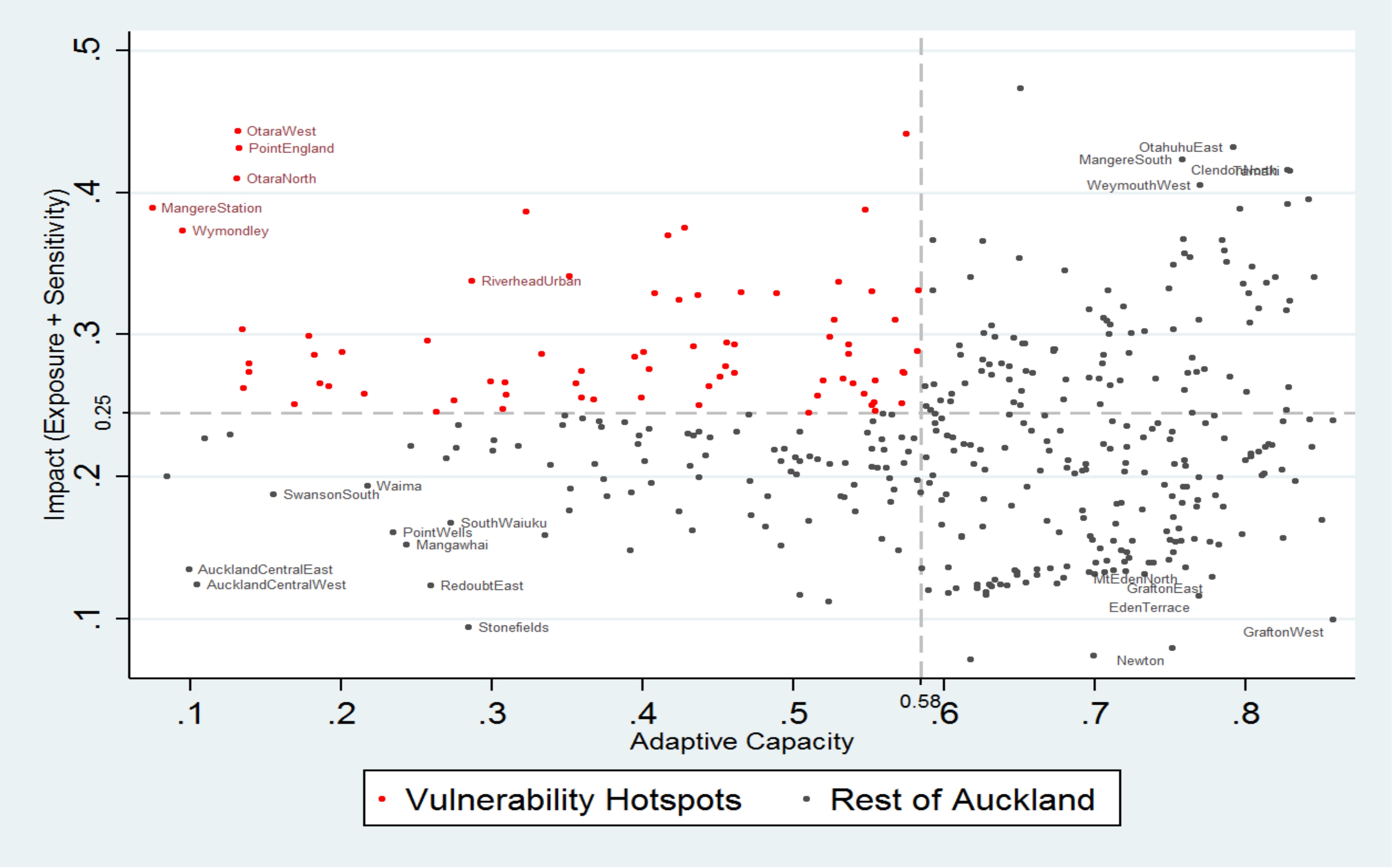
Note: Categories represent the score quintiles. Hotspots are those CAUs with high or very high II, and low or very low ACI

The II summarises the combined influence of exposure and sensitivity to climate change, with a lower score indicating a lesser relative impact of climate change. The ACI, in turn, summarises the ability of CAUs to cope with the effects of climate change. The scores of both indices are plotted in Figure 3, which is separated into four quadrants defined by II P60 (0.25) and ACI P40 (0.58). Vulnerability hotspots correspond to those CAUs with an II score above 0.25 (the high or very high II categories) and ACI score below 0.58 (the low or very low ACI categories) (Figure 3).

Five CAUs (Ōtara West, Point England, Ōtara North, Māngere Station and Wymondley) have notably high II but low ACI scores, suggesting these are the most vulnerable CAUs to the anticipated detrimental effects of climate change. In contrast, CAUs such as Otahuhu East, Māngere South, Clendon and Weymoth West report similar II scores to the hotspots but the ACI scores are much higher. Likewise, two CAUs (Auckland Central East and Auckland Central West) report ACI scores similar to the hotspots but much lower II scores. Finally, CAUs such as Grafton West, Newton, Grafton East, Eden Terrace and Mount Eden North report the lowest II but also the highest ACI scores. Appendix A presents a closer look of the pattern of vulnerability across the local boards in Auckland.

To construct a characterisation of the drivers of vulnerability, statistical analysis using mean-comparison and variance-ratio tests between hotspots and the rest of Auckland. It is found that the hotspots are characterised by CAUs with few environmental resources (i.e., relatively low proportions of cropland, grassland and forest cover); high rates of one-parent households, low average income household, high housing stress (greater income allocated to rent payments); low shares of house ownership and high deprivation index. It is worth mentioning that compensation between adaptive capacity and impact indicators occur across Auckland as several CAUs with relatively high exposure (greater II score) are not found as vulnerability hotspots, arguably because of greater adaptive capacity (greater ACI score).

Figure 3: Scores of the II and ACI Indices – Identification of vulnerability hotspots



Note: Quadrants defined by II P60 (0.25) and ACI P40 (0.58). Hotspots (in red) correspond to those CAUs with an II score above 0.25 (the high or very high II categories) and ACI score below 0.58 (the low or very low ACI categories)

4.0 Discussion

This report carries out an assessment of vulnerability to climate change in Auckland. It develops an overview of the socio-economic, climatic, and geophysical determinants of vulnerability for all CAUs in the region identified as vulnerability hotspots. The assessment provides rankings of CAUs according to the calculated scores of impact index and adaptive capacity index. These rankings and their spatial distribution are important in identifying the hotspots as priority areas for vulnerability reduction efforts (Machado and Ratick, 2017). However, to implement the assessment model, the selection of indicators is key and should be based on an extensive literature review to justify their inclusion. The approach in this report balances between the effects captured by indicators (their relationship to vulnerability), parsimony of the model, and data availability. It follows the wider literature favouring local or place-based assessments on the grounds that these produce more meaningful, detailed, and policy-relevant insights (Barnett, Lambert and Fry, 2008).

Vulnerability hotspots locate to the south of the Auckland isthmus and a few CAUs in western Auckland. Hotspots are characterised by CAUs with relatively little proportion of cropland, grassland and forest cover; high rates of one-parent households, low average household income, high housing stress (greater income allocated to rent payments); low shares of house ownership and high deprivation index. Thus, though forecasts of each socio-economic indicator may be desirable for full compatibility with the 2040 forecasts of the climatic indicators, the assessment in this report constructs an overview of the “what if” cases under an RCP8.5 scenario. Therefore, it provides an indication of whether future impacts can be partly offset by actions taken in the short term (Lung *et al.*, 2013), and suggests issues that make CAUs vulnerable in Auckland.

The assessment is constructed in terms of relative comparisons of the CAUs based on the scores of the II and ACI indices, it creates an indication of the vulnerability profies across the hotspots to inform policy making. For example, Rodney Local Board (Figure A1 in Appendix A) is a case signaling that compensation between adaptive capacity and impact indicators occurs as several CAUs with relatively high exposure (greater II score) are not identified as hotspots, arguably because of greater adaptive capacity (greater ACI score). Thus, the factors driving vulnerability are unevenly distributed across Auckland, resulting in complex spatial patterns (Tapia *et al*., 2017). Hence, the contribution of this report relies on developing a fine-grained assessment that advances the understanding of urban risks to climate change in Auckland.

Some limitations are worth of mentioning: (i) Land use may change swiftly (e.g. from agriculture to residential development), which may not be captured with the land use data used in the assessment. Those changes could affect adaptive capacity of CAUs and should be acknowledged on the interpretation of results at detailed spatial levels. (ii) The assessment assumes equal weighting for all indicators, similar to Lung *et al*., (2013). Other studies in turn suggest that weights should reflect the specific contribution of each indicator to the formation of vulnerability indices, and should be estimated through statistical methods or provided by expert panels. Nonetheless, this is an ongoing debate in the field. Future applications of the assessment model should incorporate robustness analysis to check how the implications of this report change to varying weighting assumptions. (iii) This assessment is a snapshot of likely future climatic conditions. Other modelling approaches (such as the Ordered Weighting Averages) could be used to develop the full spectrum of vulnerability profiles under different conditions.

5.0 Concluding comments

Planning for climate change impacts is complex. Auckland will face major challenges brought about by coastal inundation, heat stress, precipitation, wind and humidity changes. In addition, Auckland is the economic hub of New Zealand and its linkages with all economic sectors require that it takes the lead on developing responses to climate change.

Vulnerability assessments are key elements of climate policy because of the questions asked, knowledge produced, and policy responses prioritised (Fernandez, Bucaram, and Renteria 2017; O'Brien *et al*., 2004; O'Brien *et al*., 2007). As climate change effects vary between communities, social groups, households and even between people within a household, this assessment provides a close inspection of the drivers of vulnerability at local level and contributes to summarising the complexity of several dimensions into a single or a few vulnerability indices, which assists on shaping policy-making.

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Appendix A: Vulnerability assessment for CAUs and local boards

A closer examination of the vulnerability spatial patterns is presented in this Appendix. Spatial displays for each of the local boards in Auckland are in Figures A1 to A21. Each figure shows vulnerability scores/rankings for the Impact Index (exposure + sensitivity) and Adaptive Capacity Index as well as the vulnerability hotspots. Each local board is discussed in turn, from north to south[4]. This section is a high-level description of vulnerability profiles; the identification of specific drivers of vulnerability by CAU or local board may require a deeper approach that falls outside the scope of this report.

The Rodney Local Board contains CAUs in the very low to medium impact categories, except in areas to the west (Figure A1). Nonetheless, most of the board shows high or very high adaptive capacity. No Rodney Local Board CAUs are vulnerable hotspots, largely due to the influence of greater extent of open space or less developed land. The Hibiscus and Bays Local Board in turn shows CAUs with low to very high levels of impact (Figure A2). Most of the CAUs are between the medium and very high adaptive capacity categories. Stanmore Bay East is the only CAU in the Hibiscus and Bays Local Board identified as a vulnerability hotspot.

[4] See Table 3 for the value of quintiles and the definition of the vulnerability categories indicated in the legends of Figures 4 to 23

Figure A1: Vulnerability assessment and hotspots – Rodney Local Board

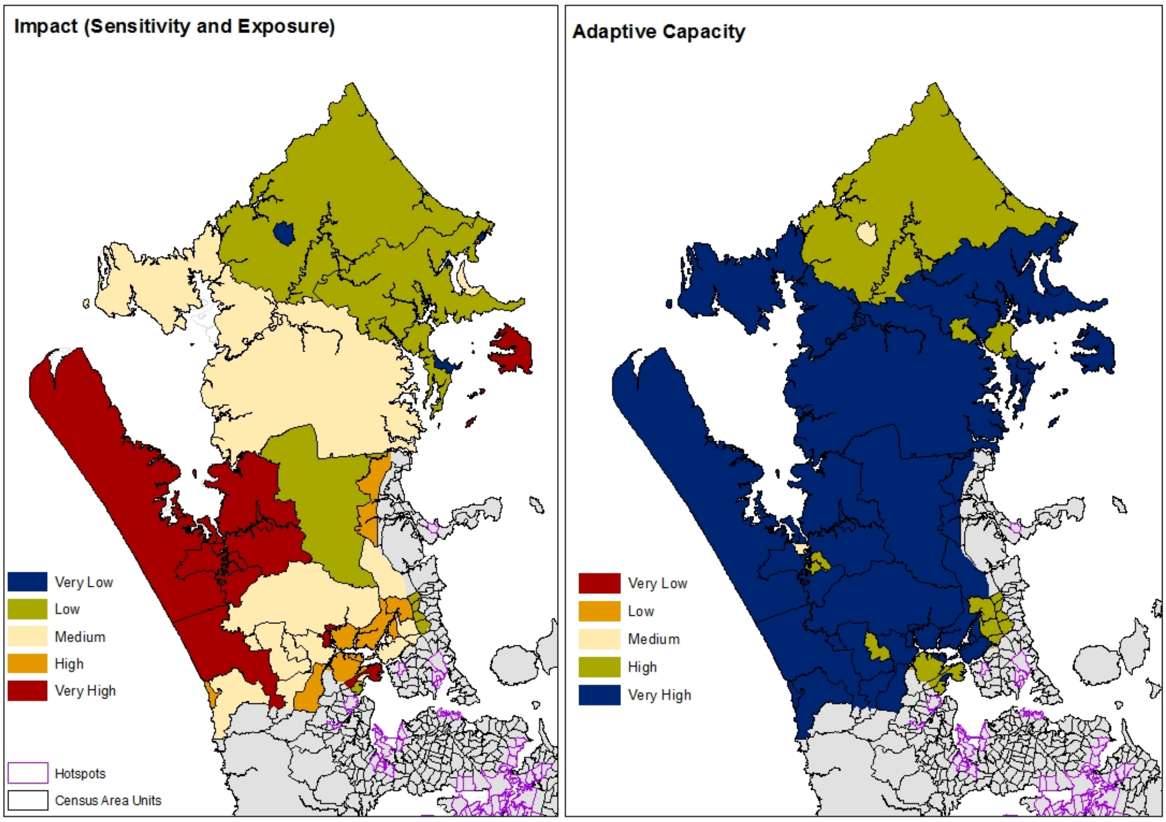
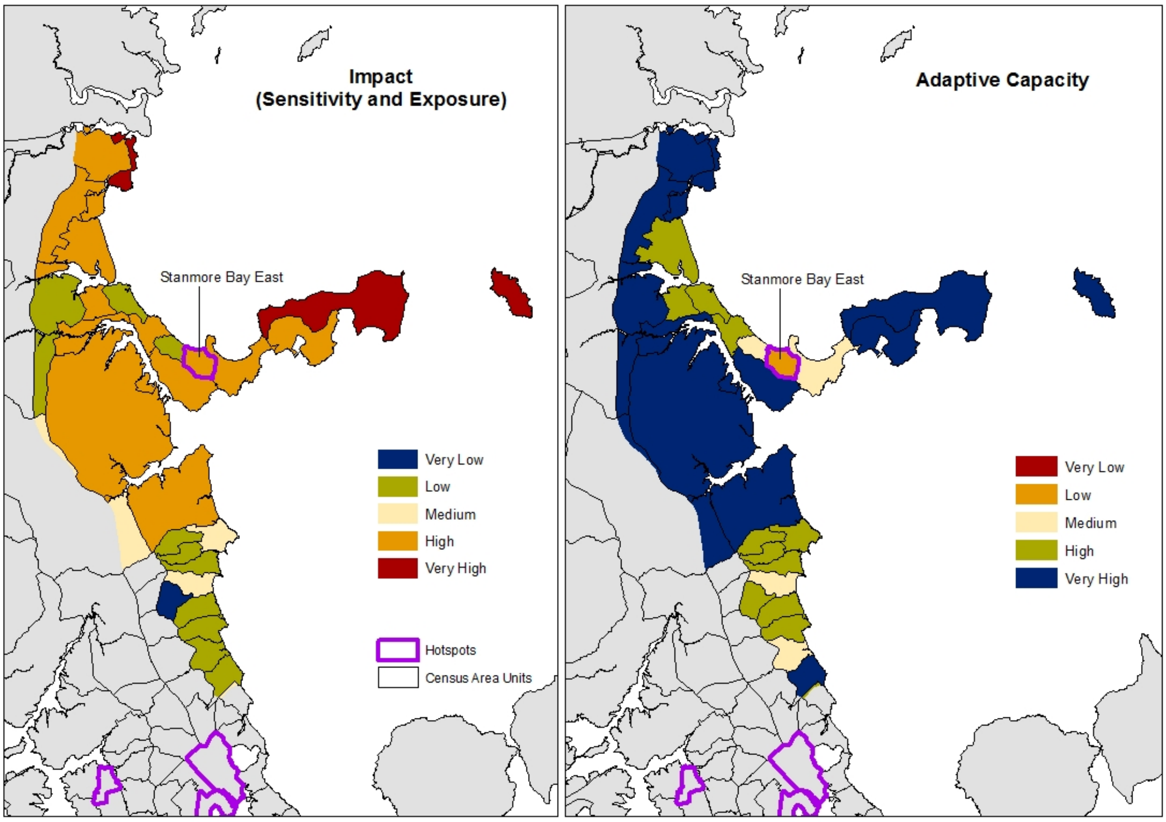


Figure A2: Vulnerability assessment and hotspots – Hibiscus and Bays Local Board



Upper Harbour Local Board shows contrasting results as CAUs are characterised by medium to very high impact levels, and high or very high adaptive capacity (Figure A3). However, southern CAUs in Upper Harbour have been subjected to intensive residential development in the last few years. Since land use data corresponds to 2012, development may have affected adaptive capacity. This is a limitation that should be acknowledged because of timing of land use datasets and their updates.

Kaipātiki Local Board shows high heterogeneity for impact levels, where none of the categories is clearly dominant (Figure A4). Regarding adaptive capacity, it ranges between low and high within the board. Birkdale North, Westlake and Tuff Crater are identified as vulnerability hotspots in the local board.

Figure A3: Vulnerability assessment and hotspots – Upper Harbour Local Board

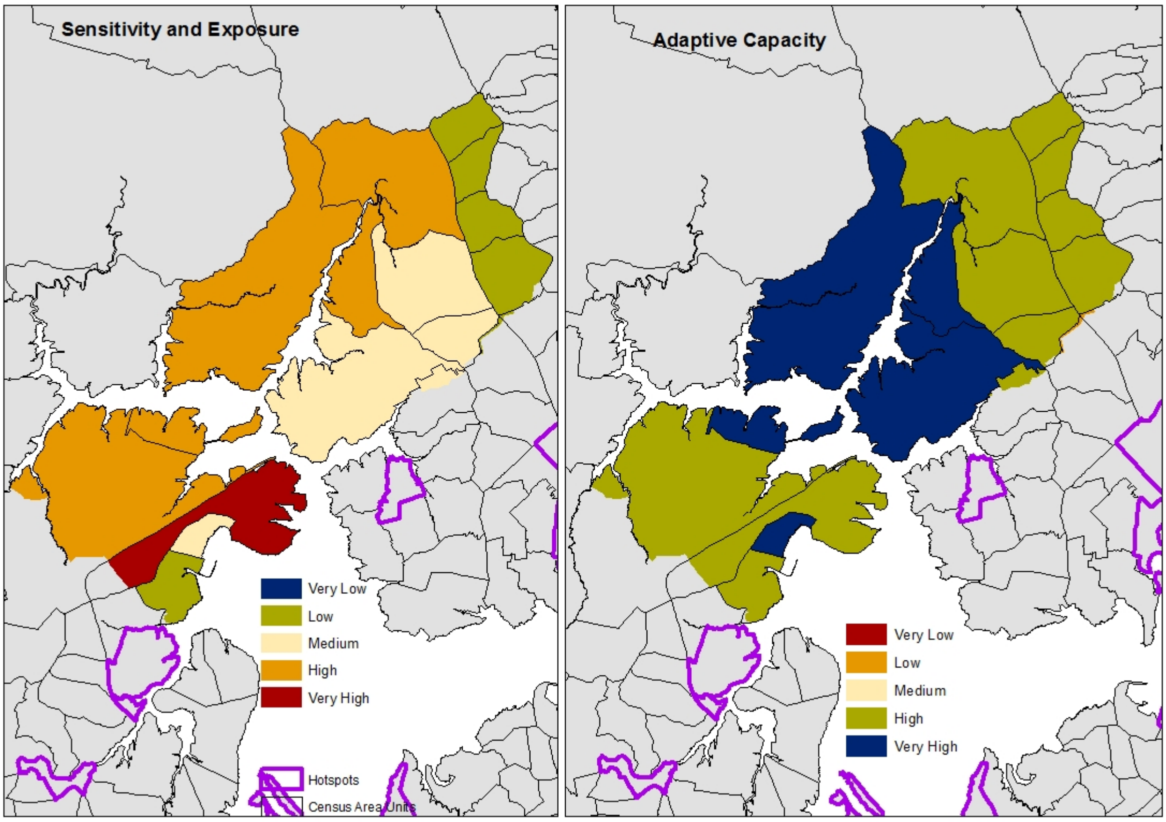
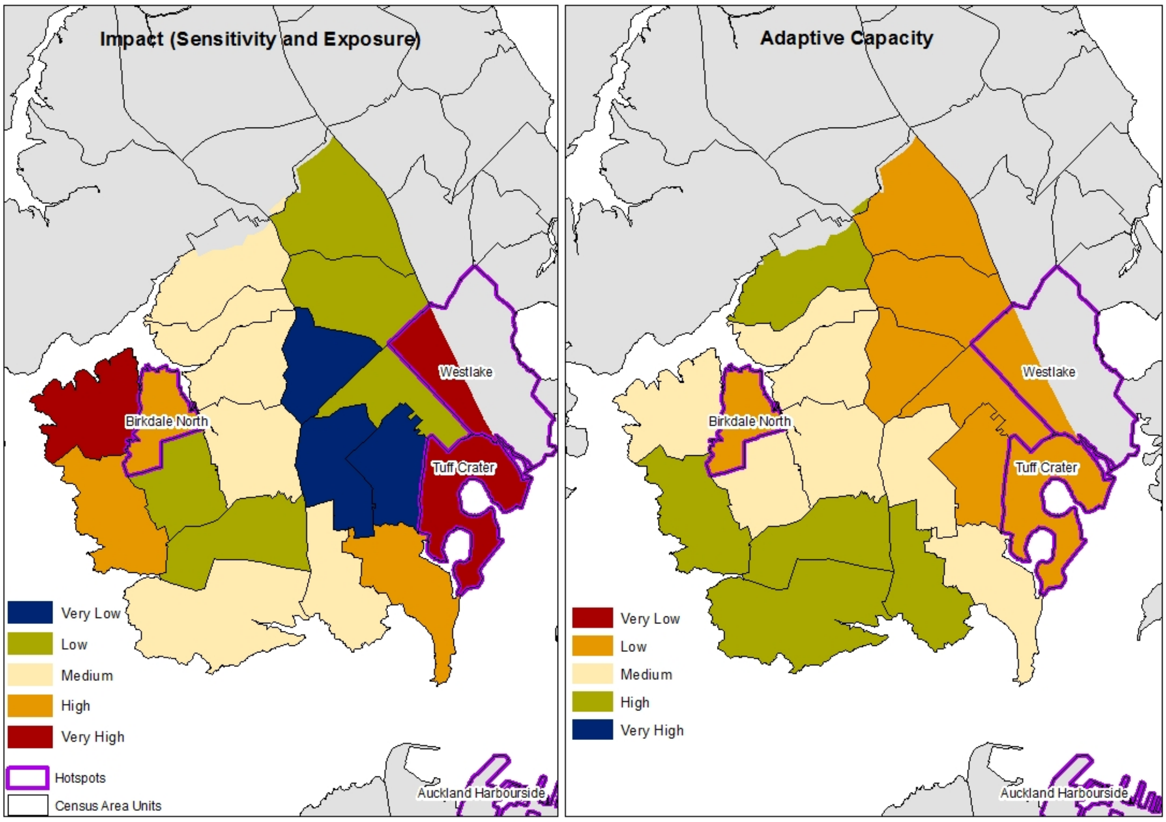


Figure A4: Vulnerability assessment and hotspots – Kaipātiki Local Board



Devonport-Takapuna Local Board has CAUs of medium to very high impact scores, but also medium to very high adaptive capacity scores (Figure A5). Most CAUs are in the medium adaptive capacity category, which are also relatively wealthy areas where, because of the geometric aggregation function, income by itself may not fully substitute or compensate for the relatively low proportion of non-built land, and its associated ecosystem services. Even so, no hotspot is identified in this board.

Some CAUs in the Henderson-Massey Local Board report very high impact scores, and locate in the western portion of the board (Figure A6). CAUs in the low and medium impact categories were generally distant from the coast. ACI is highly heterogeneous, ranging from very low to very high. Royal Heights and Starling Park are the CAUs identified as hotspots in the board.

Figure A5: Vulnerability assessment and hotspots – Devonport-Takapuna Local Board

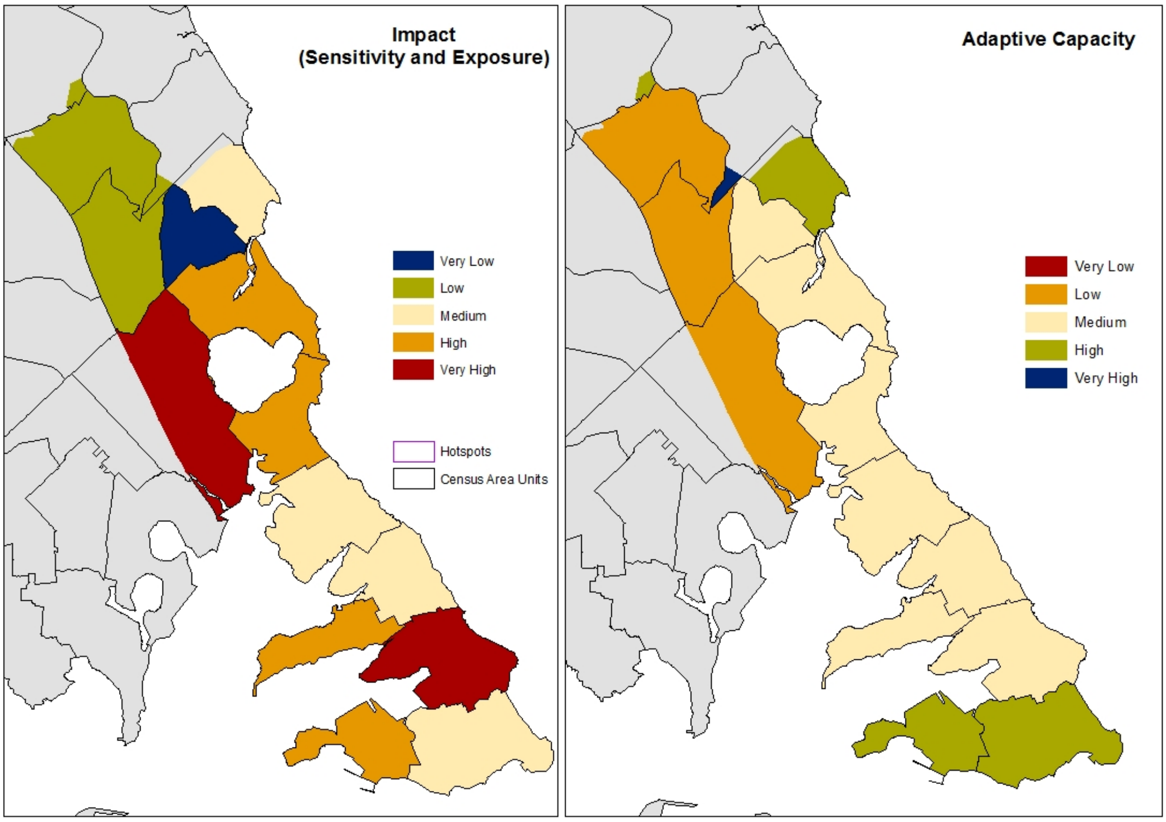
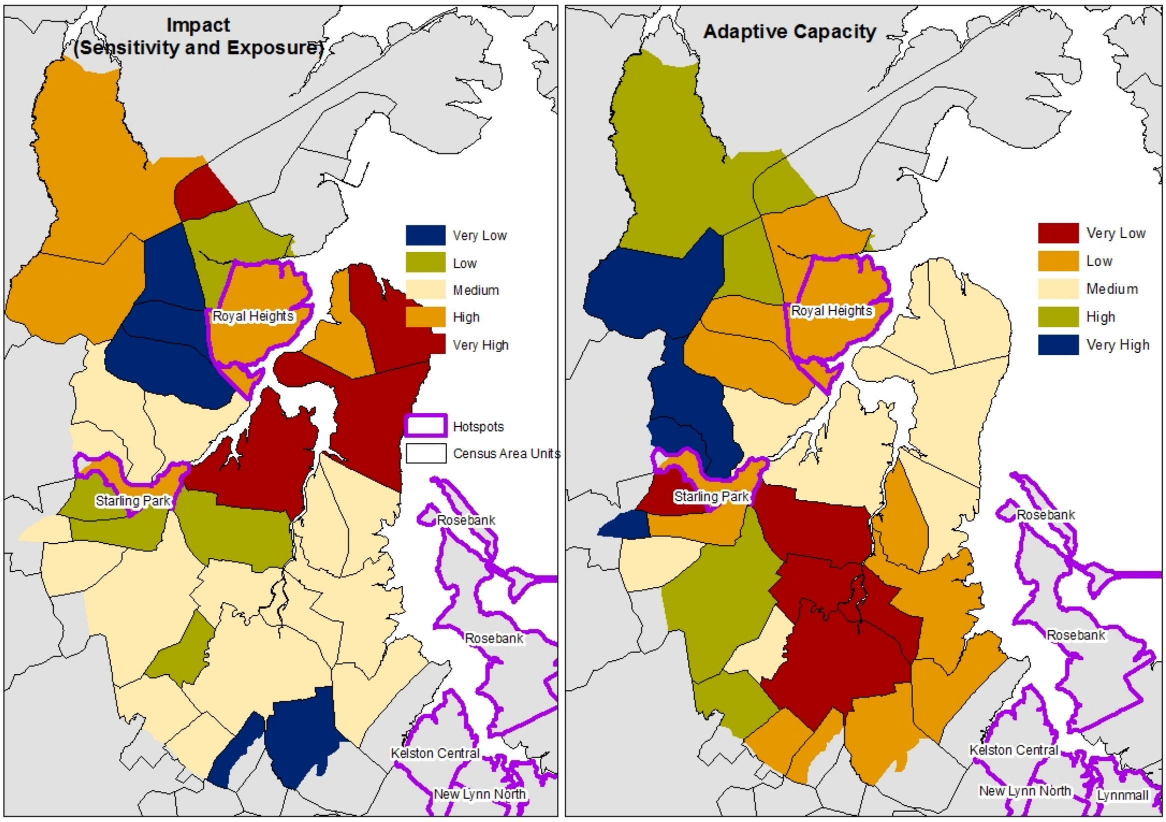


Figure A6: Vulnerability assessment and hotspots – Henderson-Massey Local Board



Waitākere Ranges Local Board is dominated by extensive tracts of forest and households with relatively high income, generally driving down the Impact Index scores and increasing the Adaptive Capacity Index ones (Figure A7). While the Great Barrier Local Board also has very high adaptive capacity because of access to ecosystem services and relatively high household income, it is in the high impact category due to its location (Figure A8).

Figure A7: Vulnerability assessment and hotspots – Waitākere Ranges Local Board

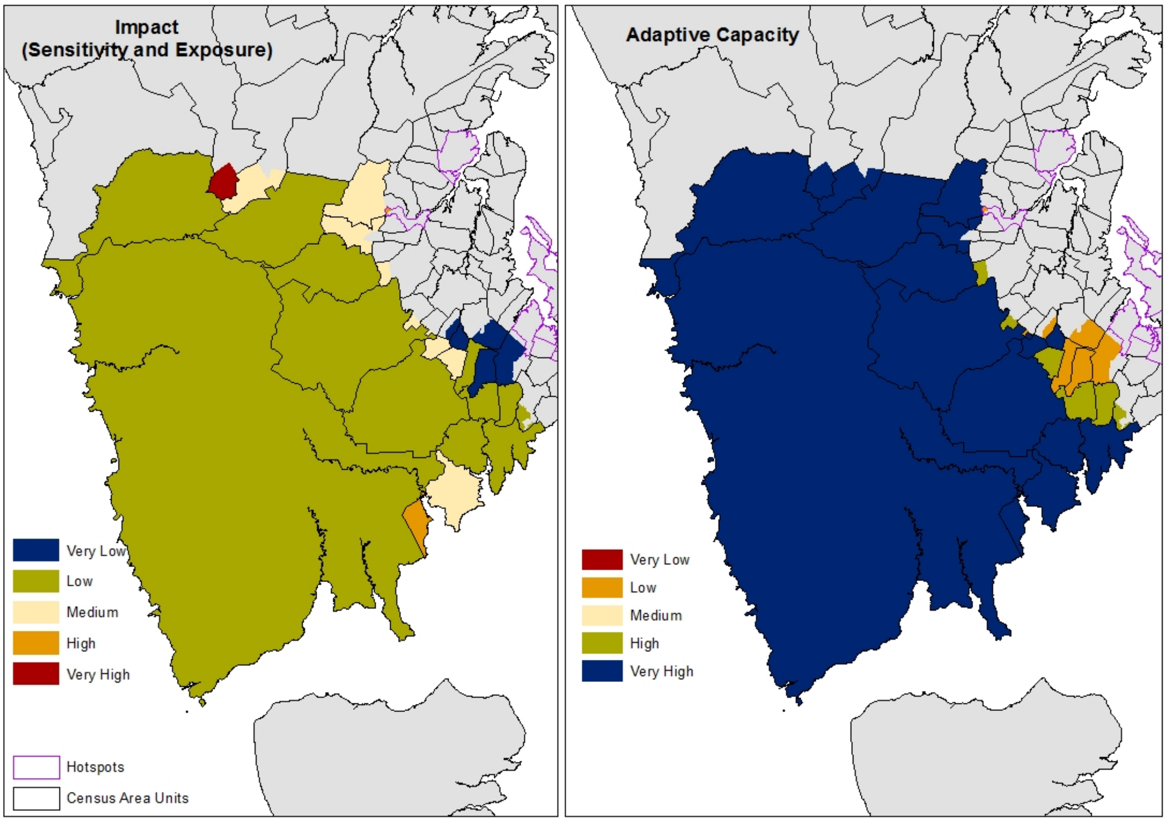
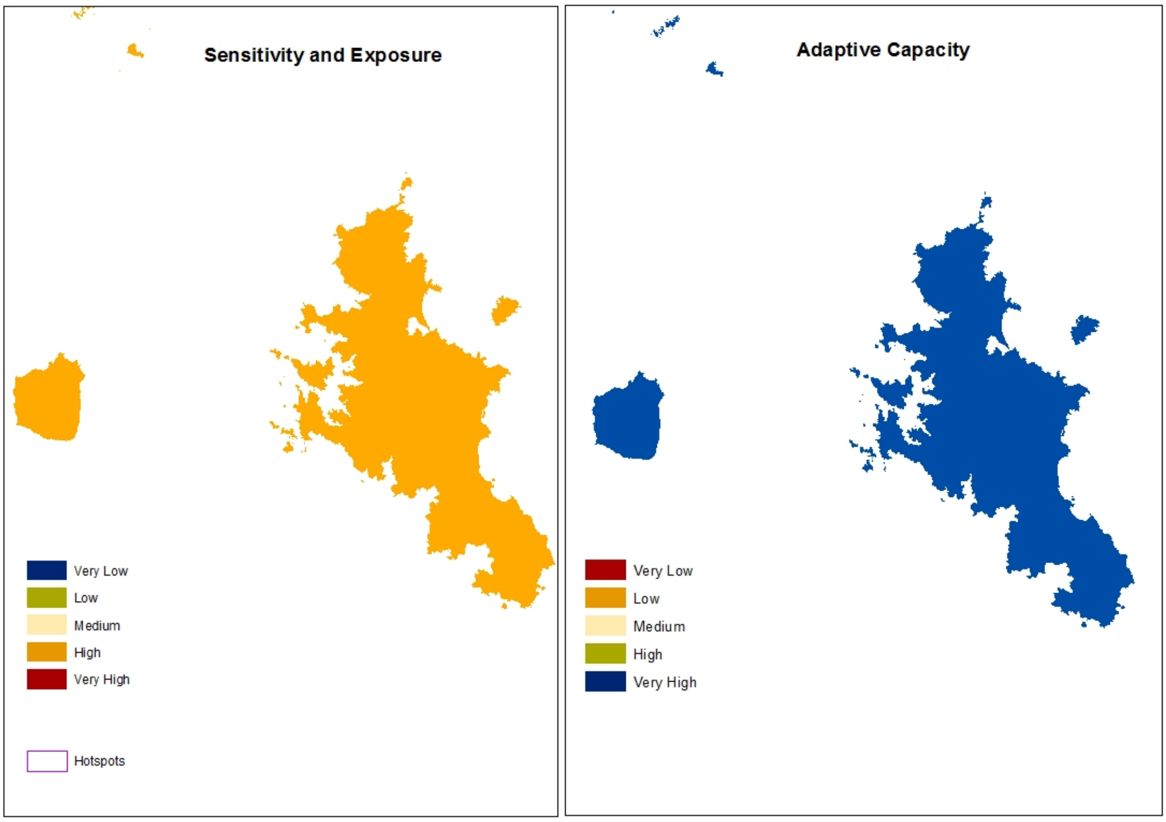


Figure A8: Vulnerability assessment and hotspots – Great Barrier Local Board



Waiheke Local Board is a CAU in the very high impact category balanced by high adaptive capacity (Figure A9) and, consequently, not identified as a hotspot.

The Waitematā Local Board comprises the CBD and waterfront areas of the Waitematā Harbour (Figure A10). The wider harbour area is a hotspot because of its high exposure and very low adaptive capacity. The CBD shows very low impact but differing degrees of adaptive capacity, ranging from very low to medium because of limited access to ecosystem services and low/mixed households income relative to other areas in Auckland.

Figure A9: Vulnerability assessment and hotspots – Waiheke Local Board

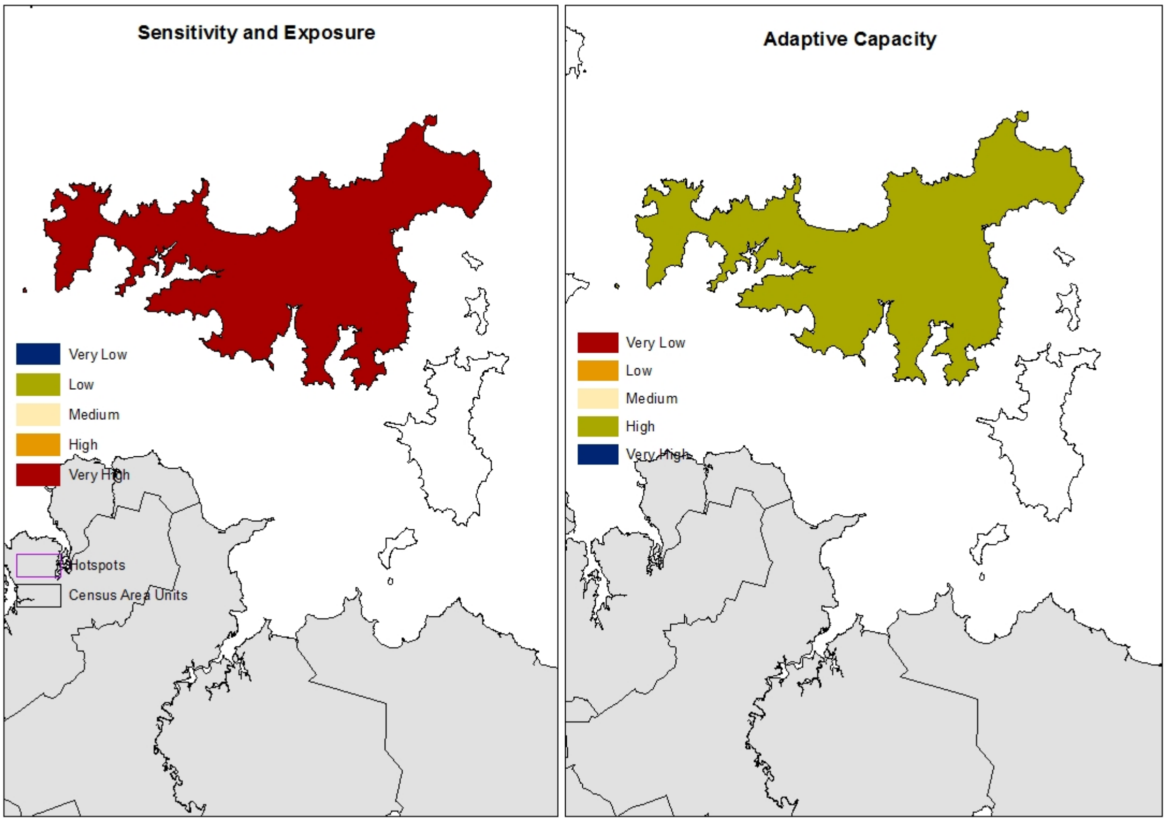
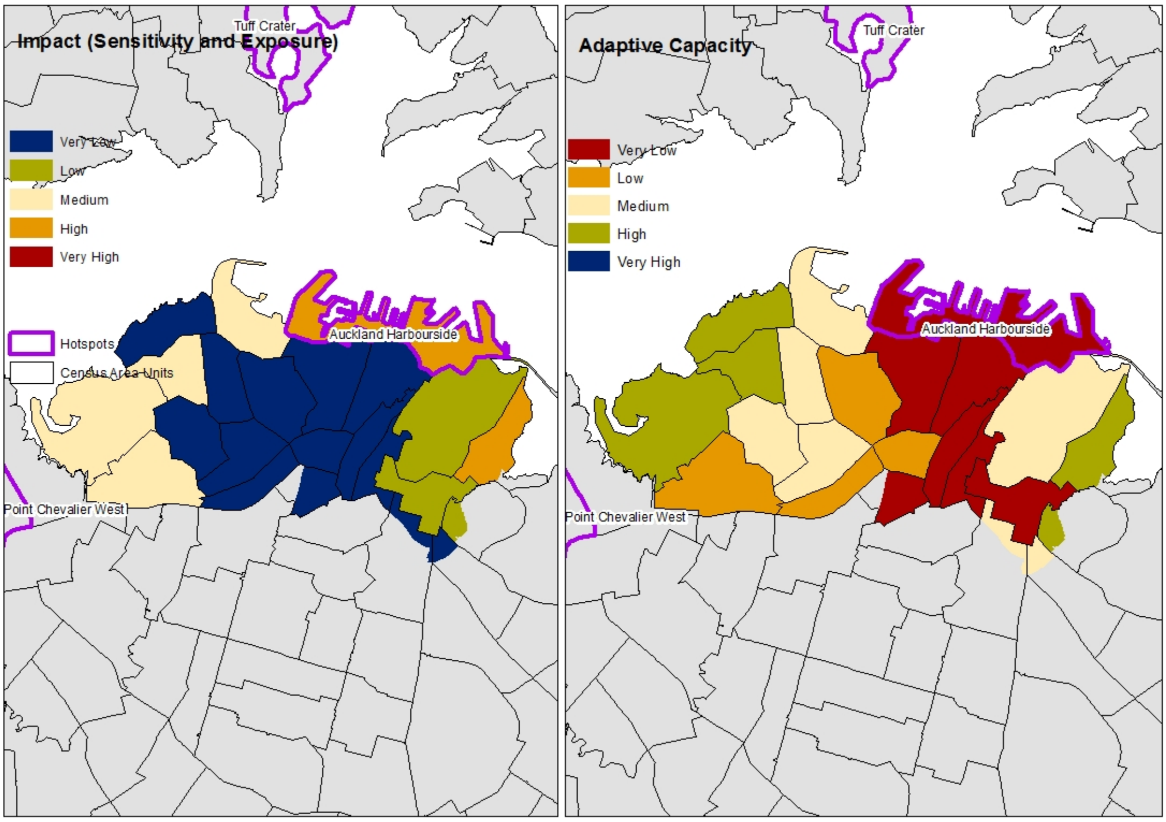


Figure A10: Vulnerability assessment and hotspots – Waitematā Local Board



The Whau Local Board contains vulnerability hotspots such as Rosebank, Kelston Central, New Lynn North and Lynn Mall (Figure A11). Relatively lower incomes in these CAUs limit their ability to compensate the climate change impacts, most likely coastal inundation. Inland areas report low or very low impact as well as medium or high adaptive capacity, because of proximity to the Waitākere Ranges and forestry ecosystem services.

The Albert-Eden Local Board comprises central areas in the Auckland isthmus of very low to medium impact levels (Figure A12). Point Chevalier West is the only vulnerability hotspot in the board arguably because of its exposure to coastal inundation due to sea level rise.

Figure A11: Vulnerability assessment and hotspots – Whau Local Board

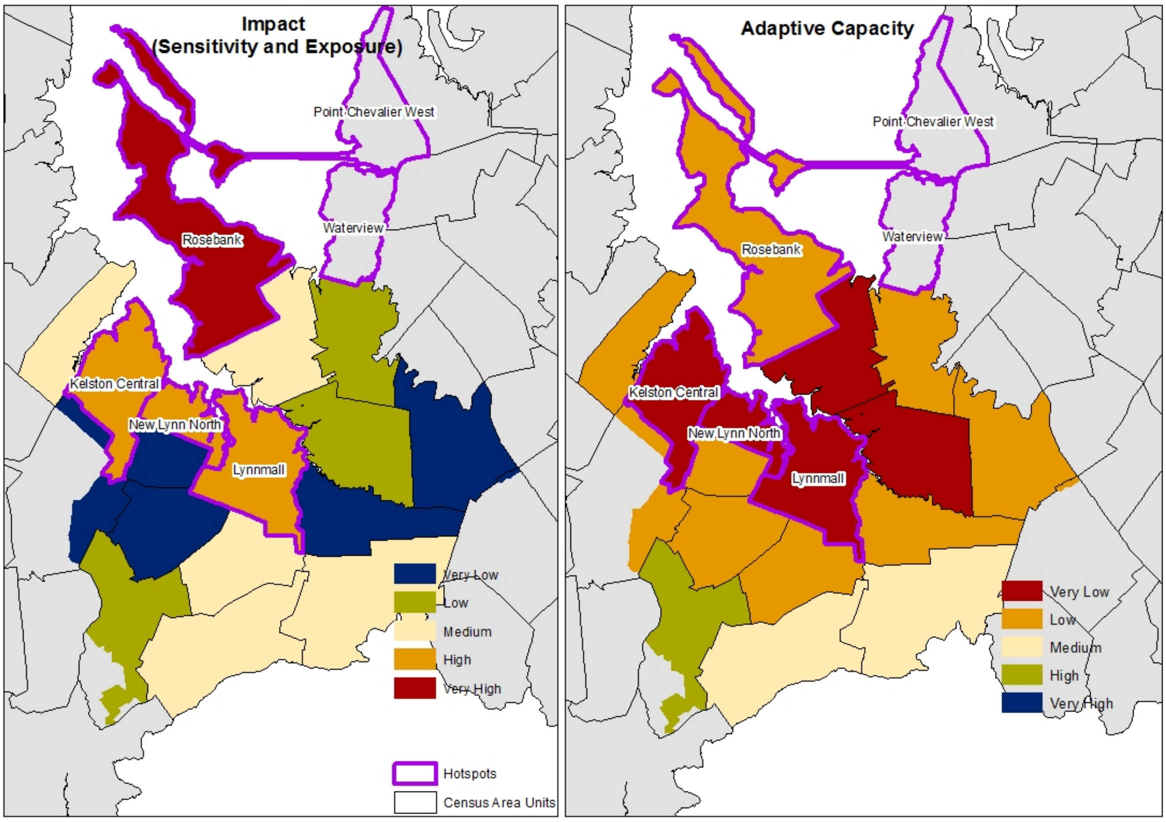
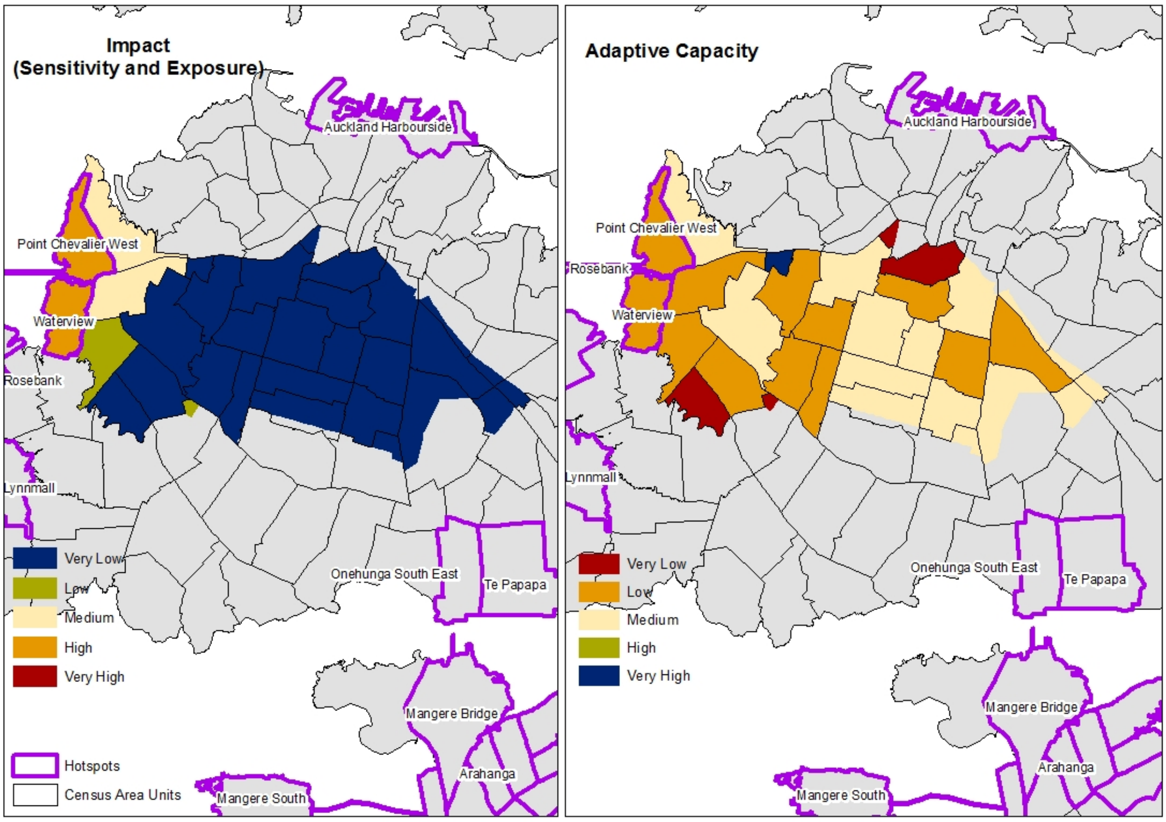


Figure A12: Vulnerability assessment and hotspots – Albert-Eden Local Board



Puketāpapa Local Board is characterised by CAUs falling in the low categories for impact, mainly in inland areas, and others falling in the low to medium impact categories in coastal areas (Figure A13). Adaptive capacity ranges between very low to medium categories. No hotspots are identified in the board.

Ōrākei shows a heterogeneous pattern of impact levels (Figure A14). Very high impact occurs in Ōrākei North, whereas it ranges from very low to medium in the rest of coastal areas in the board. In turn, adaptive capacity ranges between medium to very high because of relatively high household income or low deprivation index. The only CAUs with very low adaptive capacity are St Johns and Mt Wellington Domain.

Figure A13: Vulnerability assessment and hotspots – Puketāpapa Local Board

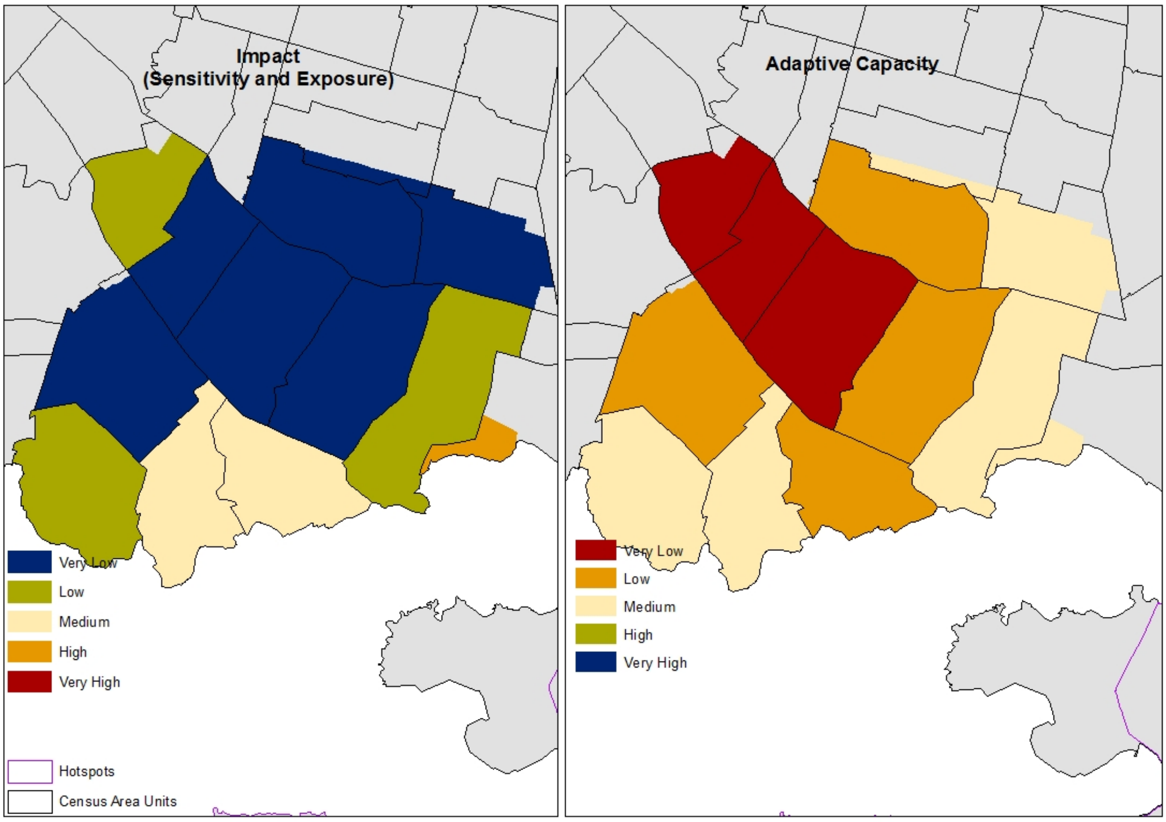
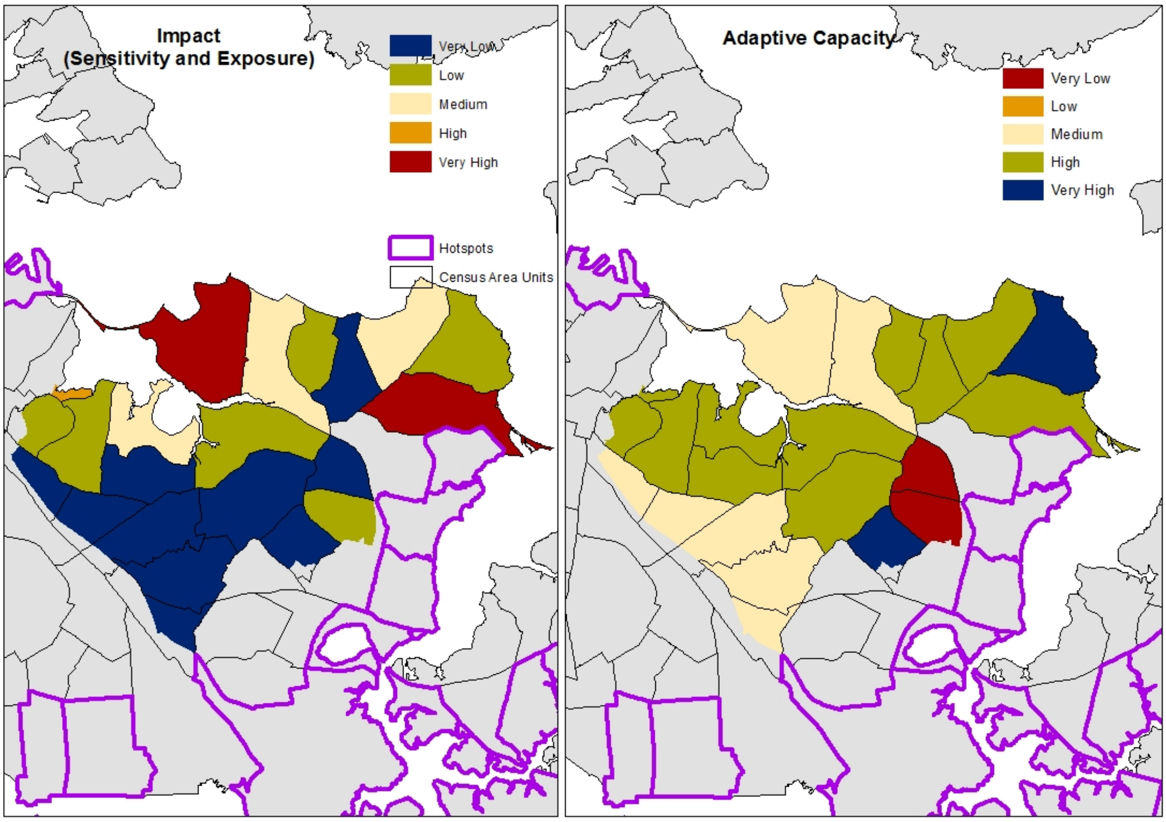


Figure A14: Vulnerability assessment and hotspots – Ōrākei Local Board



Maungakiekie-Tāmaki Local Board shows high or very high impact levels in their coastal areas (Figure A15), which coincide with low or very low adaptive capacity. All these areas are categorised as vulnerability hotspots. Similarly, Howick shows high impact levels in coastal areas in the north and western shares of the board (Figure A16). Some coincide with low or very low adaptive capacity, which result on vulnerability hotspots.

Figure A15: Vulnerability assessment and hotspots – Maungakiekie-Tāmaki Local Board

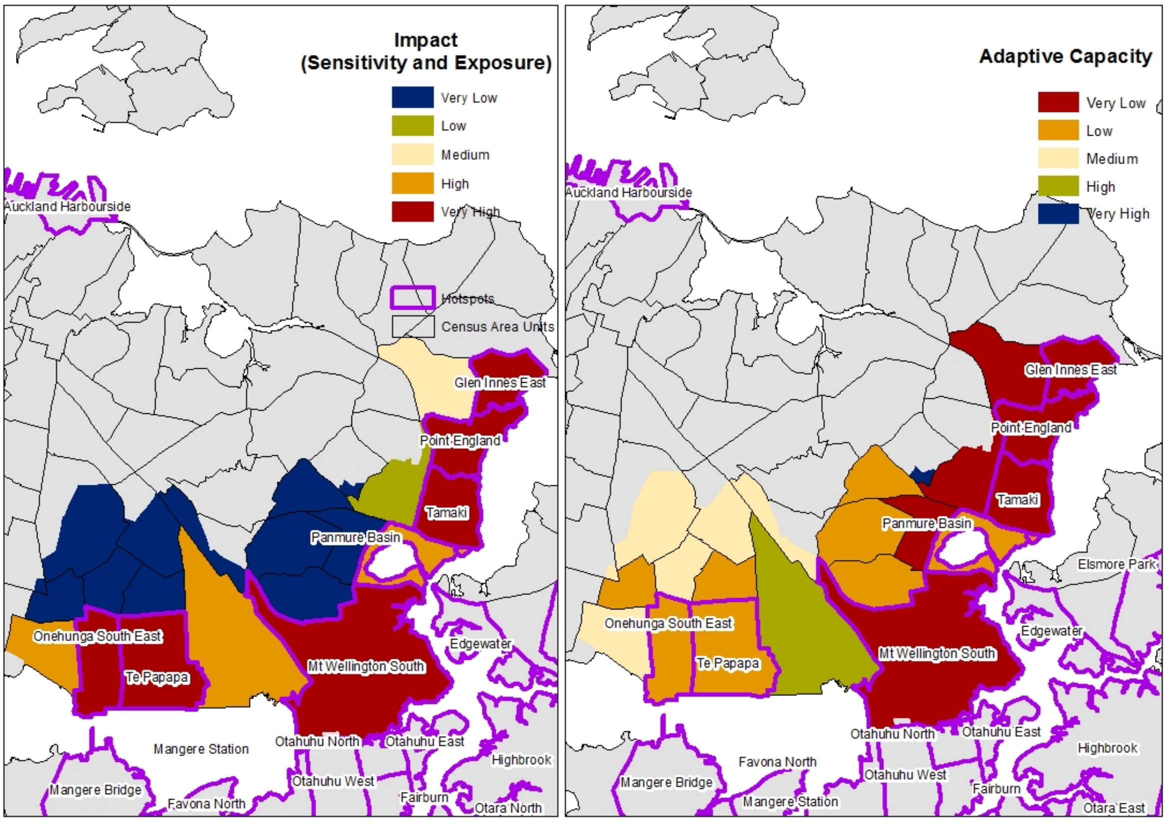
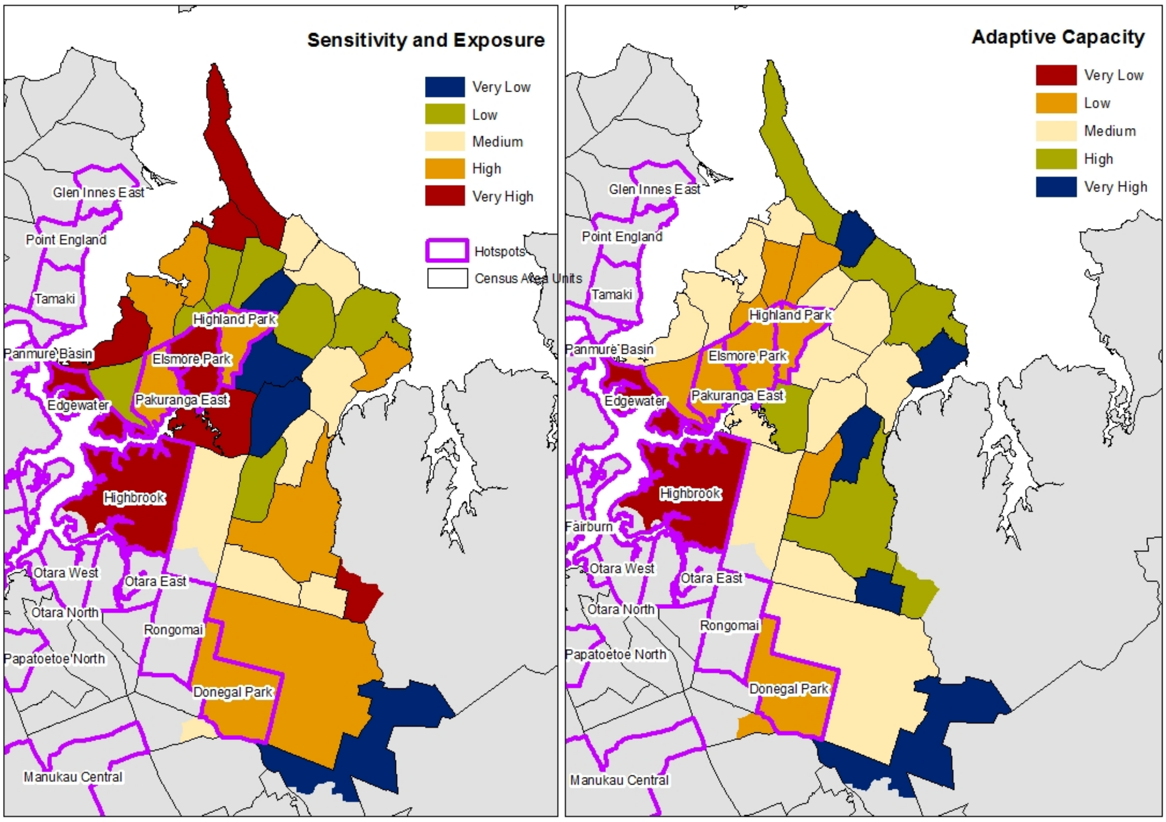


Figure A16: Vulnerability assessment and hotspots – Howick Local Board



Almost all the CAUs in Māngere-Ōtāhuhu Local Board are vulnerability hotspots (Figure A17). Very high impact occurs in coastal areas, whereas inland CAUs such as Mascot and Viscount have low to medium impact. It is noticeable that almost all the Māngere-Ōtāhuhu Local Board suffers from very low adaptive capacity. Similarly, most of the CAUs in Ōtara are vulnerability hotspots, except for Puhinui South and Papatoetoe West (Figure A18). A similar pattern also appears for Manurewa (Figure A19), and Papakura (Figure A20), with vulnerability hotspots occurring in coastal areas and inland CAUs with low to medium impact and medium to high adaptive capacity.

Figure A17: Vulnerability assessment and hotspots – Māngere-Ōtāhuhu Local Board

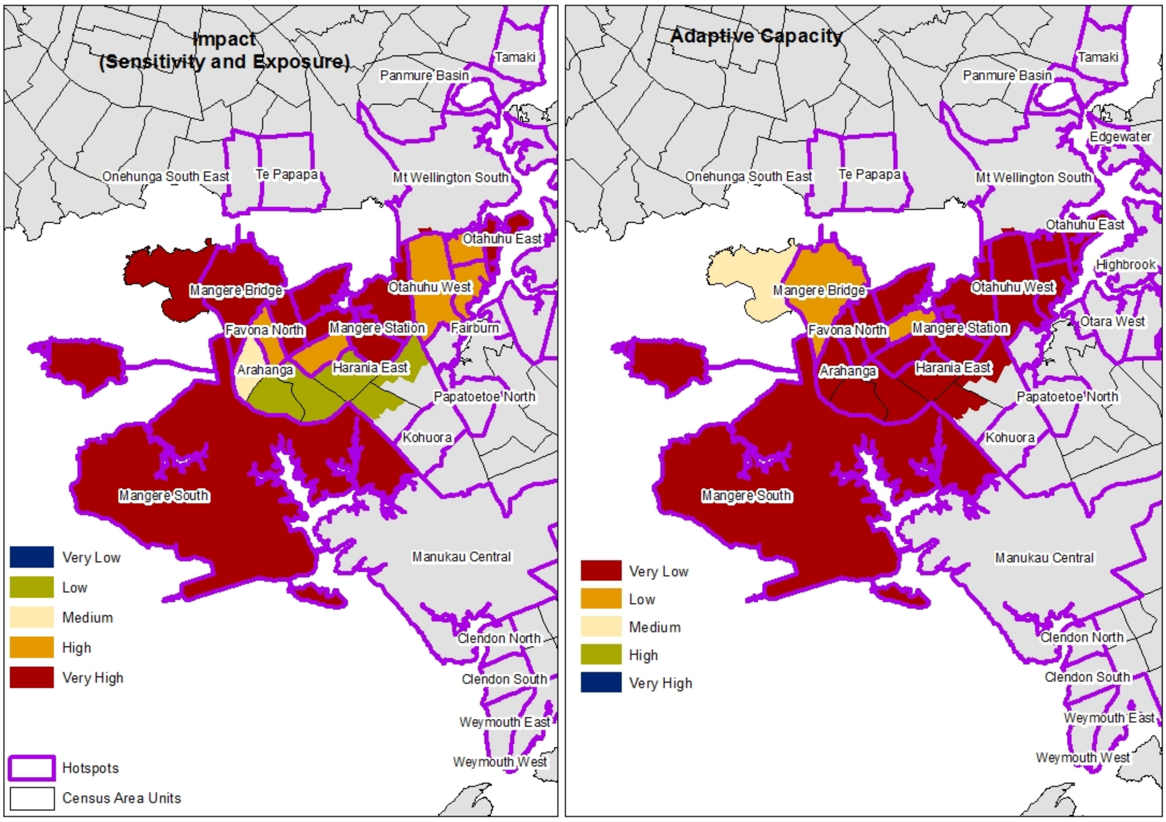


Figure A18: Vulnerability assessment and hotspots – Ōtara-Papatoetoe Local Board

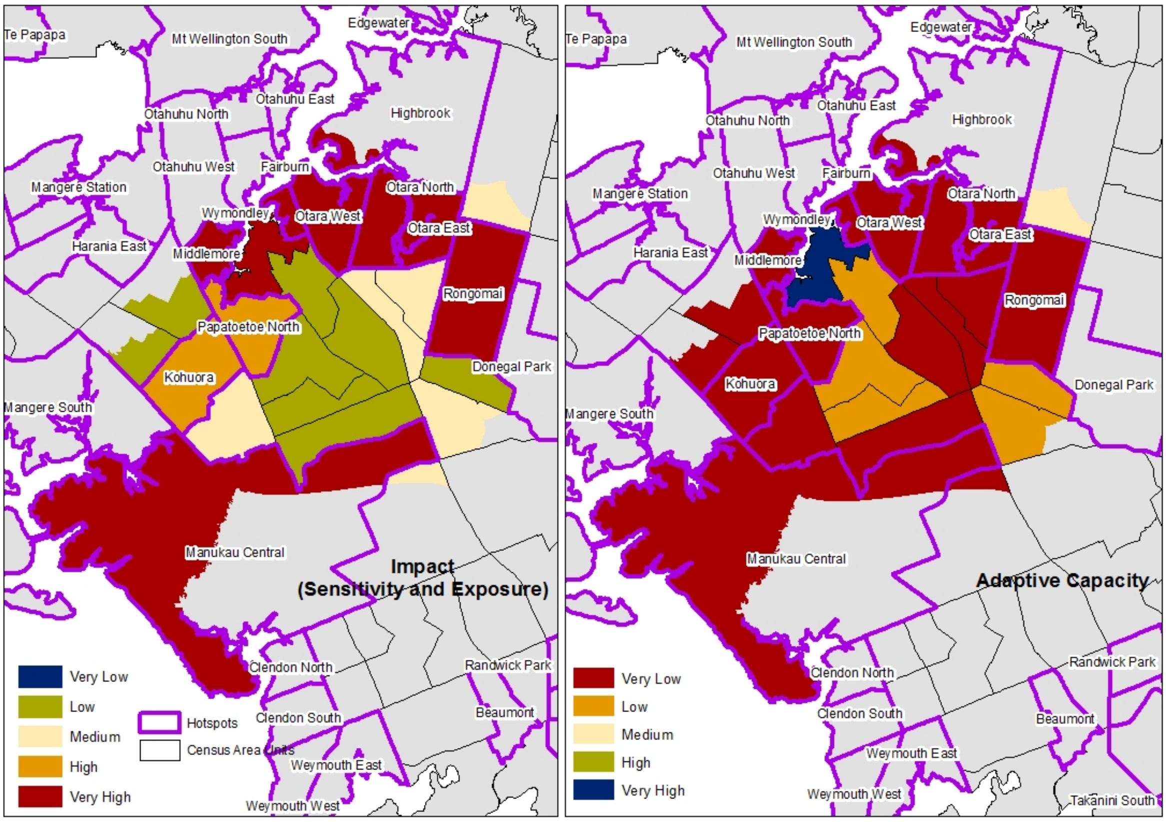


Figure A19: Vulnerability assessment and hotspots – Manurewa Local Board

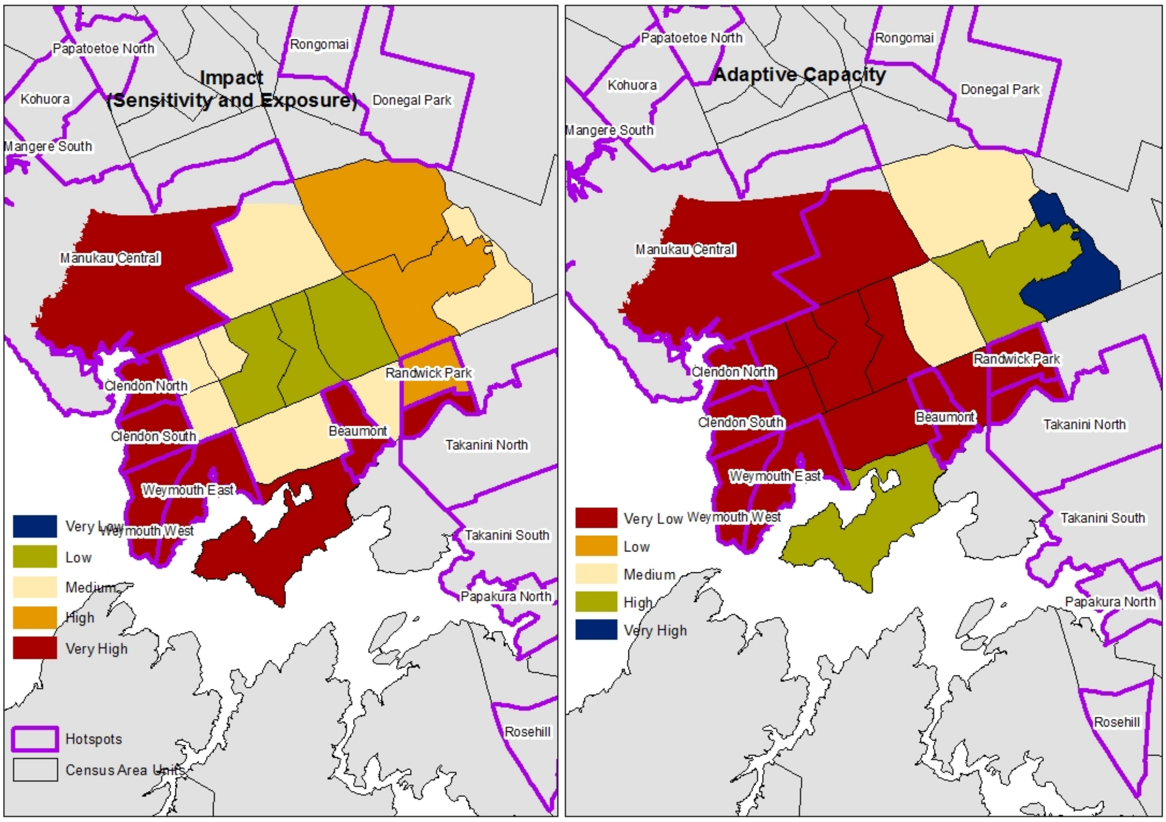
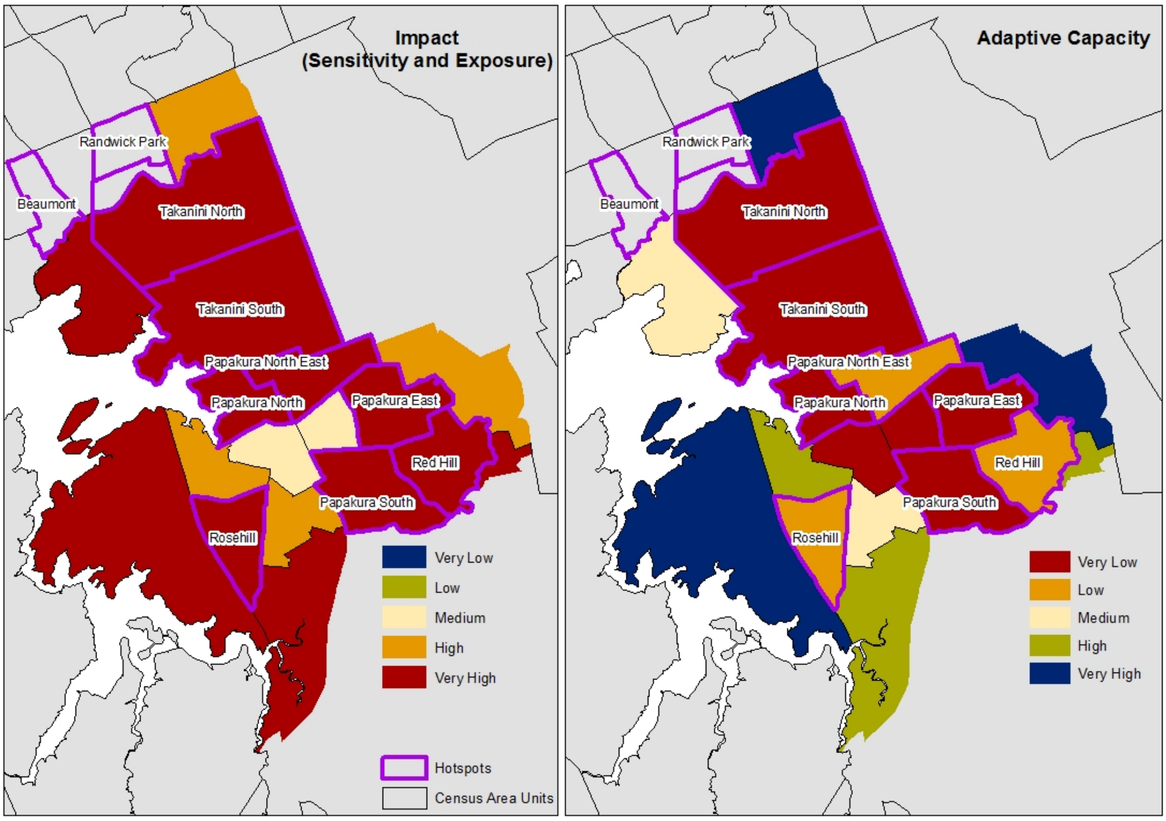
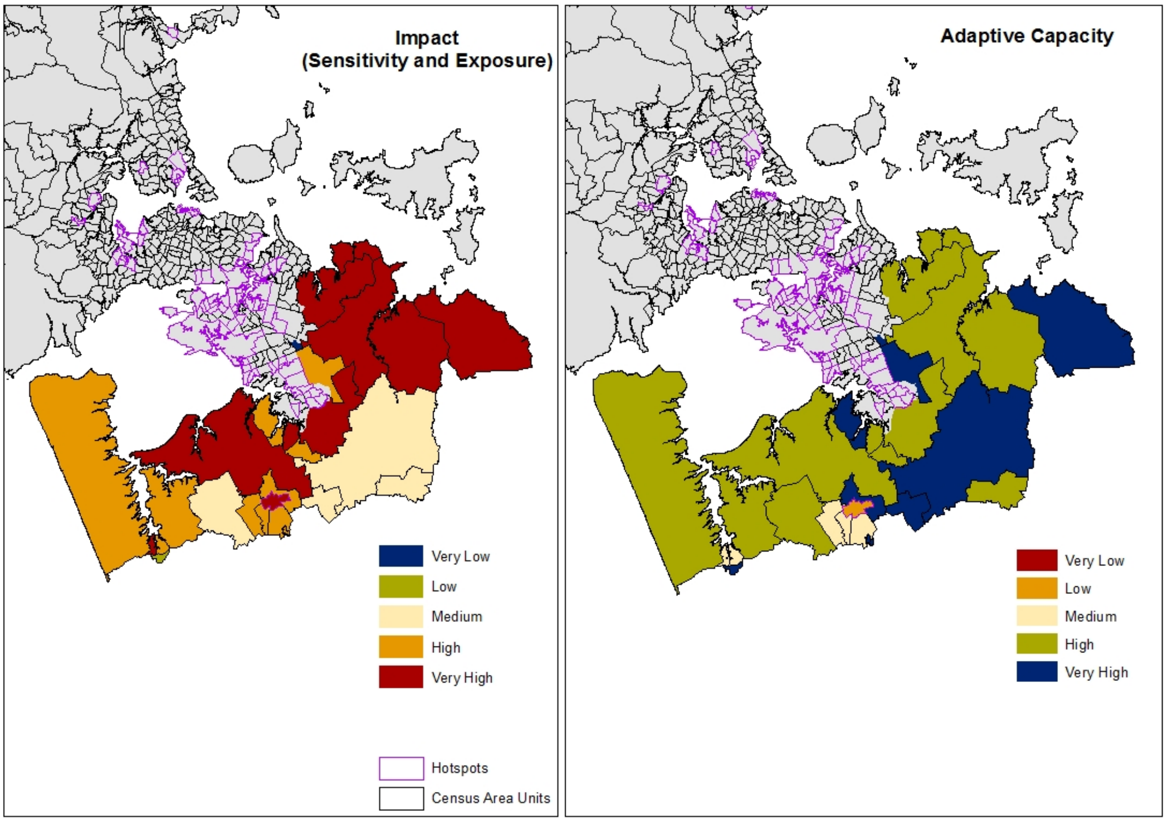


Figure A20: Vulnerability assessment and hotspots – Papakura Local Board



Finally, results for Franklin Local Board suggest that high adaptive capacity in southern areas of the board are because of access to ecosystem services as these are close to rural areas (Figure A21). These coincide with medium to high impact. Thus, only one CAU (Pukekohe North) is a hotspot in the board.

Figure A21: Vulnerability assessment and hotspots – Franklin Local Board



Appendix B: Characterisation of the vulnerability hotspots

To characterise the vulnerability profile of those CAUs identified as hotspots, tests for the equality of means and variances are estimated for the indicators, and between the hotspots and the rest of CAUs in Auckland. The mean-comparison test is used to test if both groups have the same mean, such that the difference of the means between the two groups is zero[5]. The variance equality test is used to test if the two groups have equal variances, such that the difference of the variances between the two groups is zero[6]. Any statistically significant difference (i.e. rejection of the null hypothesis) should be interpreted as a result that cannot be attributed to chance but to the phenomena inherent to the indicators or the groups. Table A1 shows the mean values of the indicators for both groups, and p-values of the two null hypotheses tested.

It is found that the hotspots characterise for having households whose incomes and house ownership ratios are significantly lower than in the rest of Auckland. Households in the hotspots spend 36.7 per cent of their income on rent, which is significantly higher than in the rest of Auckland, 30.3 per cent. Nonetheless, the dispersion in the hotspots is narrower than in the rest of Auckland, where some households report spending less than 10 per cent of income on rest, whereas no household in the hotspots spends less than 24 per cent. Furthermore, the unemployment rate, the share of one-parent households, dependency ratio and the deprivation index are also significantly higher in the hotspots than in the rest of Auckland.

Likewise, road density (as a proxy of the effect of infrastructure) is significantly lower in the hotspots than in the rest of Auckland. The hotspots also have much less land on crops, grassland and forest cover relative to the rest of Auckland. In addition, the share of populated area relative to CAU area reaches 76 per cent in the hotspots and 68 per cent in the rest of CAUs.

Regarding the climatic indicators, the exposure to coastal inundation, the number of dry days, relative humidity and the number of heavy rainfall days have a similar profile between the two groups as no significant mean differences are detected in the index values. Nonetheless, significant differences are observed in terms of the variability. On the other hand, the hotspots have higher index values for the number

[5] Null hypothesis $H_0\colon mean(Rest\ of\ Auckland) - mean(Hotspots) = 0$

[6] Null hypothesis of the Levene test for equality of variances $H_0\colon variance(Rest\ of\ Auckland) - variance(Hotspots) = 0$

of hot days, and total precipitation change, and slight differences on the index values for mean temperature and wind speed.

In summary, hotspots are characterised by CAUs having households whose incomes and housing ownership ratios are significantly lower than in the rest of Auckland. The unemployment rate, housing stress (share of income allocated to rent), the share of one-parent households, age dependency ratio and the deprivation index are also higher in the hotspots. Hotspots also show low road density and fewer environmental resources reflected as low shares of CAU land on crops, grass and forest. The hotspots show higher index values for the number of hot days, and total precipitation change, and slight differences on the index values for mean temperature and wind speed. It is worth mentioning that compensation between adaptive capacity and impact indicators occur across Auckland as several CAUs with relatively high exposure (greater II score) are not found as vulnerability hotspots, arguably because of greater adaptive capacity (greater ACI score).

Table A1: Characterisation of vulnerability hotspots

	Means			
	Hotspots	Rest of Auckland	P-value of mean-comparison tests	P-value of variance ratio tests
Household Income ($)	67,295	77,292	0.000***	0.000***
House ownership (%)	33.6	46.7	0.000***	0.137
Share of income on rent (%)	36.7	30.3	0.000***	0.000***
Unemployment (%)	7.1%	4.6%	0.000***	0.035*
Share of one-parent households (%)	16.5%	9.5%	0.000***	0.032*
Age dependency ratio	0.549	0.494	0.017***	0.660
Deprivation index	1,079	978	0.000***	0.286
Road density	0.63	0.95	0.000***	0.221
Land on crops (%)	0.01%	4.7%	0.000***	0.000***
Land on grassland (%)	0.4%	14.0%	0.000***	0.000***
Forest cover (%)	4.0%	9.0%	0.000***	0.000**
Share of populated area relative to CAU area (%)	76.0%	68.0%	0.031*	0.000***
Exposure to coastal inundation with 1 m sea level rise (index)	0.038	0.026	0.145	0.575
Number of dry days (precipitation < 1mm)	1.46	1.46	0.925	0.000***
Relative humidity (index)	-0.51	-0.51	0.188	0.007***
Number of hot days (>25) (index)	20.6	19.3	0.000***	0.714
Total precipitation change (index)	0.589	0.119	0.000***	0.622
Heavy rainfall days (>25mm) (index)	0.125	0.111	0.201	0.552
Mean temperature (index)	0.891	0.883	0.010**	0.003***
Wind speed (index)	-1.229	-1.264	0.000***	0.013**

Note: ***, ** and * denote significant differences at 99%, 95% and 90% levels, respectively

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