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CLIMATE-INDUCED SEA-LEVEL RISE

Implications for archaeological taonga at Te Pokohiwi o Kupe | Wairau Bar, Aotearoa New Zealand

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Abstract

Te Pokohiwi o Kupe | Wairau Bar in the Marlborough region is where one of Aotearoa New Zealand's earliest archaeological heritage sites is located, dating back to the early 1300s. This article describes a baseline study to map the effects of present-day and future sea levels on archaeological heritage land at Te Pokohiwi o Kupe. Results suggest that approximately 20% of the heritage land is susceptible

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to a 100-year storm-wave inundation under present climate and sea-level conditions. With 1 m of sea-level rise likely to be reached between 2070 and 2130, approximately 75% of heritage land will be compromised by a 100-year storm inundation event. These results imply that heritage land at Te Pokohiwi o Kupe is already susceptible to inundation by significant storm waves, with potential erosion and loss of archaeological sites becoming more severe as the sea level continues to rise over time.

Keywords

climate change, coastal flooding, hazard risk, taonga, wāhi tapu, Wairau Bar

Introduction

Climate-induced sea-level rise (SLR) and extreme weather events over the next century are expected to increase flood frequency and intensity in coastal low-lying areas of Aotearoa New Zealand, increasing the exposure of assets and potential losses (Paulik, Wild, et al., 2023). Indeed, the accelerating pace of climate change has reshaped global environmental systems (Kulp & Strauss, 2019; Pettorelli et al., 2021), with SLR emerging as one of the most serious consequences (Kopp et al., 2014; Neumann et al., 2015; Vitousek et al., 2017). Driven by the melting of the polar ice caps, thermal expansion of seawater and altered oceanic patterns, sea levels have risen at an unprecedented rate over the past century, with many parts of the Pacific region experiencing rates higher than the global average (World Meteorological Organization, 2024). Coastal zones, which are already ecologically sensitive and densely populated, are amongst the most vulnerable to these changes (Trégarot et al., 2024).

Apart from the immediate threats of coastal erosion, infrastructure damage, resource pressures, human displacement and biodiversity loss, there is a less visible but equally significant impact: the loss of archaeological and cultural heritage (see, e.g., Jones et al., 2024). Archaeological sites capture up to millennia of human history and provide crucial records of past societies and their interactions with the environment (Rowland et al., 2024). Such sites hold significant cultural, spiritual and social significance for local communities. However, the accelerating threat from rising sea levels, coastal erosion and storm intensification places many of these sites at imminent risk of being submerged, damaged or entirely erased from the landscape. This in turn presents challenges pertaining to (a) the loss of irreplaceable evidence and knowledge about past civilisations and (b) the severing of the cultural connections modern societies maintain with their heritage.

This article assesses the effects of climate change–induced SLR on an archaeological heritage site in Aotearoa: Te Pokohiwi o Kupe | Wairau Bar—one of Aotearoa's earliest and most significant cultural heritage sites. We map the present and future scale of sea-level inundation at the site under a warming climate and assess the implications for archaeological site loss. Findings are discussed in the context of cultural preservation and the urgency for implementing interdisciplinary strategies that combine environmental science, archaeology and heritage management to mitigate the loss of these taonga before they are inundated by the rising tides.

Study objectives

The study reported here explored the implications of climate change–induced SLR inundation and likely areas of coastal erosion on Te Pokohiwi o Kupe (see Figure 1). Using available iwi-hapū geospatial information about archaeological taonga and wāhi tapu across the northwest portion of Te Pokohiwi o Kupe, along with high-resolution topographic data of the area, we analysed and mapped the exposure risk to these sites from permanent spring tide (PST) and coastal storm inundation at present sea level and future SLR.

Future SLR was linked with climate change scenarios consistent with the latest guidance from the Intergovernmental Panel on Climate Change (IPCC, 2021) to estimate the future timing of each SLR inundation scenario. The coastal erosion hazards analysis evaluated historical erosion rates using historical aerial and satellite imagery (1947–present). The analysis also estimated the future position of the shoreline associated with slow onset SLR.

The study represents the first high-resolution assessment of SLR and coastal change for the northwest portion of Te Pokohiwi o Kupe at a local scale. Previous national-scale studies of SLR for Aotearoa that encompassed Te Pokohiwi o Kupe (e.g., Paulik, Wild, et al., 2023) were developed for SLR risk-screening purposes and were thus output at a coarser resolution than what was required for the purposes of this study. While the focus of this

FIGURE 1 Te Pokohiwi o Kupe in northeast Te Waipounamu | South Island, showing the present heritage land boundary relative to topographic contours

present study was on developing first-order, high-resolution representations of SLR to inform the dialogue on potential adaptation/rescue options associated with wāhi tapu, the area is known to be at risk from tsunami inundation as evidenced by paleotsunami studies previously carried out in the area (e.g., Clark et al., 2015; King et al., 2017).

Rationale

The northwest portion of Te Pokohiwi o Kupe is one of Aotearoa's most significant historical sites and contains the remains of some of the earliest settlers to these lands (McFadgen & Adds, 2019; Meihana & Bradley, 2018). The site is exposed to multiple hazards, including earthquakes, which can cause subsidence; tsunamis; and extreme weather events such as storms and subsequent inundation. However, there are limited studies which evaluate the longer-term influence of climate change–induced SLR and its implications in the area. This project represents the first site-specific assessment of the potential impacts on and implications for Māori heritage and archaeology of climate change–induced SLR inundation and coastal erosion. It also provides a template for evaluating the impacts of SLR on similar taonga in coastal areas around Aotearoa.

Given the high possibility that a significant proportion of Māori heritage and archaeological resources relating to Māori occupation over the past millennium will erode away unrecorded, this work aims to support knowledge exchange and decision-making about what should be rescued, recorded, why and when. While it may not be possible to answer the question of how long we have with absolute certainty, outputs of this work are expected to help focus dialogue and inform decisions about adaptation and resilience options.

Coastal inundation mapping

Topography and digital elevation model

Te Pokohiwi o Kupe is located in the Wairau Lagoons Wetland Management Reserve and is characterised by an 8 km long gravel bar that is bound to the Vernon Hills in the southeast (Clark et al., 2015; King et al., 2017) (see Figure 1). The

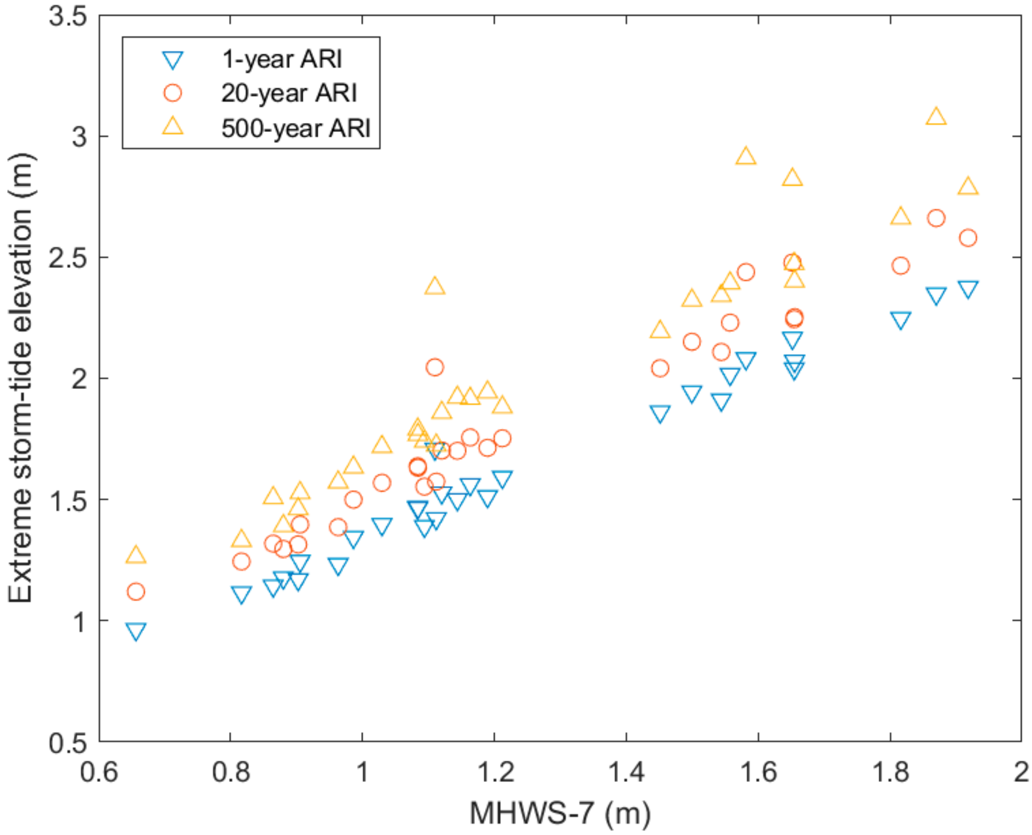

FIGURE 2 Linear relationships of stormtide and MHWS-7. Data points are from the tide and extreme value analysis of Stephens et al. (2020), which used individual tide gauge records from around Aotearoa.

FIGURE 3

1 km stretch on the northwest of the gravel bar where the heritage land is located is approximately 600 m in width, with the highest elevation approximately 4–5 m above mean sea level (MSL). Light detecting and ranging (LiDAR) topography data reveal that the heritage land is predominantly located in an area that is less than 3 m above MSL.

The availability of high-resolution LiDAR enables the development of an accurate digital elevation model (DEM) for use in simulating representative coastal inundation models in the area. A 1 m resolution DEM was created by averaging the 2014 Blenheim LiDAR point cloud (LINZ, 2018). Only points classified as "ground" were used for the DEM generation. The 1 m gridding was calculated by averaging all the point values located within 1.4142 m of each cell centre. The datum—the reference surface that defines a zero point for measuring elevations and depths—used was the New Zealand Vertical Datum 2016 (NZVD2016) (EPSG: 7839),* the same as the original dataset. Bathymetry data for the ocean and estuary were not included in the DEM. Bathymetry data are required for dynamic inundation modelling but not necessary for the static inundation modelling of this study.

Tide, datum and extreme storm tide

Analysis of coastal inundation requires an assessment of the mean high-water spring (MHWS) tidal level. For this study, MHWS was calculated as the 10th highest percentile of 18 years of astronomical high tide as predicted by the New Zealand tidal model (Goring, 2001), which is sometimes referred to as MHWS-10. The value for MHWS-10 was calculated as 0.74 m above MSL.

* EPSG stands for European Petroleum Survey Group, a scientific organisation that maintains a geodetic parameter database with standard codes. An EPSG code is a unique identifier used to represent coordinate systems and other geodetic properties like datums, spheroids and units.

Using the same methodology, the 7th highest percentile of high tides (MHWS-7) was calculated as 0.77 m above MSL. This value is useful in determining extreme storm-tide levels. Using tide gauge data for around Aotearoa, Stephens et al. (2020) found linear relationships between MHWS-7 and extreme storm-tide level for given return intervals (see Figure 2). Using these relationships, the 100-year average recurrence interval (ARI) can be calculated. The 100-year ARI represents the storm-tide conditions that are, on average, exceeded once in a 100-year period. This does not however, mean that the average period between such events is 100 years, and there is a low probability of observing such events multiple times in a given year. For Te Pokohiwi o Kupe, the 100-year ARI storm tide was calculated as 1.30 m MSL.

Wave contribution to inundation was simplified as a single value of 0.5 m of wave setup. This is an over-simplification of wave contribution to inundation, but it can provide a first-order assessment of inundation.

Converting MSL values to NZVD2016 is not trivial in the Blenheim region because of ongoing post-seismic land movement following the 2016 Kaikōura earthquake. However, Stephens and Paulik (2023) recently published an update of the relationship between MSL and NZVD2016 for New Zealand's main seaports. They report a datum shift of –0.12 to –0.13 m for the closest ports to Blenheim (i.e., Wellington and Picton).

Inundation modelling

Inundation extent and depth were calculated using a static inundation assessment, which is also referred to as a bathtub assessment. The storm-tide and wave setup level are intersected with the DEM to derive inundated surfaces. All the values of inundation level above ground are considered wet, regardless of their connectivity to the ocean or estuary. While this is a conservative estimate, it provides insight into the potential for inundation by shallow ground water that is uplifted by storm tide or spring tides.

Timing of sea-level rise scenarios

The modelled SLR scenarios were then correlated with the corresponding SLR projections for Aotearoa consistently with the Shared Socioeconomic Pathways (SSPs) as defined in the

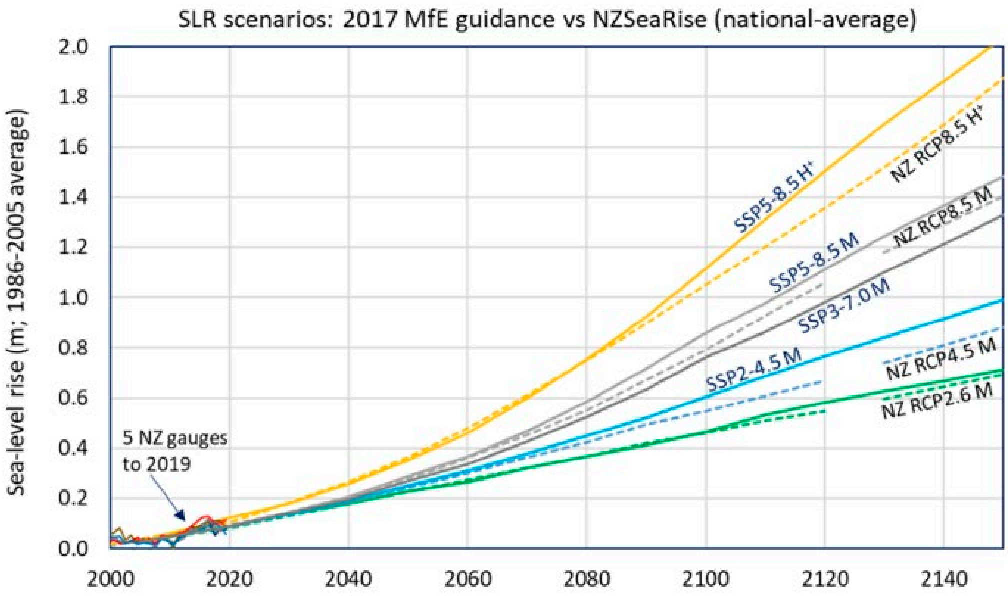

FIGURE 3 Comparison of SLR predictions for Aotearoa from the 2017 Ministry for the Environment guidance (dash lines) and the 2022 update (plain lines) (Ministry for the Environment, 2022).

RCP = Representative Concentration Pathway. RCPs are a range of scenarios used in climate change modelling that represent different levels of radiative forcing (the amount of energy imbalance caused by greenhouse gases) expected by the year 2100, ranging from 2.6 Watts/m^2 (strong mitigation) to 8.5 Watts/m^2 (high-emissions scenario) (see IPPC, 2014).
H+ = higher extreme scenario.

TABLE 1 Approximate years when various national sea-level rise increments could be reached

SLR	Year achieved for SSP1-2.6 (median)	Year achieved for SSP2-4.5 (median)	Year achieved for SSP3-7.0 (median)	Year achieved for SSP5-8.5 (median)	Year achieved for SSP5-8.5 H+ (83rd percentile)
0.3	2070	2060	2060	2055	2050
0.4	2090	2080	2070	2065	2060
0.5	2110	2090	2080	2075	2065
0.6	2130	2100	2090	2080	2070
0.7	2150	2115	2100	2090	2080
0.8	2180	2130	2110	2100	2085
0.9	2200	2140	2115	2105	2090
1.0	>2200	2155	2125	2115	2095
1.2	>2200	2185	2140	2130	2105
1.4	>2200	>2200	2160	2145	2115
1.6	>2200	>2200	2175	2160	2130
1.8	>2200	>2200	2200	2180	2140
2.0	>2200	>2200	>2200	2195	2150

Source: Ministry for the Environment (2022).

IPCC Sixth Assessment Report (2021). The SSPs are five climate change scenarios of projected socioeconomic global changes up to 2100. This allowed us to estimate the future timing at which each modelled SLR scenario is likely to be reached (see Figure 3 and Table 1).

Heritage land exposure mapping

The heritage area on the northwest portion of Te Pokohiwi o Kupe delineated by Te Rūnanga a Rangitāne o Wairau was digitised in QGIS* to produce a geospatial polygon representing the heritage land boundary. The polygon was then rasterised and gridded at the resolution of the baseline DEM (i.e., 1 m grid) using QGIS geoprocessing tools, with each grid representing a land area of 1 m^2.

This provided the exposure layer, which was then combined with each SLR scenario inundation model in the RiskScape multi-hazard impacts and loss modelling software (Paulik, Horspool, et al., 2023) to output metrics of total heritage land area (m^2) likely to be affected by inundation in each modelled scenario. That is, gridded cells from the heritage area polygon which intersected with a wet grid cell from each inundation model were output as being affected/exposed to inundation. A schema depicting the exposure modelling workflow is shown in Figure 4.

Results

Permanent spring tide inundation and heritage land exposure

The results shown in Figures 5 and 6 indicate that PST inundation with 0.5 m of SLR begins to affect approximately 16% of the heritage area by 2045–2060. With 1 m SLR, approximately 53% of the heritage area becomes affected between 2070 and 2130. By that time, the through to the east of the heritage site will be flooded by MHWS tides.

100-year storm inundation and heritage land exposure

Figures 7 and 8 show that a 100-year ARI storm inundation under present sea levels is likely to inundate approximately 20% of the heritage land area. With 1 m SLR, the 100-year storm

* QGIS is a geographic information system (GIS) software that is free and open-source (QGIS Development Team, 2024).

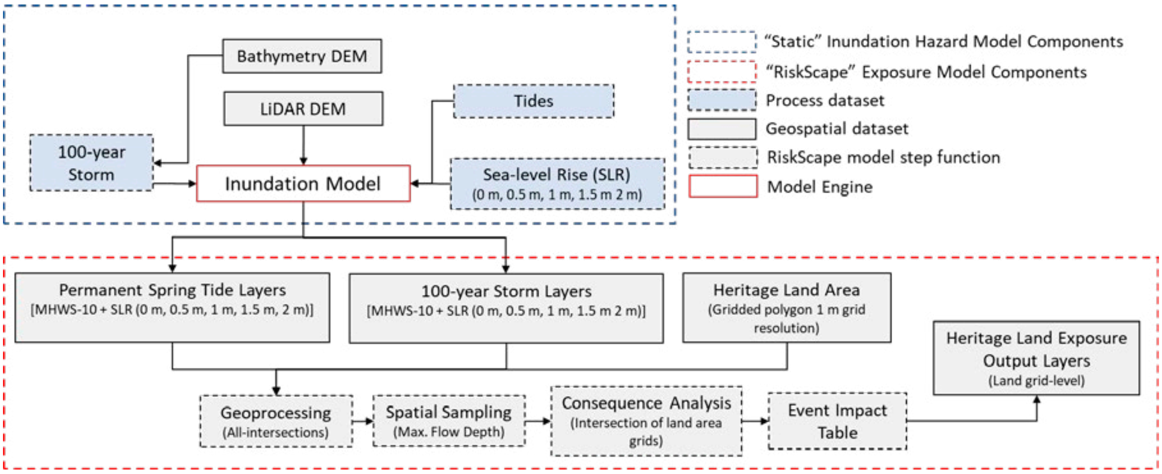

FIGURE 4 Schema of the RiskScape exposure risk workflow used to calculate the heritage land area exposure to each SLR scenario

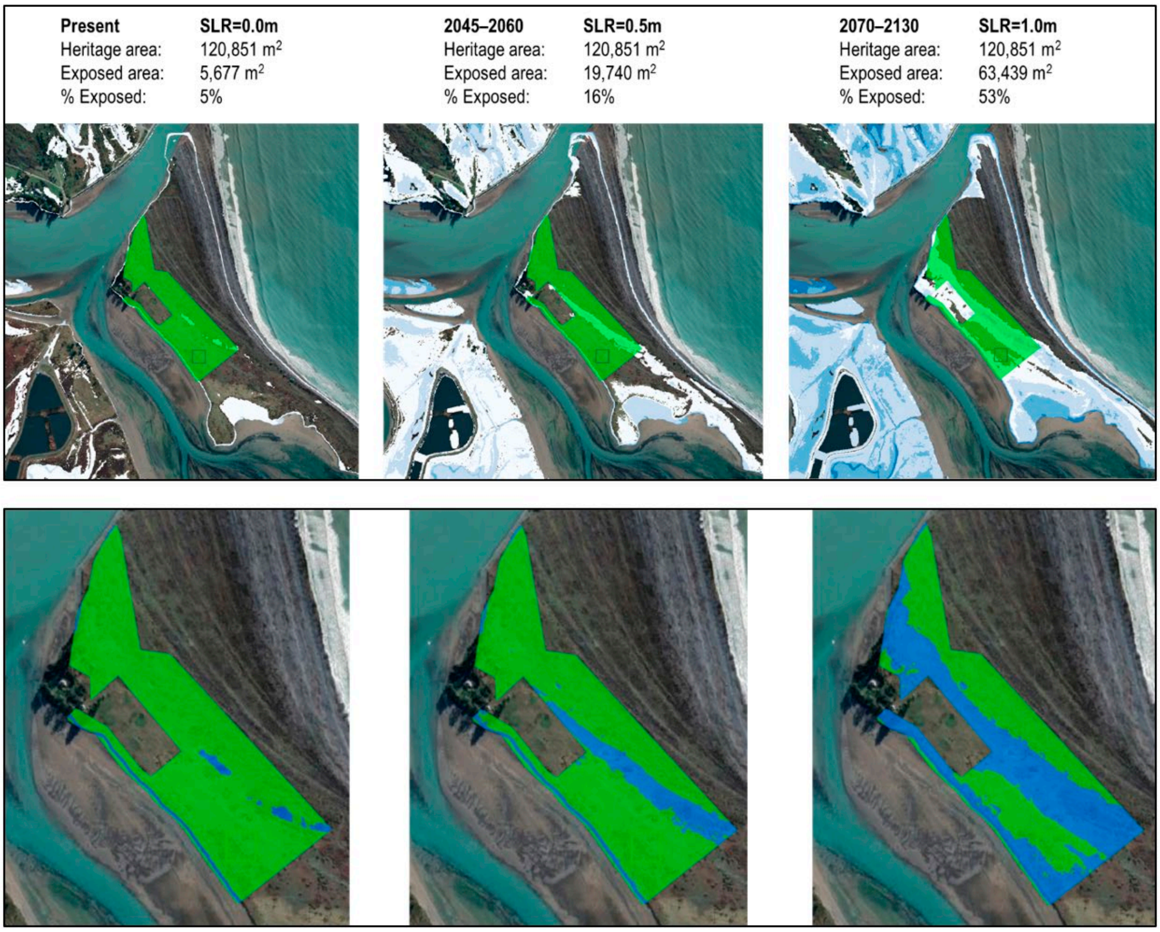

FIGURE 5 Results of heritage land area exposed to each PST inundation scenario under present and future SLR. Top panels: PST inundation of the northwest portion of Te Pokohiwi o Kupe under present sea level (left); 0.5 m of SLR (middle); and 1.0 m of SLR (right). Bottom panels: PST inundation exposure (blue shading) of Te Pokohiwi o Kupe heritage land under present sea level (left); 0.5 m of SLR (middle); and 1.0 m of SLR (right). Green shading depicts areas not inundated.

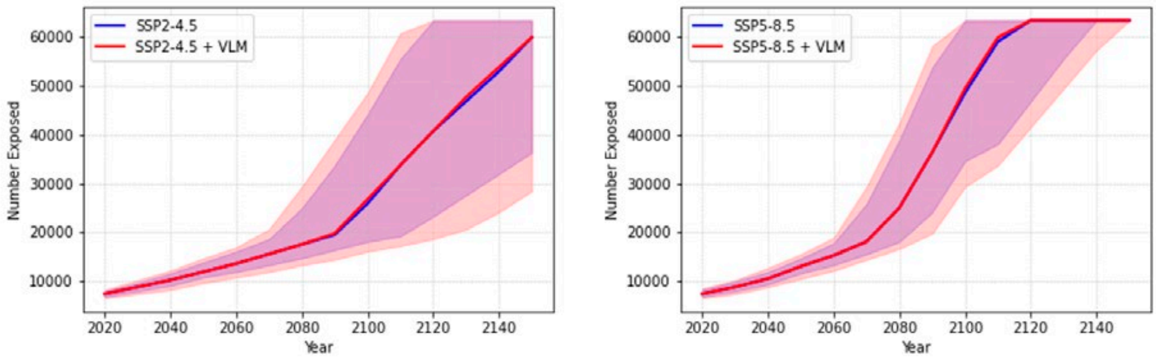

FIGURE 6 Estimated heritage land exposure (m^2) due to SLR under a warming climate for PST inundation under SSP 2-4.5 (left) and SSP 5-8.5 (right)

Note: VLM = vertical land movement (estimated for Aotearoa; see Naish et al., 2024).

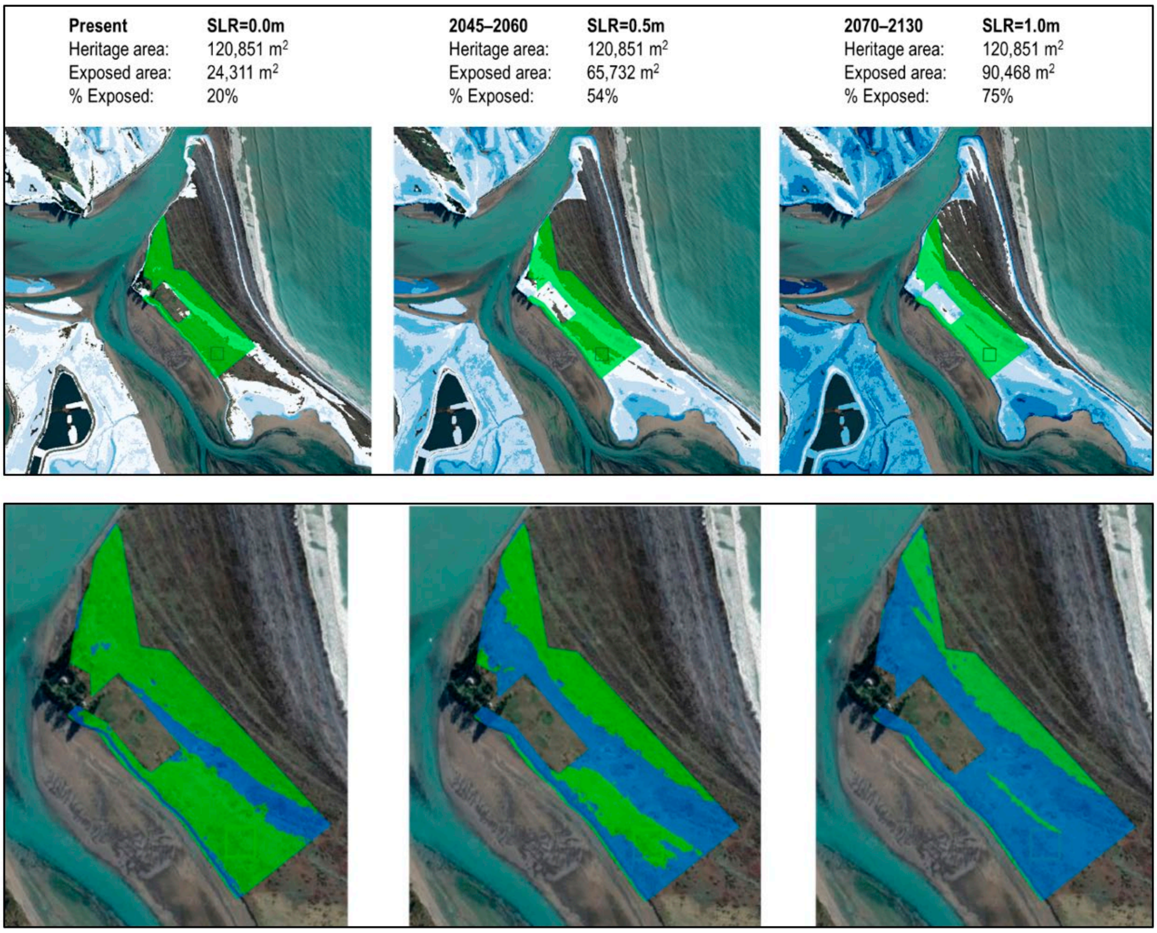

FIGURE 7 Results of heritage land area exposed to each 100-year storm inundation scenario under present and future SLR. Top panels: 100-year storm inundation of the northwest portion of Te Pokohiwi o Kupe under present sea level (left); 0.5 m of SLR (middle); and 1.0 m of SLR (right). Bottom panels: 100-year storm inundation exposure (blue shading) of Te Pokohiwi o Kupe heritage land under present sea level (left); 0.5 m of SLR (middle); and 1.0 m of SLR (right). Green shading depicts areas not inundated.

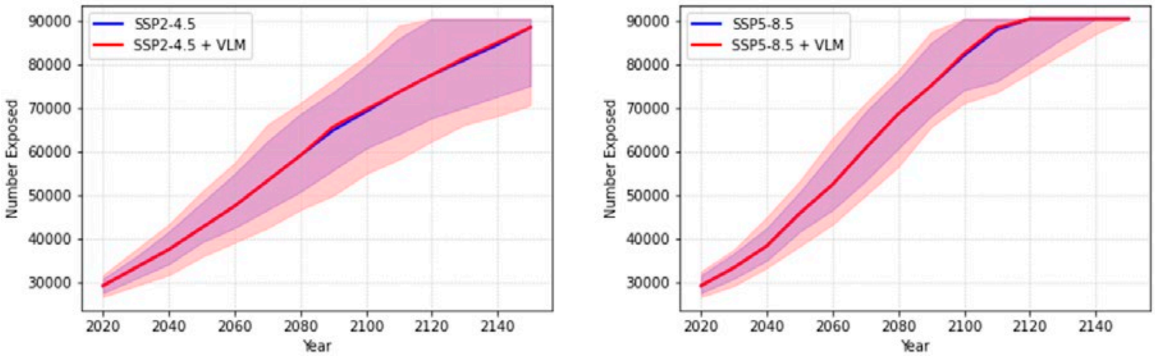

FIGURE 8 Estimated heritage land exposure (m²) due to SLR under a warming climate for PST plus 100-year ARI extreme sea-level inundation under SSP 2-4.5 (left) and SSP 5-8.5 (right).

inundation affects approximately 75% of the total heritage area between 2070 and 2130.

Discussion

The findings of this study suggest that approximately 20% of the heritage land is susceptible to a 100-year storm wave inundation under present climate and sea-level conditions. Approximately 54% of heritage land becomes affected by a 100-year storm inundation event with a 0.5 m increase in sea level, which is likely to be reached between the years 2045 and 2060 (the next 22–37 years). With 1 m of SLR likely to be reached between the decades 2070–2130 (next 47–107 years), approximately 75% of heritage land then becomes compromised by a 100-year storm inundation event.

With regard to PST inundation, heritage land gradually becomes more inundated, with approximately 16% affected once the sea level reaches 0.5 m above present levels in the next 22–37 years. When the sea level reaches 1 m above present levels—between 2070 and 2130—approximately 53% of heritage land becomes affected.

These results imply that heritage land on the northwest portion of Te Pokohiwi o Kupe is already susceptible to inundation by significant storm waves and that these effects will become more prominent as sea level continues to rise over time. In addition, close to a fifth of the total heritage area is susceptible to PST inundation alone in the next 22–37 years, with more than half susceptible by as early as the next 50 years.

Future work to complement the baseline assessment presented here will include a coastal geomorphological change analysis under a warming climate to evaluate the potential effects of coupled inundation and erosion. This would encompass incorporating the potential effects of co-seismic land movement due to the possibility of large earthquakes, which are known to induce significant subsidence and associated erosion in the area (e.g., the 1848 and 1855 earthquakes) (McFadgen & Adds, 2019), and how these processes potentially exacerbate the heritage land exposure estimates made by this study.

Implications

The first-order estimates of heritage land exposure presented above and the potential loss of archaeological taonga at Te Pokohiwi o Kupe highlight the urgency of identifying adaptation and implementation options to preserve and/or rescue wāhi tapu and taonga within the heritage area. Key questions that emerge from the evidence presented in this study include, but are not limited to:

- What level of risk is acceptable, and what level of urgency is needed for preserving wāhi tapu at the site? Are decisions and actions required now or in several years to preserve and/or relocate wāhi tapu at threat of inundation? If relocation is an option, are there protocols to support and safeguard the rescue and relocation of wāhi tapu taonga, such as karakia for exhuming ancestral remains, etc.? Is there an acceptable location identified for relocating wāhi tapu remains, if relocation is an option?
- What options are available and what needs to happen to implement potential rescue activities? Who needs to be involved, and whose endorsement and/or permission is required? What implementation logistics are required?
- What resources are available to implement adaptation and/or rescue works? What are

the main financial costs and available budget sources at local, regional and national scales?

These questions are not intended to be prescriptive, but rather to help provide guidance to support ongoing dialogue on potential next steps in relation to adaptation and rescue/relocation of archaeological taonga at the site. More importantly, the findings of this study highlight the importance of undertaking similar local-scale, site-specific analyses of SLR implications on archaeological taonga in other parts of Aotearoa and in coastal environments across the Pacific region.

Limitations

The SLR inundation models developed for this study are representative of LiDAR topography captured in 2014 and do not account for dynamic changes in the geomorphology (size/shape and composition) of the gravel bar, including potential subsidence at future points/periods in time corresponding to the SLR scenarios presented. In addition, the compounding effects of SLR plus fluvial flooding from the Wairau River on inundation at Te Pokohiwi o Kupe were not considered in this analysis. Similarly, the compounding effects of other extreme events such as tsunami inundation and how exposure risk changes over time under a warming climate (e.g., Welsh et al., 2023) have not been considered in this study.

The estimated future timing of the SLR scenarios presented here are based on climate change scenarios that are consistent with the IPCC Sixth Assessment Report (2021), providing first-order representations of likely scenario inundation under a changing climate at a localised scale. These representations can be used to inform dialogue on adaptation options associated with wāhi tapu in the area, as well as directions for future investigations.

Climate change and SLR may affect Te Pokohiwi o Kupe in ways that have not been analysed here. For example, SLR will also raise the level of groundwater and its salinity, exposing assets that are not currently affected by groundwater or saltwater intrusion (Bosserelle et al., 2022). The challenges outlined above will need to be addressed in follow-up studies at Te Pokohiwi o Kupe in order to build on the baselines presented here.

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Glossary

hapū	sub-tribe
iwi	tribe
kaitiaki	guardians
karakia	traditional prayers
taonga	Māori assets of cultural and/or historical significance; treasured belongings
wāhi tapu	sacred sites

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