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Original article

Regional implementation of coastal erosion hazard zones for archaeological applications

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ABSTRACT

Coastal archaeological heritage is in danger of being lost to coastal erosion, the risk of which is amplified by accelerating sea-level rise (SLR). In Aotearoa/New Zealand, coastal archaeological heritage is closely associated with indigenous ancestral communities, but our understanding of the spatiotemporal variability in coastal erosion risk for cultural heritage is limited. Coastal erosion hazard zones have typically been implemented to manage erosion risk to modern infrastructure at regional scales. In this study, we applied a hazard zone methodology in the context of coastal archaeological heritage for a selected region of Aotearoa (Te Tai Tokerau/Northland). Historical coastal change analyses reveal that most beaches in the region have been stable or slightly accretionary over the past ~80 years, but a reversal of this trend is likely under the projected SLR, which is expressed in the coastal erosion hazard zones. Our analyses indicate that ~8 % (155) of coastal archaeological sites in Te Tai Tokerau/Northland may be at risk of erosion with a relatively modest 20 cm of SLR, which is expected for the region by 2040, and ~19 % (356) of sites are threatened by 1 m of SLR. Scenarios are presented that should assist a broad range of stakeholders to assess heritage risk and provide an opportunity for coastal managers to include heritage within adaptive planning pathways.

Introduction

Coastal areas of Aotearoa/New Zealand are exposed to coastal hazards, such as erosion and inundation, which are expected to worsen under global climate change and accelerating sea-level rise (SLR) [1–3]. The Intergovernmental Panel on Climate Change (IPCC) projections indicate that global SLR is likely to reach between ~29 cm and ~110 cm above present sea level by 2100 [4], and around Aotearoa/New Zealand the sea level is projected to rise between ~42 cm (Representative Concentration Pathway (RCP) 2.6 M (Median) and ~102 cm (RCP8.5 H+) by the year 2100 [5]. In the near-future ~20 cm of sea-level rise is projected to occur by the year 2040 across all three scenario trajectories: RCP2.6 M, RCP4.5 M, and RCP8.5 M [5,6]. Additionally, with the RCP8.5 H+ scenario, this rise is expected to occur even earlier, around 2035 [5–8].

Sea-level rise, coupled with storm surge and wave action, is expected to lead to an increase in coastal erosion and flooding globally (e.g., [9–13]), as well as onshore migration of beaches, barrier beaches, dunes, and wetlands. Erosion and landward migration of coastal landforms will impact coastal heritage, including culturally significant archaeological sites [14–16].

To address the risks associated with coastal erosion, a variety of assessment and planning protocols have been employed worldwide (see [17,18]). Foti et al. [19] noted that methodologies vary depending on the factors considered, the specific coastal regions under examination, and the scale of application [20–23]. Various methods and terminologies are utilized in the assessment of coastal erosion hazards, such as Coastal Erosion Hazard Zones (CEHZs), weighted coastal hazard assessment, multi-criteria assessment employing the Analytic Hierarchy Process (AHP), and beach hazard indexes. These approaches collectively evaluate and quantify the risks associated with coastal erosion. CEHZs involve the

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delineation of specific erosion-prone zones based on relevant factors, such as short-term erosion, dune stability, long term recession and coastal response to sea level (Shand 2015; [10,24]). In weighted coastal hazard assessment, importance to different hazard factors is afforded through the application of weights, which culminate in a weighted sum or score that provides an overall measure of coastal vulnerability [21,25]. Conversely, multi-criteria assessment simultaneously considers various criteria using decision-making tools like AHP (Analytical Hierarchy Process), integrating environmental, social, and economic factors for a comprehensive evaluation that facilitates prioritization based on a holistic understanding of coastal hazards [26]. Some beach hazard indexes aim to simplify hazard assessment by creating an index that combines parameters like wave energy and beach slope to assess risk [27]. Despite their shared goal of assessing coastal erosion hazards, these methods differ significantly in their specific approaches, data inputs, and analytical frameworks, highlighting the diverse methodologies available for erosion hazard assessment. Fuchs et al. [28] noted that coastal hazard assessments tend to focus on evaluating the consequences for critical infrastructure and can overlook aspects such as biodiversity and archaeology [29]. Similarly, [30] emphasize the necessity of considering the indirect effects of rising sea levels and human adaptation on biodiversity and conservation, departing from a historical focus on adaptation solely for socio-economic objectives.

CEHZs or coastal setback zones have been the primary statutory tool used by local government in Aotearoa/New Zealand for managing present and future coastal development [31]. This applies to both the redevelopment of existing properties and the establishment of setbacks on greenfield development [1]. Setback lines incorporate short-term storm impacts and can be combined with long-term trends arising from rising sea levels and the progressive erosion of the shoreline [32]. At present, most CEHZ methods do not consider complex climate change effects and sensitivities associated with future changes in groundwater, beach sediment supply, catchment runoff budgets, wave conditions, storm magnitude and frequency [31–33]. All these factors influence coastal behavior and exclusion adds uncertainty to CEHZs.

CEHZs zones have incorporated SLR into their determination [31]. Historically, coastal response to SLR within New Zealand has been mainly estimated using the Bruun rule [32,34]. The Bruun rule is a simple geometric model based on the assumption that an equilibrium seabed/sand beach profile erodes directly in proportion to the rate of SLR through offshore sand transport (e.g. [35]) although modifications have been suggested in the case of onshore transport [36]. There has been extensive debate regarding the use of this model (e.g. see [14,37–40]). Empirical evidence for the Bruun-effect is limited (e.g. see [38] and [40]) and there are serious physical limitations within the model, including uncertainties surrounding the concept of closure depth, the assumption of uni-directional offshore transport, and lack of consideration of accommodation space and lateral sediment transport gradients [14,41]. However, few alternative models exist, and those that do are inevitably more difficult to apply (e.g. [39,41]).

Comparing CEHZ methodologies across all sections of Aotearoa's coast is challenging due to the diverse practices employed by regional councils [31]. Councils have typically prioritized assessing coastal hazard risk in areas considered to pose the highest economic and social risks [1]. This means that it is much less common to see CEHZs applied on undeveloped coastlines lacking substantial infrastructure. It is also apparent that CEHZs provide an indication of potential risk rather than an exact prediction of future hazards (Storbjörk and Hjerpe, 2014; [32]). Despite these limitations, CEHZs can have a useful role in assessing risk to many coastal archaeological sites in Aotearoa/New Zealand, including those in areas not typically prioritized by regional council's existing CEHZ assessments, such as less developed areas of coast [15].

In Aotearoa/New Zealand the Resource Management Act (RMA) 1991 and New Zealand Coastal Policy Statement ([42] require the identification, assessment, protection, and management of areas or sites of significance or special value to Māori, which includes archaeological sites. The NZCPS emphasizes the need for regional hazard assessments over 100-year timeframes [42]. The Māori concept of taonga, encompassing treasures such as artifacts, waka (canoe), toki (adze), and koiwi (human remains), holds significance in the context of archaeological sites that may be at risk. Of concern is loss of these sites as taonga and how the exposure of these sites through hazards such as coastal erosion could potentially lead to the illicit selling of taonga contained within, emphasizing the need for protection and preservation. Under the Heritage New Zealand Pouhere Taonga Act (2014, Aotearoa/New Zealand's governing legislation related to archaeological sites), Māori archaeological sites contain wāhi tapu: places that are sacred to Māori in the traditional, spiritual, religious, ritual, or mythological sense [43], section 6]. The NZCPS recommends the development of methods, such as alert layers and predictive methodologies, to identify areas of high potential for undiscovered Māori heritage, such as coastal pā or fishing villages [44]. However, there are few datasets available to aid in the protection and management of archaeological sites at risk (see [15] for a recent review of these datasets).

The potential scale of at-risk archaeological sites to SLR globally has prompted multiple GIS (Geographic Information System) investigations of coastal hazards and associated impacts (e.g., [20,21,45–53]). These studies typically determine hazard risk to archaeological sites using user-defined and weighted (in terms of risk) environmental variables, such as elevation, distance from site to shoreline, geology, geomorphology, and historical shoreline change. Many studies are limited by uncertainties concerning inclusion or exclusion of different environmental measures and varying attempts to weigh and score variables for indexes (see [54]). Similarly, published coastal archaeological risk assessments are limited in their handling of the dynamic nature of SLR on the coast. Some studies have attempted to model the impact of projected SLR over the next century [55–61], but this has often been done by simplistic projection of future flood elevations onto a DEM (digital elevation model), without specific consideration of coastal erosion.

In this paper we present a methodology for calculating CEHZ scenarios for archaeological sites using SLR projections and parameters relating to wave climate, dune stability, historic erosion rates, short-term coastal response to storms, and long-term coastal response to SLR. To our knowledge, it is the first specific application of a CEHZ methodology to assess archaeological risk associated with SLR-driven coastal erosion.

Research aims

Our research centers on the utilization of CEHZ scenarios to evaluate coastal archaeological sites in Aotearoa/New Zealand at the regional level. The approach presented herein encompasses dynamic coastal parameters like short-term erosion, long-term recession, dune stability, and coastal response to sea-level changes (Fig. 1). This targeted focus recognizes the susceptibility of archaeological sites to coastal hazards, particularly in the context of rising sea levels. Emphasizing the specific needs of archaeological preservation, our methodology aims to improve the applicability of CEHZs for targeting protection of culturally significant sites. The regional-level application enables a specific examination of diverse coastal landscapes, considering the distinct characteristics and vulnerabilities of archaeological sites in various areas. Consequently, the paper presents a practical tool for effectively managing and mitigating risks to coastal archaeological heritage, contributing to

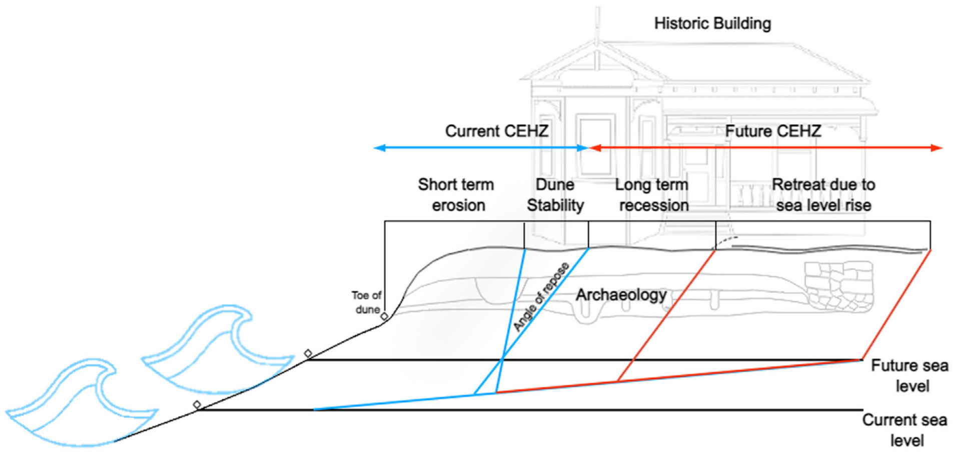

Fig. 1. Coastal hazard erosion schematic showing erosional risk to archaeological sites (subsurface) and historical buildings on unconsolidated coasts. Figure adapted from Shand et al., [32,62].

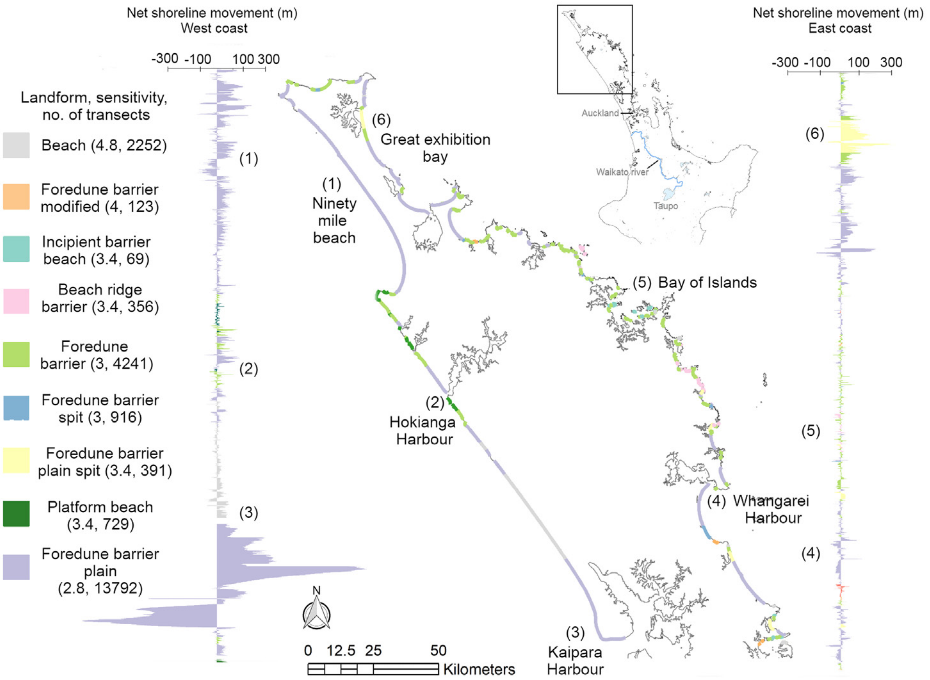

Fig. 2. Map showing Te Tai Tokerau's position within the North Island of Aotearoa/New Zealand and the distribution of coastal landforms. Adjacent graphs show the frequency of erosion and accretion from the north to the south on both the east and west coasts. Landform types are colour coded; displayed also are the sensitivity values for, (1 = low, 5 = high), and the number of transects intersecting, each landform type. The landform classification utilized in this study follows the coastal classification developed by Nigel et al., [69], and the shoreline movement is sourced from Dickson et al. (2021).

a more adept approach amid evolving environmental challenges. Additionally, it explores the integration of modern adaptive tools like Dynamic Adaptive Policy Pathways (DAPP) in this management framework.

Materials and methods

Background

Geomorphological context

Te Tai Tokerau is located in the northern region of Aotearoa/New Zealand's North Island (Te Ika a Māui) (Fig. 2). It is characterized by two distinct coastlines, with the east coast being rocky and indented with intermittent headlands, pocket beaches, and a few barrier plains, while the west coast has a straighter shoreline dominated by large composite barriers and harbors [63]. The difference in the physical nature of these coastlines is due to the small stream drainage basins in the hinterlands of the east coast, which contribute little sediment to the coastal system [64]. Most of the fluvially derived sediment for the west coast is transported to the coast by the Waikato River, which flows from the central North Island volcanic zone onto the west coast south of Auckland and is dispersed northward by strong longshore currents driven by high prevailing southwest wave action [65–67]. The east coast lacks a large external sediment supply and is exposed to low to moderate wind and wave conditions, occasionally disrupted by ex-tropical cyclones [68]. This results in divergent sediment budgets on the east and west coasts, with the east coast having relatively limited sediment supply compared to the west coast.

Dickson et.al. (2021) provide an analysis of coastal erosion and accretion patterns around Te Tai Tokerau over the past 80 years. They found localized hotspots of erosion and accretion on both

Table 1
Table showing datasets and their sources used in this paper.

Data	Description	Source
ArchSite	ArchSite is an online database that contains information about recorded archaeological sites in Aotearoa/New Zealand.	New Zealand Archaeological Association website accessed from https://nzarchaeology.org/ArchSite
LINZ mean high water	This dataset defines the Mean High-Water coastline of Aotearoa/New Zealand and offshore islands at a scale of 1:50,000	Land information data service accessed from https://data.linz.govt.nz/layer/105,085-nz-coastline-mean-high-water/
LiDAR	The DEM is available as a Northland LiDAR 1 m DEM layer (2018–2020)”	Land information data service accessed from https://data.linz.govt.nz/layer/110,757-northland-lidar-1m-dem-2018–2020/
Bathymetric data	NIWA’s bathymetry model of Aotearoa/New Zealand as a 250 m resolution raster. The 2016 model is a compilation of data digitised from published coastal charts, digital soundings archive, navy collector sheets and digital multibeam data sourced from surveys.	NIWA online data portal accessed from https://data-niwa.opendata.arcgis.com/datasets/a2582b1eb3584237a3b50418f379ca84/explore. Mitchell, J.S., Mackay, K.A., Neil, H.L., Mackay, E.J., Pallentin, A., Notman P., 2012. Undersea New Zealand, 1:5000,000.
Coastal hub SWAN Hindcast	The database comprises a set of integrated and partitioned wave parameters downscaled from a global wave hindcast with SWAN. Three-hourly data at a 9Km resolution is available for visualisation and download throughout Aotearoa.	Coastal hub data portal accessed from https://uoa-eresearch.github.io/waves/hindcast#NZ-HIST-000-HSIGN⟨13:glyph 0: name="sbnd"⟩⟨/13:glyph⟩Hsig@1993–01–01 %2000:00; Albuquerque, J., Antolínez, J. A., Méndez, F. J., & Coco, G. (2022). On the projected changes in New Zealand’s wave climate and its main drivers. New Zealand Journal of Marine and Freshwater Research, 1–38.
Historical coastal change data	80 years of historical coastal change obtained from historical aerial and satellite imagery.	RNC accessed from https://resiliencechallenge.nz/aotearoa-new-zealands-changing-coastline/
Coastal landform classification	NZ Coastal landform type – describes the different geomorphological components that occur along the shore. This variable has 25 attributes such as beach ridges, foredune barriers, deltas, spits	Accessed from NIWA data portal https://data-niwa.opendata.arcgis.com/maps/b818765d4e2c4aa79fcf89ab2d3c009c/about

coasts (e.g., sand spits, river mouths, and harbour entrances), but observed that many east coast beaches have generally been stable, whereas the west coast has been marked by a seaward advance of the coastline (indicated by the dune toe vegetation line) in many areas, attributable either to sediment-budget driven coastal accretion or revegetation of sandy areas.

Archaeological context

Numerous occupation sites were established along Aotearoa/New Zealand’s coast following the arrival of the first Polynesian settlers around 1250 CE [70–73]. In Te Tai Tokerau, rivers, bays, estuaries, and harbours were central to the earliest human activity, as they provided access to marine resources and facilitated horticulture and fishing (e.g. [74,75]). Later settlers, particularly Europeans, also focused development along the coast, particularly in harbors and estuaries, establishing homes, gardens, and industries, including sealing and whaling (e.g. Hamel 2001; Smith 2008).

Methods

This study outlines a method for implementing regional CEHZ scenarios to assess the potential impact of coastal erosion on archaeological sites within 1 km of the mean high-water mark as defined by the national mapping agency Land Information New Zealand (LINZ), and below 25 m elevation. Coastal landform categories were referenced from Nigel et al., [69]. The CEHZs are presented as scenarios because we identify SLR scenarios based on increments of sea level rise.

The method is conceptualized in Figs. 1 and 4 and follows Shand et al., [32] using Equations 1 – 4 (see also Gibb 1998, T & T 2016 and Shand et al., 2019, Appendix 3). The method uses several datasets, including high-resolution LiDAR, bathymetric data, wave hindcast, historical coastal change data and SLR projections to evaluate four key parameters of coastal change – short term erosion, dune stability, long term recession, and future SLR, the results of which are integrated to create the final CEHZ scenarios (see Appendix 3 Table 1 for datasets used). We developed a workflow (Fig. 4) that is semi-automated, utilizing ArcGIS, QGIS, R suite, and Python with geospatial libraries Geopandas, Shapely, and Rasterstats [76–78] to integrate geospatial data at 10 m intervals along the open sandy coast of the study area. Estuaries and rock coasts are not considered as this would require a different CEHZ calculation see – [32]. The calculation of key parameters is described below.

Short-term erosion

Short-term beach erosion (ST) occurs due to a single storm or clusters of storm events, seasonal fluctuations in wave climate, or changes in sediment supply, resulting in changes in the horizontal shoreline position. A comprehensive study was conducted by Shand et al. (2019) to determine short-term erosion values for the east and west coasts of Te Tai Tokerau. The researchers utilized statistical and numerical methods to compile a consolidated distribution based on wave climate. To ensure the accuracy of our analysis, we opted to use an average ST value of 15 m, which aligns with the range of moderate and high wave climate values for both coasts. This conservative estimate accounts for potential variations and uncertainties within the data, as well as the potential impact of a single storm on an archaeological site, which can be more damaging than slow long-term change (see Howland and Thompson, [79]). Given the severity of storms in the region, we deemed the choice of a 15-meter average value to be appropriate for both coasts.

Long-term recession

The long-term (decadal scale) movement of the beach profile (LT) can be influenced by changes in relative sea level, coastal sediment supply, anthropogenic influences, and long-term climate cycles [80,81]. Linking coastal change data to specific environmental drivers is difficult as multiple factors such as SLR, storm surges, high waves, sediment budgets, and engineering projects influence coastal change rates [82,83]. Long-term datasets spanning multiple decades to are needed to calculate long term coastal change rates. Within the study area, historic coastal change along all open sandy coasts has been reconstructed by Dickson et al. [84] using comparisons of the position of the vegetation edge (which often corresponds to the dune toe) from 1938 to 2020. For our analysis, we used the mapped coastal vegetation edge from Dickson et al. [84] as a shoreline proxy input for Digital Shoreline Analysis System (DSAS), which is a free extension for ArcMap that uses the point-transect intersect method to calculate rate of coastal change statistics [85]. DSAS calculates several coastal change metrics, including the End Point Rate (EPR), which measures the change in position of a shoreline proxy between two specified endpoints during a defined time. EPR values for 36,727 transects spaced every 10 m alongshore (Fig. 4) were used as the LT values in the CEHZ calculation. Positive historic LT values (accretion) were set to zero following the approach of Morton and Mckenna [86] and Shand et al., (2019). This can be considered a precautionary approach, because while the coast may have historically accreted, it is unclear whether that LT trend could be maintained under accelerating future SLR.

Dune height and stability calculation

The dune stability factor (DS) demarcates the area of potential risk to erosion landward of an erosion scarp developed on a coastal dune [32]. This factor assumes that storm erosion leads to an oversteepened scarp that adjusts to a stable angle of repose (for loose dune sand) following storm erosion. Dune slope (ds) can be calculated using Equation 1, which is derived from the dune height. DS = (Hdune / 2) * tan (a sand). To determine the dune height, it was extracted from LiDAR elevation data within a 100-meter coastal buffer within 100 m of the shoreline (Fig. 4). Subsequently, the highest elevation along each DSAS transect was identified and extracted using zonal statistics (see Appendix 1).

Given the diverse range of dune sizes in Te Tai Tokerau, some reaching heights of up to 128 m, larger dunes are likely to have a greater surplus of sediment. In such scenarios, a storm-induced scarp could lead to an overburden depositing at the dune toe, resulting in a different adjustment trajectory of the dune. Considering this, we opted to cap the dune height at 15 m, guided by the maximum value observed in the sample population of extracted dune heights (Supplementary Figure 1). This decision stems from our recognition that incorporating the original variable would lead to an overestimation of dune stability post-storm, and it inadequately considered the physical response of larger dunes to storm erosion.

Coastal response to SLR

Incremental SLR projection values of 20 cm, 40 cm, 60 cm, 80 cm, and 100 cm were used in this study (c.f. the range of 0.29 to 1.10 m by 2100 described by [4]). These values were selected to align with adaptation planning for SLR increments [8] rather than fixed timeframes. The method enables stakeholders and managers to determine when SLR projections could result in increased SLR in their regions. This approach offers the ability to adjust to changing circumstances, as it tracks the projected SLR increment instead of following a specific timeframe, which can be more challenging to manage.

The Bruun rule was used to estimate the potential coastal response due to SLR ([35,87]; Fig. 4). The shortcomings of the Bruun rule have been thoroughly reported in the literature (see [14]). We have introduced those limitations above (introduction section) and discuss the implications of them in the context of our work below (discussion section).

Potential coastal response to SLR was estimated using Equation 2: SL = (L/B + DoC) S (2) where SL is the landward retreat, depth of closure (DoC) is the maximum depth of sediment exchange, L is the distance from the shoreline to the offshore position of DoC, B is the height of the berm/dune crest within the eroded backshore, and S is the SLR. DoC was calculated from wave model and bathymetric data following Equation 3: 2.28H^12 h/y-68.5((H^2 12 h)/y÷ (gT^2 12 h)/y). DoC represents the inner closure depth beneath mean low water spring, while H12h/y signifies the effective wave height just seaward of the breaker zone that is exceeded for 12 h per year, corresponding to a significant wave height with a yearly probability of exceedance of 0.137 %. T12h/y denotes the wave period associated with H12h/y, and ’g’ stands for the acceleration of gravity. DoC and distance to DoC (L) were calculated from wave model data and bathymetric data [88]. Significant wave heights (Hs) and mean wave periods (Ts) were extracted from a decade of SWAN wave hindcast model data (see [65], Appendix 3 Table 1). The DoC for each hindcast wave point on the east and west coasts was then calculated using the inner Hallermeier equation ([89–91], 2013; Equation 3), and this value assigned to the nearest DSAS transect. Shore perpendicular chainages (L in Equation 3) were then calculated from each transect to nearest perpendicular DoC.

Intersection of CEHZs and coastal archaeology

CEHZs were calculated for all 36,727 transects (Fig. 4). CEHZ 1 – 5 were determined, where values from 1 to 5 respectively equate to scenarios of coastal recession under projected SLR of 20 cm, 40 cm, 60 cm 80 cm and 100 cm. These CEHZs values were then used as the input to buffer landward for each scenario (CEHZ 1 - 5) using the QGIS buffer function. The intersection of CEHZs and known archaeological sites was accomplished using a version of New Zealand’s national level archaeological site inventory - ArchSite - modified as discussed in Jones et al. [15] to include consistent site type classifications and filtered for coastal locations only. In this dataset, archaeological points and CEHZs zones were spatially linked using the QGIS spatial join tool.

Results

Historic coastal change and distribution of archaeological sites

Historic coastal change in Te Tai Tokerau varies across different coastal landform types on the east and west coasts (Fig. 2 and Fig. 3). Foredune barrier plains are most dynamic, exhibiting relatively high levels of Net Shoreline Movement (NSM - NSM quantifies the net change in shoreline position over time) between ∼50 to 500 m, with localized areas of both erosion and accretion. The foredune barrier plains on the west coast show areas where there is a high rate of positive movement seawards, with NSM ranging from 150 to 300 m. Modest stability of foredune barrier plains is seen on the east coast (NSM ranging from 100 to 150 m). Beaches are considered the most sensitive landform to SLR in the CSI [69], but in Te Tai Tokerau, historic coastal change data indicates this landform type has lower NSM than foredune barrier plains (NSM on the east and west coasts of −70 to 85 m, and −145 to 314 m respectively).

Jones et al. [15] analyzed the national distribution of coastal archaeological sites around Aotearoa/New Zealand, noting that ∼29 % (2660) of archaeological sites occur on foredune barrier beaches, 23 % (2059) on foredune barrier plains, 14 % (1283) on beaches, and 9 % (808) on beach ridge barriers. Within Te Tai Tokerau, ∼45 % (840) of sites occur on foredune barrier plains, about twice the national average. A large proportion of sites (∼35 %, 658) occur

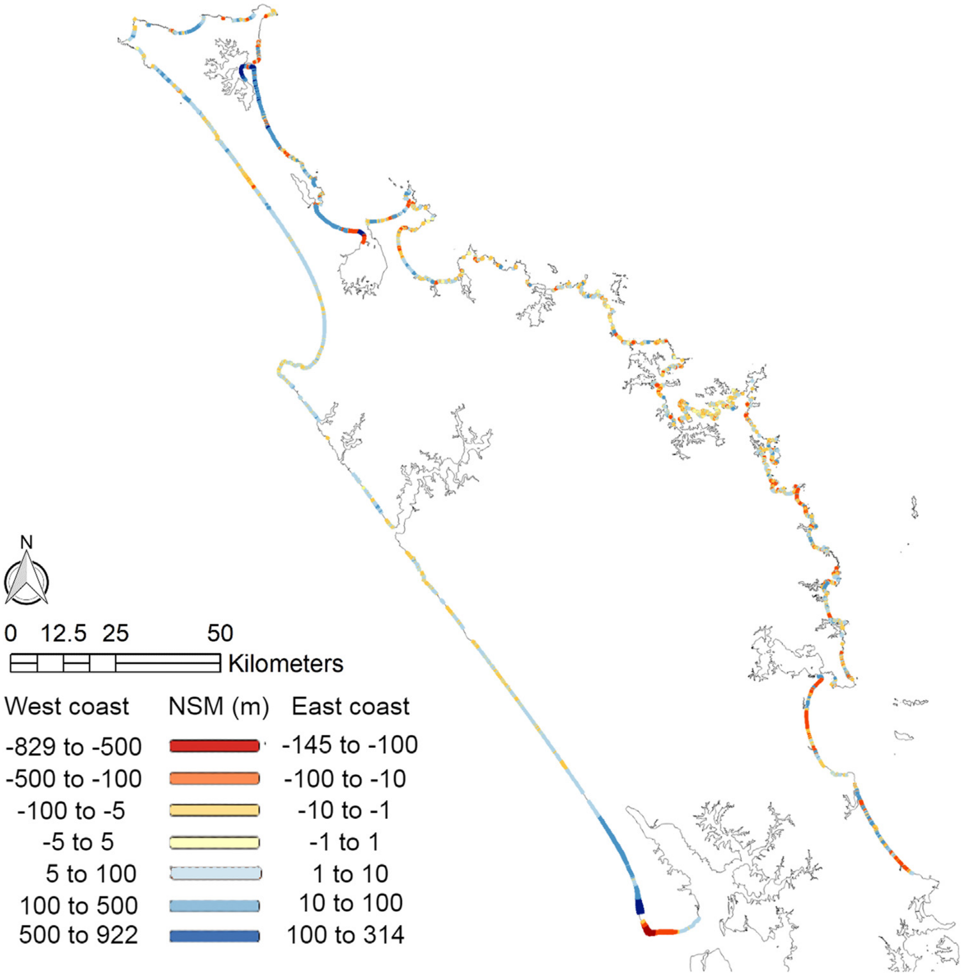

Fig. 3. Map of net shoreline movement (NSM) showing erosion (red and orange) and accretionary (blue) trends shown for Te Tai Tokerau.

on foredune barrier beaches, whereas only a relatively small proportion (0.7 %, 13) of coastal archaeological sites occur on beaches, well below the national average of 14 %.

CEHZ scenarios and archaeological sites at risk

Prior coastal hazard research in Te Tai Tokerau has focused on locations with contemporary infrastructure, such that only approximately 20 % (around 94 km, the total length is 466 km) of the region's sandy coast has an existing CEHZ (Shand et al. 2019). Our approach, calculating CEHZs for 36,727 10-m spaced transects, covers approximately 78 % (367 km) of the sandy open coast, (Fig. 5).

The five CEHZs generated in this study increase in size with the SLR projections (Fig. 6). In Te Tai Tokerau for 20 cm of SLR (CEHZ 1) the interquartile range (IQR) is narrow (∼4 m) and highly peaked near the mean of 33 m inland of the present MHWM. As SLR increases, the mean and median CEHZs increase in width landward, and the distributions widen (Fig. 6). For example, for 100 cm of SLR (CEHZ 5), the CEHZ extends between minimum and maximum values of ∼22 m and ∼124 m, indicating that coastal response to 100 cm of SLR will result in a broad range of hazard zones for different areas around the region.

Using a version of New Zealand's national level archaeological site inventory - ArchSite - modified as discussed in Jones et al. [15] to include consistent site type classifications and filtered for coastal locations only. Based on this 1855 sites recorded within 1000 m of the modern-day shoreline of Te Tai Tokerau were identified. These sites date from early Māori settlement (1250 A.D) to early European settlement (1840) (e.g. [72]) and include middens,[1] pā (fortified village), and sites related to early European farming and industry. Some of these sites have significant visible and subsurface remains such as kainga (settlement), urupā (burial ground) and pā, and there are also rare sites in the region, such as those used for Māori stone tool manufacturing or locations that contain evidence of early Polynesian settlement [92].

Our study reveals that approximately 19 % (356 out of 1855) of archaeological sites situated along the coastal zone fall within CEHZ 5, as depicted in Fig. 7. Of these, around ∼8 % (155 sites) are vulnerable to 20 cm SLR (CEHZ 1, Fig. 7). Of the archaeological site types, earthworks and middens have the highest number of sites at risk under the CEHZ 1 scenario, with 19 and 119 sites at risk, respectively. Three burial sites are impacted within CEHZ 1, and nine within CEHZ 5. Other site types, such as structures and artifacts, are mainly impacted at higher SLR projections (Fig. 7). The number of archaeological sites designated as structures (historic buildings, foundations, dwellings, whare (house) etc.) sites are low across all CEHZ scenarios with two sites identified under CEHZ 1, increasing to three in CEHZ 5 (Fig. 7). Midden and earthwork sites are widely distributed, occurring across CEHZs 2 to 5 (CEHZ5 encompasses CEHZ1-4). The highest number (242) of middens occur in CEHZ 5. Burial sites exhibit varying presence across CEHZ scenar-

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[1] Mātaita or shell middens in Aotearoa include pre-and post-contact deposits and can include but are not limited to koiwi/human remains, artefacts/taonga, faunal remains, lithic material, and charcoal.

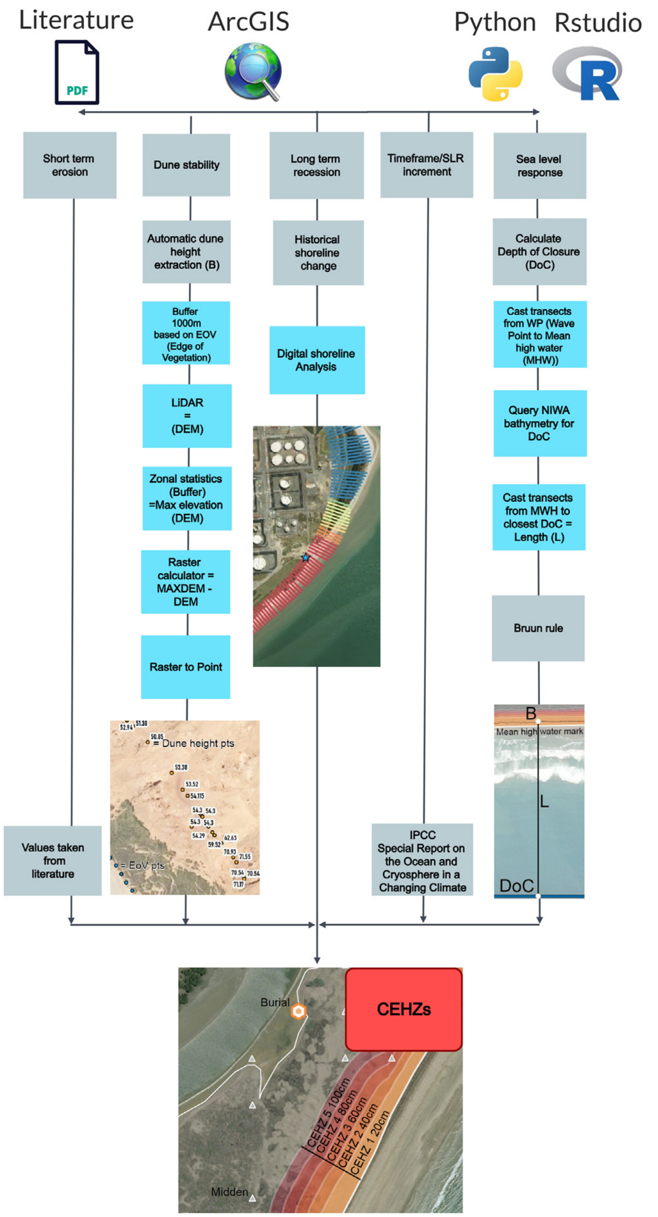

Fig. 4. Workflow diagram outlining the steps involved in calculating CEHZs. The icons indicate the programs used to calculate each step. The grey boxes indicate techniques and the blue calculations performed. Short-term erosion is based on technical reports, dune stability is calculated using ArcGIS, long-term recession is based on historical shoreline change calculated using the DSAS ArcGIS extension, and closure depth is calculated using ArcGIS suite, QGIS, Python and R based on hindcast wave data.

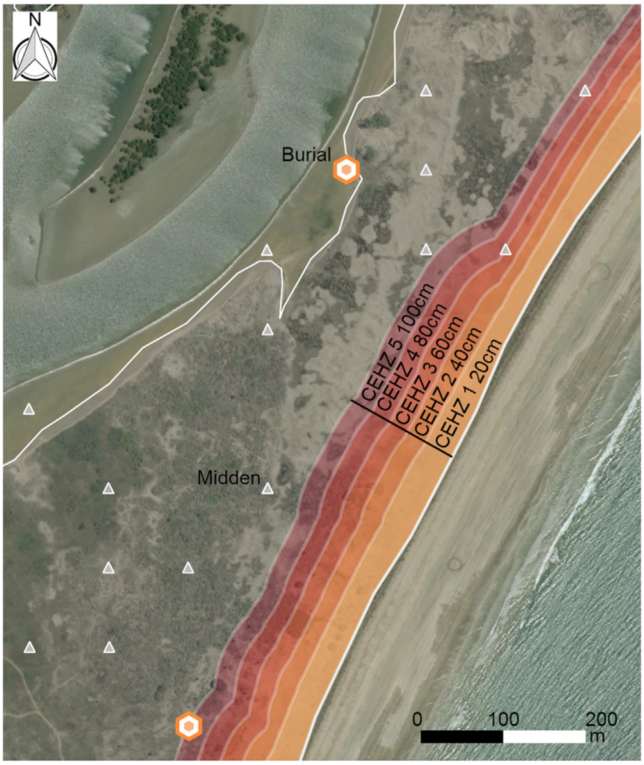

Fig. 5. Visual representation of projected CEHZs and impacted coastal archaeological sites. Grey triangles are middens, and the orange hexagons are burials.

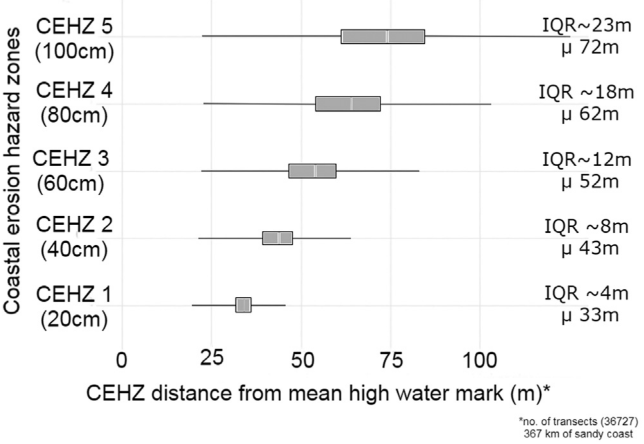

Fig. 6. CEHZ scenarios based on projected sea-level rise (cm). The boxplots show the distribution of CEHZ values for each scenario based on all calculated transects (36,727). The 0 on the y-axis is the LINZ high water mark (2021).

ios, increasing from five in CEHZ 2 to nine in CEHZ 5. Lastly, artifact sites are primarily associated with CEHZ 4, constituting four sites at risk in that scenario.

In order to provide context for the location of archaeological sites, we utilize geospatially cross-referenced coastal landform categories from Nigel et al. [69]. Archaeological site types differ across coastal landform categories for each CEHZ scenario. In this study, burial sites occur only on beaches, foredune barrier beaches, foredune barrier plains, and foredune barrier plains with spits (see Fig. 8). Middens and earthworks are concentrated within foredune barrier beaches and foredune barrier plains but occur across a broader range of landforms (Fig. 8). Structures are primarily situated in modified foredune and incipient barrier beach environments, and while only three known structures (an historic schoolhouse – ‘Matihetihe native school’ and two signal stations) are at risk across the SLR scenarios, two of these are at risk in the lowest SLR scenario (i.e., within ∼20 years).

Discussion

Coastal change is influenced by factors at local, regional, and global scales [82]. In Te Tai Tokerau, Aotearoa/New Zealand, historic coastal change has likely been influenced by factors such as longshore variability in sediment flux, human impacts, large-scale vegetation changes, and multi-decadal-scale climatic drivers [84]. It is difficult to determine the specific role of SLR amid these other influences [14,84]. Historic hotspots of erosion and accretion in Te Tai Tokerau have been localized, with large stretches of coast showing historic stability [84]. Ongoing SLR is likely to shift many histori-

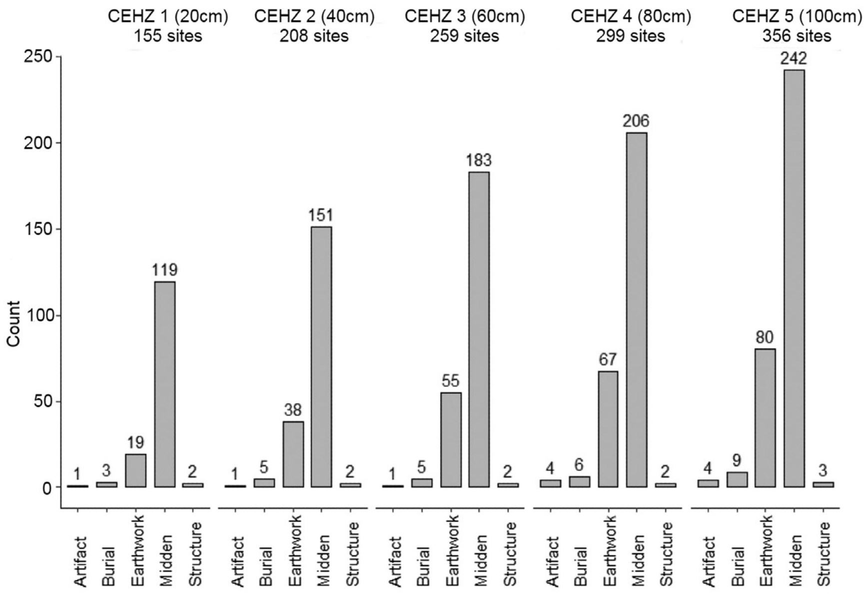

Fig. 7. Count of coastal archaeological sites in projected CEHZs.

cally stable coasts toward erosion [38,93]. These factors mean that there is considerable variability in any projection of coastline position in the future. Nonetheless, it remains important to provide estimates of CEHZs that incorporate the possibility of SLR-driven erosion, to aid in decision making processes.

Only about 20 % of open-coast sand beaches in Te Tai Tokerau of Aotearoa/New Zealand currently have a designated CEHZ, because previous work has focused on areas that have modern infrastructure; however, coastal archaeological sites occur widely outside of these areas. The method we developed for this paper enabled calculation of CEHZs for approximately 78 % of the coast, allowing important consideration of non-economic assets (Taylor et al., 2021) and more generalized climate change adaptation consideration (see Storbjörk and Hjerpe 2014).

Previous assessments of archaeological risk in the coastal zone have very little consideration of future coastal erosion risk under SLR [20,21,49,50]. One of the main limitations of these studies is their heavy focus on projections of SLR, which are subject to significant uncertainties [17]. Some assessments have considered recent erosion trends (e.g. [45,52,53]), but unlike our study, few have incorporated decadal-scale data that indicate historic erosion patterns (see [82,94–96]). No other studies we are aware of have specifically evaluated the plausible effects of SLR on future coastal erosion rates. Our CEHZ calculations used the Bruun rule to evaluate response to SLR [35]. This rule has been widely used, but its application has been intensely debated (see [12,37,39,97,98]). The limitations of the rule are well documented (see introduction section and references above). In terms of the physical limitations, in the Te Tai Tokerau region of New Zealand, the Bruun rule can be defended to the extent that most of the coast is natural (unmodified), and at least on the west-coast, there is ample sediment availability, such that shoreface translation is likely to be upward and landward with SLR, as anticipated with the Bruun model [41]. However, we understand there are many areas within the region where the model is likely to be unreliable. Our intent in using the rule is to provide a first-pass, broad-scale assessment of coastal erosion under SLR for the purposes of drawing attention to archaeological risk at many sites where there has been little urban development. Within this context, we believe a first-pass application of a highly idealized model such as the Bruun rule can be defended. However, future improvements in this regard are necessary, and achievable through refined application of the Bruun rule [36] and/or using more sophisticated models (e.g. [39,41,99,100])

Uncertainty in our calculations is not only restricted to physical coastal change. For instance, archaeological sites within the ArchSite database are referenced by a single point. It is unclear whether the point is located at the center of an archaeological site, and the size of sites is unknown. Worth noting for artifact and burial sites, these often relate to previously identified finds that have since been removed (in Aotearoa, pre-contact human remains are moved to locations chosen by communities who have genealogical association with the burials), but the numbers stand as a limited proxy for similar sites that are likely to still be extant in their vicinity.

In addition, Jones et al. [15] noted that the accuracy of archaeological site locations is subject to considerable variability in ArchSite (see Appendix 2). Further, important details about specific sites are lacking. For example, archaeological site status information documented in ArchSite suggest that in Te Tai Tokerau exposed human remains have undergone reburial or relocation due to coastal erosion, but there is little detail in respect to the current condition of burials, including the extent of the burial area and whether it contains single individual remains or multiple remains (Appendix 3, Table 2). It is apparent, considering the limitations noted above, that future work might integrate higher-resolution archaeological datasets with in-depth local-scale coastal models to improve understanding of the SLR-driven risk to coastal heritage.

Knowing the risk is only the part of the solution

The CEHZ scenarios have shown that 19 % (356) of the coastal archaeological sites in Te Tai Tokerau are at risk to 100 cm of SLR. These scenarios also allow for the identification of sites that should be prioritized or are in danger of erosion. To effectively operationalize CEHZs in archaeological risk assessments, it is crucial to establish a strong link with effective archaeological management, which involves the preservation and protection of archaeological sites, artifacts, remains, and associated materials [101,102], as well as practices such as rescue archaeology and ongoing monitoring [103,104]. Determining the most valuable archaeological sites also involves crucial decisions regarding their management. Gregory and Matthiesen [105] outline three primary options: passive preservation, where sites are left undisturbed if degradation

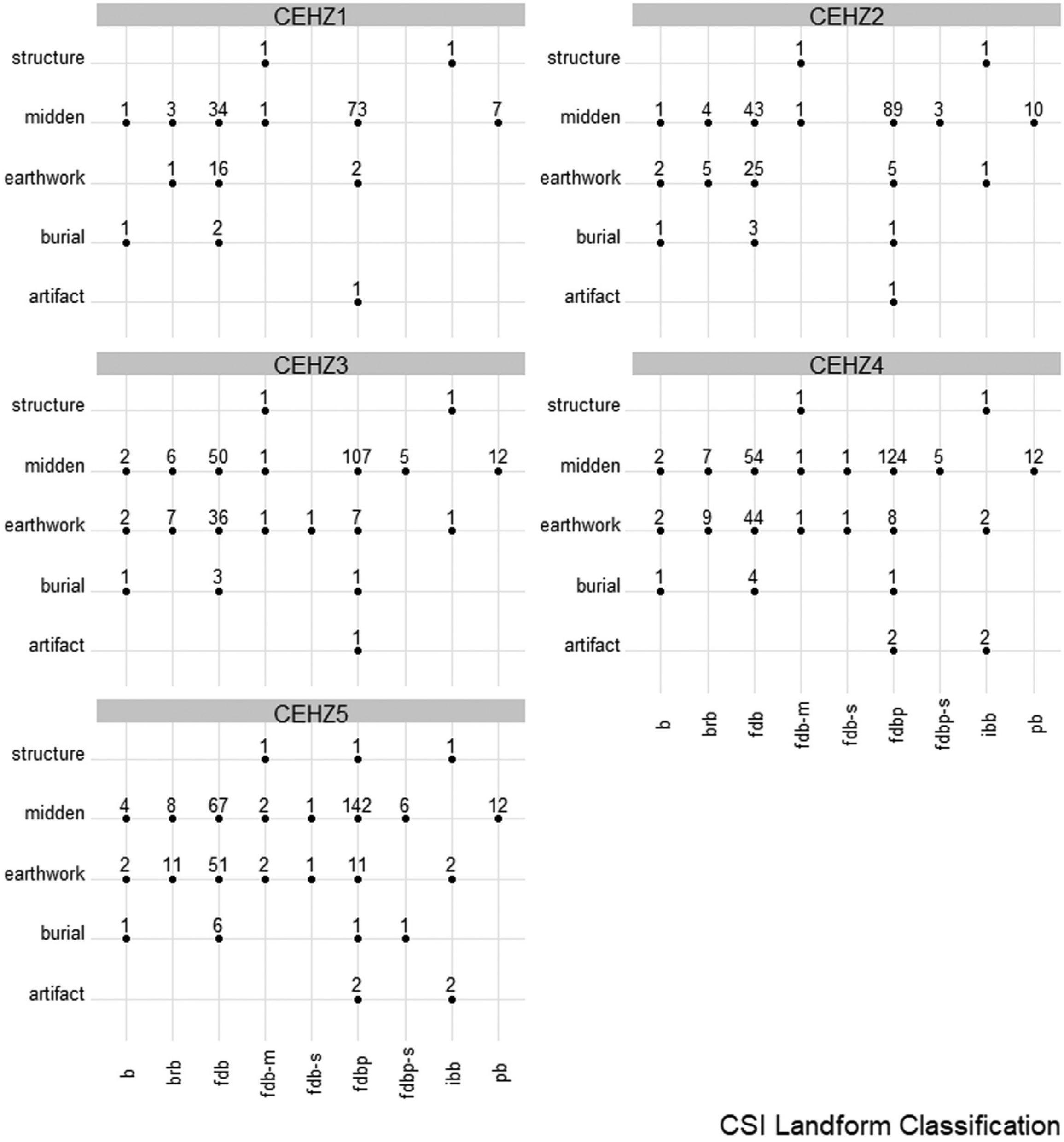

Fig. 8. Plots showing the number and distribution ofarchaeological site types that intersect with landform categories for each CEHZ scenario. Categories: beach (b), beach ridge barrier (brb), foredune barrier (fdb), foredune barrier modified (fdb-m), foredune barrier spit (fdb-s), foredune barrier plain (fdbp), foredune barrier plain spit (fdbp-s), incipient barrier beach (ibb), platform beach (pb).

Table 2
Recorded burials in ArchSite that intersect with CEHZs scenarios, including status, known threats, landform, distance to 2020 LINZ mean high water mark (m), and last known date of site visit. Landform; fdb (foredune barrier), fdbp (foredune barrier plain), fdbp-s (foredune barrier plain – spit), and b (beach).

NZAA_ID	Status	Threats	Landform	Distance to LINZ mean. high water mark (m)	Date
Q06/468	In situ	Erosion	fdbp-s	147	01/01/1998
Q05/1485	Partially removed	Erosion	fdb	22	11/22/2011
O07/109	Removed/Reburied	Erosion	b	35	07/30/2007
P04/780	Removed/Reburied	Coastal development	fdb	46	01/21/2020
O03/274	Removed/Reburied	Erosion	fdbp	54	01/01/1973
Q05/422	Removed/Reburied	Erosion	fdb	434	01/01/1965
P04/229	Unknown	Erosion	fdb	62	01/01/1967
Q04/68	Removed/Reburied	Erosion	fdb	28	2/09/1987
Q05/1541	Destroyed	Erosion	fdb	63	14/02/2014

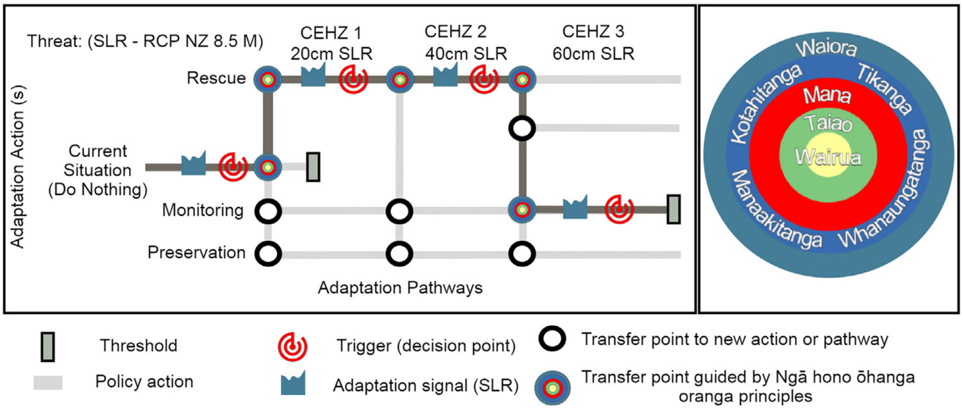

Fig. 9. Conceptual figure showing a Dynamic Adaptive Policy Pathway (DAPP) approach for the management of an at-risk archaeological site under Representative Concentration Pathway (RCP) 8.5 M (Median). Critical decision points are denoted by black circles, indicating responses to changes in sea-level rise (SLR) that trigger decisions for new pathways with specific actions. The Coastal Erosion Hazard Zone (CEHZ) scenario is juxtaposed with SLR levels. The darker grey pathway illustrates a potential preferred pathway for visualization purposes. The coloured circles represent options preferred and guided by Ngā hono ōhanga oranga principles [109].

is minimal; active preservation (protection), involving the manipulation of environmental conditions to shield archaeological deposits from factors like erosion; and, if the first two options are not viable, archaeological investigation (rescue). The implementation of the first two options becomes meaningful only when their effectiveness is periodically assessed through regular site visits and monitoring. In the context of climate change, monitoring archaeology entails consistent observation and assessment of site conditions to comprehend the ongoing impact. It serves as a crucial tool for deciding when intervention is required to rescue information before it is lost [106]. Rescue or preventative management approaches include excavating and documenting sites that are at risk of destruction [103]. The physical nature of coastal erosion implies that rescue or ‘preventative’ archaeology is likely to be particularly important in coastal areas before sites are lost [103]. Rescue archaeology may not “save” a site in the traditional sense of moving it out of harm’s way, but archaeological methods are applied to gather valuable information from these sites before they are irretrievably lost to erosion [103,104].

How could management of coastal archaeology usefully draw from dynamic planning processes?

Management of coastal archaeology under threat from coastal erosion might usefully draw inspiration from planning tools such as Dynamic Adaptive Policy Pathways (DAPP) [5,107]. Typically, the management of archaeological sites does not consider changing coastal hazard risk associated with SLR. CEHZs presented in this paper are a first step in understanding what might be at risk to coastal erosion and SLR, but decision makers need to plan for management of these sites under changing environmental conditions. DAPP is a decision-making methodology designed to enable adaptive decision-making under uncertain scenarios. It establishes a framework of short-term and long-term actions and provides guidance for future decision-making in a dynamic environment [107,108].

One example illustrating how DAPP could be used to manage the impact of an archaeologically vulnerable site under SLR is provided in Fig. 9. The DAPP scenario presents theoretical archaeological sites with pronounced susceptibility to erosion, particularly evident with a 20 cm SLR. The current situation of ‘doing nothing’ (i.e. not managing the site) would lead to a ‘threshold’ being reached, which is the irreversible point of site loss, beyond which further intervention is not possible. In the case of a 20 cm SLR, an emergency excavation is initiated, preserving site information to a certain extent. Subsequently, as SLR reaches 60 cm, ongoing monitoring is employed to detect emerging features, ultimately leading to the complete loss of the site as sea level continues to rise.

The conceptual figure designates SLR as the signal, and the DAPP development process allows for flexibility in selecting alternative indicators, such as erosion rate or distance from the coastline. The figure portrays how various adaptation pathways with different adaptation actions or approaches exist. Planned pathways can shift because of responses triggered by SLR changes (or another defined signal). Worth noting is that in the DAPP process, it is imperative to conduct stress testing [5]. Stress testing is valuable for assessing how well a preservation plan can adapt and perform in the face of uncertainties, unexpected events, or extreme conditions. For example, the impact of storms, as this high frequency but uncertain (in terms of precise magnitude, timing, and impact) events can significantly challenge preservation strategies and reveal the system’s resilience under extreme conditions where a DAPP might overtly be focused on long term erosion.

The example in Fig. 9 is entirely conceptual and illustrates how it is possible to integrate scientific data with strategic decision-making processes to help safeguard selected vulnerable archaeological sites to rising sea level. However, Bell et al. [5], see [6,8] note it is crucial to prioritize collaboration with various stakeholders, including community members, scientists, policymakers, and representatives from Indigenous communities. In Aotearoa / New Zealand this typically involves iwi/hapū (tribal/sub-tribal) entities of Māori. Māori share a direct ancestral link to many archaeological sites as these may contain wāhi tapu: places that are sacred to Māori in the traditional, spiritual, religious, ritual, or mythological sense (HZPT, section 6). Equitable goals should be met with coastal archaeological sites at risk, and communities and decision-makers need to determine and co-implement DAPP decisions with Te Ao Māori principles in mind (Fig. 9, [110–112]).

Culturally sensitive decision making is critical, ensuring that valuable insights from archaeology are obtained while respecting the priorities and perspectives of the community whose heritage is at risk. The concept of Ngā hono ōhanga oranga (Māori relational economies of well-being, Fig. 9) might help contextualize what pathways and actions are preferable (Wolfgramm et al., [109]). Archaeology is situated within this framework as part of Taiao (the natural world or resources), which is within a cascading circle that incorporates the concepts of Mana (status), Tikanga (protocols), Manaakitanga (ethics of care), Kotahitanga (stewardship), and Whanaungatanga (relationship), all situated in Waiora, or environmental protection. Finally, the Ngā hono ōhanga oranga also incorporates the of idea “taonga” and viewing archaeological sites as such. Taylor et al. [112], suggest viewing natural resources as taonga (treasured possessions) either provides a perspective which moves beyond economic considerations. Viewing cultural resources as Taonga aligns with the principles of Manaakitanga and Kaitiakitanga (guardianship) central to community and hapū management of Taiao (Taylor et al., 2021). These concepts also potentially align with western archaeological practices where value and significance are related to guardianship and ongoing care of heritage. By integrating archaeological expertise into the broader framework of decision-making, a more comprehensive and culturally sensitive approach can be achieved, ensuring that the valuable insights from archaeology are effectively utilized while respecting the priorities and perspectives of the community. While these might not always align with these above concepts, they do link well with the earlier mentioned DAPP archaeological management actions (monitoring, preservation, and rescue).

Conclusions

The coastal region of Aotearoa/New Zealand holds significant cultural, historical, and archaeological sites that face a threat of erosion-induced loss under projected SLR. This study employed a CEHZ methodology to assess the vulnerability of archaeological sites in Te Tai Tokerau/Northland. Multiple existing data sets were utilized, including wave model outputs, high-resolution topographic and bathymetric data, archaeological site locations, historical coastal change data, and future SLR projections. Findings indicate that 8 % (155) of Te Tai Tokerau’s known archaeological sites are threatened by 20 cm of SLR and 19% (356) by 100 cm SLR. Dynamic Adaptive Policy Pathways offers one approach for planning the management of the at-risk sites alongside the cultural framework of Te Ao Māori. The methodology discussed in this paper allows cultural resource management to factor in coastal erosion hazard zones when deciding how to protect at-risk archaeological sites guiding efforts to safeguard, mitigate impacts, and facilitate the recovery of archaeological data and the associated values of these important places threatened by climate change.

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Data repository Data for this article can be accessed online at https://github.com/bmcollings/calc-CEHZ.git

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.culher.2024.04.007.

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