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Evaluating Quoddy Region archaeological site vulnerability to sea-level rise and erosion through the integration of geographic information system modeling and surveys

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Abstract

Modeling archaeological site erosion often depends on regional site databases that record sites accurately but with variable precision. This study examines the impact of sea-level rise (SLR) on 10 archaeological sites in the Quoddy Region of Maine

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through comparing models and field observations. Sites were categorized as low, mid, or high priority for field excavation based on exposure to tides. These model results were compared to field reports of site condition to evaluate the accuracy of modeling SLR as an indicator of erosion and to evaluate the application of models in developing prioritization protocols for site investigations. Models for current sea level scenarios broadly underestimate the degree of erosion reported by field observations because not all site locations were recorded at the precision required for analysis. This study emphasizes the importance of field audits for sites recorded in databases to enable large-scale modeling for the prioritization of urgently threatened sites.

Keywords

Coastal archaeology, sea-level rise, Quoddy Region, Maine, coastal erosion

Introduction

Sea-level rise (SLR) modeling for erosion of coastal archaeological sites has great potential to help prioritize site investigations (e.g. Anderson et al., 2017; Elliott and Williams, 2019) but needs to be accompanied by field surveys to lend nuance to site databases and ensure accuracy. In our results, we compare model results with field reports of each site to assess the reliability and accuracy of modeling site vulnerability to erosion. We emphasize the discrepancy between field reports and model results, largely due to a lack of precise geographic site information. This, therefore, supports the need for site audits as well as the collection of accurate site polygons and depth measurements of sites to estimate volume losses due to erosion and provide more reliable model results.

In our case study, we model current sea levels, storm surge, and future SLR as an indicator of the current and future susceptibility to erosion of a local sample of 10 sites from the Quoddy Region in Maine (Figure 1). We compare the model results to field survey observations to consider the accuracy of SLR models in predicting site erosion and to evaluate the application of models in developing prioritization protocols for site investigations. We argue that while at a large scale, models have been used to predict the extent to which coastal sites are threatened by SLR (Anderson et al., 2017), high-resolution site locational data and local scales are necessary to nuance the results of those models and avoid misleading conclusions (Erlandson, 2012; Fitzpatrick et al., 2006; Torresan et al., 2008). Specifically, our case study suggests that erosion of archaeological sites due to tidal exposure has been and may continue to be more significant than models alone suggest.

SLR has accelerated since the mid-20th century primarily due to anthropogenic carbon emissions, warming the ocean, leading to thermal expansion of sea water, and melting of land ice (Fernandez et al., 2020; Frederikse et al., 2020). In addition to SLR, factors such as increasing storm intensity and associated surge, frequency,

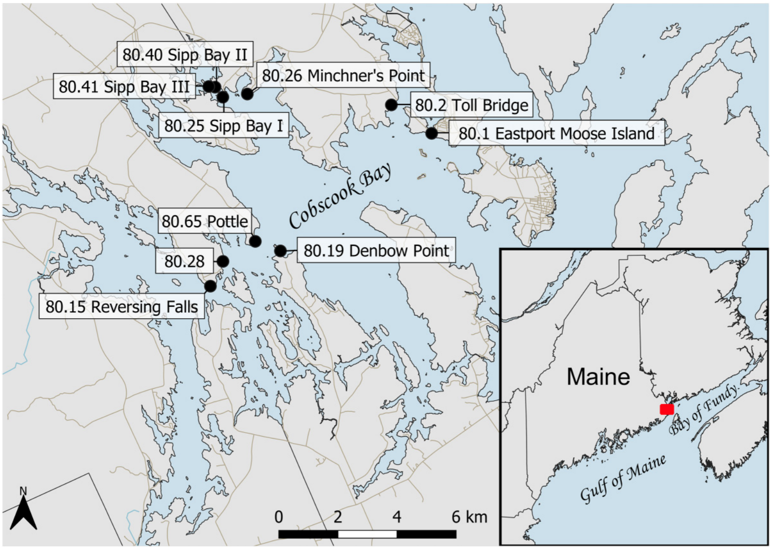

Figure 1. Location of 10 sites around Cobscook Bay, ME used in this study.

and wave action can threaten the stability and longevity of archaeology sites by increasing their risk of erosion through exposure to intensified hydrological energy (Anderson et al., 2017). In desktop models that utilize site location and elevation, SLR can be a general indicator for the extent to which sites are threatened by erosion because it influences the degree of exposure to other climate-driven threat factors. Erosion is a threat to coastal archaeology sites as it can damage shorelines that contain remnants of past human activity, resulting in the loss of archaeological material and context (Leatherman et al., 2000). Accordingly, around the world, many archaeological sites are at risk of destruction since past people preferentially lived in proximity to the oceans and depended on the rich marine environment for sustenance across the world (Erlandson, 2008; Reeder et al., 2010). At the same time, coastal archaeological sites are crucial for establishing baseline data about climate change and human adaptations to it and for shaping contemporary responses (Rick, 2023). Moreover, in North America, coastal erosion disproportionately effects Indigenous archaeological heritage, threatening evidence for the use of coastal resources by Indigenous people in the deep past (Hutchings, 2017).

Coastal archaeological sites in Maine are usually characterized by shell heaps (or “shell middens”) which are the remains of discarded marine shells from food eaten by ancestral Wabanaki people from the Archaic (10,000 cal BP–3000 cal BP) and Maritime Woodland (1000 cal BC–1500 AD) periods in what is now Maine (Betts and Hrynick, 2017, 2021). Maine’s shell heaps are usually dominated by *Mya arenaria* (soft-shell clam) remains (Spiess, 2017), or, less frequently, *Crassostrea virginica*

(American oyster) (Sanger and Sanger, 1986). The breakdown of shells releases calcium carbonate into surrounding soils, rendering Maine's ordinarily acidic soils more basic, and creating one of the few environments in the state capable of organic preservation. Shell heaps contain evidence not just of their primary shell matrix, but of other shellfish consumed in smaller amounts (see Anderson et al., 2021), and the remains of other marine and terrestrial fauna. Since these sites were formed primarily as a result of harvesting food from the ocean, important components are disproportionately lost due to their location along the littoral zone. Therefore, once erosion has begun, it becomes difficult to fully interpret and contextualize the site. Intra-site models suggest that generally speaking, large processing middens are more shoreward than houses (Betts, 2019; Hrynick, 2018; Sanger, 1996, 2010). Although this perception may be shaped by erosion, it does indicate that some aspects of pre-contact habitations are more adversely affected by erosion than others.

A large-scale pattern that has emerged clearly in the region is the differential erosion of chronological components of sites, with older components eroding first. This is due to naturally rising sea levels in the past causing horizontal, landward shifts in human occupation which expose earlier strata to erosion first. The phenomenon has been termed "chronological shingling" by Young et al. (1992) and has been well attested on sites in the Quoddy Region where older legacy collections can be analyzed (Anderson and Hrynick, 2023) and has likely resulted in a regional pattern where Archaic antecedents to more recently visible Maritime Woodland sites may be dramatically under-recognized (Anderson et al., 2024). While Maine's shell heaps are vulnerable to erosion, they remain crucial repositories of ecological and environmental information, as well as archaeological data (e.g. Johnston, 2020; Wanamaker Jr et al., 2011).

Case study: The Maine Quoddy Region

In this article, we focus specifically on the Quoddy Region of "Downeast" Maine, the homeland of the Passamaquoddy people (Figure 1). The Quoddy Region has received archaeological attention since the 19th century (e.g. Matthew, 1884), and, since that time, scholars have noted the erosion of the region's archaeological sites (e.g. Adams, 1873; Davis, 1982; Ferguson and Turnbull, 1980). Extensive archaeological surveys of the area, starting in the middle of the 20th century (Anderson and Hrynick, 2023; Sanger, 2008), were followed by some of the region's most intensive archaeological attention (e.g. Black, 2002; Pearson, 1970; Sanger, 1987). These surveys provide a reasonably fine-grained record from which to consider coastal erosion in diachronic terms.

Beginning in 2018, under the Northeastern Archaeological Survey, we audited coastal archaeological sites in the 80 quadrangle of the Maine Historic Preservation Commission's (MHPC) sites database (Maine uses a site numbering system based on 7.5 min UTM grid, with each quadrangle assigned an arbitrary number, and sites within the quadrangle given sequential numbers after the quadrangle number). This work included attempts to locate new sites via survey and contacts with local informants, but the primary focus was on auditing previously recorded sites to assess their condition and research potential. This survey was accompanied by targeted excavation of some eroding sites.

In brief, our work on this archaeological record suggests a pattern of chronological shingling (Young et al., 1992), by which the oldest sites have been almost entirely eroded. The extant archaeological record thus consists of occasional offshore finds of Archaic period artifacts, but virtually no Archaic period material from preserved contexts (Black, 1997; Spiess and Price in press). Transitional Archaic period components occur occasionally in intertidal contexts (Black, 2000, 2018). Maritime Woodland period sites are often preserved, although our recent survey suggests that many of even these more recent components have eroded away entirely, and that virtually all remaining coastal sites in the Quoddy Region are actively eroding.

The extensive tidal range of over 5 m in the Quoddy Region on Cobscook Bay, near the Bay of Fundy (Figure 1), increases the vulnerability of the coastline to erosion (Corps of Engineers, 1978; Bishop and Black, 1988; Desplanque and Mossman, 2001). This is in part due to the greater volume of water transported in the semi-diurnal cycle (twice daily), which increases current strength and water velocity. These conditions further promote coastal abrasion because sediments and debris may exert erosive forces along the shoreline as they are transported. This region's composition of fine sediments further increases its susceptibility to erosion as fine sediments are more readily transported in moving water (Mulligan et al., 2013).

Previous modeling for various coastal locations has incorporated SLR, increasing storm intensity and frequency, and coastal development to project site vulnerability (i.e. Anderson et al., 2017; Pourkerman et al., 2018). However, there has been little study on the predicted impacts of SLR on coastal archaeology sites in Maine. The objective of this case study is therefore to quantify the extent of SLR and storm surge at 10 coastal sites around Cobscook Bay in the Quoddy Region of Maine (Figure 1) using predicted sea level increases for 2050 (Maine Climate Council, 2020). Such models are often used to determine which of these sites are most at risk based on the extent of their exposure to inundation and erosion and may thus be prioritized for archaeological investigation (e.g. Elliott and Williams, 2019; Reeder et al., 2010; Torresan et al., 2008). In order to evaluate the efficacy of modeling coastal erosion, we compared the condition of 10 of these sites as reported by field surveys to the results of models that consider a theoretical site area and site elevation in comparison to current and projected sea levels with storm surge for 2050.

Methods

We chose predicted sea levels for this study based on the state of Maine's legally mandated preparations for SLR by 2050 (Maine Climate Council, 2020). Maine is *committed* to managing 0.457 m (1.5 ft; low 2050), while the state is *preparing* to manage 0.914 m (3.0 ft; high 2050) of SLR by 2050. These SLR projections were developed by the Maine Climate Council through analysis of both the magnitude and acceleration of historical SLR documented by tide gauges along the coast over the past century (Fernandez et al., 2020). The Maine Climate Council does not provide an uncertainty for the projections because they are policy targets meant to protect state investment. These estimates are likely to be on the low end of future SLR (Oppenheimer et al., 2019). The low to high 2050 projections represent their expected range of SLR for legal, social, and political applications. Since the projected levels are generalized for the entire Maine coast, certain areas may experience more or less than these estimates of SLR. However, they provide a useful framework for understanding the range of expected vulnerabilities and encompass the state's expectations for long-term planning and fund allocation. In this context, a commitment to manage refers to implementing strategies and policies aimed at mitigating the impacts of SLR, including coastal protection, infrastructure adaptation, and land use planning. Preparation for management entails readiness efforts such as contingency planning and infrastructure reinforcement in anticipation of potential challenges posed by lower probability SLR scenarios. The purpose of these SLR projections from the Maine Climate Council was to evaluate the vulnerability of Maine's coastal infrastructure as well as beaches, dunes, salt marshes, and bluffs. While the projections were not specifically intended to assess the vulnerability of coastal archaeological sites, they provide valuable insights into the potential impacts on these sites, given their location within these coastal systems and their subjection to sociopolitical decisions informed by these projections.

We project four water levels in our models: mean high water (MHW), mean higher high water (MHHW), highest astronomical tide (HAT), and HAT + storm surge. MHW is reached for almost half of all high tides, MHHW is reached for fewer high tides, and HAT and HAT + storm surge are not reached every year. Sites covered by MHW will likely be more actively eroded than sites only covered by HAT since tides more frequently reach the MHW level. All tide levels reported here are in the MHW datum, in which MHW equals 0 m. The current level of MHHW reported by the Eastport, ME tide gauge (National Oceanic and Atmospheric Administration (NOAA) station ID: 8410140) is 0.145 m. The current HAT level is 1.209 m. A high storm surge of 1.112 m occurred on 10 January 2024, which we have added to HAT to project a maximum sea level scenario of 2.321 m, though this would only occur if the maximum storm surge coincided with HAT. We added the low 2050 and high 2050 SLR increases to the current MHW, MHHW, HAT, and HAT + storm surge to predict future sea levels. The predicted MHW, MHHW, HAT, and HAT + storm surge heights for low 2050 are 0.457, 0.602, 1.666, and 2.778 m, respectively. The predicted MHW, MHHW, HAT, and HAT + storm surge heights for high 2050 are 0.914, 1.059, 2.134, and 3.235 m, respectively.

Of the 64 coastal sites in the MHPC records for the 80 quad, we selected 10 sites for analysis, which represent ~ 16% of all sites, because they had been audited, excavated, or otherwise evaluated by the Northeast Archaeological Survey. Thus, the analysis could be compared with "on the ground" information to assess the relevance of the results obtained. While there is not a consistent definition for a "coastal" archaeology site from the MHPC or other institutions, a standard of 0.5 km from the ocean has been previously used and accepted (Thomas, 1983). For our purposes, we defined coastal sites as partially in or exposed to the ocean, with all 10 sites within 100 m of the coastline. We buffered the MHPC recorded location for each site by 5 m to create a theoretical site area for this analysis. We refer to the 5 m polygon areas as area of analysis as we recognize that these buffers represent an unknown percentage of the true site area due to a lack of existing site polygon data. For this analysis, we used a digital elevation model (DEM) collected by the United States Geological Survey and downloaded from NOAA Digital Coast: Data Access Viewer. The DEM was collected in 2011 as part of a larger Northeast data from New York to Maine as a LIDAR dataset. The DEM has a reported vertical accuracy of 7.1 cm and a horizontal accuracy of 100 cm, with 1 m spatial resolution. With this DEM, we mapped the current, low 2050, and high 2050 sea level scenarios. Using geoprocessing tools in QGIS version 3.22.10, we quantified the remaining area of analysis above each sea level scenario for each site (Tables 1 to 4).

Results

According to these models, sites 80.10 (Eastport Moose Island; Figure 2), 80.20 (Toll Bridge), 80.25 (Sipp Bay I), 80.4 (Sipp Bay II), 80.41 (Sipp Bay III), and 80.65 (Pottle) are projected to be currently at risk of erosion as their areas of analysis are > 50% covered by HAT and lower tides. Sites 80.19 (Denbow Point) and 80.26 (Minchner's Point) are at lower risk of erosion as they are predicted to be exposed to tides only under the low 2050 and high 2050 models, but not currently. Sites 80.15 (Reversing Falls) and 80.28 are projected to be at minimal risk of erosion because 100% of their areas of analysis are projected to remain above sea levels under current, low 2050, and high 2050 scenarios (Tables 1 to 4).

Table 1. Sites and their corresponding area of analysis percentages above MHW for current, low 2050, and high 2050 sea level scenarios.

MHPC number and site name	% Area remaining current	% Area remaining low 2050	% Area remaining high 2050
80.1 (Eastport Moose Island)	100	100	75
80.2 (Toll Bridge)	66	53	18
80.15 (Reversing Falls)	100	100	100
80.19 (Denbow Point)	100	100	100
80.25 (Sipp Bay I)	25	16	1
80.26 (Minchner's Point)	100	100	100
80.28	100	100	100
80.40 (Sipp Bay II)	45	32	8
80.41 (Sipp Bay III)	99	93	52
80.65 (Pottle)	0	0	0

MHPC: Maine Historic Preservation Commission; MHW: mean high water.

Table 2. Sites and their corresponding area of analysis percentages above MHHW for current, low 2050, and high 2050 sea level scenarios.

MHPC number and site name	% Area remaining current	% Area remaining low 2050	% Area remaining high 2050
80.1 (Eastport Moose Island)	100	98	58
80.2 (Toll Bridge)	66	42	18
80.15 (Reversing Falls)	100	100	100
80.19 (Denbow Point)	100	100	100
80.25 (Sipp Bay I)	22	3	0
80.26 (Minchner's Point)	100	100	100
80.28	100	100	100
80.40 (Sipp Bay II)	43	6	5
80.41 (Sipp Bay III)	98	85	30
80.65 (Pottle)	0	0	0

MHPC: Maine Historic Preservation Commission; MHHW: mean higher high water.

Table 3. Sites and their corresponding area of analysis percentages above HAT for current, low 2050, and high 2050 sea level scenarios.

MHPC number and site name	% Area remaining current	% Area remaining low 2050	% Area remaining high 2050
80.1 (Eastport Moose Island)	38	0	0
80.2 (Toll Bridge)	13	4	0
80.15 (Reversing Falls)	100	100	100
80.19 (Denbow Point)	100	99	33
80.25 (Sipp Bay I)	0	0	0
80.26 (Minchner's Point)	100	31	0
80.28	100	100	100
80.40 (Sipp Bay II)	5	0	0
80.41 (Sipp Bay III)	32	0	0
80.65 (Pottle)	0	0	0

MHPC: Maine Historic Preservation Commission; HAT: highest astronomical tide.

Discussion

Models suggest that six of the 10 sites in this case study are currently vulnerable to erosion and should, therefore, be prioritized for investigations. Two of the 10 sites are predicted to be vulnerable to the current HAT + storm surge, which occurs infrequently, and to our 2050 model scenarios, suggesting investigations are not as urgent. Two of the 10 sites are not predicted to be vulnerable under any of the model scenarios which indicates investigations of these sites are least urgent (Table 5; Figure 2). However, field work contradicts some of the results of these

Table 4. Sites and their corresponding area of analysis percentages above HAT + storm surge for current, low 2050, and high 2050 sea-level scenarios.

MHPC number and site name	% Area remaining current	% Area remaining low 2050	% Area remaining high 2050
80.1 (Eastport Moose Island)	0	0	0
80.2 (Toll Bridge)	0	0	0
80.15 (Reversing Falls)	100	100	100
80.19 (Denbow Point)	0	0	0
80.25 (Sipp Bay I)	0	0	0
80.26 (Minchner's Point)	0	0	0
80.28	100	100	100
80.40 (Sipp Bay II)	0	0	0
80.41 (Sipp Bay III)	0	0	0
80.65 (Pottle)	0	0	0

MHPC: Maine Historic Preservation Commission; HAT: highest astronomical tide.

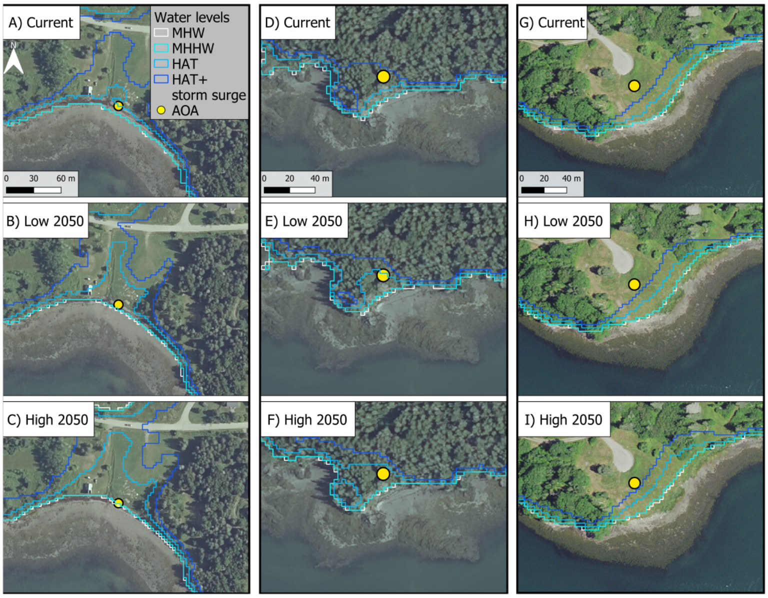

Figure 2. Model of MHW, MHHW, HAT, and HAT + storm surge (blue lines) at current, low 2050, and high 2050 levels in comparison to the area of analysis (AOA; yellow point). (A)–(C) Site 80.1 Eastport Moose Island is classified as high priority; map frames are of the same extent and scale. (D)–(F) Site 80.26 Minchner's Point is classified as mid-priority; map frames are of the same extent and scale. (G)–(I) Site 80.15 Reversing Falls classified as low priority; map frames are of the same extent and scale.
MHW: mean high water; MHHW: mean higher high water; HAT: highest astronomical tide.

Table 5. Priority categorization for each site based on the extent to which the site is affected by SLR and storm surge based on model results. High-priority sites are predicted to be exposed to current tides, ranging from MHW to HAT. Mid-priority sites are projected to be exposed to the current HAT + storm surge and all tides by 2050. Low-priority sites are predicted to not experience any exposure to tide or storm surge under all model scenarios.

Priority level	MHPC number and site name
High priority	80.1 (Eastport Moose Island)
	80.2 (Toll Bridge)
	80.25 (Sipp Bay I)
	80.40 (Sipp Bay II)
	80.41 (Sipp Bay III)
	80.65 (Pottle)
Mid-priority	80.19 (Denbow Point)
	80.26 (Minchner's Point)
Low-priority	80.15 (Reversing Falls)
	80.28

SLR: sea-level rise; MHW: mean high water; HAT: highest astronomical tide; MHPC: Maine Historic Preservation Commission.

models. Field observations broadly indicate that erosion has been more significant in the past compared to what the sea level models indicate for current tide levels. The following are comparisons of field observations and model results for all sites:

Eastport Moose Island (80.1)

David Sanger (2008) reported that the Moose Island/Eastport site has been eroding since the 1940s. Attempts to relocate the site in 1972 were not successful, suggesting it had been completely eroded. This was confirmed by our survey, which also identified extensive erosion and deflation across the entire beach area. However, the results of our sea level models indicate that the Moose Island/Eastport site would not be completely exposed to tides and eroded until SLR around 0.5 m.

Toll Bridge (80.2)

In our survey, we relocated the Toll Bridge site, which was likely reported by Kingsbury and Hadlock due to its proximity to the Moose Island site and contiguous site number. MHPC records show that it was noted as "eroded" even in the earliest paper record from the 1960s. Despite active erosion, the site exhibits intact stratigraphy. This is consistent with the model analysis presented here, showing it is exposed to current sea levels and erosion and is, therefore, a high priority for investigation.

Reversing Falls (80.15)

Reversing Falls has been excavated (Anderson et al., 2021; Honsinger et al., 2023; Hrynick et al., 2017; Patton et al., 2023; see also Spiess, 1990). Due to its unusual landscape position on a hillside sloping sharply down to the turbulent waters, it would take significant SLR and storm surge for the *entirety* of the site to be destroyed (Figure 3). However, the seemingly most densely occupied portion of the site has suffered significant erosion (3.5 m or more, see Spiess et al., 1990) since the middle of the 20th century when it was first examined. Reversing Falls is thus a complex and nuanced scenario. Our models correctly identify that some portion of the site will be unthreatened by SLR for many years but does not accurately capture the past and significant current erosion at the site.

Denbow Point (80.19)

The Denbow Point site was collected by avocational archaeologists in the 20th century, and they appear to consider the site entirely eroded by around 1950 (Anderson and Hrynick, 2023), which contemporaneous photographs largely confirm. Models show the Denbow Point site to be a medium priority based on the location of the site in MHPC records, underestimating the extent of previous and current tidal exposure. This discrepancy may stem from the accuracy limitations prior to the use of GNSS technology in recording the original location (likely added to MHPC records by Dean Snow based on topographic maps at the Robert S. Peabody Institute which had been annotated by Stoddard; see discussion below). In this case, it may simply be that the location recorded for the site, and thus the starting point for this model analysis, was the landward edge of the eroded site.

Sipp Bay I/Thompson's Point (80.25)

Sipp Bay 1 has been the focus of recent excavations which have demonstrated more intact archaeological deposits than expected despite significant erosion. The

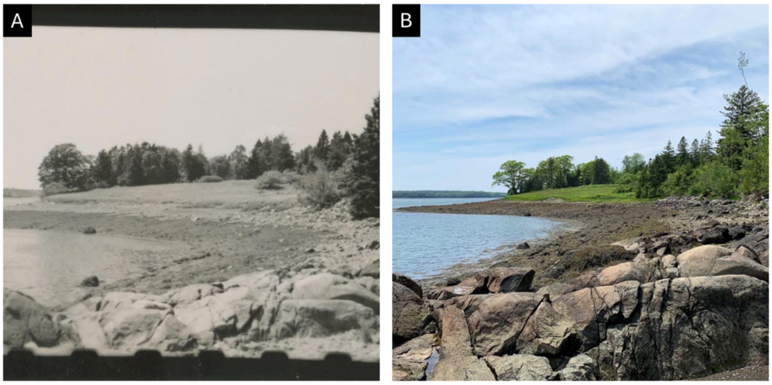

Figure 3. The site at Reversing Falls, Perry, Maine: (A) photographed in 1949 by Ted Stoddard and (B) photographed in 2021. Note the location of the large oak tree visible in both photographs. Image A: Copyright Robert S. Peabody Institute, Phillips Academy, Andover Massachusetts. All rights reserved.

determination of this site by model results as a high priority for investigation due to exposure to current tide levels is appropriate.

Minchner's Point (80.26)

The site at Minchner's Point was reconnoitered in our survey and found to be experiencing significant erosion, particularly in low-lying areas. The complex landform the large site sits on complicates the determination of erosion extent and survival of intact deposits. Overall, however, the designation of medium priority based on the model used here is consistent with our site audit.

80.28

We have visited and surface collected site 80.28. While it is clearly eroding there appear to be intact deposits, and the site stretches some way inland. Due to overgrowth, it is difficult to determine the extent of preservation and erosion on the ground. Model analysis suggests the site is low priority, not immediately threatened, which misaligns with reports of erosion since the modeled sea levels are not predicted to impact the site even by 2050. However, the site extends inland (Katherine Patton, personal communication, 2024), so the recorded point location may have been collected on the intact, landward portion of the site, resulting in a correct low-priority determination for that area.

Sipp Bay II (80.40) and III (80.41)

Based on site visits and preliminary excavation, these two sites probably represent now isolated portions of the same large, diffuse coastal site. As with 80.25, more archaeological deposits appear to remain intact upon initial excavation than expected based on the extensive visible coastal erosion at 80.40. At 80.41, however, there is little more than a patch of heavily eroded shell in an eroding bluff. The present model analysis appropriately identifies these as a high priority for investigation since these sites are both currently exposed to tidal action and erosion.

Pottle (80.65)

The Pottle site was identified through contact with a local collector and reported to the MHPC in 2018 (Hrynick and Anderson, 2021). Recent site locations, such as this one, are likely more precise in their location records than those from the 1950s due to recording points with even consumer-grade GIS rather than deriving points from USGS maps. Initial visits to the site were able to locate a patchy, small, and heavily eroded shell deposit and recovered a water-rolled biface from the location. However, the site was determined to be effectively destroyed from erosion by the time of reporting. In this case, we can confidently say that the coordinates reported to the state represent the extreme landward margin of the former site, as we have suggested may be the case at Denbow Point. This is another example of a site identified by sea level models as a high priority and currently exposed to tides in this case study which have already been reported as eroded and destroyed.

Modeling accuracy and limitations

There are thus some limitations to the method presented here for prioritizing sites for excavation or other investigation before being completely destroyed by tidal erosion and storm surge. The most consistent pattern observed when comparing model results with site audits is that the situation is more dire than it would appear from the modeling. Of the six sites considered high priority, three can be confirmed as fully destroyed. Even more concerning is that one of the two sites considered medium priority is fully destroyed and has been so since the mid-20th century. The model was potentially quite successful, however, in indicating low(er) priority sites where archaeological deposits might be expected to survive intact past 2050.

The most likely reason that this analysis often contradicts the field reports of sites is because not all site locations were recorded with modern precision in the field within the past century or so. When site locations were initially recorded, they did not need to be precise as they were not intended to be used for modern spatial analysis. However, since this study attempts to analyze the extent to which sites are eroded by tides based on their elevation and proximity to the coast, their precise geographic locations are crucial to our analysis.

In order to enable more accurate, large-scale modeling in the future, we emphasize the importance of revisiting and re-surveying sites recorded in state and other databases. This comparative study also emphasizes that all current and future-found sites should have their precise locations recorded at a high resolution, ideally as a polygon delineating specific areas as well as a point for analysis. We recommend conducting surveys with survey-grade equipment such as GNSS or Total Stations if tree cover multipath disrupts the GNSS satellite connection. These surveys will achieve centimeter-level precision in mapping site boundaries as far as can be determined on the surface. This modern GNSS accuracy would provide a sufficient level of precision needed for the present study, which could be enhanced with expert analysis of aerial imagery, notes, and sketch maps about the nature of the point measured (i.e. clarifying the relationship of the point to eroding and eroded sites, thus adding nuance to the complication of recording almost fully eroded sites such as Denbow Point and the Pottle Site). Accurate locations will allow this study to provide useful prioritizations based on models to archaeologists for the maximization of data collection from eroding and soon to be eroding sites.

Assessing the depth of sites could be insightful in evaluating vulnerability to erosion since it allows site volume to be considered along with the area. By incorporating site volume into the projected sea level and area analysis presented here, we can gain a more comprehensive understanding of potential erosion impacts. While sea level determines the extent to which sites are exposed to currents and waves and is a general indicator of erosion, integrating current and wave patterns into the models could enhance the accuracy of erosion projections (Brooks, 2004). When combined, sea levels, site area, site volume, currents, and waves would provide a more robust model for predicting erosion and informing site prioritization (Anderson et al., 2017; Elliott and Williams, 2019). Therefore, future site visits should consider collecting depth measurements and models should incorporate these variables to improve the accuracy and reliability of local-scale models in predicting site erosion.

Overall, with sea levels rising at 3.6 mm/year and accelerating in Eastport, ME (Fernandez et al., 2020), it is critical to inform proactive measures among archaeologists and resource managers. Field surveys have already reported extensive erosion of many sites in the Quoddy Region (e.g. Anderson and Hrynick, 2023). By integrating predictive SLR models with field surveys, sites most vulnerable to erosion can be identified for prioritized investigation, conservation, and mitigation efforts. Given the significance of Maine's shell heaps and other coastal sites as records of ecological, environmental, and archaeological change (e.g. Johnston, 2020; Wanamaker Jr, 2011), it is crucial that Maine includes archeological site investigation in preparation for SLR.

Conclusion

Our study has prioritized Quoddy Region archaeological sites by quantifying the impact and extent of future SLR and storm surge in terms of site area remaining above sea level. However, not all site locations were collected with the level of accuracy required for model analysis which limits the implications of our study to maximize data collection of eroding sites. Profound losses to the archaeological record have already been documented along the Maritime Peninsula due to SLR while the threat to the archaeological record is accelerating (Betts and Hrynick, 2021). Since our study was hindered by inaccurate site locations documented in the field, it is important to collect correct site location data to prioritize site investigations as they will be vulnerable to rising sea levels in the future.

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Author contributions

Katelyn Anna DeWater: conceptualization, methodology, software, validation, formal analysis, investigation, writing–original draft, and visualization. Arthur W Anderson: conceptualization, methodology, validation, formal analysis, writing–review and editing, and supervision. Gabriel Hrynick: validation, formal analysis, and writing–reviewing and editing. William Kochtitzky: conceptualization, methodology, validation, writing–reviewing and editing, and supervision.

Data availability

Sea level and storm surge data layers are available at: https://dune.une.edu/gis_data/2/. Due to site protection considerations, we are unable to openly share site location data.

Declaration of conflicting interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Ethical approval

This article does not contain any studies with human or animal participants; therefore, informed consent is not required.

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References

Adams AL (1873) *Field and forest rambles: with notes and observations on the natural history of eastern Canada*. London: Henry S. King & Co.

Anderson A, Cummings J and Hrynick G (2024) The Quoddy Region Archaic period through early collections. *Northeast Anthropology*: 93–94.

Anderson A and Hrynick G (2023) The site at Denbow Point, Cobscook Bay, and 20th century collecting in Downeast Maine. *The Maine Archaeological Society Bulletin: The Maine Archaeological Society* 63(1): 1–14.

Anderson AW, Patton AK and Hrynick MG (2021) Wabanaki subtidal shellfish harvesting: An ecological and archaeological study of horse mussels and barnacles at the Reversing Falls site, Pembroke, Maine, USA. *Archaeology of Eastern North America* 49: 73–85.

Anderson DG, Bissett TG, Yerka SJ, et al. (2017) Sea-level rise and archaeological site destruction: An example from the southeastern United States using DINAA (Digital Index of North American Archaeology). *Public Library of Science One* 12(11): 1–25.

Betts MW (2019) *Place-making in the Pretty Harbour: The archaeology of Port Joli, Nova Scotia*. Ottawa: Canadian Museum of History; University of Ottawa Press.

Betts MW and Hrynick GM (2017) Introduction: North American East Coast Shell Middens. *Journal of the North Atlantic* 10(10): v–viii.

Betts MW and Hrynick GM (2021) *The Archeology of the Atlantic Northeast*. USA: University of Toronto Press, Toronto.

Bishop JC and Black DW (1988) The lands edge also: Culture history and seasonality at the Partridge Island Shell Midden. *Canadian Journal of Archaeology* 12: 17–37.

Black DW (1997) A native artifact from the ocean floor near Indian island. *Fieldnotes: The Journal of the New Brunswick Archaeological Society* 3(2): 5–7.

Black DW (2000) Rum Beach and the Susquehanna Tradition in the Quoddy Region, Charlotte County, New Brunswick. *Canadian Journal of Archaeology* 24: 89–106.

Black DW (2002) Out of the blue and into the black: The middle-late maritime woodland transition in the Quoddy Region, New Brunswick, Canada. In: Hart JP and Rieth CB (eds) *Northeast Subsistence-Settlement Change: A.D. 700–1300*. Albany: New York State Museum Bulletin #496. University of the State of New York/State Education Department, 301–320.

Black DW (2018) *…gathering pebbles on a boundless shore…"—The Rum Beach Site and Intertidal Archaeology in the Canadian Quoddy Region*.

Brooks DA (2004) Modeling tidal circulation and exchange in Cobscook Bay, Maine. *Northeastern Naturalist* 11(2): 23–50.

Corps of Engineers Waltham, MA New England Division (1978) Plan of Study for the Tidal Power Study, Cobscook Bay, Maine, USA. Accession Number: ADA099250.

Davis SA (1982) Coastal erosion and archaeological sites in Charlotte Co., New Brunswick – 1980 survey. In: Turnbull CJ (ed) *Archaeological Resources in the Maritimes 1980, vol. 5*. Fredericton: Reports in Archaeology, Council of Maritime Premiers, 1–27.

Desplanque C and Mossman DJ (2001) Bay of Fundy Tides. *Geoscience Canada* 28(1): 1–11.

Elliott P and Williams H (2019) Evaluating sea-level rise hazards on coastal archaeological sites, Trinity Bay, Texas. *Journal of Island and Coastal Archaeology* 16(2-4): 591–609.

Erlandson JM (2008) Racing a rising tide: Global warming, rising seas, and the erosion of human history. *Journal of Island and Coastal Archaeology* 3(2): 167–169.

Erlandson JM (2012) As the world warms: Rising sea, coastal archaeology, and the erosion of maritime history. *Journal of Coastal Conservation* 16: 137–142.

Ferguson AM and Turnbill CJ (1980) Minister's Island seawall: An experiment in archaeological site preservation. In: Schemabuku DM (ed) *In Proceedings of the 1980 Conference on the Future of Archaeology in the Maritime Provinces*. Halifax.: St. Mary's University Department of Anthropology, 88–94.

Fernandez I, Birkel S, Schmitt C, et al. (2020) *Maine's Climate Future 2020 Update*. Orono, ME: University of Maine. Available at: https://climatechange.umaine.edu/climate-matters/maines-climate-future/.

Fitzpatrick SM, Kappers M and Kaye Q (2006) Coastal erosion of site destruction on Carriacou, West Indies. *Journal of Field Archaeology* 31(3): 251–262.

Frederikse T, Landerer F, Caron L, et al. (2020) The causes of sea-level rise since 1900. *Nature* 584(7821): 393–397.

Honsinger AA, Anderson AW and Hrynick MG (2023) Lithic Procurement in the Quoddy Region, Washington County, Maine: A View from the Reversing Falls Site (80.15). *Archaeology of Eastern North America* 51: 95–107

Hrynick MG (2018) Maritime Woodland period dwelling surface construction on the Coast of the Maritime Peninsula: Implications for site reuse and intra-site space. *Archaeology of Eastern North America* 46: 1–16.

Hrynick MG, Webb WJ, Shaw CE, et al. (2017) Late Maritime Woodland to protohistoric culture change and continuity at the Devil's Head Site, Calais, Maine. *Archaeology of Eastern North America* 45: 85–108.

Hutchings RM (2017) *Maritime heritage in crisis: Indigenous landscapes and global ecological breakdown*. New York, NY: Routledge.

Johnston AE (2020) Paleoclimate Reconstruction of the Gulf of Maine during the Recent Holocene (Past 5000 Years) Using Archaeological Mollusk Shells. Doctoral dissertation, University of Massachusetts, Boston, US.

Leatherman SP, Zhang K and Douglas BC (2000) Sea level rise shown to drive coastal erosion. *Edition Open Sources* 81(6): 55–57.

Maine Climate Council (2020) Scientific Assessment of Climate Change and Its Effects in Maine. A Report by the Scientific and Technical Subcommittee (STS) of the Maine Climate Council (MCC). Augusta, Maine. 370 pp.

Matthew GF (1884) Discoveries at a village of the Stone Age at Bocabec. *Bulletin of the Natural History Society of New Brunswick* 3: 6–29.

Mulligan RP, Smith PC, Hill PS, et al. (2013) Effects of tidal power generation on hydrodynamics and sediment processes in the Upper Bay of Fundy. 4th Specialty Conference on Coastal, Estuary and Offshore Engineering.

Oppenheimer M, Glavovic BC, Hinkel J, et al. (2019) Sea level rise and implications for low-lying islands, coasts and communities. In: Pörtner HO, Roberts DC, Masson-Delmotte V, et al. (eds) *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate*. Cambridge, UK and New York, NY, USA: Cambridge University Press, 321–445. https://doi.org/10.1017/9781009157964.006.

Pearson R (1970) Archaeological investigations in the St. Andrews Area, New Brunswick. *Anthropologica* 12: 181–190.

Pourkerman M, Marriner N, Morhange C, et al. (2018) Tracking shoreline erosion of "at risk" coastal archaeology: The example of ancient Siraf (Iran, Persian Gulf). *Applied Geography* 101: 45–55.

Reeder LA, Rick TC and Erlandson JM (2010) Our disappearing past: A GIS analysis of the vulnerability of coastal archaeological resources in California's Santa Barbara Channel region. *Journal of Coastal Conservation* 16: 187–197.

Rick TC (2023) Coastal archaeology and historical ecology for a changing planet. *Journal of Anthropological Research* 79(2): 153–175.

Sanger D (1987) *The Carson Site and the Late Ceramic period in Passamaquoddy Bay, New Brunswick. Mercury Series, Vol. 135*. Ottawa, Canada: National Museums of Canada.

Sanger D (1996) Testing the models: Hunter-Gatherer use of space in the Gulf of Maine, USA. *World Archaeology* 27(3): 512–526.

Sanger D (2008) Discerning regional variation: The terminal Archaic Period in the Quoddy Region of the Maritime Peninsula. *Canadian Journal of Archaeology* 32: 1–42.

Sanger D (2010) Semi-subterranean houses in the Ceramic Period along the coast of Maine. *The Maine Archaeological Society Bulletin* 50(2): 23–46.

Sanger D and Sanger MJ (1986) Boom and bust on the river: The study of the Damariscotta oyster shell heaps. *Archaeology of Eastern North America* 14: 65–78.

Spiess A (2017) People of the Clam: Shellfish and Diet in Coastal Maine Late Archaic and Ceramic Period Sites. *Journal of the North Atlantic* 10: 105–112.

Thomas MLH (1983) Marine and coastal systems of the Quoddy Region, New Brunswick. *Canadian Special Publication of Fisheries and Aquatic Sciences* 64: 306.

Torresan S, Critto A, Valle MD, et al. (2008) Assessing coastal vulnerability to climate change: Comparing segmentations at global and regional scales. *Sustainability Science* 3: 45–65.

Wanamaker Jr AD, Kreutz KJ, Br S, et al. (2011) Gulf of Maine shells reveal changes in seawater temperature seasonality during the Medieval Climate Anomaly and the Little Ice Age. *Palaeogeography, Palaeoclimatology, Palaeoecology* 302(1-2): 43–51.

Young RS, Daniel FB and David S (1992) Geoarchaeology of Johns Bay, Maine. *Geoarchaeology: An International Journal* 7(3): 209–249.

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