Sea-Level Rise Vulnerability Assessment of Coastal Resources in New Hampshire

Benjamin Curran
Michael Routhier
Gopal Mulukutla

Fig. 1. Shapley-Drisco House (white building at far right), Strawbery Banke, Portsmouth, New Hampshire. Photograph by Michael R. Routhier.

As the impacts of sea-level rise increase for coastal communities, so too will the toll on the built heritage that has come to distinguish them. Fluctuations and drastic shifts in temperature, rainfall, mean global sea-level, and the frequency and severity of storms will have adverse impacts on the natural and built landscapes that define coastal cultures. Collectively, these factors will have catastrophic effects on the connectivity of many populations to their natural and cultural environments. Additionally, these factors will adversely affect the stability of the historic structures that define the flow, pace, and timbre of coastal communities. A grant from the Waitt Foundation and the National Geographic Society in 2010 enabled the beginning of a process to connect place-specific field research on climate change to culturally sensitive areas and the historic structures that will be directly impacted by climate change and sea-level rise.

Preventative risk-evaluation measures can help to protect buildings from mean sea-level rise.

Recent studies, documented in the Snow, Water, Ice and Permafrost in the Arctic (SWIPA) report, published in 2011 by the Arctic Monitoring and Assessment Programme, estimate that at current trends, global mean sea level will increase by 0.6 meters to 1.6 meters by 2100. In corroboration with the SWIPA report, the 2013 Intergovernmental Panel on Climate Change (IPCC) Assessment Report (AR) estimates an increase in mean sea level of 0.26 meters to 0.98 meters by 2100.[1] Though the IPCC's 2013 estimates are not as high as those from the SWIPA report, they represent a substantial increase from 2007 IPCC AR estimates of 0.18 meters to 0.59 meters of sea-level rise for the same time period.[2] Since 1993 the global mean sea levels have risen by approximately 3.3 millimeters per year, a rate that has doubled over the course of the last century.[3] This doubling in the rate of sea-level rise does not account

Fig. 2. Jones House (red building at center). Photograph by Michael R. Routhier.

for contributions made by glacial melting in Greenland and Antarctica, which may become a principal driver of future sea-level rise.[4] Regionally, increases in sea level may occur even sooner than projected within these global estimates due to localized phenomena. Along the Atlantic Seaboard, for instance, a larger rise in sea level may occur due to an increased frequency of convection currents associated with the Atlantic Meridional Overturn Current, caused by the freshening of subpolar surface-water due to ice melt.[5]

Low-lying coastal regions known as Low Elevation Coastal Zones (LECZ), defined here as coastal zones 10 meters or lower in elevation, make up only 2 percent of Earth's land area, but are currently home to upwards of 10 percent of the world's population. Previous studies indicate that human populations have historically preferred settling along coasts and major rivers.[6] This inclination towards living in and around LECZ has resulted in a dense deposition of material culture and built heritage within these areas. From the standpoint of historic preservation and conservation, the growing threat of sea-level rise poses great challenges to the retention and preservation of these important components to cultural fabric.

There is a broad agreement that while climate change is a global challenge, its effects are felt regionally and locally. As a result, there is an increased urgency among scientists, engineers, and policymakers for the development of regional and local adaptation plans, inclusive of resilience measures, to deal with temperature increases, precipitation extremes, sea-level rise, and other effects of the changing climate. Unfortunately, place-specific research concerning climate-change adaptation and vulnerability within the historic-preservation and conservation fields is still sparse.[7]

In this paper, current research and methods towards a place-specific approach to climate-change adaptation are laid out by assessing the vulnerability of the historic Strawbery Banke region of Portsmouth, New Hampshire. An initial assessment led to the belief that the first step to developing mitigation strategies was to assess how sea-level rise would impact coastal water tables. Though considerable attention has been paid to the more dramatic issues of inundation, erosion, and flooding, all of these will be preceded by the slow and insidious creep of coastal water-table elevations influenced by an increasing height in sea level. A combination of techniques was used — ground survey, continuous long-term environmental-data-logger monitoring, and applications of geospatial analysis methods — to assess the vulnerability of the region to storm surge and increased tide-induced groundwater seepage.

The Strawbery Banke Museum Site

The Strawbery Banke Museum was utilized as the test site due to the historic integrity of its structures and its wealth of archaeological resources. The museum site is located in the historic district of Portsmouth, New Hampshire. Currently the site is comprised of a 10-acre living-history museum containing 11 contemporary structures and 31 historic structures ranging in origin from the late-seventeenth century to the mid-twentieth century (Figs. 1 and 2). The site is located near the outlet of the Piscataqua River and is part of the Great Bay tidal estuary, whose watershed is home to almost one-third of the state's population (Fig. 3). The Great Bay estuary is one of the largest in the eastern United States, extending up to 10 miles inland and having tidal elevation changes amounting to as much as 2.7 meters near the mouth of the estuary, where Strawbery Banke is located.

The surrounding area is known to have had a long history of pre-contact Native American habitation dating back as far as the Late Archaic Period (6000–4000 B.C.). Various styles of local and distal pottery have been found in the area, as well as hand tools and projectile points. Across the Piscataqua River in Eliot, Maine, recent excavation work indicates paleo-American habitation in the region dating as far back as 10,000 B.C.[8]

As a whole, this site typifies the stratification of histories and cultures that exemplify the evolution of coastal New England. For the last 220 years the site has been inhabited primarily by European descendants who manipulated the natural features to meet their needs. At the turn of the eighteenth century, the original salt marsh and tidal inlet of the Strawbery Banke area were turned into a port known as Puddle Dock, with English-style docks.[9]

During the latter part of the nineteenth century, the area began to suffer economically, and at the turn of the twentieth century, the Puddle Dock port was filled in to build Wallace Avenue atop the old inlet location. Though the neighborhood became an urban backwater

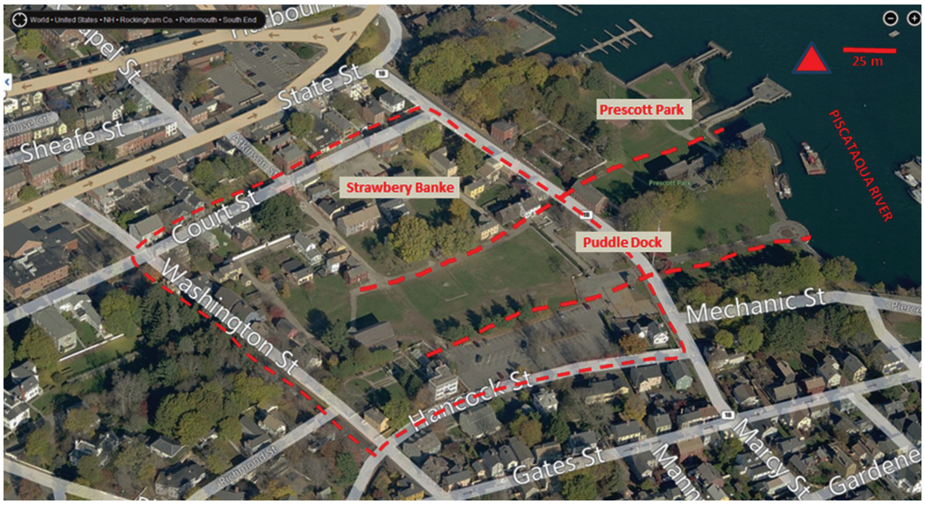


Fig. 3. Aerial view of the Strawbery Banke Museum, showing its relationship to the Piscataqua River. Image courtesy of Microsoft Corporation, Microsoft product screenshot reprinted with permission from Microsoft Corporation.

for much of the twentieth century, urban-renewal initiatives in the 1960s and 1970s caused local forces to coalesce in an effort to save the area, resulting in the creation of the Strawbery Banke Museum complex.[10]

The elevation of the site ranges from 2.3 meters to 7 meters above sea level. The houses surrounding the Puddle Dock make up the bulk of the oldest structures on the site and are located at its lowest point. The vast area that once was Puddle Dock is now an open lawn that connects to a complex known as Prescott Park, which abuts the river. The distance between the closest (northeastern-most) point of the Strawbery Banke Museum to the river is about 40 meters, and there is little change in elevation between the river and the museum.

Soil tests were conducted in and around the Puddle Dock area of Strawbery Banke in December 2004 and October 2006 in preparation for the construction of the two newest structures, a visitors' center and a building to house collections.[11] These studies identified a delineated representation of the two main soil compositions of the site. The soil samples indicated the presence of five major soil units from within the filled-Puddle Dock inlet: topsoil, fill, organic silt with seashells (tidal marsh deposits), silty clay (marine deposits), and silty sand (marine deposit). Soil samples from outside the Puddle Dock inlet area indicated the presence of varying amounts of five major soil units, which were classified as topsoil, fill, organic silt, silty clay (marine deposits), and gravelly sand with silt. In addition, information on the existing water table was gathered during the soil survey. The water table was detected at depths of 1 meter to 1.5 meters. Water levels fluctuated regularly due to tide, seasonality, and rainfall events. Groundwater movement throughout the site is exacerbated by the numerous buried utilities that crisscross the area. These underground disturbances to the soil matrix have the potential to act as conduits for water and may contribute to the increased role of saltwater intrusion into the site.

LIDAR and Ground Survey

To provide a spatial context to the study and to map sea-level rise inundation estimates across the study area, land-surface elevation for the site was measured through the use of contemporary Light Detection and Ranging (LIDAR) data obtained from NH Granit, New Hampshire's statewide Geographic Information System (GIS) clearinghouse, and verified by conventional ground-survey methods. LIDAR data is created using lasers mounted on airplanes to measure the distance between the laser and the ground through the time it takes for emitted pulses of light to reflect between the two. Resulting pulses create a dense cloud of elevation points, which are converted to form a continuous digital elevation model (DEM) containing regularly spaced cells (pixels) of uniform elevation. The resulting pixel resolution of the LIDAR DEM used for this study was 2 meters with a bare-earth (devoid of structures and vegetation) vertical accuracy of 15.0 centimeters or better. The LIDAR elevation data used for this study, acquired in the winter and spring of 2011, was of the highest resolution available for the site.

The ground-survey verification of the LIDAR data was completed using conventional surveying methods deploying GPS units, transits, and measuring rods over the extent of the Puddle Dock area. This area was chosen because it is relatively flat and devoid of structures and vegetation, requirements necessitated by the bare-earth vertical-accuracy measures of the LIDAR data-error measurements. Approximately 1,000 points were surveyed in a 2-meter resolution-grid pattern across the Puddle Dock area to match the resolution of the LIDAR data. Accuracy of the aerial LIDAR data was verified to be within 9 centimeters on average, with a standard deviation of 8 centimeters, of the conventional survey elevation data.

In order to compare these measurements with a known zero-elevation benchmark, the LIDAR data was adjusted to a commonly used tidal datum called the "mean higher high water" (MHHW) level. The National Oceanic and Atmospheric Administration (NOAA) defines MHHW as "the average of the higher high water height of each tidal day observed over the National Tidal Datum Epoch."[12] The MHHW level was measured at the nearest NOAA tide and current-monitoring station (Station ID: 8423898) at Fort Point in Newcastle, New Hampshire. This station is located approximately two miles from Strawbery Banke and is close to the mouth of the Piscataqua River. This benchmark was used for the purposes of measuring all sea-level changes from a present day, worst-case-scenario perspective, where rising tides are measured from a MHHW level. In total, this adjustment resulted in the subtraction of 1.344 meters from all LIDAR data elevations.

Using this data, a high-resolution elevation map of the area was created. This map helped to estimate the extent to which Strawbery Banke Museum buildings are susceptible to increases in sea-level height. Susceptibility estimates were based on global mean sea-level rise scenarios defined by the 2013 IPCCs Assessment Report 5 (AR5) and the 2011 SWIPA reports.[13] The AR5 scenarios are broken up into Representative Concentration Pathways (RCP) with ascribed sea-level rise projections for the year 2100. The RCP define possible greenhouse gas concentration trajectories associated with specific increases in radiant energy absorbed by the earth's atmosphere by the year 2100, relative to pre-industrial estimates. The SWIPA report had a single estimate for the year 2100. These estimates and the corresponding ranges used in this study are given in Table 1.

Data-logger Survey

The transitional boundary between freshwater and saltwater is highly dynamic and can have significant effects on the structural integrity of buildings that fall within LECZ. The water-level data-logger array provided the opportunity to better understand the complex interaction of fresh and saltwater and the role, if any, saltwater was playing above and below the ground. A coordinated monitoring system was developed; it correlates data obtained from a nearby USGS bedrock-monitoring NOAA tide gauge with an array of water-level data loggers and relative-humidity meters placed throughout the site.

The sensors were deployed within and around two structures due to their proximity to the former Puddle Dock and their relative locations to the Piscataqua River. These two structures were the Jones House (built c. 1790) and the Shapley-Drisco House (built c. 1795).

Table 1. Estimated mean sea-level increases for the year 2100

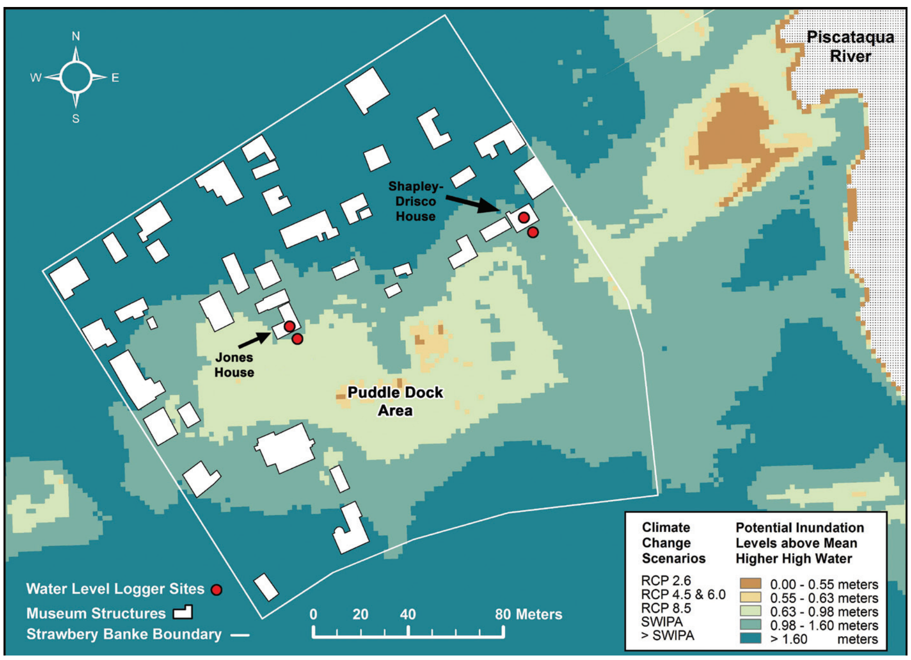
Representative Concentration Pathways (RCP) or Climate Scenario	Estimated Mean Sea-level Rise, Min. to Max. (meters)	Mean Sea-level Implemented for the Study (meters)
RCP 2.0	0.28 to 0.55	0.28 to 0.55
RCP 4.5	0.32 to 0.63	0.56 to 0.63
RCP 6.0	0.33 to 0.63	0.56 to 0.65
RCP 8.5	0.52 to 0.98	0.52 to 0.98
SWIPA	0.99 to 1.60	> 1.60

The Jones House sits just beyond the far end of the former Puddle Dock inlet, while the Shapley-Drisco House sits at the opposite end. The Shapley-Drisco House is the closest museum structure to the Piscataqua River, and it sits next to Sherburne House (c. 1695-1703), the oldest structure on the property.[14]

In the spring of 2011 water-level data loggers (model HOBO U20, Onset Computer Corporation, Bourn, Massachusetts, at a cost of $600 per unit) were installed. These data loggers contained pressure transducers that measure ambient pressure. Two data loggers were deployed in the basements of the buildings in previously existing sumps that had been constructed to collect and remove water seeps. The basement data logger at the Shapley-Drisco House was placed at 1.14 meters above MHHW; the one at the Jones House was placed 0.97 meters above MHHW. Given that the basement sumps flooded at a continuous rate, the water-level loggers within the sumps were used to measure the changes in the rates of refill after the flushing of the sumps from in situ pumps controlled by water-level float-activated switches.

Additionally, two data loggers were deployed on the grounds of buildings in wells drilled for this study. The data logger at the Shapley-Drisco House was placed approximately 1.14 meters below ground level (0.25 meters below

Fig. 4. Sea-level rise inundation levels for the Strawbery Banke Museum based on global mean sea-level rise scenarios. The Jones and Shapely-Drisco houses are shown. Map by the authors.



MHHW). The data logger at the Jones House was placed approximately 1.57 meters below ground level (0.6 meters below MHHW). Because the HOBO sensors measure water levels based on changes in hydrostatic pressure as influenced by atmospheric pressure, a fifth data logger was suspended in the air in the Shapley-Drisco basement to capture local barometric pressure values that were used to develop a compensation for the other water-level data collected. This allowed for the determination of water-level fluctuations within centimeters at each deployment.

Furthermore, because wet basements increase ambient humidity and issues related to rising damp throughout a structure, a humidity survey was also conducted for both the Jones and Shapely-Drisco houses. Humidity meters (HOBO U23 Pro temperature and humidity sensors costing $170 per unit) were deployed in the basements and on the first floors of both structures to better understand the correlation of groundwater level and sump-well recharge rates with the humidity of the air within the structures. Since higher humidity values cause higher rates of rot, oxidation, and degradation of building materials such as wood, iron, and mortar, these levels are of importance to the preservation of the structures, independent of direct flooding or inundation.

Analysis of Results

Analysis of LIDAR data. MHHW-adjusted LIDAR-elevation data values were mapped across the Strawbery Banke area to measure potential inundation levels (Fig. 4). Inundation levels were mapped based on upper-end estimates of the IPCC's Representative Concentration Pathways and the SWIPA sea-level rise scenarios for the year 2100 to form the classifications as summarized in Table 1.

Of the 44 contemporary and historic structures at Strawbery Banke, none falls within the current predicted RCP 2.6, 4.5, and 6.0 inundation zones. This is consistent spatially with the location of the old Puddle Dock inlet area itself. Two fall within or abut the RCP 8.5 inundation zone, 20 within the predicted SWIPA-inundation zone, and 22 above the SWIPA scenario-inundation zone. Thus, according to all of the current RCP scenarios, only two historic structures on site are susceptible to inundation, but 22 are susceptible according to the SWIPA-report projections (those within the lower elevation RCP zones and those within the SWIPA zone).[15]

Water level and environmental monitoring. The data collected was studied to determine the causes of variability in the water levels in the monitoring wells (Figs. 5 and 6). The monitoring well outside the Jones House was benchmarked to MHHW-depth, and data was recorded at 30-minute intervals. This data was examined along with data from a bedrock-monitoring site located near the Great Bay estuary in Greenland, New Hampshire (USGS Station Number 430212070505201 NH-GTW 141), approximately 7.6 miles from the Strawbery Banke region. A precipitation record was gathered from the NOAA Climate Reference Network station located in Durham, New Hampshire (approximately 14 miles distant). This analysis suggests that the chief driver of variability in the Jones House monitoring well is precipitation. Unlike the water level in the bedrock-monitoring well, precipitation events cause an immediate rise in the water. During Hurricane Irene, which hit New Hampshire as an extra-tropical storm, the water level in the well equaled or exceeded MHHW data for a brief period of time. Similar patterns were recorded in the water-level loggers deployed in the basements of the Jones House and the Shapley-Drisco House, albeit with levels heavily influenced by the operation of sump pumps that periodically power on to prevent flooding.

The external well at the Shapley-Drisco House also showed a similar pattern, but due to construction difficulties, the water-level sensor was deployed at a shallower depth. As a result, the well remained dry for a portion of the time. Nevertheless, the time-series data collected at the well showed fluctuations coinciding with tidal patterns as recorded by the NOAA tide gauge in the Piscataqua River. This correlation suggests that tidal forcing is pushing the interface of freshwater and saltwater upwards to flood the basements of the Shapley-Drisco and the Jones Houses through storm-induced tidal pressures. Sump-well flood rates also corroborated these findings, given that higher, tidally forced water tables corresponded with faster sump-well flooding-recharge rates.

Analysis of humidity-meter data showed that the relative-humidity levels in the basements of the Jones House and the Shapley-Drisco House do not follow the seasonal patterns normally observed in outdoor measurements (Fig. 7). Relatively low humidity levels in the summer, a direct result of relatively low seepage of groundwater, are succeeded by high humidity levels in autumn. This coincides with increased seepage of groundwater into the basement caused by precipitation and tide-induced pressure on the freshwater interface. The humidity levels remain high through winter and spring. Such high levels of humidity — coupled with relatively high temperatures in summer, fall, and spring, along with higher temperatures due to basement heating in the winter — results in conditions that are ideal for structural degradation of the foundations of these buildings and their wooden superstructures caused by microorganisms.

Monitoring of water levels at the site is ongoing and will continue for the foreseeable future without any new investment. Continuous and long-term monitoring at this temporal scale is expected to provide a wealth of data, especially with regard to future storm and hurricane response.

The relatively low cost and scientific quality of the sensors used within this study show that it is possible to gather fine spatial and temporal-scale data for preservation and conservation efforts for little money, a task unthinkable even ten years ago. Furthermore, with new availability of open-source hardware and software for use in "home-grown" sensors, purchase costs continue to fall, making sensor deployments even more economically feasible.

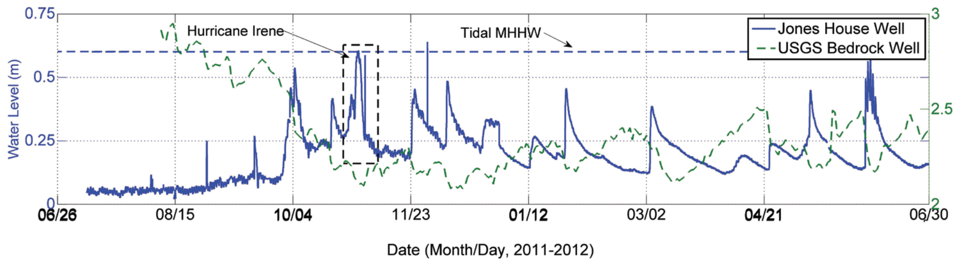


Fig. 5. Data showing the variation of water level in a shallow well next to the Jones House, June 2011 to June 2012. All charts by the authors.

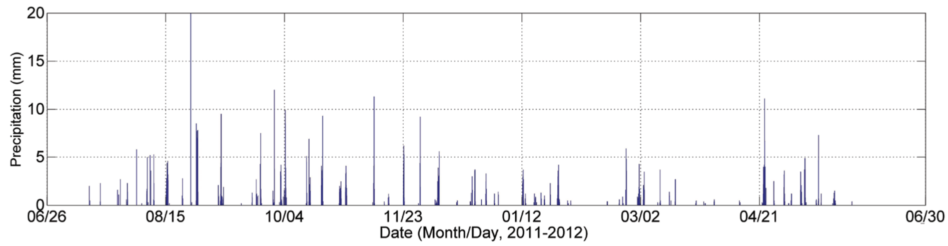


Fig. 6. Precipitation recorded at Thompson Farm, Durham, New Hampshire, a NOAA climate-reference network station (USCRN), June 2011 to June 2012.

Potential Conservation Issues

Structures within inundation zones may be subject to daily tidal submersions of their substructures and superstructures. Submersion of the substructure could result in the destabilization of the brick, stone, and mortar of foundation walls.[16] In particular, foundations comprised of brick and mortar could suffer failure due to the heavy salinization of the material and result in the leaching of soluble elements of the mortar.[17] Additionally, the full intrusion of tides into these areas could result in the erosion of the soil matrix supporting foundation walls. This change could undermine the integrity of the substructure by removing the exterior retaining material in some instances.

Salinization of the building shell may result in the deterioration of associated historic ferrous materials, such as nails, screws, hinges, door handles, and other fasteners and hardware. In the case of wooden-clad buildings, this change could exacerbate deterioration of the structure by weakening the adherence of exterior cladding and expose interior cavities to increased weathering and dampening.

Regular exposure of lower stories to cyclical wetting and drying events, as well as increased exposure to salts, may result in the deterioration of interior wall cladding, such as lathe, washboards, wainscoting, and chair rails. Increased moisture within these materials will also impact their associated decorative coatings, such as plaster, lime wash, and paint.[18] The regular saturation of building material may also introduce a variety of new intertidal microorganisms, such as tunneling bacteria, soft rot, and basidiomycetes.[19] Ultimately, many of these structures could be subjected to such high levels of in situ deterioration that they require either relocation or abandonment.[20]

Areas outside the inundation zone that will likely see the first effects of sea-level rise due to the earlier onset of the impacts of tidal forcing on the water table and salinization of the groundwater are defined as intrusion zones. The effects on these areas will precede the impacts of inundation by decades and will be precursors to further overtopping and inundation. The elevation of the water table due to the shift of the saltwater-freshwater boundary inland will result in the exposure of many structures to increased freshwater moisture issues. Without significant mitigation, the effect of the elevation of the groundwater will likely result in the regular or permanent flooding of many of the basements at Strawbery Banke.[21]

Major modification will be needed in order to contend with the increased moisture issues that will likely result, and increased mildew and mold infestation may become a greater health risk. Issues concerning substructure humidity could have one of the most notable impacts due to the destabilization of chimney systems. Elevation of the water table, rising damp, and increased ambient humidity may cause increased breakdown of hearths and their constituent salmon bricks. The shifting of the lower sections of chimney systems could induce stress on the stacks as a whole, thus increasing deterioration even in areas not affected by humidity. The shifting of the stacks would compromise the interface of the chimney system with the roof system and introduce new voids and cracks which could initiate additional water issues from above. This situation may be exacerbated by differences in humidity between below-ground spaces and acclimatized living spaces where heating and air-conditioning create a disequilibrium.

Elevation of the water table, rising damp, increased ambient humidity, and salinization of the water table may also increase the rate and scope of freeze-thaw damage. The hygroscopic nature of low concentrations of salts conveyed to exterior bricks via rising damp and interior humidity may increase their sus-

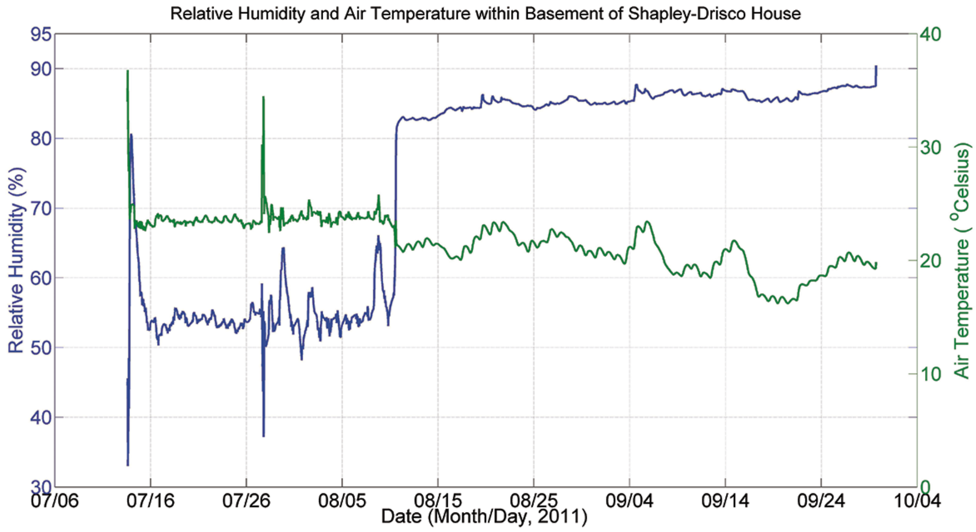


Fig. 7. Relative humidity and air temperature measured within the basement of the Shapley-Drisco House from July 2011 to October 2011.

ceptibility to freeze-thaw effects during winter months.[22]

The increased pressure exerted upon the freshwater-saltwater interface will cause freshwater, stormwater, rainwater, and saltwater to be forced through voids or disturbances in the soil matrix created by utilities, drainage infrastructure, or infill due to changes in hydrologic conductivity. Pressurized water in these conduits will enter buildings through their substructures and will likely cause long-term damage to immobile features such as concrete pads, footings, and foundations in the intrusion zone. This has already begun to occur in several structures in close proximity to Puddle Dock during extreme high tides.

Conclusion

If the preservation community is to effectively develop and implement mitigation and mediation strategies for coastal cultural heritage, it is crucial that it begins to develop a better understanding of the mechanism that climate change and sea-level rise will have on the impact of the material fabric of the built environment. Current discussions about climate change and cultural heritage are too focused on larger issues, and little progress is being made on the small, place-based, and site-specific issues that are, and will continue, destroying buildings that require preservation. In order to be prepared for the preservation and conservation tasks ahead, preservationists must begin taking a more active role in initiating localized investigation and monitoring of historic sites so that the breadth of this issue may be better understood.

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Benjamin Curran *is the department head of the historic preservation program at Savannah Technical College and the director of the Center for Traditional Craft at the college. He specializes in historic preservation, building conservation, traditional building technology, and preservation-trades education.*

Michael Routhier *is an information technology manager at the Earth Systems Research Center within the Institute for the Study of Earth, Oceans, and Space at the University of New Hampshire. His specializations include Geographic Information Systems (GIS), data archiving, remote sensing, digital-image processing, project management, and geospatial science education.*

Gopal Mulukutla *is a research scientist at the Earth Systems Research Center within the Institute for the Study of Earth, Oceans, and Space at the University of New Hampshire. He specializes in the development and deployment of sensing systems for environmental monitoring, hydrology, and water-quality studies.*

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