BEACH PROFILING IN AN URBAN HARBOR VIA PARTICIPATORY SCIENCE: BRIDGING RESEARCH AND OUTREACH IN BOSTON, MASSACHUSETTS, USA

A. O'CONNELL[1,2], M. BORRELLI[1,2] R. F. CHEN[1,2]

2. *School for the Environment, University of Massachusetts Boston, Massachusetts, USA.*
2. *Stone Living Laboratory, School for the Environment, University of Massachusetts, Boston, 100 Morrissey Blvd, Boston, MA 02125, USA.*
Anne.Oconnell002@umb.edu; Mark.Borrelli@umb.edu; Bob.Chen@umb.edu

Abstract: Participatory science programs are becoming effective mechanisms to provide members of the public opportunities to be involved in scientific research worldwide. In the city of Boston, coastal resilience research is of particular interest to researchers, policy makers, and members of the public due to the projections of up to two meters of sea level rise by the year 2100. As part of the outreach and education initiative at the Stone Living Lab, community members were trained to use the Emery method of beach profiling and conducted surveys at twelve different sites around Boston Harbor. The results of this yearlong project reveal that overall participants successfully used the Emery method to measure beach profiles at multiple sites. These time series data are useful to help scientists and the public document the evolution of beach state and better understand the impacts of wave energy, seasonal trends, and individual storm events.

Introduction

The shores of greater Boston Harbor are home to many beaches that serve as special places for recreation, exercise, and relaxation for residents of the city and surrounding towns. With sea levels rising and intense storms becoming more frequent due to climate change (City of Boston, 2016, Douglas & Kirshen, 2022), the future of many of these sites is unclear. This uncertainty for the future of greater Boston Harbor's beaches provides the scope of the problem for this participatory science project.

Beaches are highly dynamic environments that are constantly in flux (Kennedy et al., 2019). Occasional beachgoers may not realize how much change is happening, but more frequent visitors know how different beaches can look at different times year. Wind, waves, and tidal action work together to constantly change the profiles of beaches. This is most noticeable during intense storms, when coastal cliffs can suddenly be washed away (erosion), or huge amounts of sediment can wash over the beach (Webb, 2021). Beach profile changes can also happen more gradually on a seasonal basis (McPherran, 2017, Kennedy et al., 2019). During the winter, intense storms like Nor'easters pummel the shores and strip away sediment from beaches on scales of hours to months and stores the sediment in offshore sand bars. Once the fairweather conditions of summer retrun the beach has a chance to accumulate sediment again (accretion). Seasonal patterns are not necessarily seen every year. If there is a mild winter, there may not be as big of a seasonal change. In the event of an intense storm, that reservoir of offshore sand could be moved, and the beach will not be replenished that year. Measuring the profile of a beach peridocally or episodically can tell us how the beach is responding to seasonal variations in weather and storms (Webb, 2021).

As part of the Stone Living Lab's inaugural participatory science project, volunteers were trained to use a simple but effective technique called the Emery method (Emery, 1961) to measure beach profiles. The data produced using this method can be of high quality, similar to much more technically advanced methods such as Real-time Kinematic Global Positioning System (RTK-GPS) or LIDAR measurements (Ferreira et al., 2012). Different beaches around greater Boston Harbor were visited from April to December of 2021 to help document profile changes happening through the data colletion period.

To help evaluate the success of this model of a one-year limited participatory science program, several research questions were addressed. These evaluate the usefulness of the profile data gathered during this project from a scientific perspective.

1. Research Question 1: How accurate were measurements taken by participants using the Emery method?
2. Research Question 2: Did the inner harbor and outer harbor beach sites behave as expected?
3. Research Question 3: What ways can a short-term beach profile record be used?

Methodology

The Emery method of beach profiling was developed in the 1960s and is a simple but effective way to measure beach elevation profiles (Emery, 1961). It is an accurate and repeatable method of elevation measurement, and an especially good method to use for participatory science programs as the equipment is inexpensive and easy to use (Eberhardt et al., 2022). The method works by using two poles attached by a rope to take incremental measurements of elevation change starting at the top of the beach and working down towards the water line. The horizon serves at a point of reference to use while measuring elevation change.

Twelve different sites were selected to be monitored to initiate a record of beach elevation change around greater Boston Harbor (Figure 1). The sites were visited from April through December of 2021. Volunteer beach profile measurements were also taken alongside Real-Time-Kinematic GPS (RTK-GPS) elevation measurements on one occasion to establish an estimated error range.

Fig 1. Map of Beach Sites Selected for the SLL Beach Profiling Project.

Results and Discussion

Research questions designed to evaluate the data gathered by volunteers during this project were addressed. The accuracy of measurements collected using the Emery method were established, and both spatial and temporal applications of the data were explored.

I. Evaluating Profiling Methods – RTK-GPS vs. Emery

Data collected using the Emery method are considered to be precise and accurate (Krause, 2004; Eberhardt et al., 2022), but establishing an error range can help contextualize results and quantify data quality. Volunteers and researchers were able to combine efforts to produce a cursory error analysis that can be applied to the larger dataset collected throughout this project. Wollaston Beach was visited by volunteers equipped with their Emery Rod beach profiling kit and researchers with a survey grade Real-Time Kinematic GPS (RTK-GPS) instrument, a Trimble R10. Concurrent profiles with both methods were taken along three transects, starting at known benchmarks.

The average vertical error was found to be 0.05 meters with a standard deviation of 0.18m, which is close to values found in literature (Turner et al., 2016, Ward et al., 2021) (Table 1). Additionally, error was found to have a cumulative effect, growing from the beginning of the profile towards the end as systematic errors consistently skewed results.

Table 1. Comparison of Emery Error Range Estimates

Source	**Mean Vertical Deviation**	**STD Deviation**	**Range (68% of points)**
SLL Study	-0.05 m	0.18 m	-0.23 – 0.13 m
Turner et al., 2016	-0.03 m	0.13 m	-0.16 – 0.1 m
Ward et al., 2021	n/a	n/a	-0.2 – 0.2 m (est.)

Understanding that there is an uncertainty range involved with these measurements, even skewed data is still useful as it reliably captures the morphological shape of beaches. It also helps the public better understand soruces of unceraitny in scientific data and the rigor with which scientists address uncertainty. Beach profile graphs are visual tools that can convey information about coastal change. Much like building a database of coastal images is useful (Harley & Kinsela, 2022) to understand change in an area, having detailed graphs that show if a beach is more flat or uneven at different times of year or after storm events is illuminating.

II. Inner Harbor vs. Outer Harbor Sites

Twelve beach sites were selected for this project. Some beach sites were located along the outer harbor, facing the North Atlantic Ocean with little protection from storm waves. Other sites were partially protected from wind and wave action by the islands within the harbor (Figure 1). Observing how different beaches in different physical environments evolve throughout the year and as a response to episodic storms can inform us about what an expected range of change at a specific site may look like (Ashton et al., 2008; Chaumillon et al., 2017). It was expected that in general, the beaches in the inner harbor that are protected by the harbor islands would undergo less change over the course of the project than beaches facing the Atlantic Ocean.

A collection of profiles called a beach profile envelope was assembled with all profile measurements included to illustrate the range of elevation change between visits for each beach site. For all sites with 4 or more visits in the April – December period, the maximum spread of beach profile elevation differences was determined. The results showed that most of the inner harbor sites were lower energy, having less than 2 feet of observed maximum elevation range. Sites

....

situated on the outer harbor were higher energy, with elevation ranges of more than 2 feet (Figure 2).

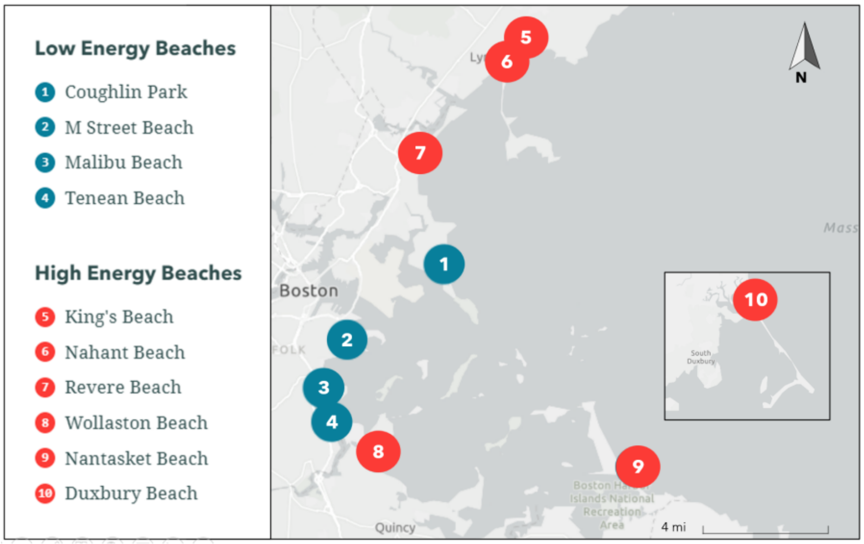

Fig 2. Observed Low (<2 ft elevation range) and High (>2 ft range) Energy Beach Sites.

Figure 3 was taken from a Feasibility of Harbor-wide Barrier Systems report (Kirshen et al., 2018) and depicts modeled wave heights that are expected around Boston Harbor in the event of a Moderate Coastal Nor'easter storm. The graphic illustrates how during episodic storm events, wave height can be rapidly reduced as their energy becomes dissipated within the harbor because of the harbor islands. Model projections like this are of great value and interest as sea level rise increases and coastal storms become more frequent and intense (Kirshen et al., 2008; Douglas & Fairbank, 2010; Douglas & Kirshen, 2022). The maximum observed elevation ranges were compared to modeled storm wave height to see if the beaches respond as expected. Duxbury Beach was not included in the wave height model graphic, so conditions were assumed to be similar to those at Nantasket Beach.

Generally, as the maximum wave height model increased, the observed maximum spread between beach profiles also increased (Figure 4). The four sites with maximum wave height under 2 feet in the model also had variations of beach elevations under 2 feet observed during the duration of this project. All four of these sites were sheltered behind the Boston Harbor islands and peninsulas, so this observed smaller range of variation was expected. The other six sites with modeled storm wave heights above 2 feet showed a greater range in profile elevations between visits. These sites are all more directly exposed to the North

Atlantic Ocean, so this larger range of variation also reflects what was expected to occur.

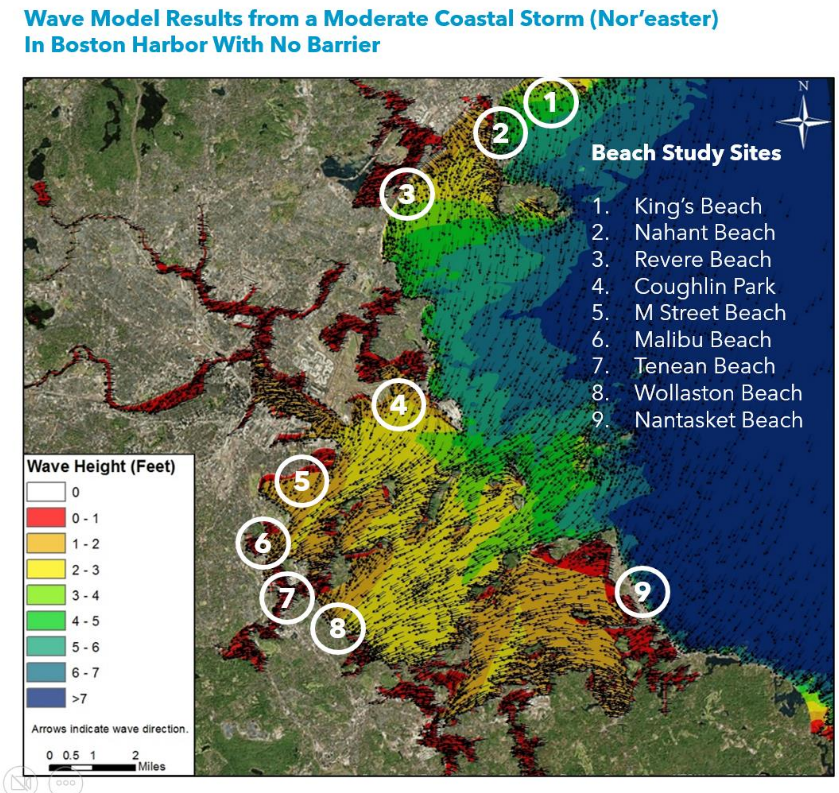

Fig 3. Wave Model Results for Project Sites (Source: Kirshen et al., 2018)

However, when compared with the modeled maximum wave heights, the observed profile elevation ranges of Wollaston Beach, Nahant Beach, and Nantasket Beach were somewhat unexpected (Figure 4). Wollaston Beach (site number 8) had a maximum modeled wave height of 3 feet, the same as for King's Beach (1) and Revere Beach (3), but had a profile range of 6.5 feet, 2 feet higher than at Revere. The elevation range was closer to what was seen on Duxbury Beach (10), a site with much higher expected wave heights during a storm.

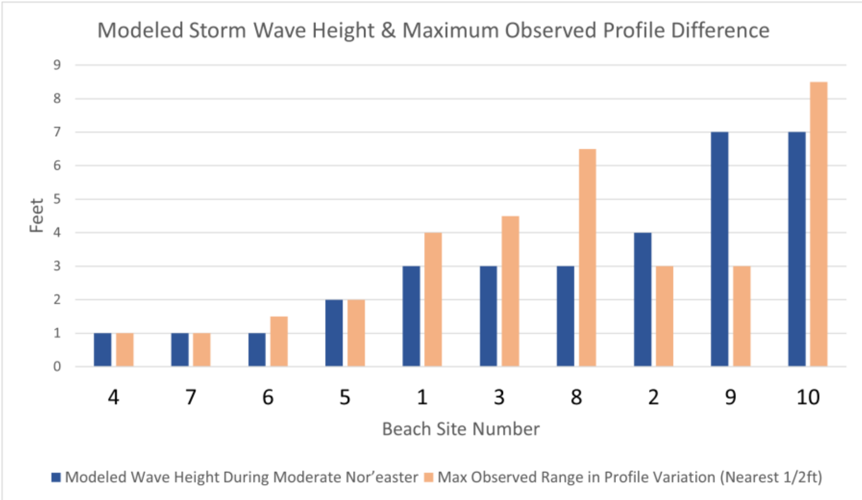

Fig 4. Graph of Modeled Storm Wave Height & Max Observed Profile Difference. Beach site numbers correspond to Fig. 3. *Duxbury beach was assumed similar to Nantasket Beach.

The expected pattern was also not followed at Nahant Beach (2) and Nantasket Beach (9). While they still had variations of over 2 feet between profiles, this was much smaller than at both Wollaston (8) and Duxbury Beach (10). Based on the moderate nor'easter high wave height potential at both sites due to being on the Atlantic Ocean with no protection from barriers, more variation was expected at these two sites. This could be explained by the topography of these sites. Both sites were very wide at low tide – Nantasket reached 400 feet while Nahant reached 650 feet. Both beaches are very flat for most of the profiles. Perhaps the amount of possible variation here is limited because of the flat, low-relief topography of these sites.

It is important to understand and acknowledge that there is error involved the Emery method that adds to uncertainty of the actual range of beach elevations at each site. For all profiles, it should be noted that error with the Emery method is cumulative and increases toward the end of the profile – this is also where the largest range in variation was for most of the profiles. Finally, some beach sites were visited more frequently than others, so may be displaying an artificially higher range in beach elevations than less-visited beaches for that reason. A final limitation of this analysis is the estimation of wave height for Duxbury Beach (10) under these same moderate nor'easter conditions.

Understanding the above limitations, it is still a useful exercise to how best utilize a beach profile dataset that is too short-term to confidently establish seasonal trends. This is an example of how a short-term project can play more to spatial strengths when long term temporal analysis is not possible. Analyses that raise questions are useful for improving models, generating new research questions, and helping to quality check data.

III. Case Study: Wollaston Beach

The short timeframe of this project limits the amount of in-depth analysis that can be done, but emerging patterns can be analyzed so that if more profiles are taken in the future, there are benchmarks to compare the new profiles with past ones. Volunteers managed to visit Wollaston Beach 12 times from April – December of 2021, and also in May of 2022. Typically, beaches will build up in elevation over the summer months and lose elevation with intense winter storms (Kennedy et al., 2019; Eichentopf et al., 2020). From the profiles available, it seems that generally the warmer months had less change in elevation and overall area between visits, while the months of October – December had very variable beach profile elevations (Figure 5). More data are needed to determine whether the observed profile changes do indeed follow cyclic seasonal patterns.

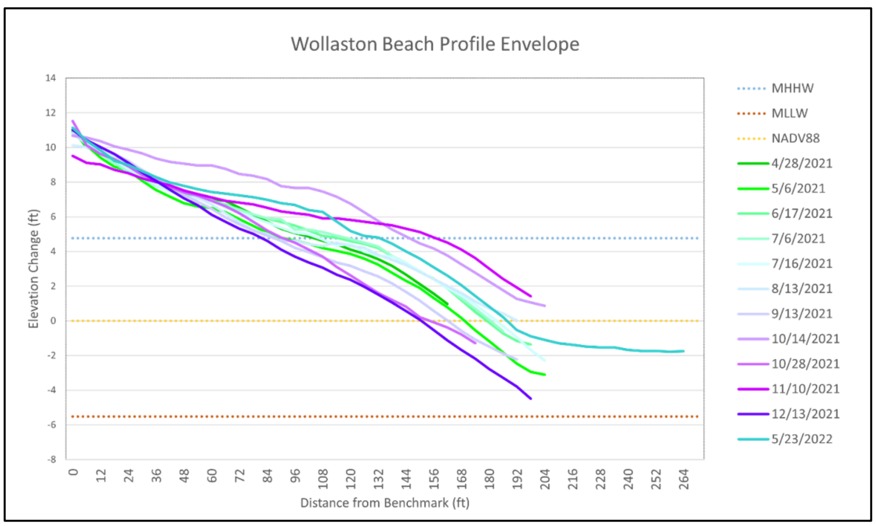

Fig 2. Wollaston Beach Complete Beach Profile Envelope (n = 12)

Another impactful way to utilize short-term records is to utilize pre- and post-storm beach elevation profiles to analyze a beach's response to episodic events. The most rapid and dramatic changes in beach profile elevations happen after episodic events, which are more common during certain times of year but unpredictable in timing and intensity (Burvingt et al., 2017; Kennedy et al., 2019). In an effort to capture the impacts of these episodic events, volunteers at

Wollaston Beach were able to take pre- and post- storm profiles for two different storms. In the context of a short-term record, these measurements are perhaps the most impactful profiles participants can measure (Eichentopf et al., 2020). The first storm was a larger precipitation event on July 9th, 2021. The second storm was a Nor'easter on October 27th, 2021 (Table 2).

Table 2: Volumetric Analysis for July and October Storms

Event	July	October
Transect 1 (ft^2 change)	-35.42	35.1
Transect 2 (ft^2 change)	-13.42	-293.3
Transect 3 (ft^2 change)	32.32	115.4
Average (ft^2 change)	-5.51	-47.63
Approx ft^3 Sediment moved (Across 800 ft Distance)	-4,405.33	-38,106.7

The profiles from both storms demonstrate that for this stretch of Wollaston Beach, sediment elevation change along different transects does not respond uniformly to storms. Within a relatively short distance, all three transects behaved somewhat differently. Two groin-like structures sticking out into the water on either side of Transect 3 likely helped it hold on to this sediment (Figure 6), but

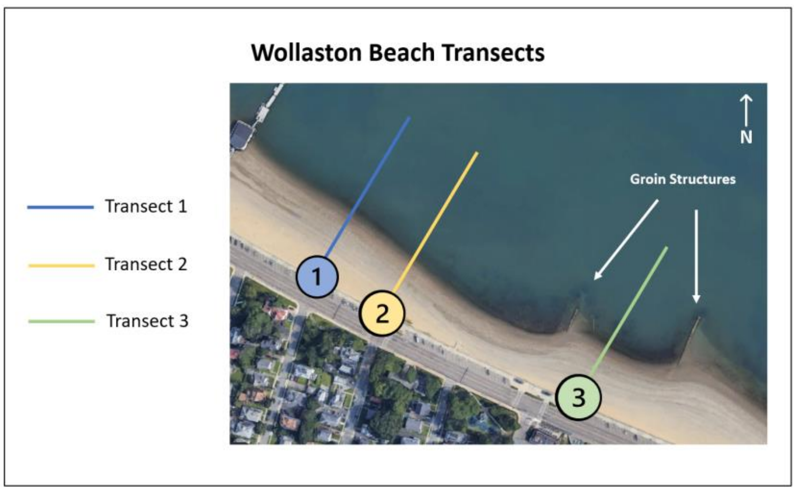

Fig 6. Wollaston Transects 1-3 and Groins

Transect 1 and 2 also behaved differently during the two storm events. This points to Wollaston Beach responding to storms by redistributing the sand along its coast, rather than consistently eroding or accreting sediment. This is supported by volunteers telling us that they noticed sand up covering up one of the usual benchmarks. Pictures from before and after the storm were taken from Transect 2 facing Transect 3 and illustrate this redistribution of sand (Figure 7). This observed variability along a short stretch of beach reenforces the need to collect these types of data with as much spatial resolution as possible.

Fig 7. Wollaston Beach Photos Pre- and Post Nor'easter

Conclusion

The results of this project have been useful both in terms of collecting scientific data, broadening the number of shoreline change measurements collected than what was possible for the Stone Living Lab core research team to do alone, and engaging participants in authentic, meaningful coastal research.

The first year of participatory science at the Stone Living Lab generated 172 beach profiles at 12 different beaches around Boston Harbor. This is a unique dataset to the area, and while it is still a relatively short record, it can be expanded upon in the future to create a picture of long-term trends and changes at these beaches. Initial evaluations of the data collected using the Emery method of beach profiling have shown that even though there is some error with the method, the elevation profiles can be useful to depict geomorphology, emerging seasonal trends, and storm analysis.

An initial analysis of the beach profiling data collected throughout the April – December extent of the project shows that there are a variety of uses for the information gathered. An error analysis estimated that on average, measurements made by volunteers using our Emery rod kits would likely have fallen somewhere between 0.4 feet below and 0.8 feet (0.13 and 0.23 m, respectively) above the actual beach elevation for each point. It also revealed that this error appeared to be cumulative, increasing in size as the Emery rod user moves from the beginning of the profile towards the water line. These errors could be a product of the Emery method itself (the cumulative nature especially) but also could be due to our specific profiling kits. Even with the error, the profiling method was shown to be capable of capturing the general geomorphology of the beach. Knowing how the shape of the beach changes is useful information even if there is an error offset to the actual elevation numbers, especially when paired with photographs taken from the same vantage point (Figure 7). Similar photographs of beaches are being used in the global participatory science program CoastSnap, and detailed profiling data could be used to strengthen estimations of beach elevation change observed in photographs over time (Hart, 2021; Harley & Kinsela, 2022). Understanding that the method has associated error, the data were also used to explore energy levels of sites, seasonal trends, and sediment volume change analysis due to storms.

With the limitations of a short-term record, focusing on spatial and episodic differences in elevation change across beaches is an impactful way to use the dataset to generate further research questions and interest in the participatory science program. Particularly exciting applications could include using participant generated beach profiling data to refine regional models of wave action during storms, investigate impacts of individual storms, and establish expected seasonal trends.

Acknowledgements

This project would not have been possible without the dedication of our volunteers Chris Mancini, Ed Dobbins, Wendy Fox, Heidi Baker, Roseann Trionfi-Mazzuchelli, Kathleen Kennedy, Amina Miliani, Jeremy Reger, Yue Ma, Monica Peng, Maria Lyons, Judy O'Leary, Gwendolyn Tisch, Lanci Valentine, Peter MacLearn, Gwen MacLean, Joyce Pun-Flynn, Sara Grady, Julianne Sullivan, Jacquelyn Devin, Deedy Wyman, Calista Wyan, Jason McCann, and more! Further support from Dr. Bob Chen, Dr. Mark Borrelli, Bryan McCormack, Rebecca Shoer, and Kayla Bradley with the Stone Living Lab made this project a big success.

References

Ashton, A. D., Donnelly, J. P., & Evans, R. L. (2008). A discussion of the potential impacts of climate change on the shorelines of the Northeastern USA. *Mitigation and Adaptation Strategies for Global Change*, *13*(7), 719–743. https://doi.org/10.1007/s11027-007-9124-3

Burvingt, O., Masselink, G., Russell, P., & Scott, T. (2017). Classification of beach response to extreme storms. *Geomorphology*, *295*, 722–737. https://doi.org/10.1016/J.GEOMORPH.2017.07.022

Chaumillon, E., Bertin, X., Fortunato, A. B., Bajo, M., Schneider, J. L., Dezileau, L., Walsh, J. P., Michelot, A., Chauveau, E., Créach, A., Hénaff, A., Sauzeau, T., Waeles, B., Gervais, B., Jan, G., Baumann, J., Breilh, J. F., & Pedreros, R. (2017). Storm-induced marine flooding: Lessons from a multidisciplinary approach. *Earth-Science Reviews*, *165*, 151–184. https://doi.org/10.1016/J.EARSCIREV.2016.12.005

City of Boston. (2016). *Climate Ready Boston - The Boston Research Advisory Group Report*. https://www.boston.gov/sites/default/files/document-file-12-2016/brag_report_-_final.pdf

Douglas, E. M., & Fairbank, C. A. (2010). Is Precipitation in Northern New England Becoming More Extreme? Statistical Analysis of Extreme Rainfall in Massachusetts, New Hampshire, and Maine and Updated Estimates of the 100-Year Storm. *Journal of Hydrologic Engineering*, *16*(3), 203–217. https://doi.org/10.1061/(ASCE)HE.1943-5584.0000303

Eberhardt, A. L., Ward, L. G., Morrison, R. C., Costello, W., & Williams, C. (2022). Connecting science and community: Volunteer beach profiling to increase coastal resilience. *Continental Shelf Research*, *242*, 104733. https://doi.org/10.1016/J.CSR.2022.104733

Eichentopf, S., Alsina, J. M., Christou, M., Kuriyama, Y., & Karunarathna, H. (2020). Storm sequencing and beach profile variability at Hasaki, Japan. *Marine Geology*, *424*, 106153. https://doi.org/10.1016/J.MARGEO.2020.106153

Emery, K. O. (1961). A Simple Method of Measuring Beach Profiles. *Limnology and Oceanography*, *6*(1), 90–93. https://doi.org/10.4319/LO.1961.6.1.0090

Ferreira, M. A., Soares, L., & Andrade, F. (2012). Educating citizens about their coastal environments: Beach profiling in the Coastwatch project. *Journal of Coastal Conservation*, *16*(4), 567–574. https://doi.org/10.1007/S11852-012-0203-6/TABLES/1

Harley, M. D., & Kinsela, M. A. (2022). CoastSnap: A global citizen science program to monitor changing coastlines. *Continental Shelf Research*, *245*, 104796. https://doi.org/10.1016/J.CSR.2022.104796

Harley, M. D., Turner, I. L., Short, A. D., & Ranasinghe, R. (2011). Assessment and integration of conventional, RTK-GPS and image-derived beach survey methods for daily to decadal coastal monitoring. *Coastal Engineering*, *58*(2), 194–205. https://doi.org/10.1016/J.COASTALENG.2010.09.006

Hart, J. (2021). *Low cost coastal data collection using citizen science — the University of Bath's research portal*. https://researchportal.bath.ac.uk/en/studentTheses/low-cost-coastal-data-collection-using-citizen-science

Kennedy, D., McInnes, K., & Ierodiaconou, D. (2019). *Understanding coastal erosion on beaches*.

Kirshen, P., Borrelli, M., Byrnes, J., Chen, R., Lockwood, L., Watson, C., Herst, R., Starbuck, K., Novelly, A., Wiggin, J., Uiterwyk, K., Jin, D., Bosma, K., Thurson, K., McMann, B., Foster, C., Sprague, H., & Roberts, H. (2018). *Feasibility of Harbor-wide Barrier Systems: Preliminary Analysis for Boston Harbor*. https://www.umb.edu/editor_uploads/images/centers_institutes/sustainable_solutions_lab/umb_rpt_BosHarbor_5.18_15-optimized.pdf

Krause, G. (2004). The "Emery-Method" revisited - Performance of an inexpensive method of measuring beach profiles and modifications. *Journal of Coastal Research*, *20*(1), 340–346. https://doi.org/10.2112/1551-5036(2004)20[340:teroai]2.0.co;2

McPherran, K. A. (2017). *Seasonal Changes in Geomorphology and Sediment Volume of New Hampshire Beaches: Insights into a Highly-Engineered, Paraglacial, Bedrock Influenced Mixed Sand and Gravel Coastal System*. University of New Hampshire.

Turner, I. L., Harley, M. D., Short, A. D., Simmons, J. A., Bracs, M. A., Phillips, M. S., & Splinter, K. D. (2016). A multi-decade dataset of monthly beach profile surveys and inshore wave forcing at Narrabeen, Australia. *Scientific Data*, *3*. https://doi.org/10.1038/SDATA.2016.24

Ward, L., Morrison, R., Eberhardt, A., Costello, W., McAvoy, Z., & Mandeville, C. (2021). *Erosion and Accretion Trends of New Hampshire Beaches from December 2016 to March 2020: Results of the Volunteer Beach Profile Monitoring Program*. https://doi.org/10.34051/p/2021.34

Webb, P. (2021). *Introduction to Oceanography*. Pressbooks. http://rwu.pressbooks.pub/webboceanography