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The Application of Geographic Information Technology and Ground-Penetrating Radar in the Study of the Evolution of the Charles River Basin

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THE APPLICATION OF GEOGRAPHIC INFORMATION TECHNOLOGY AND GROUND-PENETRATING RADAR IN THE STUDY OF THE EVOLUTION OF THE CHARLES RIVER BASIN

A Thesis Proposal

by

LARS E. ANDERAS

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ABSTRACT

THE APPLICATION OF GEOGRAPHIC INFORMATION TECHNOLOGY AND GROUND-PENETRATING RADAR IN THE STUDY OF THE EVOLUTION OF THE CHARLES RIVER BASIN

August 2013

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A two-part study was conducted on the evolution of the shoreline of the Charles River basin on a city-wide scale as well as in finer detail in Magazine Beach Park, along the Cambridge shore of the river. Both parts of the study utilized geographic information technology (GIT) to integrate and analyze data from modern and historical sources, including maps, digital elevation models (DEMs), and orthographic and oblique photography. The city-scale portion of the study produced estimates of the total area of new land made within the study area since Boston's founding in 1630, 14.3 km^2, of which 6.5 km^2 was added in the Back Bay area alone. Efforts were also made to quantify the total volume of new land added using the 2002 MassGIS DEM, but that estimate, 30

million m^3, was based on somewhat speculative estimates of the original mudflat and salt marsh elevations and is a less robust estimate than those of the surface area.

The GIT was also used to display the integrated spatial data in both 2D (map or orthographic view) and 3D (oblique view) to facilitate visualization of historical landscape changes. This technology was also used to produce a 3D time series of landmaking by vertically extruding historical map-based polygon layers in proportion to the length of time between successive layers. This presented a unique opportunity to depict what would normally be shown as a 2D graph of area vs. time instead as a graphic that shows area and time but also shoreline shape at several points in history, thus providing a more full picture of how the basin evolved over time.

In addition, the study of Magazine Beach Park centered around a survey-scale 500 MHz ground-penetrating radar exploration of the entire park, which yielded some clues about the park's stratigraphy and recent anthropogenic changes, including the location and extent of the former beach that used to extend half the length of the park. However, the wide spacing of the GPR survey lines and high level of sediment disturbance and fill in some parts of the park limited the success of the survey.

ACKNOWLEDGEMENTS

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CHAPTER 1

INTRODUCTION

1.1 Background

The Boston metropolitan area is rich with sites of historical interest, sometimes dating back to the first European settlers nearly four hundred years ago. Because of its extensive development in the intervening centuries, the area has also lost many artifacts and sites to building and landmaking. As a consequence, those areas that are still mostly undeveloped are of great interest, both for preserving those landmarks that are currently known and unearthing those that are yet to be discovered.

Magazine Beach Park in Cambridge is such a site. At its center stands the dilapidated stone building that was once an important gunpowder magazine supplying the defenses of Boston in the early 19^{th} century, at a time when attack or invasion by a foreign power was still a real threat (recall the burning of Washington, D.C. by the British army in 1814). Possibly buried nearby are the remains of an earlier military structure, a small cannon battery that may have defended the water approach to General Washington's Cambridge headquarters up the Charles River during the Siege of Boston (1775-76). Employing geographic information technology (GIT) and ground-penetrating radar (GPR) to the study of the park itself and its surroundings will not only help uncover as-

yet unknown structures, but it will also help interested stakeholders apprise the historical value of the magazine and assess the need for its restoration.

1.1.1 The Siege of Boston

Following their defeat at the battle of Lexington and Concord on April 19, 1775, the British forces retreated to Boston, where they remained under siege for eleven months (McCullough, 2005). At the time Boston was a peninsula, connected to the mainland to the south at high tide by only a narrow isthmus or neck and surrounded by expansive mudflats (Figure 1.1). This made the town easily defensible for the British, but by the same token also facilitated the siege of the town by rebel forces (McCullough, 2005). Boston was overlooked from high points on two nearby peninsulas, Dorchester Heights to the southeast and Bunker Hill and Breed's Hill on Charlestown peninsula to the northwest. For the first two months of the conflict these points remained unoccupied by either side.

Upon learning of British plans to occupy these strategic hills, 1200 American militia soldiers under the command of Colonel William Prescott moved under cover of darkness to fortify Breed's Hill, overlooking Charlestown and Boston, on the night of April 16 (French, 1911). The next day British forces under General William Howe rowed across the harbor from Boston and undertook several frontal assaults on the American redoubt before ultimately prevailing, but at the cost of more than 1000 casualties (McCullough, 2005). Although the high ground above Charlestown was in British hands, any further advances against fortified positions would likely have proven similarly

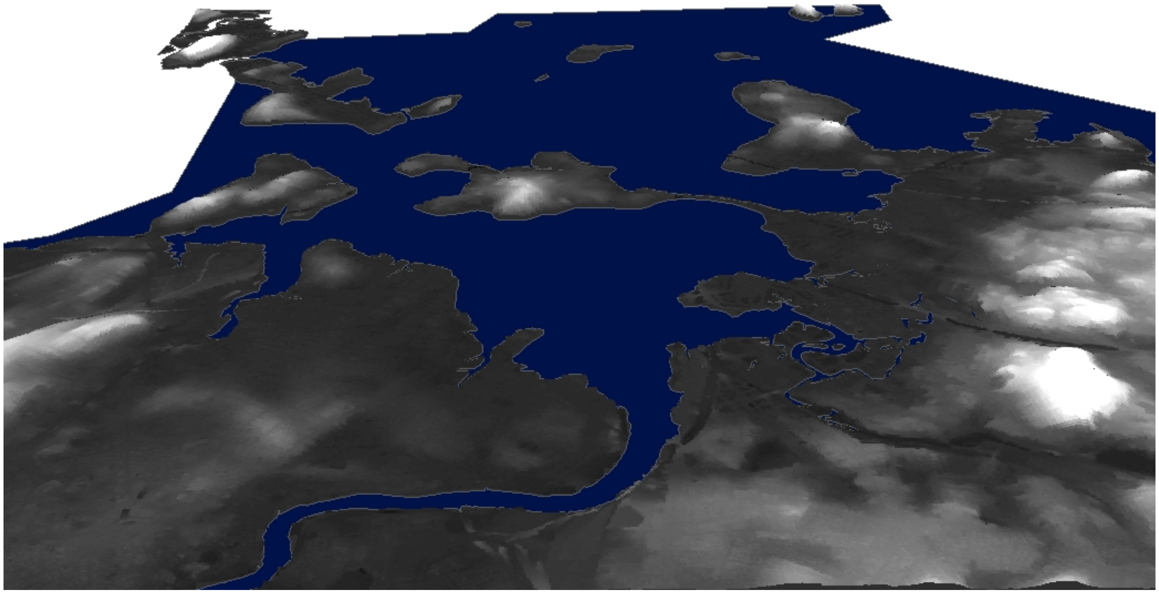


Figure 1.1a Boston in 1630 (adapted from *Gaining Ground: A History of Landmaking in Boston* by Nancy Seasholes, 2003).

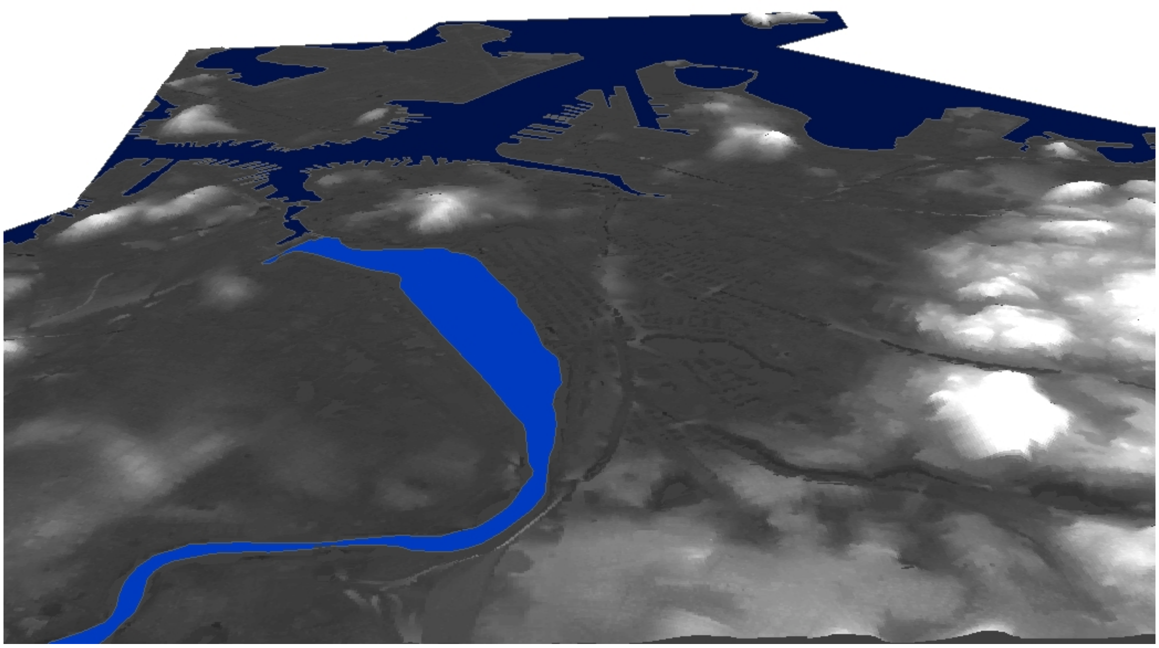


Figure 1.1b. Boston in 2012 (from MassGIS coast and inland water bodies shapefiles).

deadly, so the siege lasted well into the following winter. The Americans remained encamped at Prospect Hill to the north of the Charlestown peninsula, with other units near Boston Neck at Roxbury to the south and at Cambridge along the Charles River to the west (McCullough, 2005).

After the arrival of General George Washington, commander-in-chief of the American army, several additional small fortifications were constructed along the Cambridge side of the Charles River to augment the encirclement of Boston and to protect the approach to the town of Cambridge up the Charles. Of these redoubts, a "3 gun battery"erected on Captain's Island likely had a field of fire that covered the river from that point down to the next bend near Cambridge itself (Paige, 1877). According to Paige, this battery was likely leveled during the construction of the former powder magazine which still stands on the island today. Some early maps, such as Henry Pelham's detailed 1777 map, do not show a battery on Captain's Island. It is uncertain whether Pelham, a Massachusetts Loyalist who would not have been able to travel outside of the Boston and Charlestown peninsulas during the siege, was simply not able to see the Captain's Island redoubt from his position or whether the other sources placing a battery on the island are mistaken. Either way there is no trace of the redoubt above ground today (nor was there in 1877).

These small cannon emplacements along the Charles probably served as an effective deterrent against British troops attempting to land on the Cambridge side of the river, as well as preventing floating batteries from coming close to American forces. These batteries, simple barges carrying cannon, were employed by both sides during the

siege to temporarily place firepower closer to the enemy. Because of the effectiveness of the defenses of both sides, neither the floating batteries nor the periodic small-scale infantry raids of both armies had a significant effect on the siege after Bunker Hill (Heath, 1798). The stalemate continued until March 4, 1776, when American forces, again under the cover of night, fortified Dorchester Heights with cannon taken from Fort Ticonderoga in upstate New York in 1775, allowing Boston to be bombarded with impunity. Rather than face another deadly Bunker Hill-type direct assault, British forces under General Howe withdrew from Boston and Charlestown on March 17 by sea, thus ending the 11-month siege with an American victory (McCullough, 2005).

The landscape of Boston and the surrounding area has changed dramatically since the American Revolution. The only fortification from the siege that survives is Fort Washington in Cambridge. It was a 3 gun battery, like the one that reportedly stood on Captain's Island. It was not actually a fort but a half-moon earthworks about 30 meters across with three positions for guns, set at roughly 30-45 degrees to one another (Figure 1.2). The Captain's Island battery would have had the same firepower, but it is unclear how the earthworks would have been arranged on the small hill that was formerly an island at high tide. It is also unclear what the boundaries of the island were in 1775, because the park has been extensively modified multiple times since then.

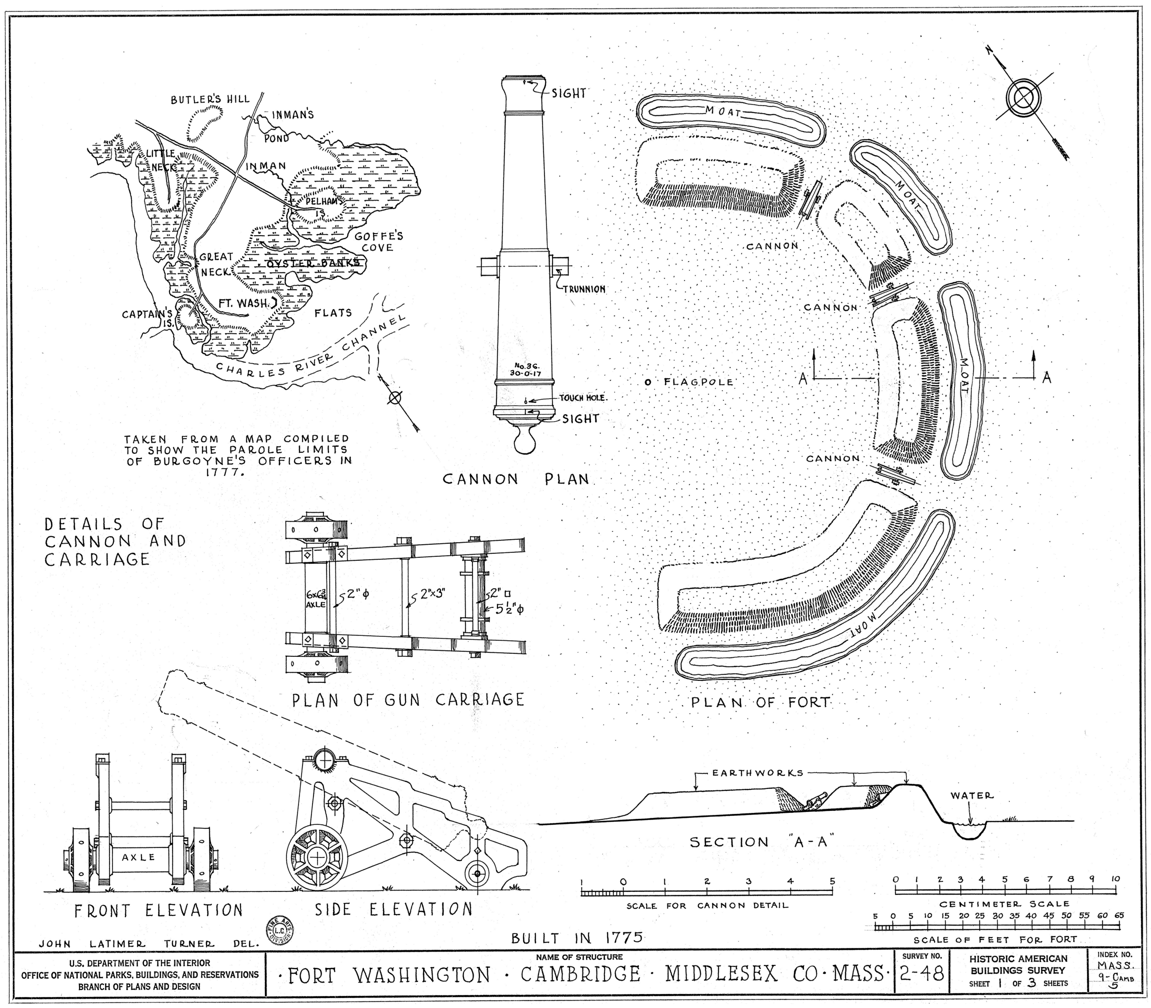


Figure 1.2. A National Park Service plan of Fort Washington in Cambridge, which is a similar design to the one that may have once stood on or near Captain's Island.

1.2. Study Site

Prior to its damming in 1910 between West Boston and East Cambridge the Charles River was an estuary fringed by mudflats and—further upland—salt marshes. The 1847 Coast Survey map, one of the best maps of the area from the 19th century,

shows Captain's Island as surrounded by salt marshes. The island was just upstream of the point where the estuary widened out from the river channel present today to a wide intertidal zone between modern-day Cambridgeport and Boston that has since been extensively filled-in. Mudflats extended from Boston upriver to Brookline and salt marshes reached roughly to the Cambridge-Watertown boundary.

Today the island is a hill in the center of Magazine Beach park (Figure 1.3 for a before-and-after comparison). Much of the low-lying area around the hill was likely marsh that has since been filled and covered in soil. The park consists of playing fields on the downstream side of the island and a narrow grassy field, a parking lot, and a swimming pool facility on the upstream side. The park is named for the stone powder magazine that still stands on the center of the island. It was built in 1818 to replace the magazine in Charlestown. After the Civil War it was no longer used as a magazine and in 1899 the building was converted into a changing area for the swimming beach just upstream (Figure 1.4), where a parking lot is now. In the 1950s the building was converted to be a storage garage and it has since fallen into disuse and disrepair.

Due simply to the fact that much of the park is still open land, unlike so much of the Boston area that has been thoroughly developed, it has the potential to be quite useful for studying the Charles River as it was before its flats and marshes were drained and filled. Aside from the insights to be gained about the changes to the natural landscape of the river, studying the park could reveal sub-surface remnants of historical structures such as the reputed gun battery, which could expand our knowledge and understanding of that important chapter in the history of the city and the nation.

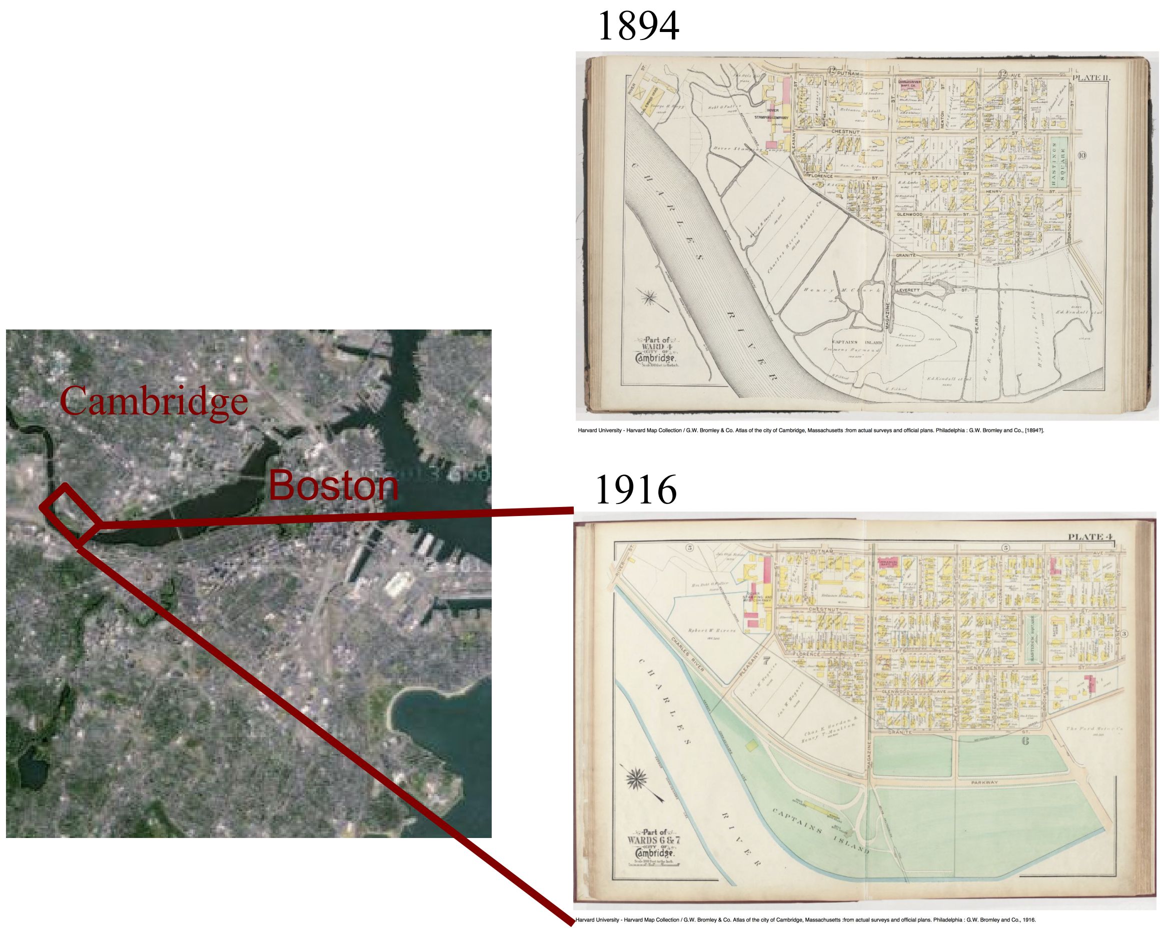


Figure 1.3 1894 and 1916 Bromley & Co. atlas of Cambridge, MA
(Harvard University Map Collection, Google Maps).

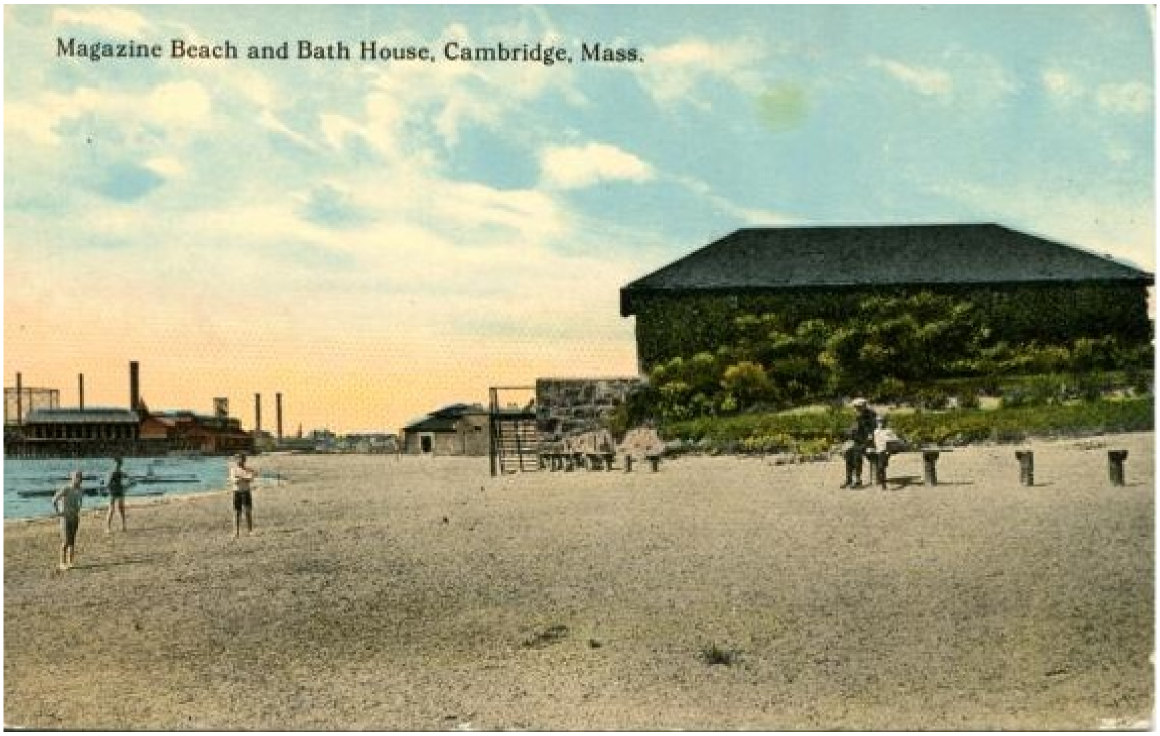


Figure 1.4. Magazine Beach, circa 1913 (from Cambridgehistory.org)

1.3 Geologic History

The Charles River basin and the surrounding towns and cities lie within the Boston Basin, a tectonic lowland underlain by late Paleozoic bedrock and bounded by highlands composed of more resistant Pre-Cambrian to middle Paleozoic bedrock (Dincauze, 1974). The surface of much of the Boston Basin is covered in glacial till and clay, and the hills and harbor islands originated as a drumlin swarm, all deposited during or shortly after the Wisconsin Glacial Period; the course of the Charles and Mystic Rivers is largely determined by this glacial landscape rather than any pre-glacial features (Dincausze, 1974). After the retreat of the ice sheets local sea level in Massachusetts

reached a highstand at 33 meters above sea level 14,000 years ago, followed by a lowstand of -43 meters 12,000 years ago and then a gradual rise to the current sea level (Oldale, et al., 1993). The rapid intrusion of the sea would have briefly inundated much of the study area after the retreat of the ice, but with the shoreline regression that followed would have left the paleo-Charles River a freshwater body within the modern river basin area for thousands of years. With the slow transgression of the shoreline after lowstand 12,000 years ago, salt water reached Magazine beach only about 5000 years before present (Dincauze, 1974).

1.4 Research Aims

The goals of this study involve the study of shoreline change in the Charles River basin—specifically the conversion of mudflats and salt marshes to dry land—using different tools and techniques to investigate these changes on differing spatial scales. The first tool, and the one that works on the finest scale, is ground penetrating radar (GPR). GPR works "by generation, transmission, propagation, reflection, and reception of discrete pulses of high-frequency electromagnetic energy in the megahertz (MHz = 10^6 Hz, 1 Hz = 1 cycle/s) frequency range (Neal, 2003)." In order to study the changes that have shaped Magazine Beach and Captain's Island, GPR was used to non-invasively probe the shallow subsurface of the entire park. This technology was applied to better understand the stratigraphy of the park and how it has changed over the centuries.

In an effort to integrate this geologic knowledge with a geographic understanding of the area around the park and the Charles River basin as a whole, geographic

information technology (GIT) was used to compare spatial information of varied spatial extent and resolution, and from varied sources. Through the use of a computerized geographic information system (GIS), one application of GIT, this information could be gathered and compared to better understand the geography and geology not only on different spatial scales, but also at different points in history.

CHAPTER 2

METHODS

2.1 Introduction

This study is composed of two parts. First, historical maps from the 18th through the 20th centuries were analyzed using Esri ArcGIS 10 software. The digitized maps we used to study the anthropomorphic changes that have transformed the entire basin and the park itself. Second, a ground-penetrating radar (GPR) survey was conducted over the entire park in order to be able to identify features of the past landscape and to locate any large objects of historical significance.

Mapping shoreline change over the course of several centuries is a serious challenge that requires the integration of several data types of varying precision and accuracy. Compared with more rural areas, cities tend to have the greatest number of historical maps going back to their earliest days, but those maps also tend to decrease in cartographic quality the older they are. A geographic information system (GIS) is a good tool for combining these disparate spatial data sources in layers that can be overlaid, allowing them to be compared both qualitatively and quantitatively to study shoreline change through time. In some cases insights can be gained from more accurate later maps which can be used to correct features on earlier maps, or at the very least to identify

which areas are reliably mapped and which are not.

On a smaller scale, ground-penetrating radar (GPR) is another tool that can be useful in the study of shoreline evolution. Radar has the advantage of having very fine spatial resolution, with the tradeoff that it lacks temporal resolution (meaning that other methods must be used to date any particular layer or object). GPR is useful for precisely mapping a small geographic area, but time, money, and other practical constraints limit its use over a wider area. It is therefore useful to combine GPR data with map and photographic data in a GIS to reduce the shortcomings of each data type. Other data types can aid the interpretation and analysis of GPR data. The GPR data can in turn clarify and add precision to otherwise uncertain areas of historical maps. This is especially apparent in the study of marshlands on the fringe of a city such as Boston. These features would generally have not necessitated cartographic precision and accuracy, especially on historical city maps whose purpose was mainly to show the layout of streets and buildings. In this case maps tend to give a general picture of the landscape, but GPR can be used to add precision to the picture.

GIS analysis of GPR- and map-derived data has already been used to study historical sites and shoreline evolution in the Boston area (Gontz, et al., 2011; Maio, et al., 2011), and GPR has been in use in the study of archeological sites since the 1970s (Kenyon, 1977), so the technology and procedures are well-established and sound. This study of the evolution of the Charles River basin in Boston and Cambridge and the specific changes made to Magazine Beach on the Cambridge shore takes advantage of all

the above data types. A large number of historical maps from the 19th and even 18th centuries were utilized to develop a time series of shoreline change, due almost entirely to human actions. Aerial photographs were rare until the early 20th century, so modern orthographically-corrected (map-like vertical view) photographs or orthophotos were used to compare earlier versions of the river to its current form. Maps of the area surrounding the Charles sometimes include Magazine Beach, but it is usually only on the periphery of each map, and not usually in precise detail. GPR was used as the primary source of data on the park, augmented by late 19th century and modern sources. Together these analyses present the evolution of the basin as a whole and also focus on one specific area (the park) for more in-depth and precise analysis.

2.2 GIS Methods

A geographic information system (GIS), specifically Esri ArcGIS 10, was used to provide a modern and historical context for the park and the GPR data. Recent orthographic photographs, a LiDAR-derived digital elevation model (DEM), and shapefiles representing the modern Charles River basin and the adjacent sea coast were obtained from MassGIS and clipped to the extent of the study area. The modern geography was then compared to selected high-quality digitized and georeferenced historical maps. These varied data sources from different time periods within the past 400 years allowed for the integration of map documents to study how the Charles River estuary and its surrounding mudflats and marshes were filled and developed by the

people of Boston. The varying quality and extent of these historical data sources presented problems when attempting to integrate them, but a careful comparison with modern features allowed some distortions and inaccuracies to be corrected.

2.2.1 Data Sources

Map data were obtained digitally from a variety of sources. The Massachusetts Office of Geographic Information (MassGIS) was particularly important as a source of aerial photographic imagery, digital elevation models (DEMs), and geographic feature-based shapefiles. Another major contributor to the data for this project was Boston Public Library's Norman B. Leventhal Map Collection, which includes hundreds of maps of the Boston area from throughout its recorded history, which are all available as high resolution downloads on their website. Other maps were obtained from several other sources, including the Massachusetts Office of Coastal Zone Management, the Harvard University Map Collection, and the Cambridge Historical Society.

2.2.1.1 Coast Survey Maps

The primary historical map in this study was the 1847 Coastal Survey map, which was obtained from the Massachusetts Office of Coastal Zone Management in a georeferenced .tiff format. In contrast to earlier Revolutionary War era maps, which were accurate enough for their day but were produced from imprecise measurements of distances and shapes of landforms, the Coast Survey map was very precisely measured

and as a result has been georeferenced without much distortion. Even the best 18th century maps do not have this level of precision, which places limits on their use for analysis.

The 1847 Coast Survey map was quite detailed, but the map sheet obtained for this study did not extend as far as Boston itself. To fill in the gap, the 1854 Coast Survey map was downloaded from the Leventhal collection and georeferenced to the 1847 map and the modern orthophotos. This hybrid approach was used because the maps contained some useful overlap, but not enough to accurately georeference. A note on the 1854 map shows that it was itself a hybrid:

> The water lines and soundings on Mystic River, the east shore of East Boston, South Bay and below South Boston were furnished by the U.S. Coast Survey...the remainder was compiled from data in the City Engineer's Office.
>
> by W.H. Bradley.
>
> Boston, Nov. 1854

One effect of the hybrid nature of the map is that marshes are clearly marked on all areas covered by the Coast Survey, but the marshes of the Charles River are not distinguished from the upland itself. Because of this it was necessary to use the two Coast Survey maps together to create a map of the marshes and mudflats as they were in the mid-19th century.

2.2.1.2 Leventhal Collection Maps

Besides the 1854 Coast Survey map, several other maps were obtained from the Boston Public Library's Leventhal Map Collection online database. Some maps in the collection date back several centuries, which allowed this study to use maps from throughout Boston's long history.

The earliest map used in this study is the 1722 map "The Town of Boston in New England" by Captain John Bonner. It is a very detailed look at early Boston with individual houses and some features that can still be seen in Boston today, including Long Wharf, Boston Common, the Burying Place, and Beacon Hill. While the shoreline is very different from today's coast, many streets and landmarks are unchanged, making this map useful for georeferencing and shoreline change analysis.

The next map, "A Plan of Boston in New England with its Environs, Including Milton, Dorchester, Roxbury, Brooklin[e], Cambridge, Medford, Charlestown, Parts of Malden and Chelsea, With the Military Works Constructed in those Places in the Years 1775 and 1776," produced by Henry Pelham, a Massachusetts Loyalist, and published in 1777, shows a similar view of Boston to the 1722 map, but within its geographic context. Although by modern standards there is significant distortion of scale and shape in the outlying areas of the map, there is also an incredible amount of detail in the map that sheds much needed light on the areas outside of Boston in the early days of its history. Knowing which areas were settled and which were still forest or farmland in the 1770s is enormously helpful in determining what those areas may have looked like in 1630.

The nautical “Chart of Boston Harbour, Surveyed in 1817 by Alex.[R] S. Wadsworth U.S.N. By Order of Com.[E] William Bainbridge” is an early precursor to the 1847 Coast Survey map. Consisting of detailed shorelines of Boston, part of Charlestown, and Boston Harbor with depth soundings, but also some simple features on land, such as the outline of the Boston Common and an unlabeled street grid, make this chart useful for shoreline study and makes it possible to georeference it to modern-day features. The lack of street names adds additional work to the georeferencing process but does not make it impossible. Because this chart was created for use by the navy, it is reasonable to assume that the shoreline delineated is relatively accurate, but that assumption will be tested during the georeferencing process.

The 1826 “Plan of Boston Comprising a Part of Charlestown and Cambridge,” surveyed by S.P. Fuller is the earliest map in this study to show the 1821 Mill Dam across Back Bay. Although it does not show the full extent of the “full basin” which would later be transformed into the Fens, it does show the receiving basin bordering the western edge of Boston. Although like many maps from this era it shows the planned streets and land that had not yet been made, it also shows the shoreline of Boston and Roxbury as it presumably still was in 1826. It also shows all of the still-expanding city of Boston, complete with labeled streets and wharves, thus simplifying the process of georeferencing and shoreline delineation.

A series of maps entitled “A New & Complete Map of the City of Boston With part of Charlestown, Cambridge & Roxbury,” created by G.W. Boynton in 1839, 1841,

1846, and 1850 provide an interesting opportunity to see the changes to the Boston shoreline as viewed by one man, with the same projection and spatial extent. The extent is the same as that of the 1826 map, although the Boynton maps are oriented toward the west rather than the north. With other map comparisons, some differences may be attributed to different cartographers with a different perspectives or techniques rather than actual differences in terrain. This cartographic difference is obvious when studying the salt marshes that appear in the receiving basin in the 1847 Coast Survey map. The other features in the basin, the two railway causeways that cross in the basin, are present in the 1846 and 1850 Boynton maps and the 1847 Coast survey map, but neither Boynton map shows the marshes. This probably indicates that the marshes were not a significant feature for the purposes of Boynton, who was creating a city street map, rather than indicating that the marshes only existed for less than four years. Although minimal changes occur from 1839 to 1850 in the Boynton maps, they provide a useful comparison with other contemporary maps and amongst themselves.

The next historical map used in the study is the "Map of Boston, Showing Health Districts and Undrained and Filled Land" from 1870. The large spatial extent and high level of accuracy allows for the effective land change comparison for the entire study area. In addition it has color coded shading distinguishing salt marsh, "low and swampy" terrain and filled land. Assuming that the difference between salt marsh and "low and swampy" is marine versus freshwater habitats, it shows which areas had been separated from the tidal flow of the Charles River by 1870.

The 1880 “Plan Showing Encroachments Upon the Inner Basins of Boston Harbor” produced for the annual Report of Harbor and Land Commissioners, shows with crosshatching the original land, land that had been made up to that point, and the area that could potentially filled in the future. The remaining salt marshes were not delineated, making delineation of the upland in places impossible, but Boston and Back Bay at that point were edged with made land, indicating that there were no salt marshes remaining in those areas. Therefore this very precisely surveyed map is useful for studying Boston and Back Bay, but not the Upper Charles and East Cambridge.

The 1900 United States Coast and Geodetic Survey's “Boston Inner Harbor, Massachusetts,” like the 1847 Coast Survey map, combines a precise street map of the Boston area with a nautical chart of the shoreline that distinguishes filled areas and salt marshes, with the addition of labels on all streets and geographic features. This level of detail and precision makes the 1900 map useful for examination of shoreline change in the entire study area.

The 1948 Boston City Planning Board map is less detailed than the 1900 map, but no less accurate, making it possible to georeference it without distortion and accurately map the shoreline.

2.2.1.3 Nancy Seasholes' 1630 shoreline

Another map that has proven useful is the historical shoreline reconstruction by Nancy Seasholes from her book, *Gaining Ground: A History of Landmaking in Boston*

(2003). Her reconstruction, based on several historical maps, depicts the approximate high tide shoreline of the Shawmut peninsula (on which Boston would be built) and the surrounding area as it was in 1630.

2.2.1.4 MassGIS Shapefiles

In addition to map layers created directly from historical maps, modern sources such as the MassGIS website, were also used to provide relevant shapefiles of modern features, such as the 1:25,000 Coast polyline and USGS Large Pond polygon layers. As part of this project these layers were geoprocessed to create a modern shoreline polygon layer for use in analyzing the area and volume of land that has been created.

2.2.1.5 Modern Orthographic Photographs

Two distinct sources were used for obtaining georeferenced orthographic photographs. The first source was MassGIS, which provided 15 cm resolution color orthophotograph tiles of some areas of Massachusetts. The data were collected in April 2008 by an aircraft flying approximately 4800 feet above mean ground level. Photographs of urban areas in Boston were obtained using the "true ortho" method to reduce the effect of tall building lean observed in slightly oblique portions of aerial photographs (http://www.mass.gov/anf/research-and-tech/it-serv-and-support/application-serv/office-of-geographic-information-massgis/datalayers/colororthos2008.html). The images were downloaded as 10 adjacent 1500 meter square tiles in the MrSID Generation

2 format. The 10 tiles covered the entire Charles River basin as well as a portion of the river upstream, and included the Magazine Beach study site. These photographs were georeferenced by MassGIS to a high degree of precision (a root mean square error of less than 60 cm).

The second source is a built-in basemap option in ArcMap. Under the “Add Data” tab there is the option to add imagery, street maps, and topography, along with several other types of basemaps. These basemaps are not stored as a file, but rather make use of an internet connection to display the basemap at whatever scale or location necessary. The “Imagery” layer is based on the Bing maps website and it works very similarly to it. The Imagery layer proved very useful for georeferencing historical maps, with the downside that it required an internet connection and slowed down processing time somewhat. The imagery basemap also has the option of showing street names, which was very helpful during the georeferencing process.

2.2.1.6 LIDAR Datasets

Two LiDAR-derived digital elevation models (DEMs) were obtained from MassGIS for analysis of the modern terrain. The 2002 Boston Area DEM, projected in Massachusetts State Plane (unit: meters) and possessing a horizontal resolution of 1 meter, was used for most city-scale applications in this study. Because of recent landscape changes in Magazine Beach park it was also necessary to use the 2009 City of Boston DEM, projected in Massachusetts State Plane (unit: feet) with the same resolution.

2.2.2 Data Management

All GIS work was conducted using Esri ArcGIS 10 software to integrate paper-based historical maps with modern orthophotos and maps. Historical maps were either scanned or photographed from an orthographic angle and uploaded into the GIS as a .jpg or .tiff file type. Using control points that were common to both the modern and historical maps, the historical maps were georeferenced and somewhat warped by the computer to create the best fit. All map files in this study used the Massachusetts State Plane projected coordinate system, which is based on the Lambert Conformal Conic projection. For any raster or vector files that were already georeferenced, they were easily added to the map document because the GIS can convert any projection into any other automatically using mathematical conversions. During georeferencing, however, the map being added is often in an unknown projection system and the GIS must rely on control points to convert the map to the proper projection rather than relying on a known conversion algorithm.

These control points were selected based on their commonality between the maps. Street intersections were most commonly used, with control points generally selected in the center rather than the corner of the intersection. This was necessary for two reasons: first, the maps likely showed the streets in a symbolic way and there was no way of knowing whether the true width was represented; and second, because the width of the streets was quite likely to change over the course of many decades. Natural features such as shorelines were generally avoided for use as control points because they are known to have changed, sometimes drastically (as in the Charles River basin) and sometimes more

subtly (further upstream, where the river was narrow). Another reason is that they often appear to only have been drawn approximately, especially when the purpose of the map was mainly to show the layout of city streets and parks. The 1817 Wadsworth map and the 1847 and 1854 Coast Survey maps are obvious exceptions because they were at least partly nautical charts, but this was generally the case.

Once 10-20 well-distributed control points had been selected, a table of the residuals (or root mean square error) for each point was opened, and the points with the highest residuals were examined . Often a strong outlier would turn out to be mistakenly placed, but they were not removed simply because of the high residual. A justification was necessary to remove any particular point (Bolstad, p. 154).

The residual window display also offered the possibility to select which transformation to use for the map. These transformations were very similar to the techniques used in least squares regression. A first order transformation uses a linear equation which causes minimal, linear warping, turning a square map into a parallelogram (Figure 2.1). Second order transformations use quadratic equations to warp the map, which tends to reduce residuals but at the cost of more extreme distortion in the periphery of the map (Figure 2.2). Third order transformations use cubic functions, which exhibit the same tradeoffs even more severely (Figure 2.3).

Depending on the degree of difference between the two maps and the spatial accuracy of the historical map, a first, second, or third order polynomial transformation was applied. Third order transformations cause the greatest warping of the historical map,

so they were only used when deemed necessary to correctly correlate certain parts of the map to their modern counterparts. For the most part only 1^{st} order polynomial transformations were used in this study to minimize peripheral distortion.

Figure 2.1. An 1841 map with a 1^{st} order transformation. Note the ground control points visible as red and green crosses.

Figure 2.2. The same 1841 map with 2^{nd} order transformation. Note the concave-right curvature of the warped map.

Figure 2.3. The 1841 map with 3^{rd} order transformation. Note the top of the map, which has a different concavity (left) than the rest of the transformed map.

2.2.2.1 Coast Survey Maps

The 1847 Coast Survey map section covering Roxbury, Cambridge, and Medford, which was surveyed by H.L. Whiting under the superintendence of A.D. Bache, was obtained as a georeferenced TIFF file from the Massachusetts Office of Coastal Zone Management. This map is incredibly detailed and precisely surveyed, with the result that it required very little distortion to georeference it to modern features. Among those details are the salt marshes along the banks of the Charles and Mystic River estuaries. Unlike other 19th century map depictions of marshes, which usually only have imprecise renderings of the marshes if they show them at all, the Coast Survey map has an almost photographic quality. The marshes are very detailed and their tidal inlets have a very natural riparian appearance, including one meander that has nearly become an oxbow lake. Because of this unparalleled precision and real (in the case of persistent features like roads) and apparent (features that no longer exist) accuracy, It was chosen as the historical base map which could be used to modify imprecisely or inaccurately drawn natural features in other historical maps.

The 1854 Coast Survey map was obtained as a high-quality JPEG file from the Leventhal collection website and added it to the ArcMap document. I started the georeferencing process by zooming to a location and scale similar to that of the 1854 map and then used the “Fit to display” tool on the Georeference menu to make the map fill the screen. Without doing this, an ungeoreferenced image or map would not be visible within the ArcMap document. I then selected two rough starting georeference points, one

common to the 1847 Coast Survey map on the west and the other to the Seasholes map on the east. Because of the limited extent of the 1847 map it was necessary to georeference to the Seasholes map to get well-distributed points.

After adding several more precisely placed control points it was possible to remove the first two, which had not been placed with much care, but rather served the purpose of holding the map in the right place to make the other control points easier to connect. This is not strictly necessary but it likely saves time when first positioning the map. The permanent control points were often road intersections, but the shorelines of the harbor islands on the Seasholes maps were used as well, due to their close similarity to the 1854 map. The 1854 map had a pre-colonial shoreline reconstruction of its own superimposed on the then-current shoreline map, which greatly aided in georeferencing. Once satisfied with the fit (after checking for outliers on the "Link Table" window) I updated the georeferencing and saved the map document to make the position permanent.

2.2.2.2 Nancy Seasholes' 1630 shoreline

Nancy Seasholes' reconstructed pre-colonial (1630) shoreline was overlaid on maps and bird's-eye views of modern city, with street names labeled. I digitized several neighborhood maps (North End, West End, Back Bay, etc.) as well as a map of the entire area directly from the book using a scanner. The resulting images were then saved in TIFF format and georeferenced in ArcGIS using control points based on the modern street intersections in both the Seasholes maps and the modern orthophoto basemap layer based on Bing maps.

2.2.2.3 Historical Maps

In addition to the 1854 Coast Survey map, several other maps were downloaded from the Leventhal online collection. None of these maps were obtained in georeferenced form, so they were all georeferenced with ArcGIS 10. For most maps, even those dating back to the early 18th century, there were sufficient streets and other man-made features marked on them that still exist, which were used for ground control points in the georeferencing process. Shorelines were generally avoided because of the amount of change that has occurred over the centuries, but they were used for the 1880 map, which did not have any streets marked. Instead, recognizable wharves and other features were georeferenced either to the modern orthophoto layer or the 1900 Coast and Geodetic Survey map, which was so precisely and accurately surveyed that it showed very little distortion and corresponded closely to the modern map.

2.2.3 Feature Delineation

Once the maps were georeferenced in the correct projected coordinate system, they could be digitally traced along features of interest, such as shorelines, salt marshes, railroads, and streets. The traced features were saved as shapefiles or feature classes (different but basically equivalent file types) of point, line, or polygon types and could be used as map layers which could be overlaid on any other map features to display the landscape changes that occurred between certain dates. These layers were not only useful

for display, but also contained quantitative information such as number, length, and area.

Due to the varying extent of the historical maps being used, the first step in comparing shoreline change was simply to develop rough limits to the area of interest. At first this area was the Charles River basin only, but it eventually expanded to include the entire Shawmut peninsula (Boston) in order to give a more complete context for the landmaking that would eventually envelop the basin. Some of the historical maps do not cover the entire extent of this study area, so the shorelines were initially simply traced as far as possible.

2.2.3.1 Coast Survey Maps

The 1847 Coast Survey map was traced using feature classes that were created to represent such features as salt and freshwater marshes, tidal inlets, roads, railroads, and deciduous trees (in regular patterns that suggest they were orchards). Although it represents the area seventy-two years after the Siege of Boston, it provides a spatially-accurate snapshot of the marshy tidal basin that is now covered by the Back Bay neighborhood of Boston, and precisely locates other natural features which have long since been destroyed. However, the 1847 map does not cover the entire study area, so the shoreline feature was extended onto the 1854 Coast Survey map. Because the landmaking at that time was happening primarily along the western fringe of Boston (the area covered by the 1854 map) and a visual comparison of the rest of Back Bay on the two maps suggests no significant changes during the intervening seven years, the hybrid shoreline shapefile can be considered to date from 1854.

There are two reasons for using this hybrid method rather than simply using the 1854 map alone to trace the shoreline and other features. First is because the 1854 map does not extend to Magazine Beach or the upper Charles River. Its western edge is near the point where the river widens into the tidal basin. Second is the fact that the Back Bay portion of the 1854 map was provided by the City Engineer's Office rather than the Coast Survey, which in practical terms means that the Back Bay both lacks the variety of features provided by the 1847 map and also fails to reach the same level of precision. For these reasons the hybrid approach served the study's purposes well.

2.2.3.2 Nancy Seasholes' reconstruction

After georeferencing the Seasholes shoreline, I created a polygon feature class to represent the upland area and traced the 1630 shoreline of Boston, Back Bay, Cambridge, Charlestown, and the Harbor Islands. However, because the land delineated in the Seasholes map included salt marshes rather than depicting only dry land, it was necessary to use historical maps to edit the marshy areas out of the 1630 shoreline layer.

2.2.3.3 Historical Maps

As in the case of the Seasholes map, it was important to trace only dry upland when delineating the shoreline features of historical maps. When possible this was accomplished, although some maps, such as the 1880 map, show the shoreline as the

marsh-flat boundary rather than the upland-marsh boundary. In these cases the shorelines were traced fully anyway, but the analysis was limited to areas that could be determined to be dry land rather than salt marsh by comparison with contemporary maps.

2.2.4 Feature Processing

After the historical shorelines had been traced as polygon feature classes, further processing was necessary for two main reasons. The first issue was that the georeferencing process has its limits and cannot correct errors of shape or proportion that are present in the original maps. The other issue was that all of the maps have differing extents, which makes area change analysis over several centuries more difficult. Expanding and adjusting the raw historical shore polygons was necessary as a precondition to conducting this analysis.

2.2.4.1 The 1826 Shoreline

The errors of shape and proportion became apparent after overlaying the 1826 and 1854 shoreline polygons. The 1826 shoreline fits well around the city, but Mill Dam across Back Bay and Cross Dam across Gravelly Point appeared to be shadows to the northwest of those same features of the 1854 map. The discrepancy was solved by comparing the historical maps to the labeled modern orthophoto layer. Examining the 1847 Coast Survey map, on which this portion of the 1854 hybrid is based, reveals that the mill dam coincides precisely with modern-day Beacon Street, and the Cross Dam that

divided eastern Back Bay from what would become the Fens coincides with Hemenway Street. This was good evidence on its own, but double checking the 1870 map solidified the conclusion that the 1847 map correctly portrays these features. The 1870 map depicts the Mill Dam and Cross Dam, but the land to the east of Cross Dam had been filled and developed by 1870, and Beacon Street and Parker Street (which today turns into Hemenway Street near to Beacon Street) are shown in their modern positions along the two former dams. Given this evidence, it was reasonable to edit the 1826 shoreline to correct the location of the dams and the adjacent Gravelly Point.

The same shadow effect is visible at the base of the Boston Neck to the west and south of the bay when the 1826 map is compared with the original 1630 shoreline from Seasholes. As a check on the 1630 shoreline, the 1854 map also has a reconstructed 1630 shoreline that follows very closely with the Seasholes reconstruction. Because of this and the fact that the 1826 map is known to be distorted in this area (Gravelly point and the dams), the shadowed portion was adjusted to coincide more closely with the Seasholes polygon. In effect the entire Back Bay area of the revised 1826 polygon is a hybrid of the historical 1826, 1847 and 1854 maps, as well as the Seasholes map. Despite its patchwork of sources, it appears to spatially closer to the actual 1826 shoreline.

2.2.4.2 The 1870 shoreline

The 1870 map required no editing because of the comparatively minor amount of distortion and its spatial extent that included the entire study area. However the initial shoreline layer was created in error because I had traced the boundaries between the salt

marsh and the flats rather than the upland-salt marsh boundary. It was relatively simple to edit the shoreline to exclude the marshes, but this error highlights the difficulty with properly defining the shoreline. The Seasholes map and the 1854 map's reconstruction of the 1630 shoreline both included salt marshes in the landward side of the boundary, which meant that the study's reconstructed 1630 shoreline also needed to be adjusted.

2.2.4.3 Nancy Seasholes' 1630 Shoreline

After comparison with other historical maps, such as the 1847 Coast Survey map, it was clear that much of the shoreline included salt marshes and needed to be edited to create a true upland boundary. The first step was to use the Erase tool in ArcMap to erase the 1847 salt marsh polygon from the Seasholes map. Because of the many roads and causeways that crisscrossed the marshes in the 1847, the resulting geoprocessed feature class, called “Coast_1630b” possessed those same causeways and roads, which needed to be removed. By highlighting a polygon and using the “Edit Vertices” tool, all the vertices became visible and could be erased en masse by highlighting them, which greatly speeded the editing process. Isolated polygons could also be entirely removed by highlighting them and deleting them.

Initially this hybrid, which essentially showed the 1847 upland in Back Bay, the Upper Charles and East Cambridge and the Seasholes shoreline of the Boston peninsula and the Harbor Islands, was deemed sufficiently close to the 1630 shoreline, but it still possessed many areas that seemed suspiciously linear. Later a comparison with the 1777 Pelham map allowed a better estimate of the original shoreline to be made.

The Pelham map was originally deemed spatially-accurate enough to allow the tracing of the Boston peninsula. The map was produced by Henry Pelham, a Massachusetts loyalist who was given permission to travel freely throughout the British lines during the Siege of Boston in order to create an accurate map of the British and American positions and the surrounding terrain. Although the outlying areas of the map on the western side of Back Bay and the Cambridge side of the river are not spatially-accurate enough to use a literal trace of them, they are qualitatively very useful in locating the original shoreline. Comparing the 1847 marshes with the marshes in the 1777 map (labeled as “salt meadows”) made it very clear which areas had been filled in the seventy years between the maps. For example, in 1777 Gravelly Point was a salt marsh with roughly the same outline as the upland it would become in the 1800s. Using this as a reference, the coastline was trimmed back to the south in Back Bay, to the north in East Cambridge, and narrowed on both sides of the land just south of Boston Neck.

2.2.4.4 The 1777 Shoreline

The 1777 shoreline itself was traced in a literal sense along the entire coast of the Boston peninsula north of the Boston Neck. South of the neck, the edited 1630 shoreline, which itself was partially based on the 1777 map, was copied and pasted from the Coast_1630b layer to the Coast_1777 layer. The two polygons were then edited to connect smoothly at the neck, creating a hybrid layer to represent the 1777 coast. Because the 1777 map shows the areas outside Boston as being relatively rural and undeveloped

along the shoreline, it was considered to be essentially identical to the 1630 shoreline in those areas.

2.2.4.5 The 1723 Shoreline

Because the shoreline outside of Boston was assumed to be unchanged between 1630 and 1777, the same procedure was used to create the 1723 shoreline. The shoreline of the city was traced and then joined with a copy of the 1630 shoreline at the Boston Neck.

2.2.4.6 The 1817 Shoreline

The 1817 map is another one that doesn't cover the whole study area. It was traced along the shore of Boston to the neck, at which point it was again joined to the 1630 shoreline. This map, however, shows the land south of the neck as being entirely land, with no salt marsh remaining. This would be ambiguous because of the differing habits of mapmakers in how they depicted salt marshes, but there is a clearly defined marsh across the channel on the Dorchester peninsula. This indicates that the land south of the neck was in fact entirely upland. Because the shoreline again resembles a shadow of the unprocessed Seasholes shoreline, it was used as a guide to trace this portion of the 1817 shoreline. The 1817 map does not show all of Back Bay, so the rest of the shoreline was is purely speculative. The Coast_1630b layer was again copied and pasted into the 1817 layer and minor changes were made to it to join it to the rest of the shoreline. Because the changes made to parts of the Back Bay portion of this shoreline file were speculative, the

area change analysis was only performed on the Boston area itself for the 1817 shoreline.

2.2.5 Data Analysis

In order to conduct quantitative analysis of shoreline change using a variety of spatial sources with varying extents, it is necessary to create standardized areas. I delineated four adjacent areas that were present in all processed historical shoreline files: Upper Charles, East Cambridge, Back Bay, and Boston. I created a feature class for each of them, labeled Upper_sub[section], Cambridge_sub, Backbay_sub, and Boston_sub, which could then be used to clip the historical shoreline files. The eleven shoreline files used were the processed 1630 reconstruction, the modified 1723, 1777, 1817, and 1826 shorelines, the 1847-1854 hybrid, the 1870 Health District map, the 1880 Harbor and Land Commissioners map, the 1900 U.S. Coast and Geodetic Survey map, the 1948 City Planning Board map and the 2013 hybrid created using the MassGIS Coast polygon shapefile and my own modern orthophoto-based Charles River polygon.

Using the “Clip (analysis)” tool in ArcMap, I clipped each shoreline file using each of the four subsection polygon feature classes. This resulted in 32 feature classes rather than the full 44 possible because the limited extent of the early maps limited their usefulness to Boston and sometimes Back Bay. In addition, the 1880 map defines the shoreline as the seaward edge of the salt marshes, which made it only applicable to Boston and Back Bay, despite the map's large extent. Prior to clipping, some of the

shoreline files required minor adjustments to ensure that they filled the entire landward extent of the four subset polygons. In one case this involved extending the shoreline of the 1948 file a short distance using the 1900 shoreline as a guide, but otherwise the extensions were entirely within land and required no shoreline extrapolation, but merely changing the arbitrary landward boundaries.

2.2.5.1 Area Change Analysis

Following the clipping process, I reordered the 22 feature classes into the four geographic (rather than temporal) groups and examined their attribute tables individually. Highlighting the area column of each table and opening the statistics table allowed me to obtain the total area in square meters. Copying and pasting these figures into an Open Office spreadsheet allowed me to organize the area data into columns, convert them into square kilometers (by dividing by 10^6), and graph the change over time.

The raw area data is essentially meaningless on its own because it is the area of my arbitrarily created polygons. In order to make more sense of the data I subtracted the 1630 area from each of the up to eleven area measurements in each subsection. This set the zero-area datum at 1630, meaning that all other area measurements now represent land created since the arrival of Europeans that year. This allows us to see not only the total land area created by each date, but also visualize how the rate of landmaking changed over time.

2.2.5.2 Volume Change Analysis

Estimating the volume of land added to each area since colonization is more speculative in nature than measuring area because early maps did not quantify elevation. The procedure for this volume estimate is simplistic and by necessity based on certain unavoidable assumptions. The first assumption is that upland height has not significantly changed and therefore only areas once covered by mudflats or marshes must be considered. In the case of Boston this is not true because some material for filling the original mill pond next to the North End was taken from Beacon Hill (Seasholes). However, much of the material that filled Back Bay was gravel brought in by train from Needham, so the assumption holds more water for the Back Bay subsection (Seasholes).

The next assumption involves estimating the average height of the marshes and flats. An average height of 1.41 meters for the marshes was obtained from a similar study (Maio, et al, 2012). The mudflats were more problematic because they tend not to be as flat and consistent in height as marshes. Because the waterline would have been roughly along the modern shore of the Charles during low tide and along the fringes of the marshes and upland during high tide, I made a rough estimate for the average mudflat elevation as mean sea level (MSL) or zero meters.

After making those assumptions for mean heights of the pre-colonial terrain, the volume of fill added could be determined by comparing them with the mean heights on the modern terrain using the 2002 MassGIS LiDAR-based DEM. But first it was necessary to clip the DEM to the dimensions of each marsh and mudflat. To do this I used

the Erase tool on each of the four 2013 shoreline subsections from the area analysis section. From each of these modern shoreline sections I erased the 1630 shoreline polygon layer, which resulted in an intermediate feature class representing the total area filled, and then I erased the 1630 salt marsh layer from the intermediate feature class in order to create a feature class to represent just the former mud flats. Because there was already a 1630 salt marsh polygon layer, I could create the salt marsh subsections in a single step using the "Clip (Analysis)" tool to clip the 2013 shoreline subsections to the dimensions of the salt marsh layer.

With the resulting four salt marsh and four mud flat subsection feature classes, it was now possible to clip the DEM to the dimensions of each of those eight features. Using the "Clip (Data Management)" tool, the raster equivalent of the "Clip (Analysis)" tool, I produced eight smaller DEMs, one for each of the subsections. Once the DEMs were produced, I simply opened the layer properties window and looked up the mean raster value (elevation) for each of the DEMs. Then using an Open Office spreadsheet I subtracted the assumed pre-colonial averages discussed above from the modern averages. Multiplying the average thickness of the fill by the area of each feature produced a volume estimate in cubic meters (which could then be converted to cubic kilometers by dividing by 10^9).

2.2.5.3 Time Series Mapping

Time series mapping represents the qualitative aspect of this study. It is important to not only measure but to be able to visualize the changes that took place over the course of centuries and to develop an understanding of how those changes were carried out. There are a number of different ways to spatially depict change in shorelines over time, with a mix of quantitative and qualitative aspects.

The simplest way to map change over time is to compare two-dimensional (2D) maps. They can either be laid out side by side for clarity or overlaid for better comparison. There is a tradeoff with either one: Maps that have several layers can be too data-dense to be useful, but adjacent maps require more work to recognize and estimate the size of changes from one map to another. Either of these methods can be accomplished with ArcMap, but there is another useful tool that provides a different perspective.

Esri ArcScene software allows the three-dimensional (3D) display of spatial data. Examining DEMs in ArcScene from different angles gives the viewer a greater feeling of being present in that environment and a greater understanding of the terrain. However, polygon files do not show the same texture as raster DEMs in a 3D display. In order to make use of this software I substituted time (in years) for elevation in ArcScene.

After creating a scene document with the Massachusetts State Plane projection system I added several shoreline polygon files to the document, including the 1630 layer. Under the Base Heights tab of the properties window I set the base height to zero for the

1630 layer. Under the Extrusion tab I set the value of extrusion to -196, which is the number of years from 1630 to the next shoreline layer, 1826. This extrusion gives the polygon a constant thickness proportional to elapsed time. For the 1826 map I set the base height to -196 and the extrusion to -24, which is the number of years to the next layer, the 1850 shoreline. This method was continued for all layers in chronological order up to the 2013 layer, which was itself extruded down 20 years to give it a significant depth and make it more visible.

These methods produced a visual display that I would characterize as a "geo-graph". It conveys a similar story of land change to that of the land area scatter plots, but in three dimensions.

I also used ArcScene to depict topographic change over time. The goal was to get an oblique bird's-eye view of the area from different time periods. The topography was based on the 2002 LIDAR-based DEM from MassGIS. ArcScene rendered the DEM in 3D and I applied a 300% vertical exaggeration due to the flatness of the terrain. In order to create different landscapes with the same underlying terrain I used the polygons representing water to erase those parts of the DEM. I relied on the same assumption used during volumetric calculations, that the rest of the terrain for the most part has not changed significantly because of the extensive and labor-intensive nature of the filling. Most of the landmaking energy was spent on the marshes and mudflats rather than on areas that were already dry ground. With this assumption I displayed the salt marsh polygons as having an elevation of roughly 1.5 meters (also exaggerated 3X). Adjacent to

this we displayed the water polygon with an elevation of zero (sea level). Together these two polygons and the rendering of the DEM created a sense of actually being able to see the landscape as it was in the pre-colonial period.

2.3 GPR Methods

2.3.1 GPR Background

Radar has been in use for the better part of a century, but it is only in the last forty years that this technology has been applied to geophysical work (Kenyon, 1977). Although operating in a different medium, ground-penetrating radar works on the same basic principals as aerial radar. A radio transmitter on the ground sends a short pulse of electromagnetic energy into the earth. The radio waves pass through certain materials without significant attenuation or reflection, but tend to be reflected by strong stratigraphic discontinuities or large objects. These reflections are received by the GPR unit and the depth of the reflector is calculated using the speed of light in the ground (which varies based on sediment type but which can be obtained experimentally or in the literature). The speed is multiplied by the time it takes for the light to return to the antenna to calculate the total distance traveled and divided by two to obtain the depth. For each pulse of electromagnetic energy released, the GPR unit collects amplitude data for a certain amount of time (in our case 2048 nanoseconds) after the pulse and then stops recording data until the next pulse. The depth versus amplitude record for each pulse is known as a trace. After collecting a series of traces the data is combined into an

amplitude/depth profile known as a radargram. The horizontal distance on the radargram can be determined by field measurements, a survey wheel that controls the pulses so that they are sent on predetermined spatial intervals, or via coupled GPS measurements taken simultaneously with the radar data.

2.3.2 Data Acquisition

Magazine Beach park was surveyed using a 500 MHz ground-penetrating radar (GPR) unit coupled with 3-axis GPS coordinates. The unit was towed at a relatively constant speed behind a golf cart and data points were collected at a fixed time interval. The GPR data were collected in 76 segments in a grid pattern roughly perpendicular and parallel to shore, following the curve of the river. Certain areas proved inaccessible to the GPR unit, including a small recently-created wetland and the land covered by the magazine itself and a nearby fountain. Nonetheless the park was widely and thoroughly surveyed, both in the low-lying fields on either end and Captain's Island in the center.

2.3.3 GPR Data Management

The radargrams appear to be stratigraphic cross-sections of the sediment, but they should be regarded as radar surfaces and facies (Neal, 2004). The data must also be processed and filtered to provide clearer images that better approximate the subsurface features. The data in this study were analyzed in GPR-Slice software, which performed this processing. The first step after adding the raw data to the “Slice” folder was to apply

a user-defined gain to the traces. The raw traces have very high amplitudes near the surface, but attenuation by the soil rapidly decreases the strength of returns from deeper reflectors. Gain is meant to boost the signals of the faint deeper reflectors and possibly even lower the strength of very strong returns at the near-surface. We divided the trace vertically into 16 equal segments and applied a gain (starting at the surface) of -1, 1, 10, 60, 100, 200, 250, and 250 for all subsequent depths. This boosted the signal but also the noise from the deeper reflectors, which limited the depth of penetration to the first 1.5 meters (of 5). Below that there is still data on the radargram, but it is too noisy to be able to distinguish any stratigraphic features.

The next step is resampling the data. This step has several parts. The first part involves finding the true 0 nanosecond (ns) depth. A significant portion of the EM pulse from the antenna reflects off the ground and returns to the receiver. GPR-Slice has an function within the Slice and Resample window called “Search 0 ns.” This function automatically finds the time it takes for the initial ground wave to return and adjusts the time/depth profile so that the ground surface is at 0 ns.

The next part of the resampling step is setting the number of time slices and setting the thickness of each slice. In order to ensure that no data was missed between slices I set the thickness at approximately 1 ns and set a slice overlap of 25%. Then it was necessary to set the cut parameter, which is the method of averaging the amplitude of each trace over the thickness of each slice. Because the signal is a wave, any given amplitude can be positive or negative. I set the cut parameter to squared amplitude to

avoid any amplitude cancellation in the averages. This setting takes the square of each amplitude measurement to make sure that it is positive and then averages it. The other options were to average the raw amplitudes or the absolute values, but squared amplitude parameter is recommended by the GPR-Slice manual for most applications (Goodman and Klein, 2010).

The slice thickness and parameter were settings for vertical averaging, but the slice and resample process also averages horizontally along GPR lines. Setting the cuts per mark tells the software at which horizontal spatial intervals to average the amplitude data. For this study the cuts per mark was set to create 1 meter intervals.

Finally, clicking the Slice & Resample & XYZ button performs the slice and resample operation and also assigns XYZ coordinates (UTM projected coordinates, in meters) to each resampled point, which allows the information to be integrated with a GIS.

After resampling the data is passed through a bandpass filter to eliminate frequencies that are unlikely to have originated from the GPR unit pulse. Radio signals come from various outside sources, including telecommunications signals. Our unit was shielded from outside sources, but it is still possible (or likely, given the urban location) that there was signal contamination. The peak signal emitted by the GPR antenna is 500 MHz but each individual photon has a variable frequency, with a distribution roughly equivalent to a bell curve. Through experimentation with different frequency ranges we found that a range of 350-625 MHz was the best to include most of the signal while

ignoring much of the outside EM radiation. The bandpass filter went through each trace and eliminated the amplitude contributed by radio waves outside of this range.

Another filter that we could have used is migration. It is designed to make radar anomalies known as hyperbolas more closely resemble the real physical objects they represent. A hyperbola is an artifact that results from the fact that the radar pulse and returns do not move solely in a vertical direction. The pulse is directed in a conical pattern downward, but it spreads out as it moves deeper. The analysis software must assume that all returns come from below when creating radargrams, which is usually a fair assumption. This assumes that each radar surface acts like a mirror and only perfectly vertical radar waves will be reflected back to the antenna. If, however, there is a reflector that is a point or circular object rather than a plane, it will still present a reflective surface to the antenna even when it is not directly over the reflector. This results in a calculated depth for the object that is greater than the true depth. As the antenna moves closer to the object the calculated depth approaches the true depth, and as it passes and moves away from the reflector the depth increases again. This creates a hyperbolic shape when in fact a true cross-section would show a circular shape. The migration filter in GPR-Slice recognizes hyperbolas and removes them, resulting in more uniform layering patterns. This is a useful filter for some applications, but we chose not to use it because the hyperbola can actually serve to highlight significant anomalies on the radargram. The fact that the radargram is not a true cross-sectional picture must be kept in mind, but the hyperbolas can be quite helpful in locating subsurface anomalies that justify further investigation.

The next process that was performed on the data was the topographic transformation. Elevation data was collected in the field by the GPS unit and can be integrated into the radargrams to simply add the elevation to each individual trace. This produces a simple topographically corrected radargram, which eases the interpretation of subsurface features and facilitates comparison to surface topographic features.

After all processing was completed, the finished radargrams were exported as 76 JPEG image files for visual inspection and analysis. To create a geographic frame of reference for each line and to show how they are interrelated, the raw COR files from the GPR data acquisition phase, which record the geographic coordinates and elevation for each GPS record of each GPR line, were copied and pasted into an Open Office spreadsheet for conversion to a format compatible with GIS. The raw coordinate data was recorded in positive geographic coordinates with a column for West or East for the longitude and North or South for latitude. In contrast, ArcGIS 10 uses a positive/negative sign convention, with East and North positive and West and South negative. In this study the latitude coordinates were already the correct sign, but each longitude coordinate needed to be changed to a negative number. Without this simple correction the GPR lines would have been displayed somewhere in central Asia rather than Massachusetts. After correcting the longitude for each of the 76 lines, I used the Add Data button on ArcMap to add each Excel file to my ArcMap document and then exported the XY data as a shapefile using the format “Line_[number].”

The 76 point shapefiles created for the GPR lines were displayed with geographic coordinates. However, the historical maps were analyzed in the Massachusetts State Plane projected coordinate system and the GPR-Slice software displayed the radargrams with coordinates in the UTM (zone 19N) projected coordinate system. In order to use the GPR shapefiles in either of these systems, it was simply necessary to define the data frame for the map document as either one of the projected systems and then the GPR shapefiles could be added. The shapefiles themselves remained in the geographic system, but they were displayed in the projected system, allowing an integration of the two systems for data analysis.

2.3.4 GPR Data Analysis

Analysis of the radargrams was a painstaking process that integrated a careful inspection and interpretation of individual radargrams with a comparison to the other lines using ArcGIS. Without the use of ground-truthing data, it was also important to integrate historical maps and photographs to guide the interpretation of subsurface features.

Although most maps from the 19th and early 20th century do not show the park itself in much detail, a comparison of as many sources as possible was important to understand the general progression of landscape change over many decades.

A look at line 47, which stretches from one end of the park to the other, shows just how complicated the analysis of the subsurface could be. This line covers areas that are very clearly stratified, stratified with disturbances, unstratified but highly reflective, and

even places that appear entirely transparent to the radar. To further complicate the picture are the water table, which looks very similar to a sediment layer, and hyperbolas from pipes and other large buried objects.

The first step in interpreting the data was to understand the general layout of the land before it was filled. The 1847 Coast Survey map shows that the area was formerly a small teardrop-shaped island surrounded by salt marsh that bordered the then-estuarine Charles River. The island was connected to the mainland by a short causeway. The 1894 Bromley Atlas map shows a similar image of the island and marsh, with the main difference being that the landward side of the island had been filled in extensively on the downstream side of the causeway. In 1899, according to a Cambridge Chronicle article, some of the park was converted to a swimming beach. This beach does not appear on any maps used in this study, but a photograph from around 1913 shows that it extended around at least part of Captain's Island and along to upstream part of the marsh. A pair of oblique aerial photographs from around 1925 show the downstream edge of the beach at the bulge in the shoreline just downstream from the island, the approximate position of the photographer from the 1913 picture. Although the magnified detail of the two aerial photographs are low-resolution, they clearly show the same teardrop shape of the island as in the 1894 map, and the marsh downstream appears to be little topographically changed, apart from having a walking path along the waterline and no longer having drainage ditches. Modern images, such as the 2008 MassGIS orthophoto, show a similar shoreline to the earlier airphotos, but with grass where the beach used to be and the tail of the island no longer visible. In addition, a large granite retaining wall now stabilized the

land beneath the magazine, replacing the smaller one visible in earlier photographs. The imagery basemap layer in ArcMap, which contains more up-to-date orthophoto imagery, shows further changes to the park, including the creation of a wetland in part of the downstream field, and the transformation of a crude baseball field to a well-defined soccer field.

The 2002 and 2009 LiDAR-based DEMs helped shed more light on the recent changes to the topography of the park. After converting the 2009 DEM to meters from feet using the "Times" function to multiply all elevation values by 0.3048, the two DEMs could be compared to highlight the areas that are known to have a significant amount of man-made fill. To simplify this task, the "Minus" tool was used to subtract the 2002 elevation values from the 2009 values to create a DEM of elevation change over those seven years. One area in particular, a small man-made knoll approximately 30 meters long, was composed of fill up to a meter thick. This knoll was crossed by lines 41-47, which was important to keep in mind during analysis, because the maximum depth at which features can be discerned on the radargrams is just over one meter.

The DEMs were also used for comparison with a salt marsh that still exists, Rumney Marsh in Saugus and Revere, Massachusetts. The 2002 DEM covered both Rumney Marsh and the study area, making a direct comparison possible. Rumney Marsh generally ranges from 1.0 to 1.5 meters in elevation, while the downstream portion of the Magazine Beach marshes, which was not part of the beach itself, ranges from 0.7 to 1.8 meters (not including the area that constituted Captain's Island in the 1894 map).

Elevations in the 2009 DEM tend to be even higher, reaching 2.0-2.6 meters on the landward edge of the area surveyed with GPR. Assuming that the Magazine Beach salt marsh is at roughly the same elevation as the Rumney marsh, this allows a rough estimation of the depth of fill to be made on the fly while comparing any given point in a radargram with its modern elevation on the DEM. The original height profile of the marsh is of course not known, but roughly estimating it can be helpful in the qualitative analysis of the radargrams.

Using this general knowledge of the way the park has changed in the past century and a half, I attempted to classify subsurface anomalies into categories that I could map using polygon shapefiles. Initially there were four shapefiles to delineate areas with stratified, disturbed stratified, unstratified/reflective, and transparent radar profiles. This is inherently problematic for two main reasons. First, although the four categories are by definition discrete, the actual subsurface rarely fits perfectly into just one category. Second, the there can be two or more distinct types of soil on top of one another, making a two-dimensional map difficult to delineate.

Despite these challenges, I attempted to map these four features, often analyzing several parallel lines and then checking perpendicular lines to assess the accuracy the interpolated lines connecting subsurface features in adjacent GPR lines. I also looked for patterns or features in the two DEMs and the two orthophoto layers, as well as the historical sources, in an effort to better understand what the subsurface anomalies most likely represent.

CHAPTER 3

RESULTS

3.1 GPR Analysis

The GPR analysis was closely tied to other forms of evidence such as historical photographs and maps. The 1894 G.W. Bromley & Company Atlas of Cambridge was used as the primary historical reference for the geography of Captain's Island and the surrounding marshes before the area was developed into a beach and later a park. The stratigraphy interpreted from the GPR lines was compared to the hypothetical stratigraphy that would be predicted from the historical map. Unfortunately there have been multiple major landscaping events in the intervening time that have disrupted the stratigraphy, to the point where much of the area within the park is composed of chaotic fill rather than stratified layers of sediment.

There are two types of fill that are associated with different fill materials. The first type is a very strong return, which means that there were high amplitudes of EM energy reflected by the sediment. This fill type tends to be associated with the low-lying areas upstream and along the river side of the island. Historical photographs show these areas to be the part of the salt marsh that was converted to a beach in 1899 (Figure 1.4). The second type of fill is transparent, which is most often present in low-lying areas that historical maps indicate are former salt marshes. Both fill types are visible in the 69th

GPR line, which transects the beach area near the island (Figure 3.1).

Selected GPR Lines

Figure 3.1. Selected GPR lines used for analysis.

3.1.1 The Beach

Parts of the beach area are also partially stratified, possibly from the reworking of the deposited sand by wave action during the beach's 50 years of existence (and tidal currents for its first decade). The radargram for line 69 supports this interpretation. The

first 8 meters from the shore is composed of highly reflective, semi-stratified material dipping toward the water, covered by a layer of less-reflective material, likely fill deposited after the closure of the beach (Figure 3.2). This segment is followed by 8-10 meters of transitional material that is somewhat stratified in places, but less distinctly than in the first 8 meters. Behind this is about 10 meters of chaotic, strongly reflecting fill. This material is likely the upper part of the beach sand that was far enough from the water to remain essentially the same as when it was first deposited in 1899.

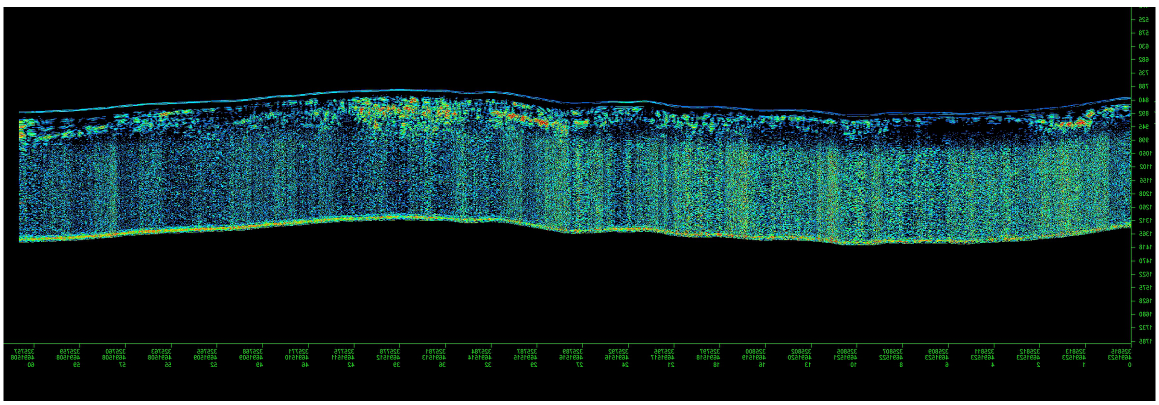


Figure 3.2 The radargram for line 69.

On the landward edge of this strongly reflecting fill is a relatively sharp transition to partially stratified sediment that constitutes the other half of the GPR line, with the exception of a gap of 5 meters near the end that is largely transparent. After referencing the 1894 marsh shapefile it is clear that this area is former salt marsh covered in a thin

layer of soil. The high level of disturbance in these layers is likely due to bioturbation while it was still a salt marsh. The transparent gap correlates reasonably well with a drainage channel in the 1894 salt marsh map, which suggests that it was in fact a channel that was filled with a material distinct from the sand fill on the beach.

Exactly in the center of line 69, at the transition between sand fill and salt marsh, is another feature with possible significance to the surrounding area. It appears to be strongly reflective, well stratified sediment that is dipping away from the river and underneath the salt marsh. This 5 meter long layer closely resembles the well-stratified sediments found within Captain's Island, suggesting that it is a continuation of the island itself that is dipping underneath the salt marsh. In the 1894 map the island is only 5 meters away from this part of line 69, and a similar transition in line 47, which is perpendicular to line 69, is less than 9 meters from line 69 (Figure 3.3). In addition, the approximately horizontal orientation of the well-stratified sediments in line 47 strongly supports the idea that they are one continuous layer.

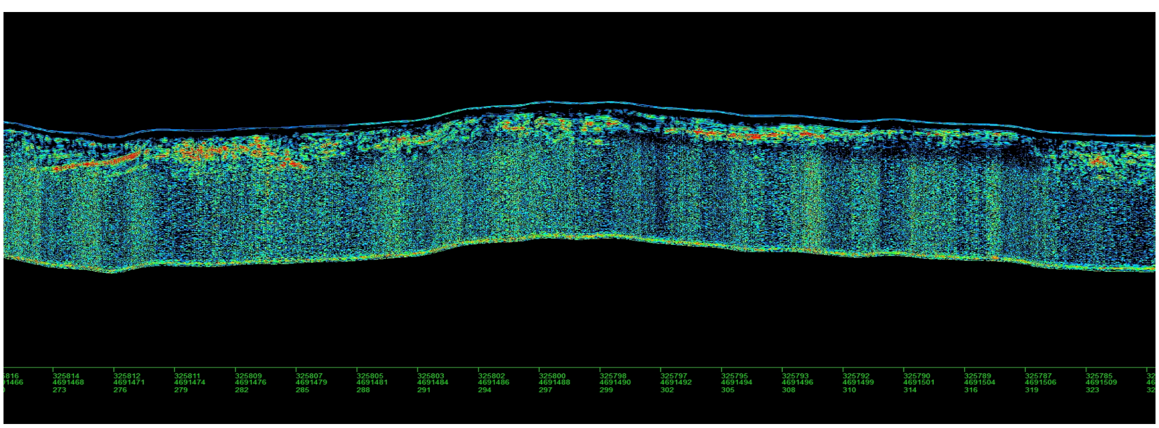


Figure 3.3 A section of line 47.

3.1.2 Captain's Island

The stratigraphy of Captain's Island is more complicated than that of the beach area. Line 47 presents a longitudinal cross-section of the island and shows both the natural sedimentary layers and the areas deposited by humans. Starting at the leading edge of the island, at the transition from unstratified beach sand, there is an 18-meter segment of horizontal, well-stratified, and highly reflective sediment. Similarly reflective material makes up much of the rest of the island, but the the orientation of the strata varies spatially. For example, downstream from this 18-meter section are two 7-meter segments of unstratified sediment separated by a 3-meter section composed of downstream dipping layers. Similar well-stratified areas are present further down line 47 within the island, with the same downstream dip (Figure 3.4). Line 73, which cuts across the leading edge of the island roughly perpendicular to the shore and line 47, has similar strata dipping away from the centerline of the island in both directions (Figure 3.5). Line 62, which runs diagonally both downstream and downhill toward the river, has an isolated 3-meter segment of stratified sediment that is also dipping away from the centerline of the island and downstream (Figure 3.6).

Overall there does not appear to be just one orientation to the island's strata; instead they tend to slope down laterally away from the island, and in some cases longitudinally (downstream). Because the material is similar in reflectivity to the areas known to be composed of sand, it is likely that the island is also composed of sand, which may have been deposited by the river at a time when its current was strong enough to

transport sand.

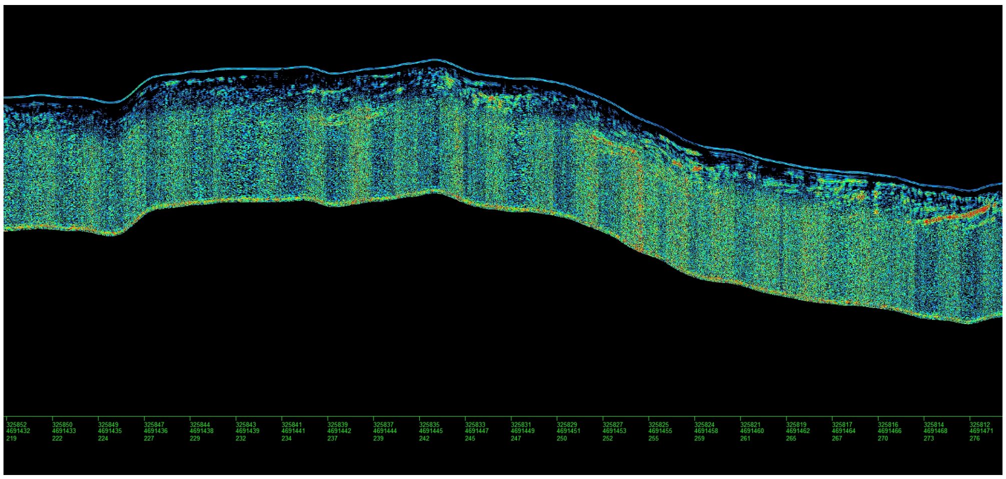


Figure 3.4 Line 47 at Captain's Island.

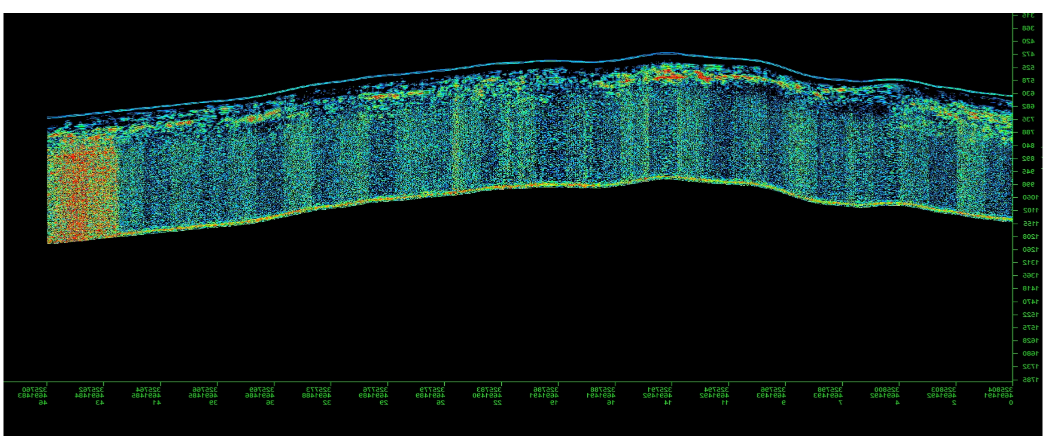


Figure 3.5 Line 73.

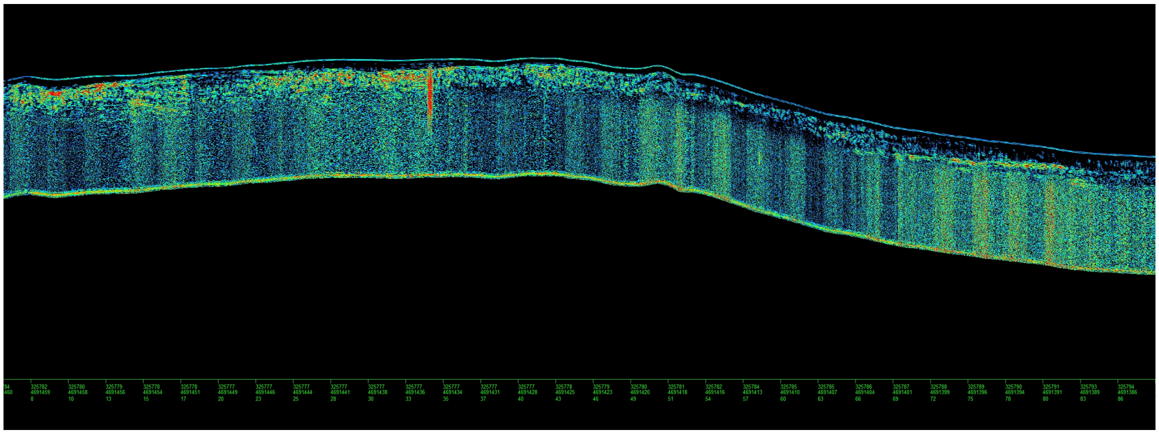


Figure 3.6 Line 62.

The river side of the island appears to be highly modified by human actions. In line 62 there is a 15-meter long low-lying stretch of strongly reflecting sediment that appears to be beach sand reworked and stratified by wave and tidal action in the same way that part of line 69 was reworked. At the downhill end of this section the stratum fades out until it is indistinguishable from the fill above it. The uphill end of the stratum similarly disappears into unstratified fill, but instead of fading out simply continues below the depth of penetration of the GPR where the slope of the hill becomes much steeper than the slope of the beach deposit. The gentle slope is visible in the 1913 photograph of the beach, which appears to have been taken from a location near the downhill end of line 62, facing the island and the magazine. In this photograph the beach sand rises gently until reaching the vegetated area immediately in front of the magazine and the retaining wall just left of the building. The area stabilized by the vegetation in 1913 had a much greater slope, rising quickly to the level of the magazine's foundation.

This is very different from the current profile of the hill, which rises quickly near the shore and slopes gently upward the rest of the way to the magazine. This new profile, visible in the radargram of line 62, is made up of strongly reflecting fill deposited sometime after the beach sand, but likely composed of a similar material. The fill extends the length of the remainder of the line, with the exception of the 3-meter stratified section mentioned above, which is likely material from the original core of the island that was protected from disturbance by its proximity to the magazine.

The downstream half of the island, which resembles a triangle on historical maps and the 1925 and 1930 aerial photographs, is difficult to study with GPR because of a number of recent anthropogenic changes to the landscape. The most obvious of these changes is the wetland that was created in 2009 between the soccer field and the river. The landward side of the island is also inaccessible to GPR because it is now partially covered by Memorial Drive and a large pedestrian bridge over the street. Accessible areas have also been affected by changes in land surface elevation, which are visible in the difference between the 2002 and 2009 DEMs. Parts of the island gained 0.5 to 1 meters, while other places lost up to 0.2 meters. Land use on this part of the island has also changed over the past century. On the present location of the soccer field there was a baseball diamond in the 2008 orthophoto. In the 1925 airphoto there also appears to be a baseball field in a similar location, but with a different orientation from the 2008 field. Each field required at least some changes to the land surface, such as the addition of sand or soil, which makes it difficult to distinguish parts of the original island and salt marsh from later fill material.

Despite these obstacles, some features can still be discerned on the radargrams. Line 40, which is perpendicular to the shoreline, appears to show the tail end of the original Captain's Island before it was expanded by landmaking (Figure 3.7). There is a 5-meter flat section of stratified sediment with outward-dipping 5-meter sections on either side. Line 41, which is parallel to line 40 and slightly closer to the center of the island, shows a slightly different picture, with a gentle 10-meter slope on the landward side and a steeper 5-meter slope composed of several layers on the river side (Figure 3.8). Line 47, which crosses lines 40 and 41 at a right angle, has slightly disturbed but still discernible downstream sloping strata at the same location, with mostly unstratified material on either side (Figure 3.9). This evidence suggests that the trailing edge of the island may have been formed as a point bar that extended out and downstream from the island.

Other areas around this patch of stratified sediment were initially classified as disturbed but stratified and mapped thoroughly using a polygon shapefile. However, on further analysis I realized that much of the polygon layer corresponded closely with areas with the greatest height of increases between the two DEMs. A re-examination of the radargrams, such as line 47 and the lines that cross it, supported the conclusion that these areas of reflective sediment are anthropogenic and shed no new light on the shape of Captain's Island.

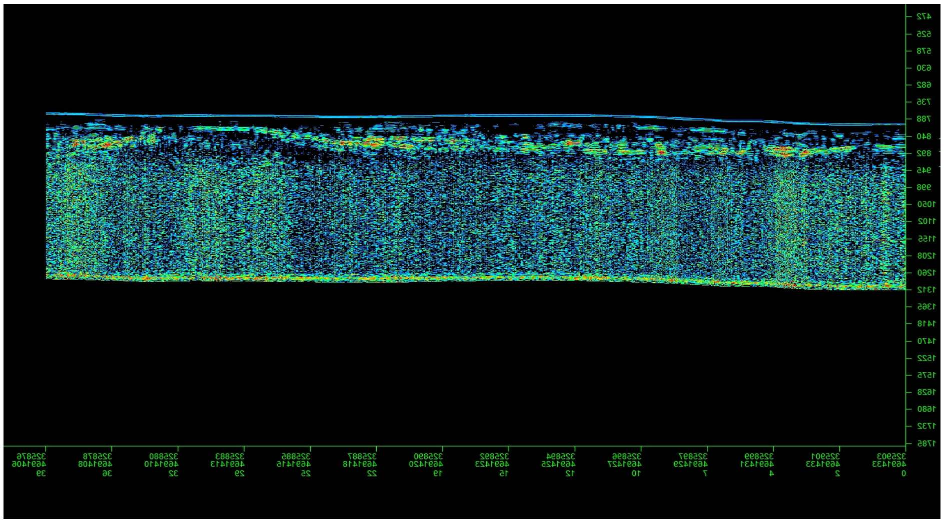


Figure 3.7 Line 40.

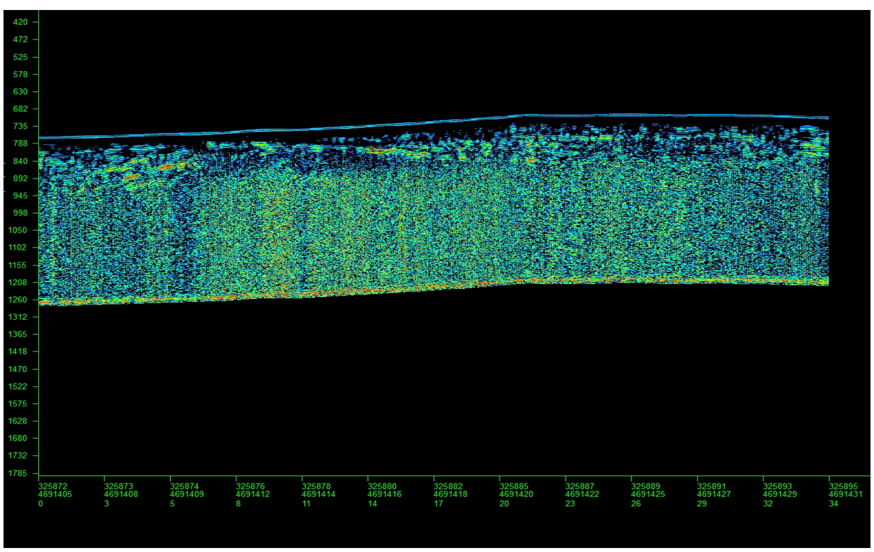


Figure 3.8 Line 41.

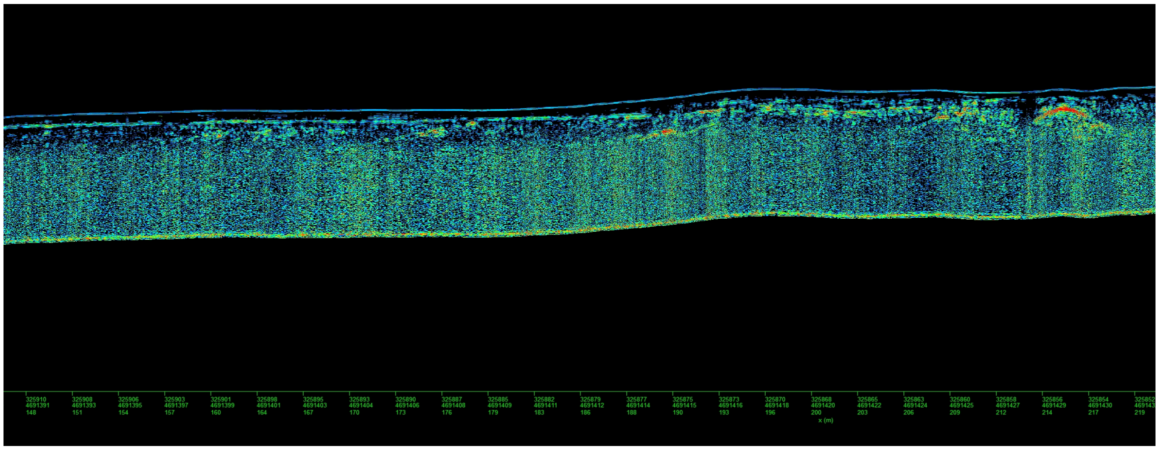


Figure 3.9 Line 47 where it crosses lines 40 and 41.

3.1.3 The Salt Marsh

Remnants of the salt marsh upstream of Captain's Island were clearly visible in line 69. Judging by the extent of the marsh in the 1847 Coast Survey map, the original (pre-colonial) marsh likely completely encircled Captain's Island. The area around line 69 had not been filled by 1894, but that map does show a great deal of filling downstream of the Magazine Street causeway. As discussed above, this filling and reworking of the sediment along Memorial Drive destroyed or covered much of the evidence for the position of the salt marshes and their drainage ditches, which are visible in both the 1847 and 1894 maps.

3.1.4 Drainage Channels

Although GPR was not useful in mapping most of the salt marsh, a close look at the 2002 LiDAR may have clues about the position of the man-made drainage ditches

within the marsh. There are linear patterns of bare earth between the two baseball fields in the 2008 orthophoto layer which line up somewhat with the drainage ditches in the two historical maps. In theory, even if the ditches were initially completely filled, the fill material likely subsided as it compacted over time, leaving a very shallow remnant of the ditches that would be visible on the surface, as well as in a high-resolution DEM. LiDAR-derived DEMs have been used to locate ancient buried river channels in Holland, so the technique may also be applicable on a smaller scale (Possel, 2009).

Using the “Contour List” tool in ArcGIS, I was able use the 2002 DEM to create a contour map from elevations 0.6 to 1.8 meters at 0.05 meter intervals. Overlaying the contours on the DEM itself, with the color ramp limited to 0.5-2.5 meters elevation to maximize the contrast, the same same tidal inlet patterns became obvious at once. Measuring from the height of the land separating the two depressions, each one had a maximum depth of 0.2 meters, providing reasonably strong support to the idea that they are former tidal inlets. Tracing the inlets from the top, I drew a line through the deepest part of the depressions. Halfway to the river the inlets became much more poorly defined, so I drew the remainder of the lines approximately perpendicular to all contour lines encountered (Figure 3.10).

Possible Tidal Inlet Locations

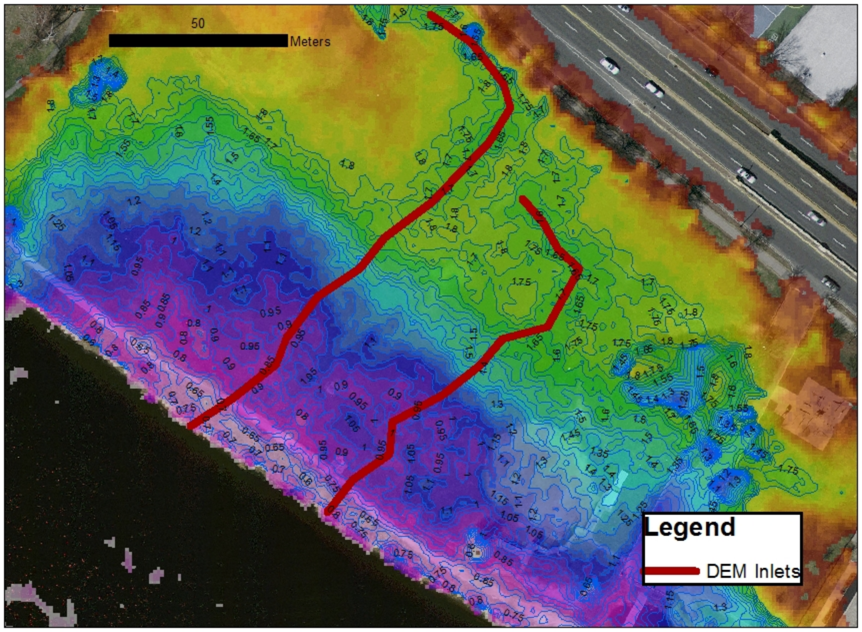


Figure 3.10 The 2002 DEM with two possible tidal inlets in red.

After tracing the potential drainage ditches with polylines I compared them to traces I had previously made of the 1847 and 1894 inlets (Figure 3.11). The first inlet matched both of the historical maps very well. The 1847 ditch does not extend the entire length of the other two, but it is likely that the ditch was simply lengthened between 1847 and 1894. The second ditch derived from the DEM was roughly parallel to the second ditch in both of the historical maps, but was 20 meters upstream of the 1894 ditch and 40 meters upstream of the 1847 ditch. In addition, only the DEM reconstruction hooked to the left at the top in a similar way to the first DEM ditch.

Possible Tidal Inlet Locations

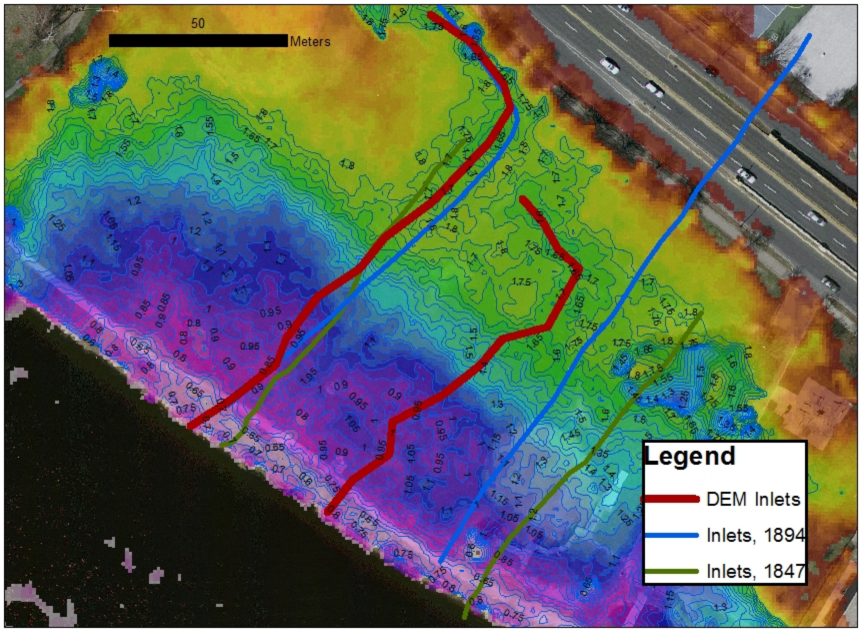


Figure 3.11 The same map with the tidal inlets from the 1847 and 1894 maps also displayed. Note the close correlation of the three lines on the left, but lack of correlation of the three other lines.

There are a number of possibilities to explain these discrepancies. My DEM reconstruction could be in error and the second depression could have been caused by something other than a buried ditch. However, the pattern and depth of the second depression is so similar to the first ditch, which does match the historical maps, that it seems unlikely to have been created independently. The historical maps might simply have the wrong location for the second ditch, which would not be entirely unexpected considering how minor a feature the ditch might have appeared in the eyes of a 19th

century cartographer. A third possibility is that the second ditch was dug after 1894 between the two marked on either of the historical maps. There is no apparent third ditch on the DEM near the unmatched historical ditches, but it is quite possible that there once was and it was simply more effectively disguised topographically by the effect of the baseball field, a large tree, and other features that intersect one or both of the lines (Figure 3.12). Whether the third ditch exists or not, it is probable that the two derived from the DEM are accurate approximations of the salt marsh drainage ditches.

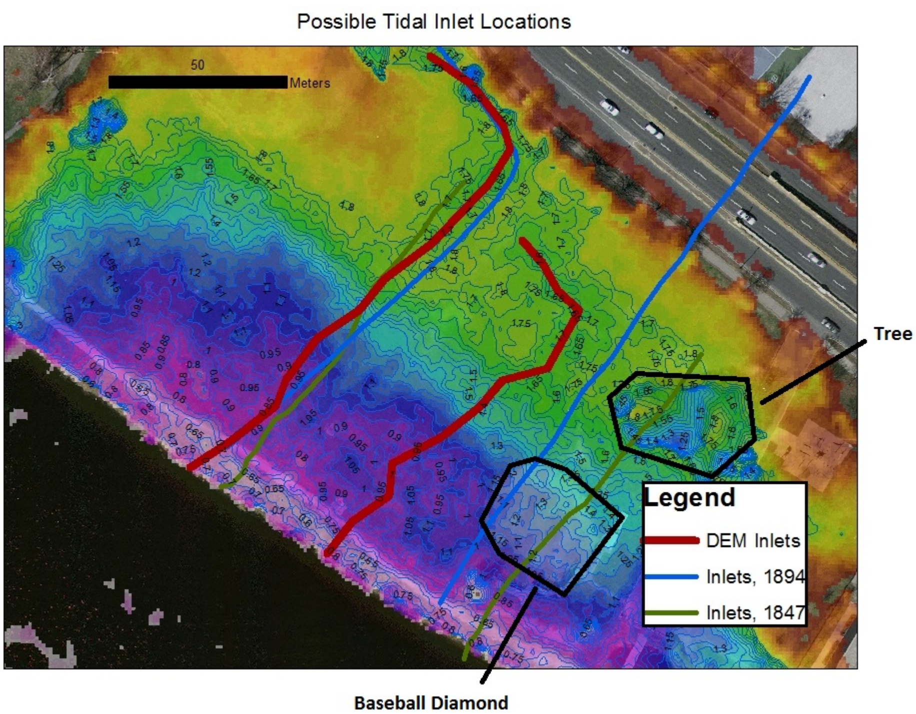


Figure 3.12 The same map with sources of interference identified.

3.2 GIS Analysis

The GIS analysis was conducted in both quantitative and qualitative ways. The shoreline maps were created in order to estimate growth in both area and volume, but they have also been used to better understand the way in which the area changed over time and how the environment reacted to those changes.

3.2.1 Area Change Analysis

Area change analysis is a very basic way to look at landmaking's effect over the past four centuries. Because of the varied sources and extents of those sources, a GIS is necessary to bring the information together in a standardized way and measure how landscape changes have taken place.

3.2.1.1 Boston

The subsection polygon used for measuring land area change in Boston represents about three quarters of the original shoreline. The stretch from Boston Common to the western shore of Boston Neck to the south was included as part of the Back Bay polygon in order to provide greater continuity of data going back to 1630, because the only measurable filling of the Back Bay in the first few centuries consisted of activity along this shoreline. As a consequence, all of the data representing the growth of Boston itself reflects growth in the remainder of its coastline from just north of Boston Common, around the West and North Ends and down the eastern shore of the city.

Starting from the baseline of zero in 1630 Boston initially grew slowly and at a steadily increasing rate, with 0.13 km^2 added by 1723, another 0.16 km^2 by 1777, and 0.50 km^2 more by 1817 (Figure 3.13). The peak growth rate occurred between 1817 and 1826, when an average of 0.026 km^2 was being added to the city each year, and it only decreased slightly between 1826 and 1854, when the rate was 0.023 km^2 of new land per year (Figure 3.14). From that point on landmaking has continued, but at a generally decreasing rate. Growth began to plateau in the 20th century, with only 0.28 km^2 added from 1900 to 2013.

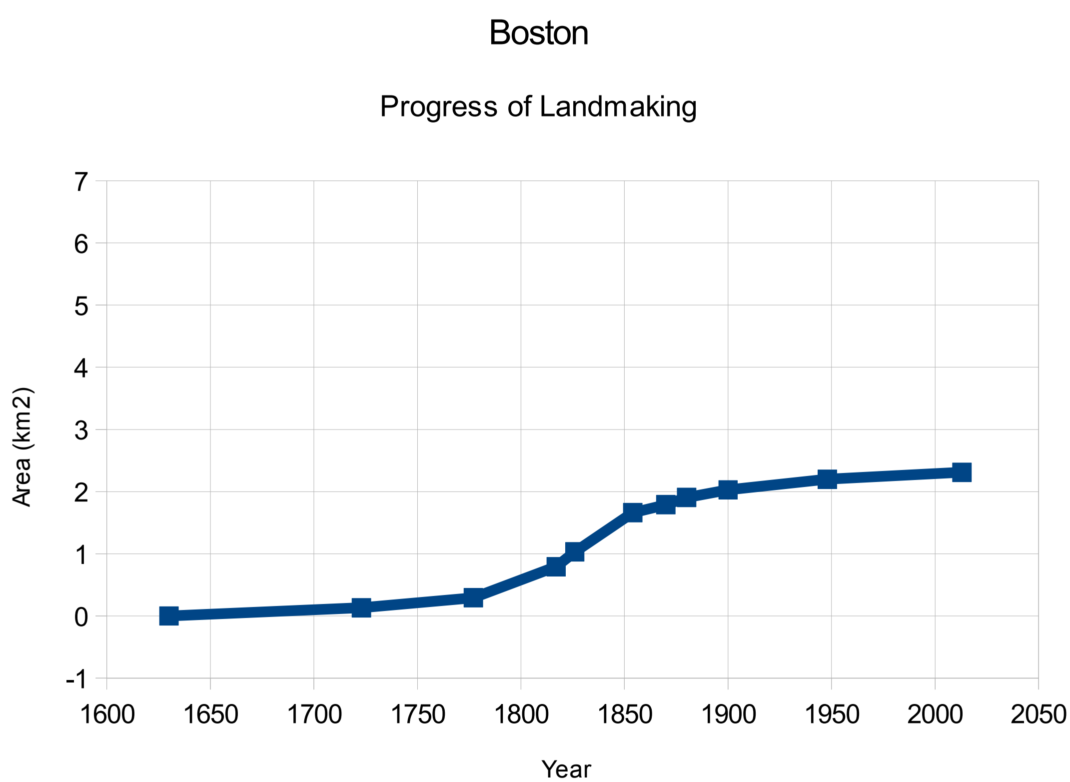


Figure 3.13 Cumulative area of made land in Boston.

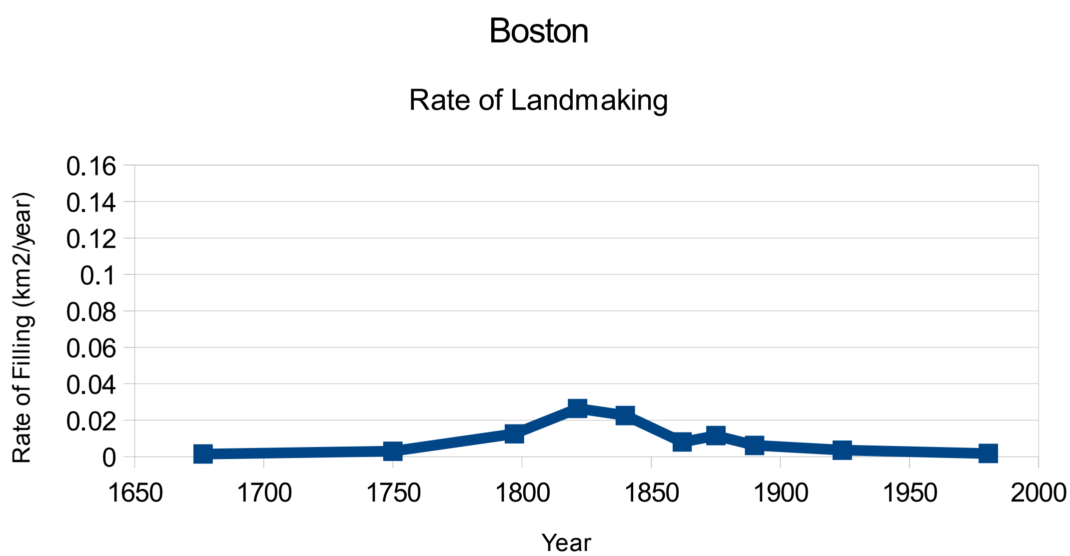


Figure 3.14 The rate of landmaking in Boston.

The pattern of growth in Boston is a nearly perfect sigmoid (S-shaped) curve (Figure 3.13). Growth was initially slow, then began it increase rapidly and finally leveled off again with the amount of available places that could be filled greatly diminished. This pattern is present in all four subsections, with the main differences being the time growth peaked and the total amount filled.

3.2.1.2 Back Bay and the Fens

The area encompassing the Back Bay and the Fens changed very little during the 17th and 18th centuries, as can be seen in the scatter-plot of the area data. From the time of the original English colonists in 1630 until 1777 only 0.09 square kilometers of land was added to the area (Figure 3.15). The rate of landmaking then began to increase quite

quickly, with 0.86 to 1.41 km^2 added from 1777 to 1826 (the map does not cover the whole bay, which requires a range estimate rather than a single number). In the second half of the 19th century landmaking exploded, with the cumulative amount of new land growing from 2.20 km^2 in 1854 to 6.05 km^2 by 1900, a nearly three-fold increase. At that point the rate of change dropped back to very low levels similar to those seen in the first two centuries of growth. Now the cumulative amount of new land has essentially leveled off at 6.51 km^2, an increase of only 0.15 km^2 since 1948.

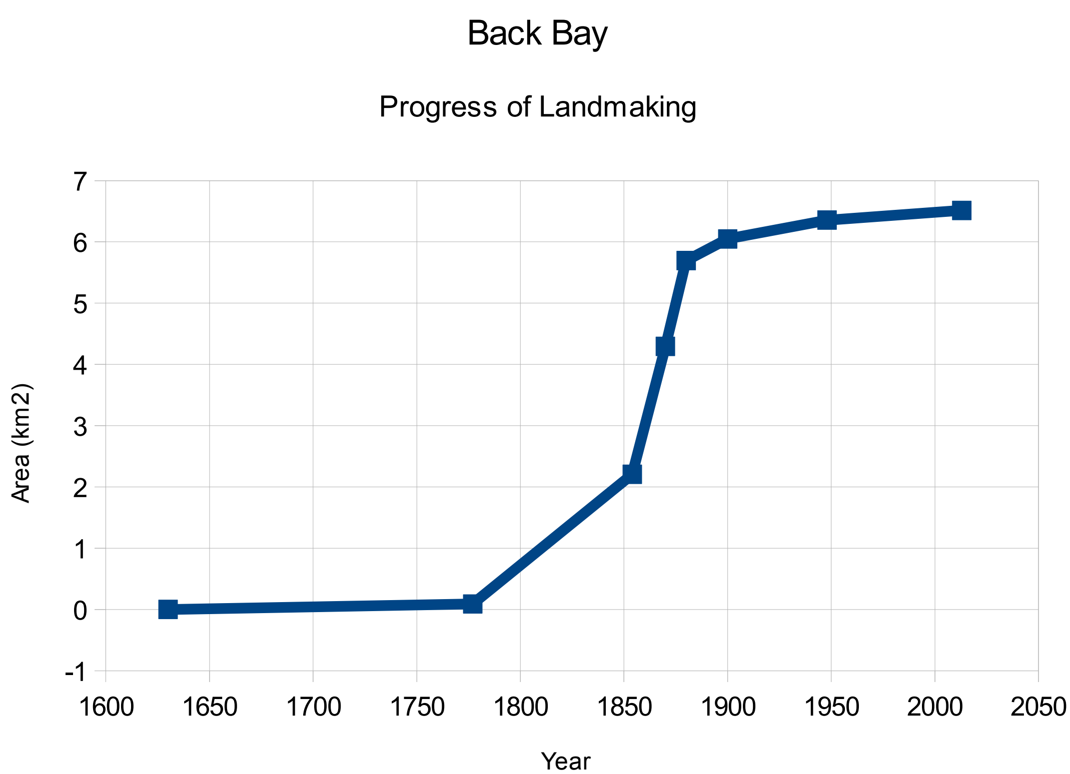


Figure 3.15 Cumulative area of made land in Back Bay.

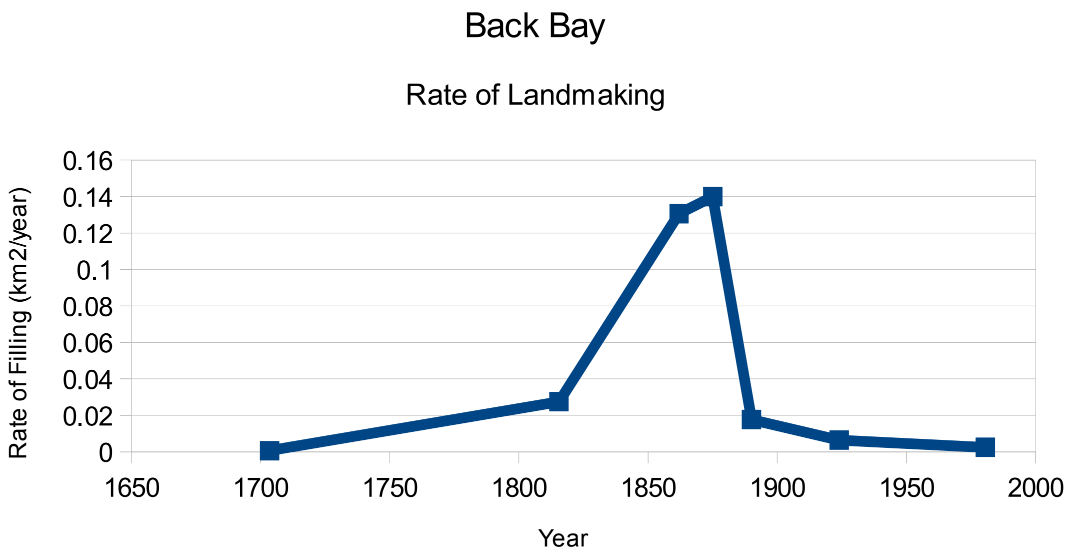


Figure 3.16 The rate of landmaking in Back Bay.

The cumulative growth graph itself resembles a sigmoid curve, which makes sense considering the limits of filling along a river. Initially there was over 6 km^2 to fill in the Back Bay and the fens but little demand for new land. The rate of filling gradually increased until it peaked in the mid-to-late-19th century (Figure 3.16), when the new land began encroaching on the Charles River channel itself. Now, with high demand for land but nowhere else to go, landmaking has leveled off. This pattern is repeated in the other three subsections, with minor local differences.

3.2.1.3 East Cambridge

The second largest amount of landmaking occurred in the East Cambridge subsection, which is essentially the other half of the Charles River basin. The 1826 map did not cover this area completely, so the first time interval is from 1630 to 1854, during which time 0.98 km^2 was filled (Figure 3.17). Over the course of the next 46 years the total jumped to 3.80 km^2. Following the pattern of Back Bay and Boston, landmaking was much less pronounced during the 20th century, with another 0.47 km^2 added by 1948, and a final 0.08 km^2 since then.

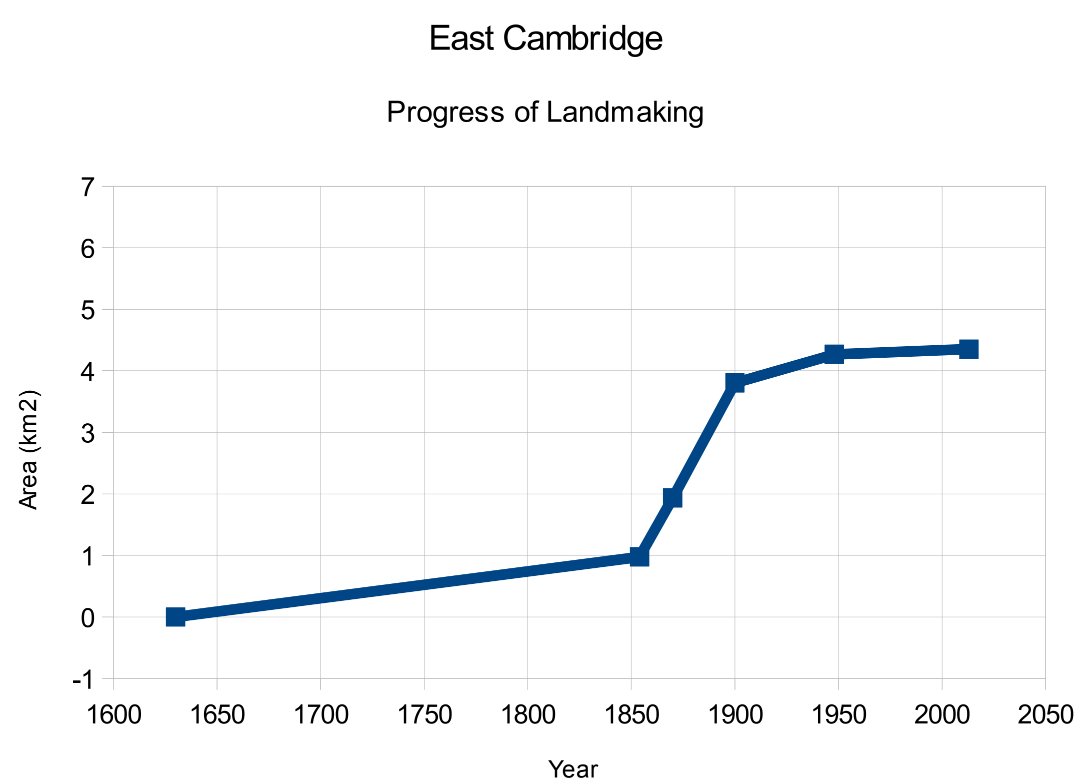


Figure 3.17 Cumulative area of made land in East Cambridge.

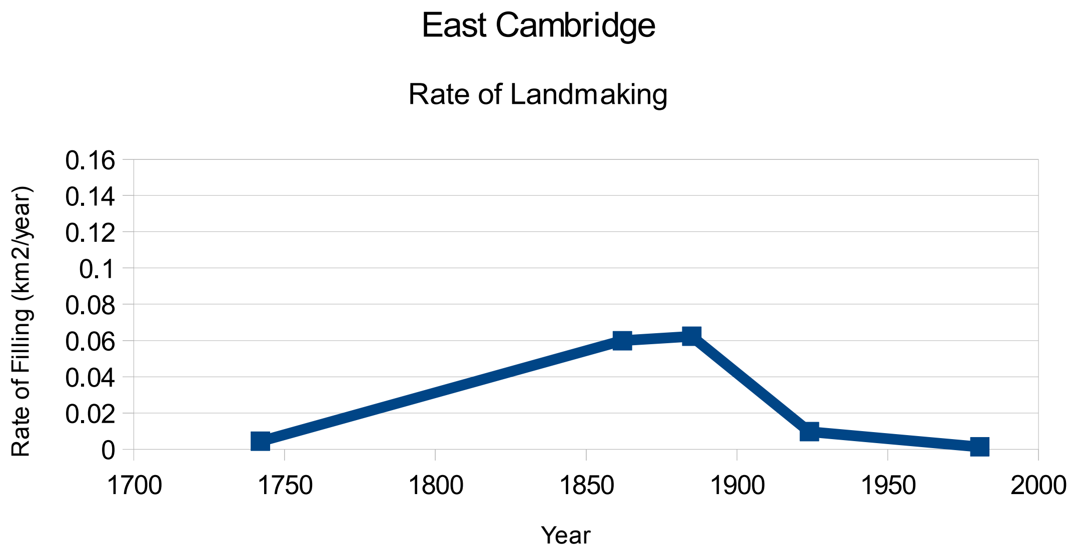


Figure 3.18 The rate of landmaking in East Cambridge.

3.2.1.4 Upper Charles River

Landmaking in the Upper Charles River again follows the same pattern as the other subsections, but with much less overall change and slower growth rates. The area, consisting of the mostly unchanged channel of the present-day river, bounded on either side with salt marshes, experienced only 0.08 km^2 of landmaking from 1630 to 1854 (Fig.3.19). The rate of landmaking increased slowly and peaked later than most areas, between 1870 and 1900, with the gradual conversion of 0.44 km^2 marshland to upland. The 20th century saw continued slow growth, with 0.40 km^2 more added by 1948. Since then there has been very little change, with only 0.03 km^2 of new land since then.

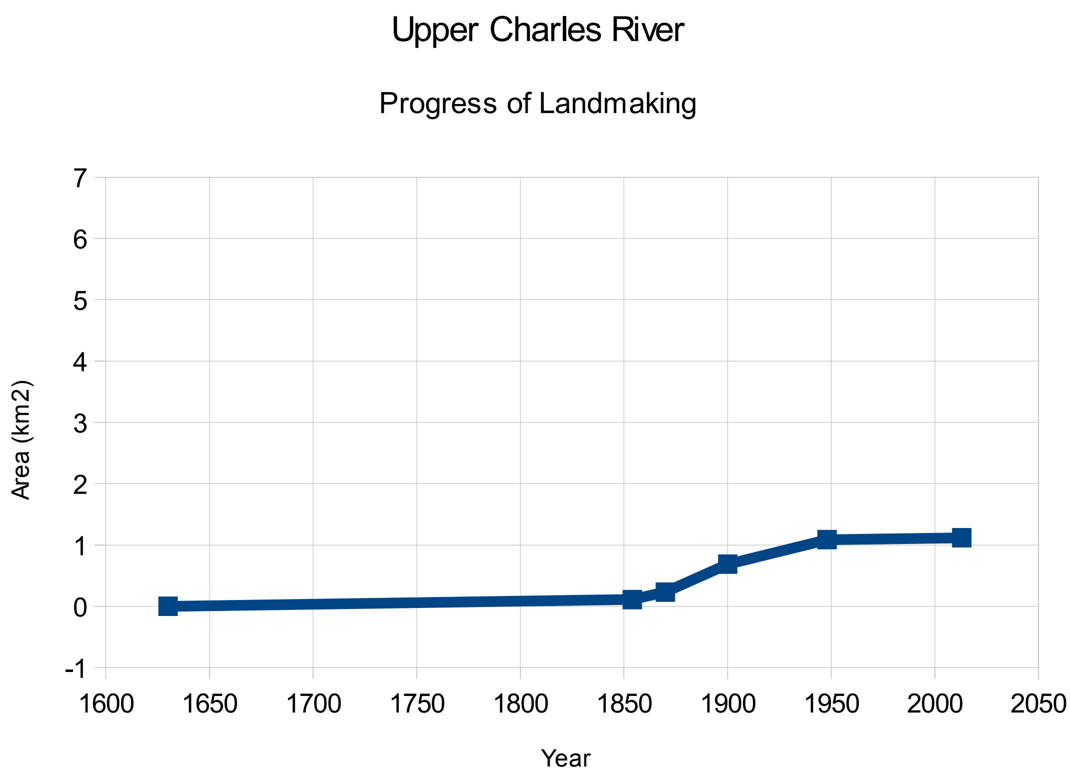


Figure 3.19 Cumulative area of made land in the Upper Charles River.

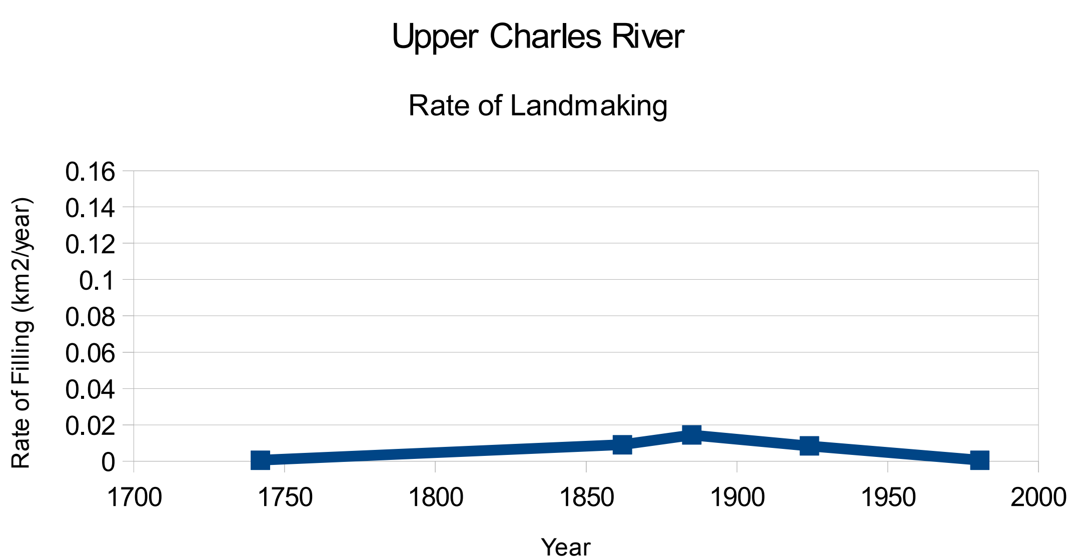


Figure 3.20 The rate of landmaking in the Upper Charles River.

Year	Boston	Back Bay	East Cambridge	Upper Charles
1630	0.00	0.00	0.00	0.00
1723	0.13			
1777	0.29	0.09		
1817	0.79			
1826	1.03	0.95-1.50		
1854	1.66	2.20	0.98	0.08
1870	1.79	4.29	1.93	0.25
1880	1.90	5.69		
1900	2.03	6.05	3.80	0.69
1948	2.20	6.36	4.27	1.09
2013	2.31	6.51	4.35	1.12

Table 3.1 Cumulative landmaking (km^2) in the four subsections. Blank areas represent historic maps that did not adequately cover the study area.

3.2.2 Volume Change Analysis

The volume change portion of this study is simpler than the area analysis in that it is just a before-and-after look at the pre-colonial and modern terrain. However, its simplicity also allows a more detailed look at the proportion of salt marsh versus mudflat that was filled in each subsection. For example, of the 2.31 km^2 of land created in Boston over its entire history, only 0.04 km^2 or 1.8% of the total was created from salt marsh (Figure 3.21). The rest of made land in Boston, 98.2%, is former mudflats. In stark contrast, only 5.9% (0.07 km^2) of the 1.12 km^2 of new land along the Upper Charles River was formerly mudflats (or channels within the marshes), with the balance (1.05 km^2) created from salt marshes. Back Bay and East Cambridge were much more moderate, with 46.3% marsh and 53.7% mud in Back Bay, and 49.4% marsh and 50.6% mud in East Cambridge.

In terms of average modern (2002) elevation in the filled areas, they were all very similar. The minimum average height was 2.50 meters above mean sea level in the mud portion of the Upper Charles subsection and the maximum was 3.34 meters in the marsh portion of Back Bay, a range of just 0.84 meters. Using the height assumptions discussed above, mudflats having had a mean elevation of zero meters and marshes having had a height of 1.41 meters above sea level, the estimated fill thicknesses have a greater range of variability. The range of fill thickness in marsh areas is from 1.32 meters in East Cambridge to 1.93 meters in Back Bay. The mud areas had thicker fill layers, with a range of 2.50 meters in Boston to 3.07 meters in East Cambridge.

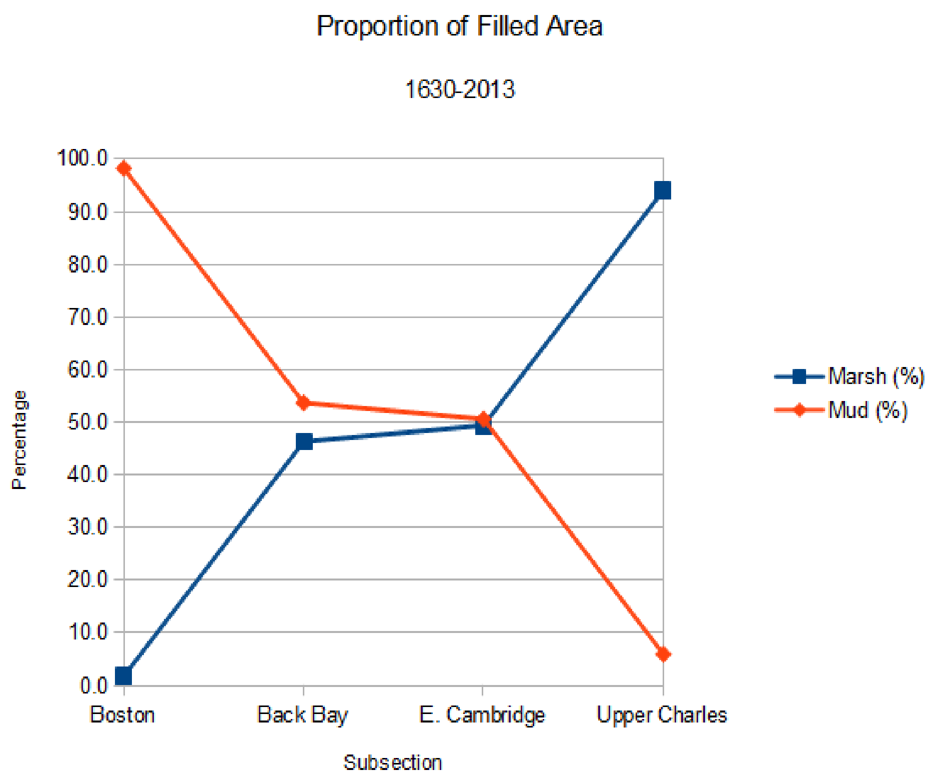


Figure 3.21 The proportion of mudflat and salt marsh areas filled. Note that upriver areas tend to be more marsh-dominated than downriver areas.

Volume estimates show that more than two-thirds of the fill material went to areas that were originally mud flats (23.6 million cubic meters), with the remainder (10.6 million cubic meters) going to former marshes, with a total of 34.1 million million m^3. This makes sense considering two factors. First, the mud flats were on average 1.41 meters lower, thus requiring that much more fill material to reach the level of the filled marsh areas. Second, the mudflats made up 56.2% of the original area, which would also mean that they required more fill than the marshy areas.

The Back Bay/Fens subsection received much more fill than any of the other sections, 15.8 million m^3, nearly half of the total. Nearly two-thirds of that, 10.0 million m^3 was in the mudflat portion. The next most significant area, East Cambridge, received 9.6 million m^3, with over two-thirds (6.8 million m^3) going to the mudflat portion. Boston received 6.7 million m^3 of fill, of which 99% went to the mudflat portion. The Upper Charles was the only subsection with a majority of the fill in the marshy areas, 1.9 million m^3 out of a total of 2.0 million m^3.

		Boston	Back Bay	East Cambridge	Upper Charles
Area (km^2)	Marsh	0.04	3.02	2.15	1.05
	Mud	2.27	3.50	2.20	0.07
Modern Height (m)	Marsh	3.08	3.34	2.73	3.18
	Mud	2.93	2.85	3.07	2.50
Fill Thickness (m)	Marsh	1.67	1.93	1.32	1.77
	Mud	2.93	2.85	3.07	2.50
Fill Volume (m^3)	Marsh	67,910	5,834,156	2,826,819	1,862,467
	Mud	6,653,892	9,982,889	6,753,276	166,008

Table 3.2 The height, area, and volume analysis data.

3.2.3 Time Series Mapping

The time series “geo-graphs” depict similar information to the area graphs discussed above, but with added spatial information. The geo-graphs show the pace of landmaking and also where and how that landmaking took place. Figure 3.22, showing Boston from the north, makes it clear that new land in Boston was largely added by the building of wharves and the eventual filling of the space between them. In the right side of the image another mode of landmaking is visible. The first mill dam, connecting the North and West Ends, was originally used to harness tidal power. Eventually, as Boston expanded on all sides, the space behind the mill dam was filled, which is visible in this map as the difference between the 1777 and 1817 layers. The peak era of landmaking in Boston, from 1826 to 1854, is also clearly visible as jump from a shore closely paralleling the original shoreline to one that closely parallels the modern shoreline. Note that the thickness of each layer is directly proportional to the length of time between the map upon which it is based and that of the layer below it. This gives meaning to the slope of any given imaginary shore-perpendicular transect that is analogous to (but the inverse of) the slope of the cumulative area graphs. A flat slope on the 3D map indicates rapid growth, while a vertical slope indicates shoreline stability.

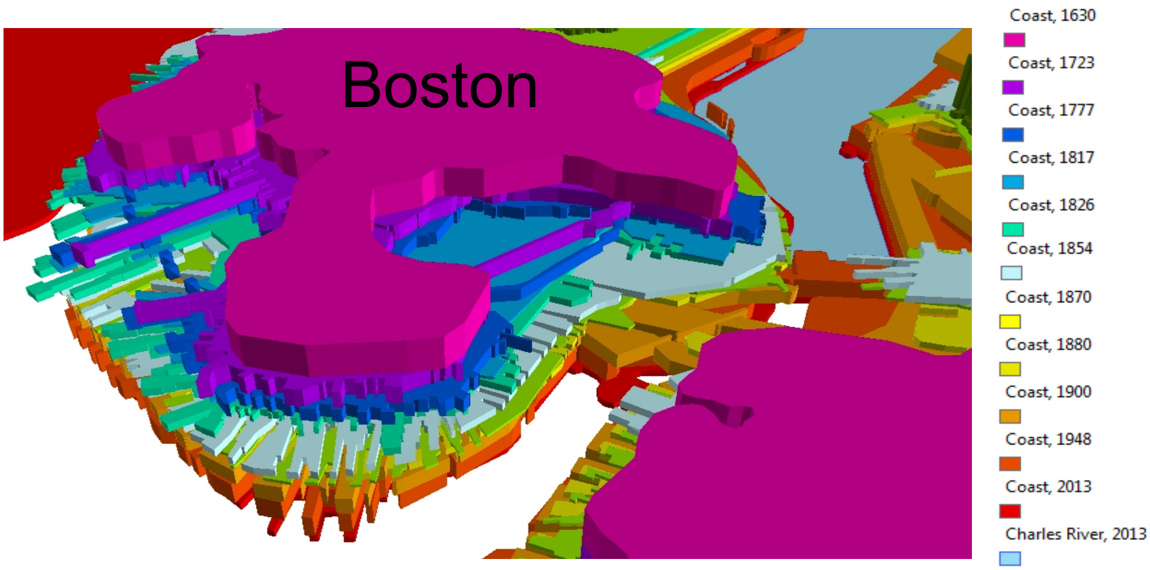


Figure 3.22 A "geo-graph" of land building vs. time. The thickness of each layer is proportional to the time between them.

This same principle of the slope's relation to the speed of landmaking can be applied to other views of the study area. In Back Bay the only major growth up to the 19th century is along the western shore of the Boston peninsula (Figure 3.23). Note that the 1630 salt marsh layer (Figure 3.24) is about 200 years thick, reflecting the negligible changes to it during that time. In Figure 3.25, which has the 1630 salt marsh layer removed to reveal the features underneath, the most important factor for landmaking in Back Bay is clear: Mill Dam parallel to the Charles River and Cross Dam dividing Back Bay and the area that would become the Fens. The immediate effect of the dams is clear when comparing the maps with and without the 1630 salt marsh. Gravelly Point, the peninsula dividing the basin, went from a salt marsh to dry land because the water level

in the Back Bay mill pond was kept lower than it would be naturally. This change is visible in the 1826 layer, which depicts the area five years after the completion of the dams in 1821 (Seasholes).

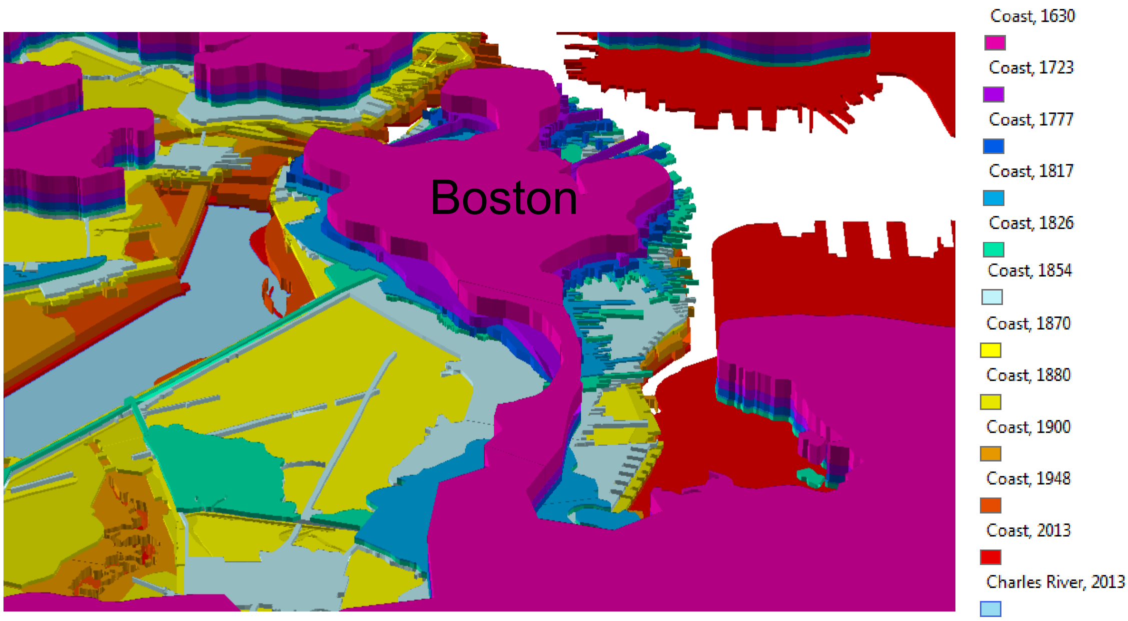


Figure 3.23 The same geo-graph, but looking toward the north.

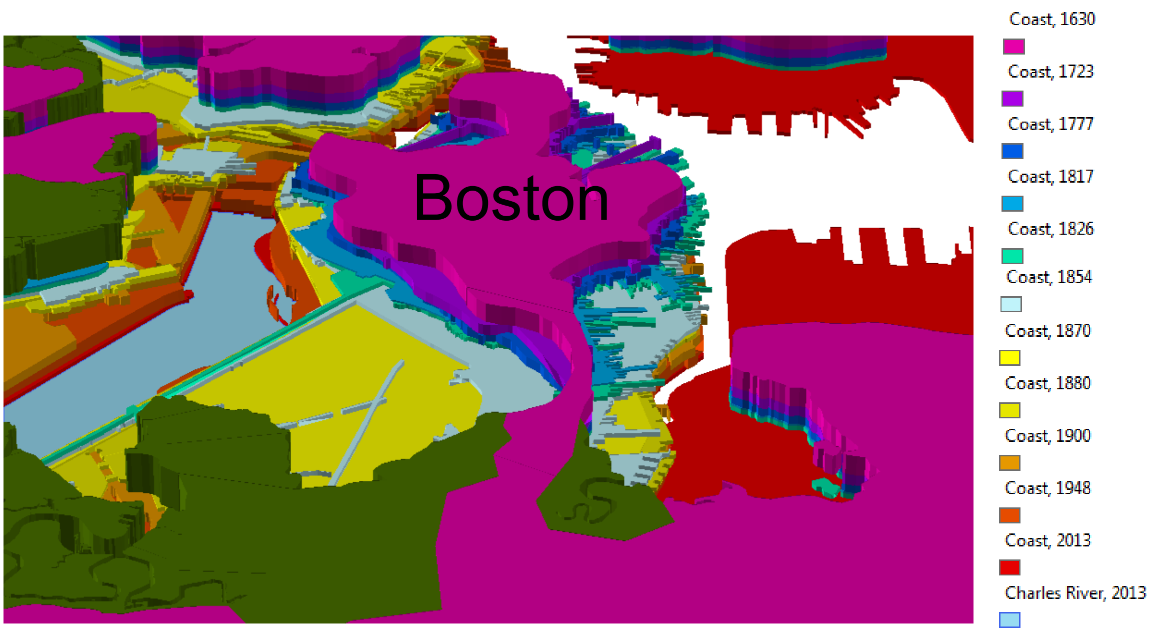


Figure 3.24 The same figure as above with the 1630 salt marsh layer added.

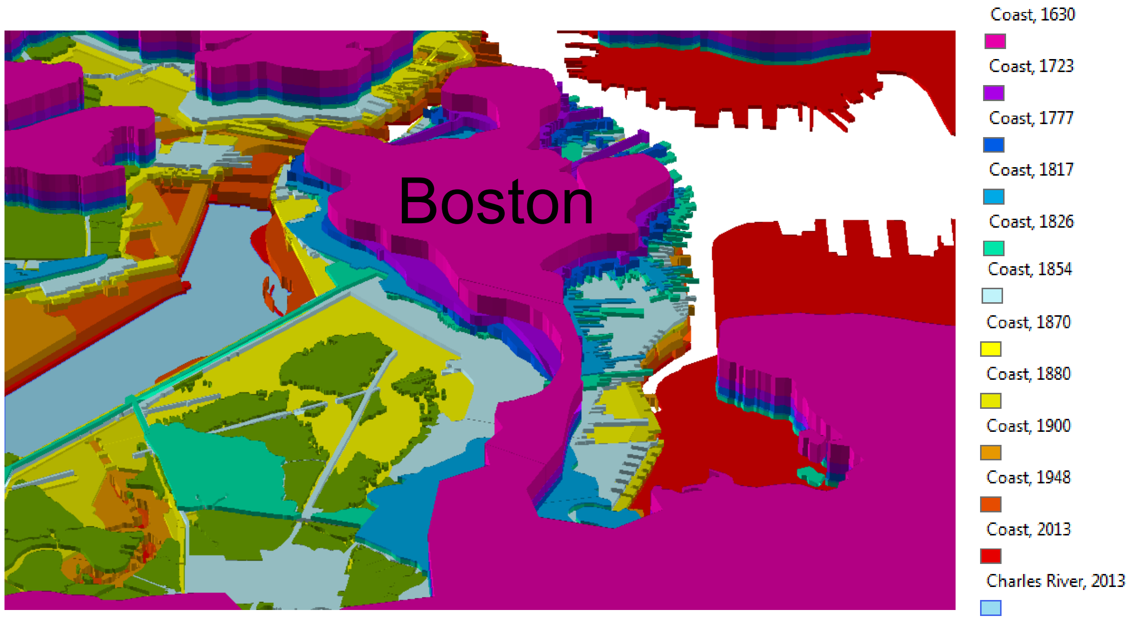


Figure 3.25 The same figure as above with the 1847 salt marsh layer.

Another significant change is the colonization of the Back Bay flats by salt marsh grasses, which was made possible by the change in water level (Figure 3.26 and 3.27). The expansion of the salt marshes is visible in the 1847 salt marsh layer, but it was short-lived because of the eventual filling of the entire Back Bay, as can be seen in the 1870 and 1880 layers. The new marshes appear to have been somewhat sheltered and anchored by the addition of two railway causeways that cross in the middle of the bay in the 1854 layer, which may have helped them become established initially.

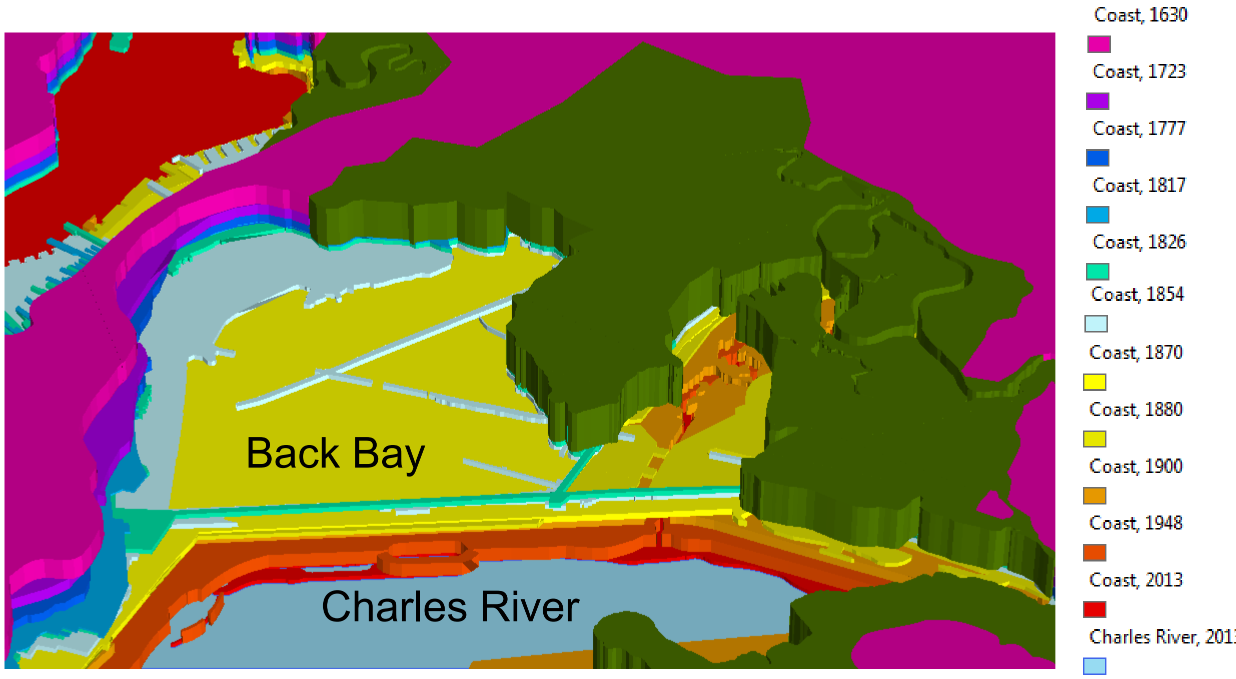


Figure 3.26 Back Bay, looking to the south with the 1630 salt marsh layer added.

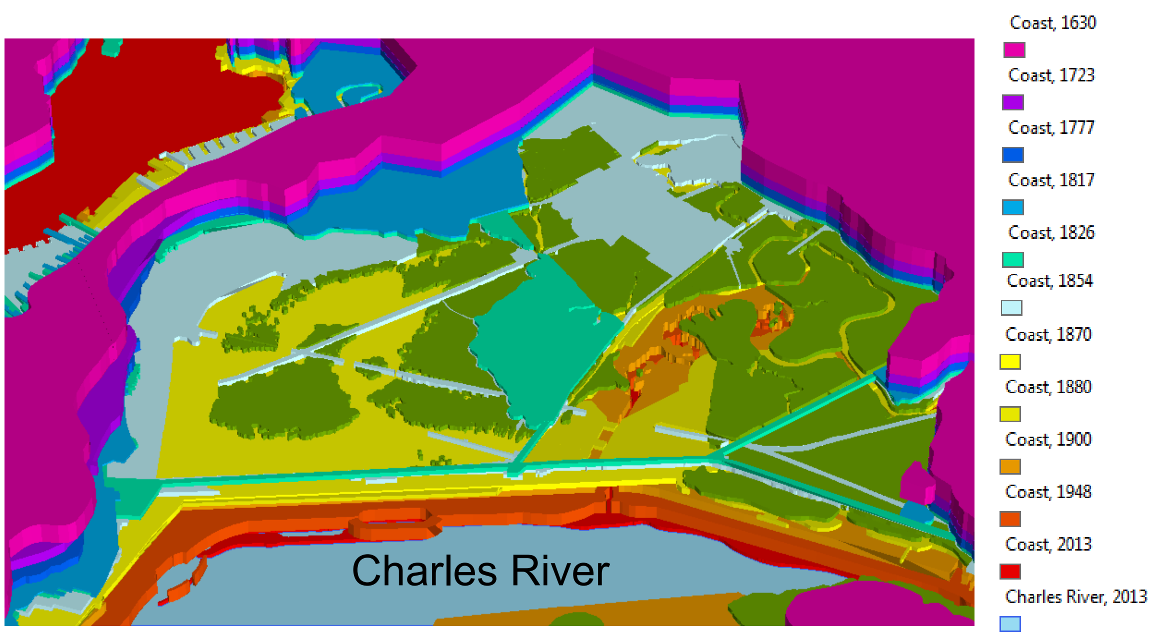


Figure 3.27 Back Bay with the 1847 salt marsh layer.

The first major wave of landmaking spread from east to west across Back Bay to Cross Dam (Figure 3.28). After that, the Muddy River area to the west was encroached from both sides between 1870 and 1900, resulting in the freshwater Fenway that is still present today. It is clearly marked on the 1870 map itself that the area had already been transformed from salt marsh to freshwater swamp by the mill dam, which at that point was no longer functioning as a tidal mill, thus likely isolating the area of the Fens from the brackish water of the Charles River. After the filling of the area around the Fens was completed in the latter part of the 19th century, the only place available to create more land was the bank of the Charles itself. During the 20th century various projects extended the shoreline further into the Charles River, culminating in an artificial island that is visible in the 1948 layer and greatly extended in the 2013 layer.

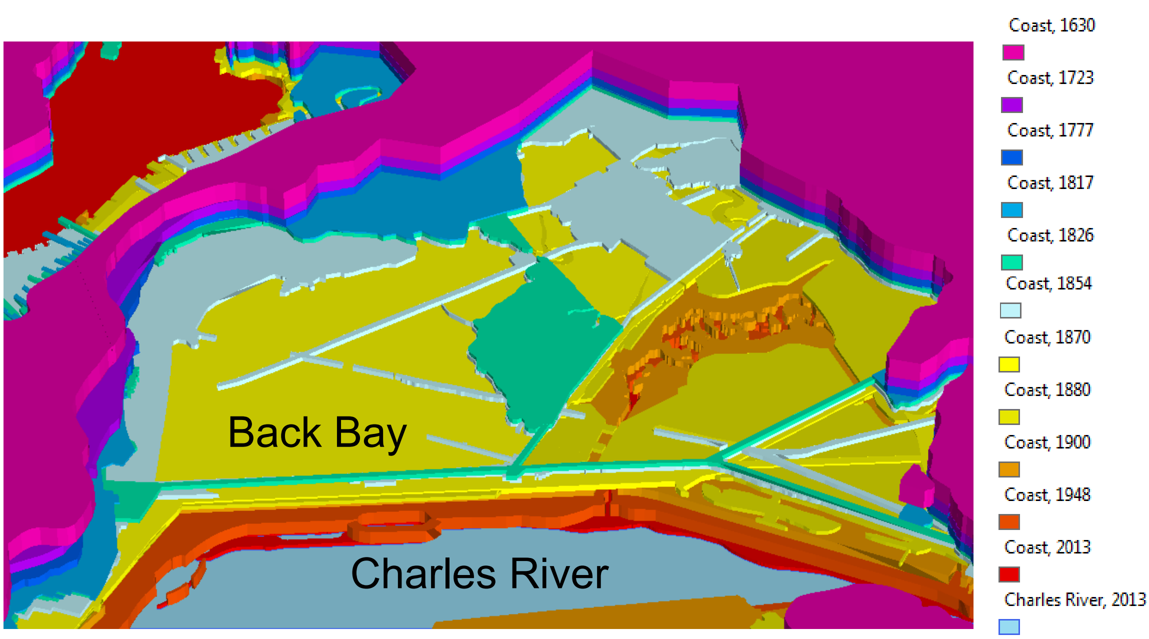


Figure 3.28 Back Bay without salt marsh layers.

The East Cambridge shoreline across the Charles was in many ways very similar to Back Bay in the early colonial period, with its wide expanses of marsh and mudflats, but it evolved differently during the 19th and 20th centuries. No great mill dam separated the marshes and flats from the river and filling was much more sporadic and on a smaller scale than was the case in Back Bay (Figure 3.29 and 3.30). As late as 1900 there was still a patch of salt marsh on the upstream end of East Cambridge and it isn't until the 1948 layer that it fully resembles the modern, straightened form that the Boston side of the river had acquired in the late 19th century.

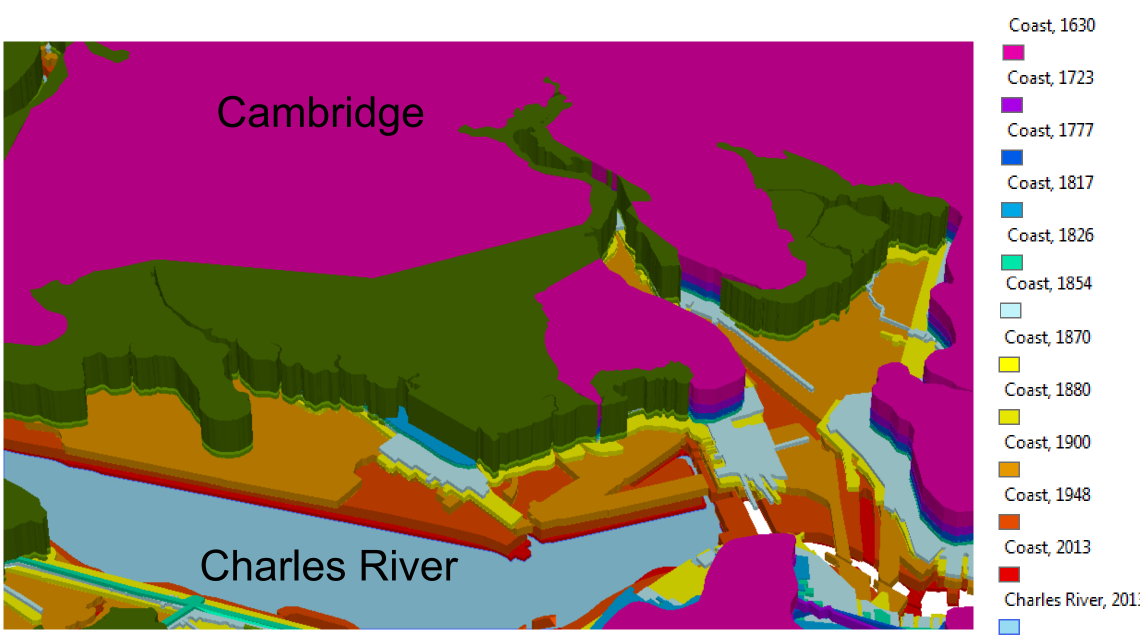


Figure 3.29 East Cambridge, looking to the northwest.

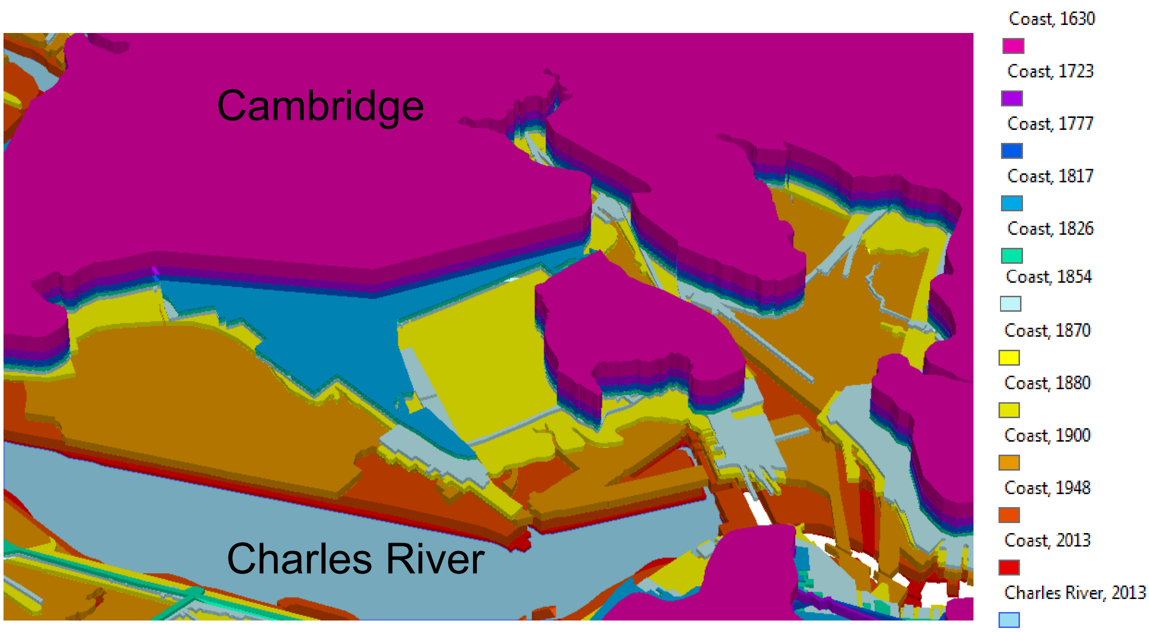


Figure 3.30 East Cambridge without the 1630 salt marsh layer.

The Upper Charles was the slowest to change and the least changed of the subsections. Even in 1630 the river side of the salt marshes closely resembled the modern shape of the river, with the main difference that it is now no longer wetland. For this reason, when the time series map is displayed with the salt marsh layers, the Upper Charles looks like a canyon, with completely vertical walls (Figure 3.31). Without them visible it is clear that the marshes in the mid 19th century were not very different from the original (17th century) marshes and it was only over the course of the next several decades, into the 20th century, that they were gradually filled (Figure 3.32).

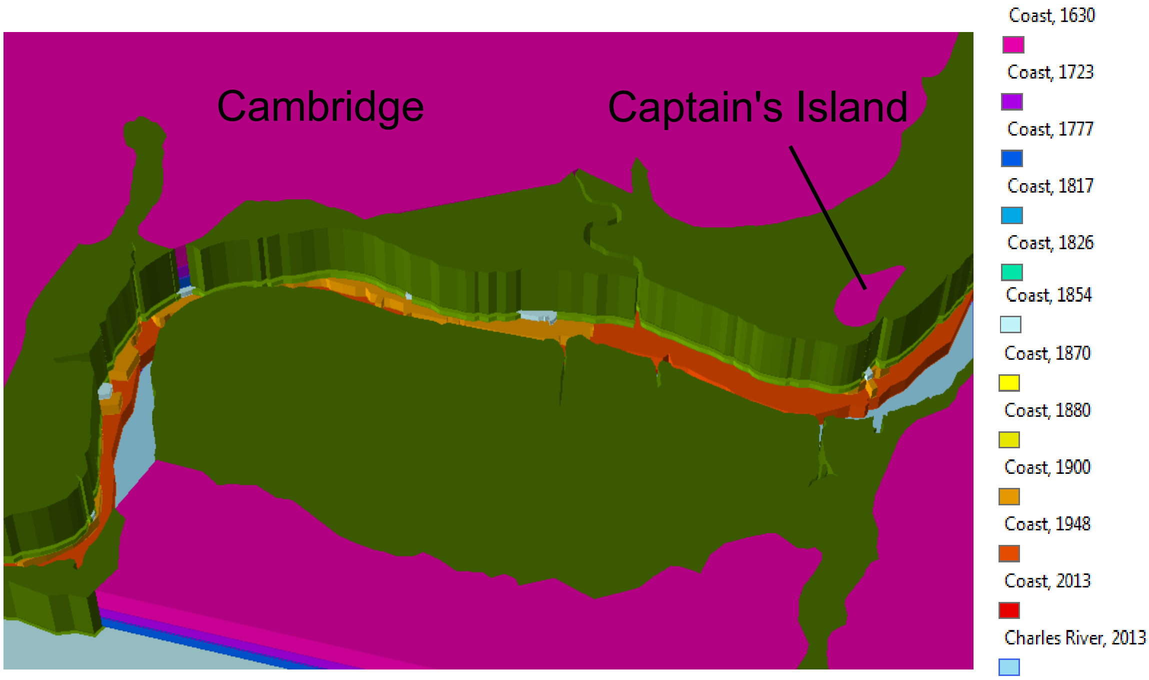


Figure 3.31 The Upper Charles River, looking to the northeast.

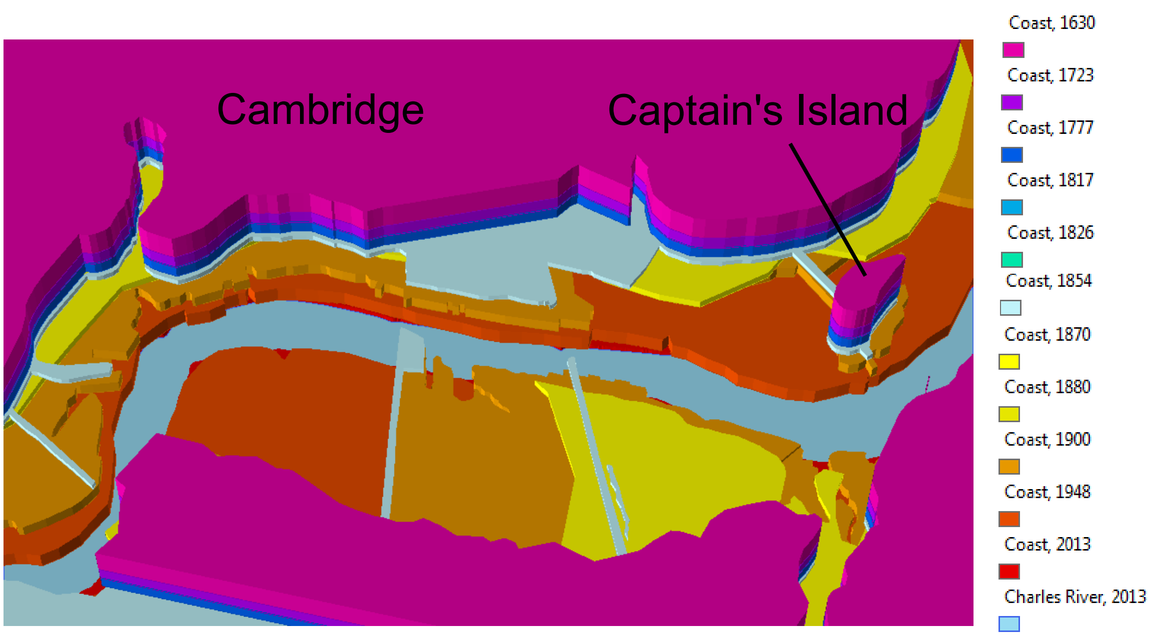


Figure 3.32 The Upper Charles River without the 1630 salt marsh layer.

CHAPTER 4

DISCUSSION

4.1 GPR

4.1.1 Significant Findings

The most significant findings of the GPR survey were in the area of Captain's Island itself, which seems to have the least amount of fill of all areas in the park. While the results were patchy because of soil disturbance, it appears that the original island closely corresponds to the upstream half of the island depicted in the 1894 map. The bottom half shows an island enlarged by fill, which is borne out by the location of the stratified “tail” of the old island, surrounded by a triangle of fill.

The island's sedimentary structure contains evidence that the island was laid down or at least reworked by the river to a depth of at least 1 meter, rather than being composed entirely of unsorted glacial till. There are some areas that show evidence of downstream-dipping cross-bedding, but a more concentrated GPR survey will be necessary to more precisely categorize the island's sedimentary structures and depositional environment.

Also of interest was the area of the beach, which showed strong evidence of reworking and stratification along the shore, in contrast to the landward portion of the beach, which appears highly disturbed and unstratified, essentially in the same state as

when it was first deposited by humans over a century ago. The landward edge of the beach was also revealed by the sharp vertical discontinuity between the former salt marsh and the beach sand, but the downstream boundary was not easily determined from the GPR data and had to be determined by referencing historical air photos.

The salt marsh appears to be visible upstream of the island in the radargrams, where a former channel within the marsh is also apparent. However, the downstream half of the salt marsh appears to be highly disturbed by recent landscaping activities and evidence for its location had to be acquired from historical maps and from interpretation of DEMs.

4.1.2 Limiting Factors

There are a number of reasons for the limited success of the GPR survey in locating salt marsh drainage channels and any possible historical structures that may have left remnants in the subsurface of Magazine Beach park. One possibility is that the moisture content of the soil during the survey had a negative effect on the results. According to Conyers (2004) dry clayey soils can be difficult to interpret with GPR when the object being sought out is made of the same material, while the same soil when wet will exhibit good contrast and make it easier to interpret. According to Boston Water and Sewer Commission records, the only rain in nearby Allston, Massachusetts in the two weeks leading up to the survey date (April 17, 2012) was 0.33 cm on April 12 (bwsc.org). This suggests that lack of saturation may have hindered GPR results on much of the low-lying former marsh.

The level of soil disturbance and fill most likely also hindered results. GPR has been shown to be useful in locating historical fortifications, but only when the site has not been highly disturbed or filled (Whittaker, 2009). Although nothing can be done to undo the disturbance to the soil, it is possible to use a lower frequency GPR antenna, which would allow for greater depth of penetration with lower resolution.

Lack of accessibility to the entire island meant that the a complete survey was not possible. The magazine itself is a permanent obstacle to geophysical study, but other man-made objects obstructed the survey. A large construction trailer, a water fountain, old wooden playground equipment and the granite retaining wall along the western edge of the magazine all presented barriers to the GPR equipment, which limited the thoroughness of the survey.

4.2 GIS

4.2.1 Past Landmaking Trends

As noted above, the amount of made land has generally increased in an S-pattern, beginning and ending in near zero growth, with a period of rapid increase as the transition between the two. The main difference among the four curves is when peak growth occurred. Landmaking in the study area began in Boston in the 17th century, much earlier than the other areas, which is why it peaked first, around 1822. As Boston expanded to its limits, developers looked outside of Boston itself to build new land in places like Back Bay and East Cambridge, which peaked around 1875 and 1885, respectively. The Upper

Charles also peaked around 1885, but like Boston it grew much more gradually and less systematically.

Interestingly, the geographic hotspots for landmaking at a given time period tend to mirror the geographic extents of the historical maps from that time, because maps tended to focus on the heavily populated areas. As filling activity moved further from Boston itself, and the cities and towns in the area expanded and coalesced into a continuous metropolitan area, the maps expanded as well, often including Cambridge in maps made in the second half of the 19th century and later. Earlier maps usually centered on the Boston peninsula and parts of Charlestown. The 1777 Pelham map is an exception that stands out in its detailed depiction of the American and British military positions during the Revolutionary War, with the conflict providing the connection between Boston and Cambridge that was absent in many maps before and after.

Although the pattern of landmaking was similar amongst the four areas, the mode of change differed substantially. For example, 98% of the area filled in Boston is former mudflats. Because of this, early Bostonians built wharves out into deeper water to facilitate access to ships; later the space between many of these wharves was filled to produce new land, a process known as "wharfing out" (Seasholes). The Upper Charles was the inverse case, with about 94% of the area filled being former salt marshes. The land made in this area prior to the damming of the Charles River was most likely filled by adding new material to build up the height of the land, but much less material was needed because the marshes were already at a higher elevation than the flats. After the dam,

which first cut the river off from the salt water and the influence of the tides in 1908 (Seasholes), the salt marshes that remained may have simply been left high and dry because of the drop in maximum water level (according to Seasholes, the dam was designed to maintain the water in the Charles River basin above mean sea level but below high tide). Aerial photographs dating from around 1925 support this idea, showing the former marshland in Magazine Beach park very close to the level of the river, but still dry land, shielded from the river by a sand or gravel walking path. This is the same mode of transformation known to have made Gravelly Point into upland after it was partially cut off from the tides by the Mill and Cross Dams in 1821. The main differences between the two transformations is that the Back Bay still had large mudflats and somewhat fluctuating salt water levels, which allowed the salt marshes to quickly adapt by colonizing the flats. Magazine Beach and other marshlands in the Upper Charles bordered relatively insignificant mudflats which, combined with the fact that the river became completely fresh after 1908, meant that the marsh grasses had nowhere to colonize and were eventually replaced by land grasses.

4.2.2 Future Landmaking Trends

It is clear from examining the maps and graphs of the growth of the land surrounding the Charles River basin that landmaking has leveled off, at least in terms of area. It may be possible for East Cambridge and Back Bay to expand slightly further into the river, but there is clearly a limit to any further expansion. Judging by the average

heights in areas that have thus far been filled—all more or less three meters above mean sea level—growth in Boston is likely to be in a vertical rather than horizontal direction. With conservative estimates for global sea level rise ranging from 0.18 to 0.59 m by the end of the century (IPCC, 2007), it is likely that some low-lying areas may need to be built up to a safer elevation with fill. There is historical precedent for such drastic action going back to the beginning of the 20th century, when the buildings and land of Galveston, Texas were raised to heights of up to 5 m in an effort to protect against hurricanes, one of which had devastated the town in 1900 (texasalmanac.com). The risk from coastal flooding is only very gradually increasing with sea level rise and climate change, so it seems unlikely that such a massive and concentrated effort would be necessary or even possible in Boston. Nevertheless, it is likely that a piecemeal approach will be taken to raising the structures and land surfaces in Boston over the coming decades and even centuries.

4.3 Further Study

The most interesting area for continuing research on Magazine Beach is the effort to locate the salt marsh drainage channels using the 2002 DEM. Although the 500 MHz GPR survey failed to confirm these findings, it is possible that a lower frequency antenna could penetrate below the disturbed near-surface sediment to whatever remains of the salt marsh below.

More conclusive results will also be more likely with a shift to a more focused

grid-based scan with much closer and more regular line spacing. The park-wide, GPS-linked survey was useful for providing a broad picture of the park's subsurface, but the wide line spacing meant that interpolation of features between lines had to be accomplished manually. Closer line spacing would allow the GPR-Slice software to interpolate map-view “time slices” that display the reflections at a given depth, which removes some of the subjectivity from the interpretation process.

CHAPTER 5

CONCLUSIONS

This study has approached the evolution of the Charles River basin from two directions: Analyzing small-scale changes in the stratigraphy of Magazine Beach Park and mapping the changing shoreline of the entire area throughout its recorded history. Although some of the results from the GPR survey of the park were inconclusive and some of the early maps used in the shoreline analysis were incomplete in extent or inaccurate, the study as a whole made several conclusions based on the analysis of the combined data. The most important conclusions of the study are as follows:

5.1 Boston and Cambridge include over 14 km^2 of made land.

Back Bay and East Cambridge have the most made land—6.5 and 4.4 km^2, respectively—due to the expansive size of their former marshes and flats. Boston and the banks of the Upper Charles River, on the other hand, have much less made land: 2.3 and 1.1 km^2. Back Bay and East Cambridge were both filled much faster than the other two sections, with more than half of each area filled during the second half of the 19th century. Boston peaked earlier, in the early 19th century, but its landmaking was carried out more continuously over the course of nearly four centuries. The Upper Charles was also filled

gradually, but its growth peaked around the same time as East Cambridge, in the late 19th century.

5.2 Mudflats received over two-thirds of the total volume of fill.

Although the surface area of new land created from mudflats was 56% of the total, 69% of the volume of new land was in those areas. The modern elevation in the four salt marsh areas is not significantly different from the four mudflat areas, according to a two-tailed paired samples t-test ($p=0.36$), but the original height of the flats was lower than that of the marshes, meaning that the fill in those areas is significantly thicker ($p=0.014$).

5.3 Captain's Island is likely composed of stratified sand.

The similarity between radar profile of the beach sediments and the islands sediments strongly suggests that the island is composed of sand. Most undisturbed segments of GPR lines that cross the island show clear stratification, which indicates that it was likely formed or at least reworked by the river during a time when the current was faster than it has been historically. It is apparent from the original teardrop-shape of the island that there was formerly a strong unidirectional flow around both sides of the island, at least periodically, which suggests that the shape of the island in 1630 was largely formed when the sea level was lower and this reach of the river was not strongly tidally influenced. Further, more concentrated GPR surveying is necessary to learn more about the island's formation and stratigraphy.

APPENDIX

HISTORICAL MAP SOURCES

HISTORIC MAP	SOURCE
A plan of Boston in New England with its environs [1777]	

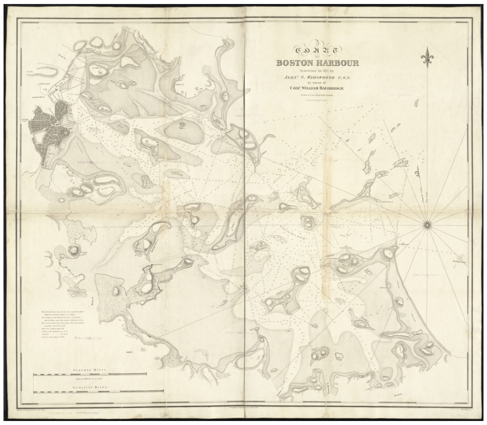
This non-georeferenced TIFF image was obtained from the website of Boston Public Library's Norman B. Leventhal Map Center. The original map was created by Henry Pelham, a Loyalist Bostonian, during the Siege of Boston and published in 1777 (maps.bpl.org).

Map of Boston in the state of Massachusetts [1814]

This non-georeferenced TIFF image was obtained from the website of Boston Public Library's Norman B. Leventhal Map Center. The original map was created by John Groves Hales.

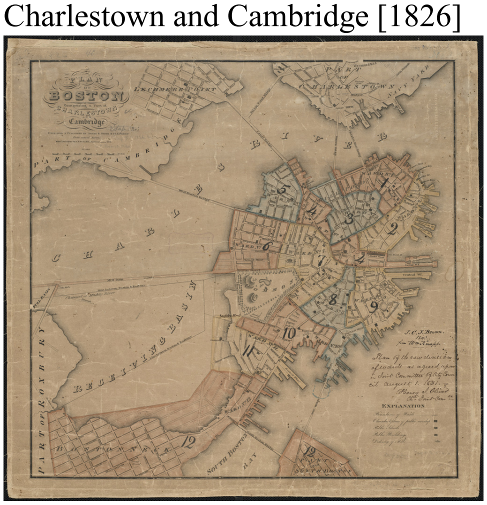
HISTORIC MAP | SOURCE

Chart of Boston Harbor, surveyed in 1817



This non-georeferenced TIFF image was obtained from the website of Boston Public Library's Norman B. Leventhal Map Center. The original map was created by Alexander Wadsworth, a U.S. Navy officer.

Plan of Boston comprising a part of Charlestown and Cambridge [1826]



This non-georeferenced TIFF image was obtained from the website of Boston Public Library's Norman B. Leventhal Map Center. The original map was created by Stephen P. Fuller. http://maps.bpl.org/id/10344

HISTORIC MAP | SOURCE

A new & complete map of the city of Boston, with part of Charlestown, Cambridge & Roxbury [1841]

This non-georeferenced TIFF image was obtained from the website of Boston Public Library's Norman B. Leventhal Map Center. The original map was created by George W. Boynton.

Roxbury, Cambridge, and Medford, Massachusetts [1847]

This georeferenced TIFF image was obtained from the Massachusetts Office of Coastal Zone Management. The original map was created for the Coast Survey by H.L. Whiting under the Superintendence of A.D. Bache.

HISTORIC MAP | SOURCE

A new & complete map of the city of Boston, and precincts including part of Charlestown, Cambridge & Roxbury [1850]

This non-georeferenced TIFF image was obtained from the website of Boston Public Library's Norman B. Leventhal Map Center. The original map was created by George W. Boynton.

Map of Boston, showing health districts and undrained and drained land [1870]

This non-georeferenced TIFF image was obtained from the website of Boston Public Library's Norman B. Leventhal Map Center. The original map was published by the Heliotype Printing Co.

HISTORIC MAP | SOURCE

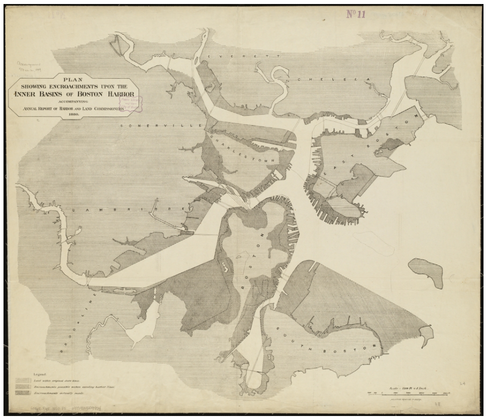
Map of parts of Boston Harbor and its tributaries [1854]

This non-georeferenced TIFF image was obtained from the website of Boston Public Library's Norman B. Leventhal Map Center. The original map was created by the Coast Survey as an update to the 1847 survey.

HISTORIC MAP

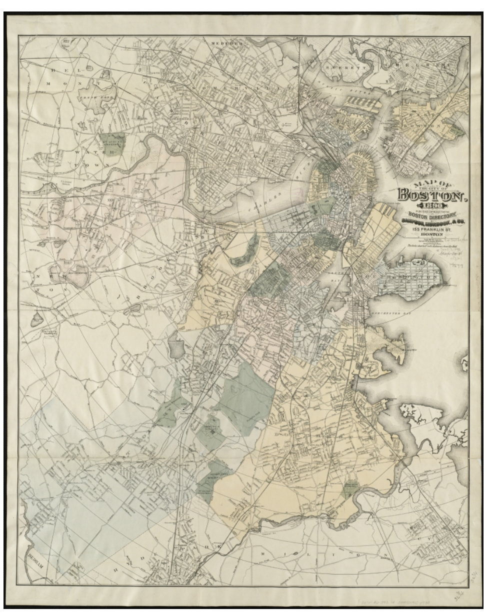
SOURCE

Plan showing encroachments upon the inner basins of Boston Harbor [1880]

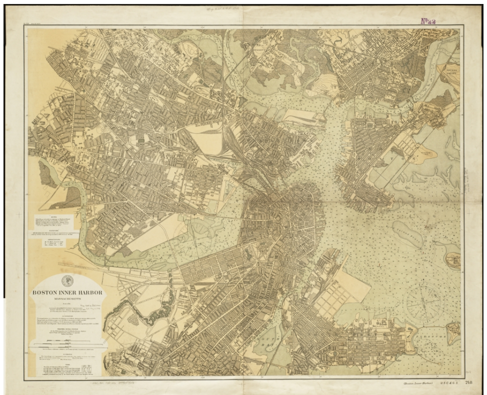
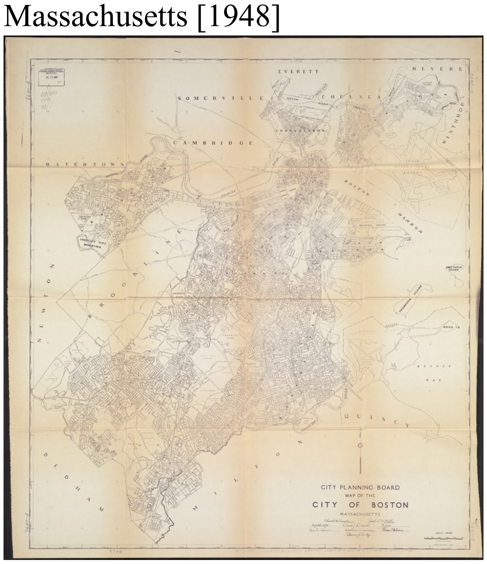


This non-georeferenced TIFF image was obtained from the website of Boston Public Library's Norman B. Leventhal Map Center. The original map was published by the Board of Harbor and Land Commissioners of Massachusetts.

Map of the city of Boston, for 1890



This non-georeferenced TIFF image was obtained from the website of Boston Public Library's Norman B. Leventhal Map Center. The original map was published by Sampson, Murdock & Co.

HISTORIC MAP	SOURCE
Boston Inner Harbor, Massachusetts [1900] 	This non-georeferenced TIFF image was obtained from the website of Boston Public Library's Norman B. Leventhal Map Center. The original map was published by the U.S. Coast and Geodetic Survey.
Map of the City of Boston, Massachusetts [1948] 	This non-georeferenced TIFF image was obtained from the website of Boston Public Library's Norman B. Leventhal Map Center. The original map was published by the City Planning Board of Boston.

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