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Original article

Application of geographic information technologies to historical landscape reconstruction and military terrain analysis of an American Revolution Battlefield: Preservation potential of historic lands in urbanized settings, Boston, Massachusetts, USA

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ABSTRACT

Through funding from the National Park Service's American Battlefield Protection Program, geographic information technologies were employed to create a high resolution, spatially accurate representation of the 1775 landscape of Boston's Inner Harbor and to conduct a geospatial and temporal assessment of the location, extent, and preservation potential of an American Revolutionary War battlefield and its associated cultural resources. Geographic information technologies provide the tools and methodologies to accurately create digital representations of historical landscapes. These tools enable the visualization and geospatial analysis of landscapes and significant historical events, greatly enhancing the understanding of temporal and spatial interactions between these events and the physical landscape upon which they occurred. Data sources include historical bibliographic and cartographic records, high resolution orthophotographs, constant value raster grids, and LIDAR data. A military terrain model was created utilizing American Battlefield Protection Program's KOCSA system categories, in order to identify defining features of the battlefield. KOCSA is an acronym which stands for Key terrain, Obstacles, Cover and Concealment, Observation and Fields of Fire, and Avenues of Advancement and Withdrawal. The KOCSA analysis provides an established method for identifying critical defining features of the battle and determining the influence of the landscape on the ephemeral battle events. The base map was created utilizing U.S. Navy Coast Survey maps dating from the mid-19th century. A digital elevation model was created to represent the 1775 topography, utilizing LIDAR data and constant value raster layers. The military terrain analysis provided valuable insights into battlefield events and decisions. Defining features of the battle were also identified and mapped. A detailed Environmental Systems Research Institute's ArcGIS Citation Data Model was used to link landscape and KOCSA features to the historical sources they were derived from. A comprehensive source table was created as part of this effort. The results of this investigation have provided a high resolution dataset of Boston's historical landscape during the time of the American Revolution. The geospatial analysis will aid in the development of long-range management strategies for the Chelsea Creek Battlefield and facilitate the assessment of threats to cultural resources posed by both anthropogenic activities and environmental change. The methodologies and interdisciplinary approach will also be applicable to other investigations seeking to recreate historical landscapes within a geographic information system.

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1. Research aims

The research goal for this investigation was to employ geographic information technologies (GIT) and traditional historical research to recreate the historical landscape and topography of Boston's Inner Harbor during the 1775 American Revolutionary War Battle of Chelsea Creek. Employing this base-level dataset, we sought to assess the military landscape upon which the battle

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occurred. In addition, we compared historical and current spatial data to determine the preservation potential for sites associated with the battle. To achieve these aims, we had four main objectives:

- utilize survey-based historical maps to accurately recreate the topographic and landscape features of the study site;
- integrate historical records and maps within an Environmental Systems Research Institute's (Esri) ArcGIS Citation Data Model (CDM) to map and reference the defining features of the battle and their associated cultural resources;
- conduct a military terrain analysis to delineate the "battlefield" and identify defining features using the American Battlefield Protection Program (ABPP) KOCO standards (KOCO is an acronym that stands for: **K**ey or Decisive Terrain; **O**bservation and Fields of Fire; **C**over and Concealment; **O**bstacles; **A**venues of Advance and Withdrawal);
- identify and map areas within the battlefield having preservation potential which may provide future archeological, educational, and conservation opportunities.

2. Experimental

2.1. Introduction

A geographic information system (GIS) integrates computer software with spatial and temporal data for the purposes of organizing, analyzing, and depicting geographically-referenced digital information. GIS technology provides a set of versatile tools that enable the visualization and interpretation of data in a variety of ways, dramatically enhancing the user's ability to understand and interpret complicated space and time relationships [1]. By displaying data in a way that is quickly understood and easily shared, its use enables us to address a variety of questions and problems. Recently, GIT have been successfully employed in the study of important historical events through the recreation of the physical landscapes over which they occurred [2].

Historical GIS utilizes GIT to display, store, and analyze historical geographic information and allows for landscape comparisons over time. The use of historical GIS developed through the integration of the fields of historical geography and geographic information science [3]. Its implementation has dramatically improved historical research, education, and conservation activities. It is a powerful tool when used to: investigate and create geospatial and temporal data and; produce highly accurate digital and paper maps that depict past landscapes and their topography. Further, it also allows for the integration of multiple datasets, including historical geographic and bibliographic information. We have employed historical GIS methodologies to investigate the 1775 landscape of Boston Harbor associated with the Battle of Chelsea Creek (Fig. 1). These techniques have allowed us to integrate traditional historical research and GIT.

2.1.1. Historical background

The 1775 Battle of Chelsea Creek was the first offensive battle of the American Revolution and proved disastrous to British forces who suffered numerous casualties and the loss of the armed schooner H.M.S. *Diana* [4]. The Battle of Chelsea Creek has long been overshadowed by the better-known defensive Battles at Lexington, Concord, and Bunker Hill. As a result of the growing interest in this forgotten battle, the National Park Service's ABPP provided grant funding to employ GIS to digitally recreate the historical landscape of Boston's Inner Harbor and analyze the Battle of Chelsea Creek.

The Battle of Chelsea Creek is the name given to the military actions that occurred along Chelsea Creek in the northern area of Boston's Inner Harbor on May 27–28, 1775 [5]. The battle began

as a large-scale livestock raid by Provincial (American) militia and developed into a series of running skirmishes as British marines moved to intercept Provincial forces [4]. This action culminated in a vicious encounter at the Ferry Ways in Winnisimmet Village, where the HMS *Diana* was attacked by hundreds of Provincial troops and artillery. The Ferry Ways is located on the north shore of present Chelsea near the confluence of Chelsea Creek and the Mystic River (Fig. 2). The attack resulted in the grounding and abandonment of the HMS *Diana*. The British schooner was subsequently looted and burned by Provincial forces. This brought the battle to a close and provided the Provincial's with their first offensive victory of the American Revolution [6].

2.1.2. Previous research

Over the past decade, numerous investigations have employed GIS for historical landscape reconstruction and military terrain analysis [2]. Historical GIS was successfully employed by Knowles (2008) to reconstruct and analyze the landscape of the American Civil War Battle of Gettysburg [3]. That investigation created a digital representation of the historical terrain and carried out viewshed analysis providing valuable insights into the influence of the military landscape on the battles outcome.

Frye (2008) developed the Esri ArcGIS CDM to recreate the 1775 landscape surrounding the American Revolutionary War Battle of Bunker Hill [7]. The Battle of Bunker Hill actually took place on Breeds Hill located within our delineated study site. Frye (2012) later utilized Esri's CDM to depict and analyze the landscape surrounding the path of his ancestor, Isaac Frye, during the American Revolutionary War [8]. The closely related Frye (2008) study provided a template and methodology which greatly benefited our investigation.

The rapid development of GIS for creating and representing virtual worlds of the past has dramatically improved our ability to capture and inventory salient aspects of the historical landscape and to effectively communicate them to a broad array of audiences [9]. An investigation was conducted in West Oxfordshire, England, which utilized a three-dimensional (3D) analysis toolset to recreate and visualize the Royal Hunting Forest of Wychwood. In that study, contemporary aerial photography, a digital elevation model (DEM), and historical maps were integrated within a GIS to reconstruct landscape change and deliver 3D visualizations to a geographically diverse audience [10]. The study documented the importance of map quality and the realistic depiction of historical topography. We attempted to follow these concepts by producing visually pleasing and accessible map deliverables.

A number of investigations in the Massachusetts area have relied on the 19th Century United States Navy Coast Survey (Coast Survey) maps for base-level data. These highly accurate survey-derived maps cover most of the Massachusetts coastline at scales of 1:5000 to 1:10,000. Giese et al. (2009) undertook the georeferencing of 19th Century Coast Survey maps within a GIS to carry out a high resolution analysis of coastal landscape change in Massachusetts along the Cape Cod barrier beaches of Chatham and Nauset [11]. The Geise et al. (2009) investigation mapped the location of relict tidal inlets for the purposes of estimating future shoreline configuration and conditions.

Mague (2011) was successful at recovering 19th century Coast Survey benchmarks in order to reduce vertical datum uncertainty for the purposes of investigating long-term coastal change on Cape Cod [12]. In another related investigation, Mague (2009) developed a base-level shoreline derived from the mid-19th century Coast Survey maps. He then used this shoreline to georeference an abundance of earlier cartographic sources allowing him to meticulously identify and map Boston's pre-colonial shoreline [13]. Methods developed by Mague (2009) have been duplicated in this study.

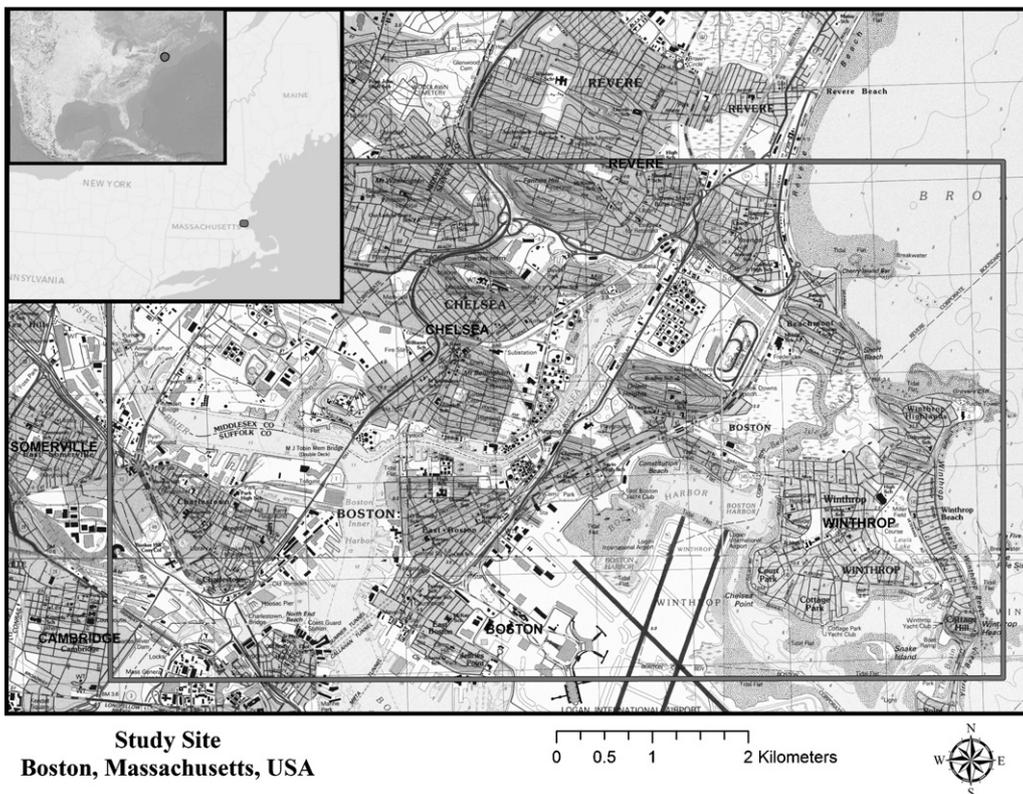


Fig. 1. USGS topographical map of the study site located in the vicinity of Boston, Massachusetts, USA. The area designated as the study site is shown within the bold rectangle. The study site has an area of nearly 50 km² and has been heavily modified by urbanization. We applied geospatial analysis within the study site to create a digital representation of the historical landscape.

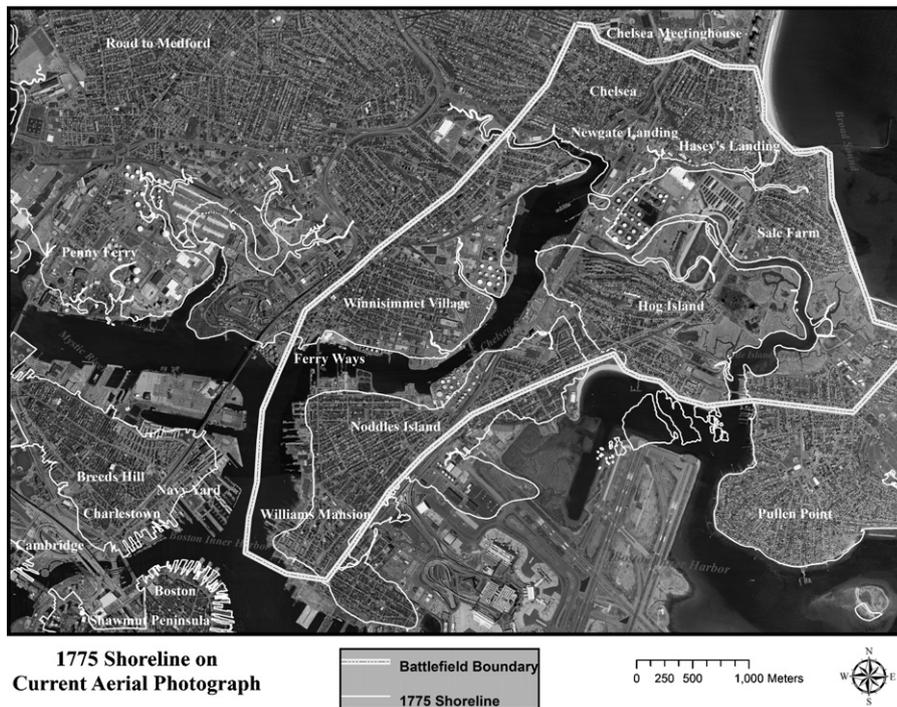


Fig. 2. 2008 orthophotograph of study site shown with 1775 shoreline and historical locations in white. The battlefield boundary shown in gray with black dashed line represents the area of the study site most directly related to the Battle of Chelsea Creek. The figure shows the dramatic anthropogenic modifications that have occurred within the study site including the filling of tidal lands to build Logan International Airport within current East Boston, which lays just south of what once was Noddles Island.

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A major contribution to historical landscape reconstruction in Massachusetts was carried out by the Boston Survey Consultants, Inc. (BSC) working under the Massachusetts Office of Coastal Zone Management Historic Mapping Project (Mass-CZM Mapping Project) [14]. The Mass-CZM Mapping Project was a rigorous research project established to identify historic cartographic sources that could be used to accurately identify the most landward pre-colonial shoreline within Massachusetts. A carto-bibliography of over 2,600 plans was developed with numerous historical maps being georeferenced within a GIS [14]. BSC verified the accuracy of the Coast Survey maps and as with Mague (2009), relied heavily on them to georeference earlier cartographic sources. The entire Mass-CZM Mapping Project database was provided to this investigation and served as the foundation for our geospatial analysis.

2.1.3. Study site

Boston and the surrounding vicinity have experienced major shoreline and harbor modifications since 1775 [15]. Shallow subtidal and intertidal areas have been filled to make room for development and industrialization, while other areas have been heavily dredged to facilitate marine shipping and commerce. The study area is delineated as a rectangular area encompassing nearly 50 km² (Fig. 1). The study area is located within the northern portion of Boston's Inner Harbor encompassing the present-day municipalities of Chelsea, East Boston, Boston, Somerville, Cambridge, Revere, Winthrop, and Medford, Massachusetts. The communities surrounding this portion of Boston Harbor are situated on the vast lowland basin created by the Charles River and Mystic River systems that widens to include most of the coastline around Massachusetts Bay.

In 1775, Boston's Inner Harbor was a large and ecologically productive estuarine system with numerous saltmarshes and tidal creeks which fed into the larger tributaries of Chelsea Creek and the Mystic River. The central and unifying geographic feature of our study area is Chelsea Creek, which flows into the Mystic River as it meets Boston Harbor. The majority of the battle took place on Noddles and Hog Islands, along the mainland of Chelsea, and at the Ferry Ways located on the shoreline of Winnisimmet Village (Fig. 2). Chelsea Creek separated the mainland and island areas and served as the main approach for the British Navy. These locations were located within a smaller area delineated within the larger study site that we identified as the battlefield. The majority of the significant battle events occurred within the battlefield boundary.

To gain a more complete understanding of how anthropogenic modifications occurring within the study site impacted the preservation potential of the historical landscape associated with the Battle of Chelsea Creek, it is important to briefly review how and why some of these modifications took place. To facilitate this discussion, we turn to Nancy Seashole's book, *Gaining Ground: A History of Landmaking in Boston*, for a summary of the anthropomorphic influences on Boston Harbor during the periods before and after the Battle of Chelsea Creek [16].

By the 18th century, there had been nearly 150 years of colonization and Boston was a bustling colony quickly running out of room for further expansion. Between the time of its founding in 1630 and 1775, the development and expansion of the growing British colony took place primarily on upland areas of the narrow Shawmut Peninsula [16]. At this time, landmaking was predominantly undertaken by wharfing out; this is a technique where a large timber wall is constructed along tidal lands and then filled with a variety of debris on the landward side [16].

Boston's increased trade and transportation needs, immigration, and large public works projects were major drivers of landscape modification occurring continuously until present. During the period following the American Revolution, Boston's population doubled in response to its development and involvement with

global trade. This resulted in a large increase in landmaking activities including areas for housing, parks, railroad, and wharves [16].

The largest landscape modifications effecting areas directly related to the Battle of Chelsea Creek did not occur until the 20th century with the advent of rapid advancements in the transportation industry. During this period, development and filling was no longer contained in Boston Proper, but expanded out to adjacent lands including present-day East Boston [16]. Another significant change is that filling and wharfing out was now used in conjunction with the leveling of area hills. The process of leveling hills and using those materials to fill adjacent tidelands enabled the further expansion of the railroad and the development of large depot facilities along the East Boston waterfront [16].

The largest landmaking project in the history of Boston came with the onset of aviation [16]. As airfield facilities became in high demand during WWII, the foundations for present-day Logan International Airport began to be laid south of Noddles and Hog Islands [16]. The first airfield was built during the 1920's and, through the process of leveling and filling, quickly grew throughout the 20th century. This led to the creation of over 566 hectares of new land, making it the most modified area within the study site [16].

The rapid urbanization which has occurred in Boston provides a unique opportunity to apply GIS to investigate the impact of anthropogenic modifications on the preservation potential of the historical landscape. The combined drivers of landscape modification in Boston led to the filling of tide lands and the leveling of hills at unprecedented levels. No other city in North America has experienced landscape changes on this scale [16]. The urbanization and industrialization of the historic landscape was not without serious environmental cost, including the loss of natural lands and the pollution of harbor waters and ecosystems. In addition, these modifications present challenges to this investigation as they have major implications for the preservation potential of cultural resources associated with the Battle of Chelsea Creek.

2.2. Methodology

2.2.1. Data sources and integration

Boston's rich history and prominence in Colonial America's economy and politics presented unique circumstances leading to substantial investments made in the development of survey-based maps of Boston's marine and terrestrial environments. Unlike many other geographic areas, the Boston Basin has been accurately surveyed and mapped for over 200 years providing an abundance of reliable cartographic data, which documented these changes through time and enabled the successful reconstruction of this historical landscape.

The ability to integrate and analyze multiple datasets at varying temporal and spatial scales within a GIS was an integral part of this investigation. Multiple data sources were obtained through the Massachusetts Offices of Geographic and Environmental Information (MassGIS) including georeferenced historical maps, orthophotographs, and high resolution LIDAR data. MassGIS is a state government agency offering a variety of high-resolution geospatial datasets free for public download [17].

The single most important dataset obtained for this investigation came from the Mass-CZM Mapping Project data created by BSC. The data represents the original paper Coast Survey maps dating from the mid-19th Century that had been collected, digitized, and georeferenced by the Mass-CZM Mapping Project. The data was provided as a series of raster grids with a 1 m by 1 m cell size. The horizontal accuracy for coastal features shown on the raster imagery was determined by BSC to be less than 10 m, which is far more accurate than other cartographic sources from the time period [14]. The importance of this data cannot be understated and was crucial for the overall success of the project.

The foundation of the Mass-CZM Mapping Project dataset was obtained through the original topographic and hydrographic sheets from the Coast Surveys. As discussed above, Mague (2009) determined these Coast Surveys the most accurate source for historical shoreline positions and cultural landscape features in the area of the study site [13]. In this study, we utilized the series of 1847 Coast Survey maps as the primary cartographic source for the creation of our digital representation of the historical landscape.

The series of 1847 Coast Survey maps by A.D. Bache were utilized in this study as the primary source for the creation of the base map. The absence of any significant filling or change to the coastal areas within the battlefield boundary prior to 1847 deemed the Coast Survey maps the most accurate data source for base-level information. The accuracies of the 1847 survey are quantifiable and verifiable, far exceeding National Map Accuracy Standards at the compilation scale of 1:10,000 and probably closer to 1:5,000 [18]. The 1817 Coast Survey map by A.S. Wadsworth was not as accurate as the 1847 series and served as the secondary source for our study.

Other important data sources were obtained through the Norman B. Leventhal Map Center, at the Boston Public Library (BPL Map Center). The BPL Map Center, through its extensive cartographic holdings stretching back to the 15th century, collects, digitizes, and preserves maps and atlases and promotes scientific research and innovative educational opportunities [19]. Several maps obtained through the collection dated from the 18th century. Although these maps were often not survey-based and georeferenced within a GIS, they nonetheless were useful to this study in identifying landscape changes occurring in the 37 years between 1775 and the first 1817 Coast Survey maps. They were also important in identifying place names and cultural locations identified on this project's maps. For example, road names were not often identified on the Coast Survey maps, but could be found on the digitized 18th and 19th century maps provided online by BPL.

Through the integration of multiple cartographic sources and high-resolution geospatial data, this investigation was able to achieve a detailed and accurate digital representation of the 1775 landscape. The 1847 Coast Survey maps served as the primary source for the landscape reconstruction, while the 1817 Coast Survey maps were used as the secondary source. Individual landscape features were digitized from the raster imagery of the Coast Survey maps and then annotated using maps obtained online from the BPL Map Center. Modern datasets obtained through MassGIS were used to visualize the impact of urbanization on the preservation potential of the historical landscape.

2.2.2. Citation Data Model

The CDM provided our team with the framework to organize and integrate historical records and geospatial data within a GIS. A CDM is a model and methodology that organizes and relates the historical sources to the points, lines, and polygons that make up vector GIS data [7]. The template for the CDM utilized in this project was obtained through Esri's online Mapping Center [7]. All spatial data linked to the CDM is housed in an Esri ArcGIS Personal Geodatabase (geodatabase). A geodatabase is a proprietary database schema used to organize geospatial data within ArcGIS [7]. Through the CDM, each feature created in the GIS is linked to the source from which it was derived. Each source is entered into a row within the Source table and assigned a unique identifier which serves as the foreign key in a geodatabase relationship class [7]. Features on the map (e.g. buildings, key terrain) are assigned a unique identifier which is then used as the primary key in the relationship class. For example, a feature representing a cannon position mentioned within an historical text would be assigned the unique identifier associated with the historical source text. Many of the physical

features on the map, such as the shoreline and saltmarshes are linked to the database in this way.

2.2.3. Base map creation

One of the most important aspects of developing the digital representation of the 1775 landscape was the creation of the base map. The base map serves as the foundation for the entire dataset and it is crucial for the accuracy of the military terrain analysis and the mapping of defining features and potential archeological resources. To achieve the desired accuracy, the previously digitized and georeferenced 1817 and 1847 Coast Survey maps were used as the reference layer for all major landscape and topographic features.

The cornerstone for the development of the base map was the accurate delineation of the shoreline. The most landward shoreline shown on 1847 Coast Survey maps is associated with the High Water Line (HWL). We digitized the 1847 HWL from the Coast Survey raster imagery to represent the 1775 shoreline within the GIS [20].

In areas where the 1847 shoreline was not representative of the 1775 shoreline, the 1817 Coast Survey maps were used as the secondary source. The landscape modifications occurring within the study site between 1775 and 1847 did not have a significant impact on areas associated with the battle [16]. However, there were significant alterations to the Shawmut Peninsula, Charlestown, and the Western shoreline of Noddles Island due to the building of new wharves and railroad facilities. The use of the less accurate 1817 Coast Survey map to delineate the shoreline introduced some uncertainty to our digital representation of the historical landscape in these areas. It is also likely that some landscape changes occurred during the time period between 1775 and 1817 and therefore some features we digitized on the base map were likely not in existence in 1775.

The HWL shoreline served as a guide for georeferencing non-registered historical maps. It was also the starting point for the digitization of spatial data shown on the Coast Survey maps representing aspects of the physical landscape (i.e. navigable waters, upland, rivers, salt marshes) (Fig. 3). The associated historic map from which each feature was digitized is cited within the attribute table and related to the Source table within the CDM.

In some cases, digitized historical maps obtained through the BPL Map Center were used to identify place names used in annotations. These included an 1859 map by Henry Francis Walling, titled *Map of Boston and its vicinity, from actual surveys*, and an 1852 map by James C. Sydney, titled *Boston (Mass.), Boston and vicinity* [19]. Both maps had detailed annotations of property owners, buildings, and roads and were available digitized from the BPL Map Center [19]. We referred to these maps to label roads, creeks, and historical locations. For example, the mainland area east of Hog Island was known as "Sales Farm" but was not identified on the Coast Survey maps (Fig. 2). Sales Farm was referred to in primary historical documents as the location where Provincial troops waited for favorable tides to cross onto Hog Island. The identification of Sales Farm from these cartographic sources allowed us to accurately delineate troop movements during this phase of the battle.

While the physical landscape had changed very little during the period between 1775 and the Coast Survey of 1847, there was extensive development with respect to buildings, roads, and wharfs [16]. As Boston was a major hub of commerce in America, modifications of the coastal landscape had already been occurring for over 150 years, with extensive modifications made in the form of wharfs and roads. For example, the roads depicted on the 1847 map represent a significant increase over those that existed in 1775, particularly in the areas of Boston and Charlestown. In addition, wharfs were continually added and expanded along the waterfront of the Shawmut Peninsula and Charlestown. As a result, we digitized roads and other anthropogenic landscape features from

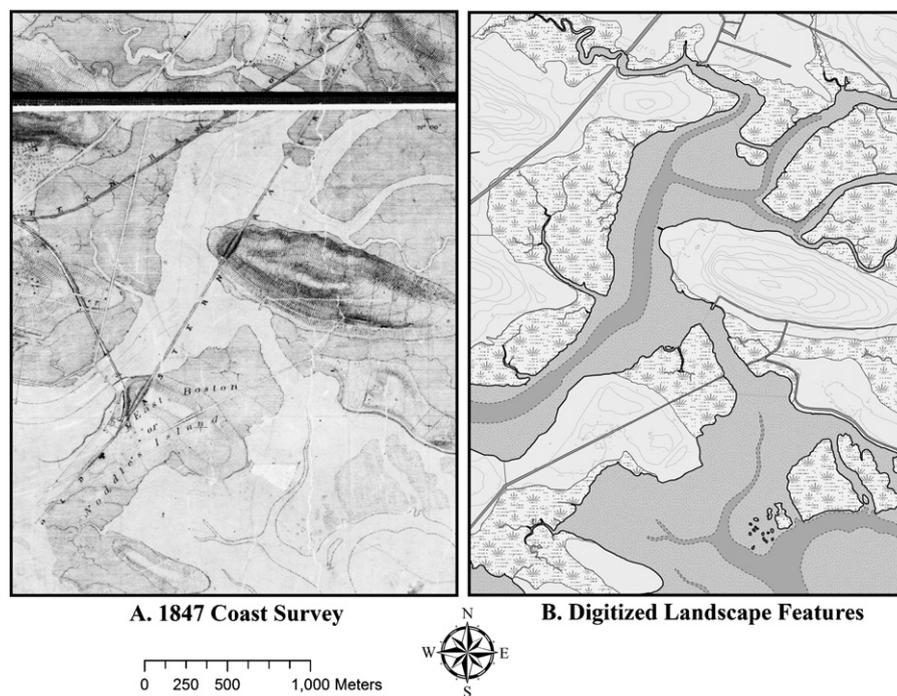


Fig. 3. Digitized landscape features compared to source map features from which they were derived. A. Raster imagery of 1847 Coast Survey map used as the primary cartographic source for the creation of the digital representation of the historical landscape. The map depicts various natural features of the historical landscape including saltmarshes identified with parallel horizontal lines, High Water Line shoreline, and upland areas shown with vertical line shading and contours. Other features shown on the map include a dashed navigable water line, roads, buildings, and railroad lines. B. Landscape features digitally delineated from the 1847 Coast Survey map as polyline and polygon feature classes. Digitized features include the HWL shoreline, upland, saltmarshes, tidal creeks, roads, navigable water, and low water. The features were integrated together to create the base map. The digitized features have an uncertainty of less than 10 m. The horizontal black line marks the boundary between the upper and lower sections of the historical paper map series shown layered within the GIS.

the 1847 maps that could also be identified on the earlier non-registered maps dating from the 18th and 19th centuries.

Due to the rapid changes during this time, some features (wharfs, roads, buildings) shown on the base map likely post-date 1775. As the majority of these modifications occurred in the vicinity of the Shawmut Peninsula, which lies outside the battlefield boundary, we infer that any inaccuracies to our digital representation of the historical landscape did not impact our military terrain analysis or understanding of the battle.

2.2.4. Historical Digital Elevation Model

We developed a historical DEM representing the 1775 topography to carry out viewshed analysis and accurately depict contours on the base map. We produced the historical DEM through the integration of the 2002 MassGIS LIDAR data, which provided coverage of the uplands, and constant value raster grids representing the salt marshes and water bodies. Water bodies were identified as all marine areas sea-ward of the HWL shoreline were delineated from the Coast Survey maps. Uplands and salt marshes were located landward of the HWL and digitized based on Coast Survey symbology. Based on these definitions, we developed three separate DEM's (Upland, Salt marshes, and Water bodies) that were integrated together within the GIS and used to represent the historical terrain of the study site. The historical DEM was then used to create topographical contours and carry out viewshed analysis.

The 2002 LIDAR data covering Boston Harbor was provided as a processed bare-earth rasterized DEM with a horizontal accuracy of approximately 1 m and a vertical accuracy of 30 cm. Each 1 m by 1 m raster cell contained a single elevation value correlating to the center of its location [21]. LIDAR is one of the most promising technological developments in topographical analysis. In a related study carried out on Rainsford Island within Boston Harbor, the same 2002 LIDAR data greatly enhanced the geospatial analysis

and flood hazard prediction of this culturally significant coastal site [22].

The use of modern LIDAR data to depict the 1775 upland topography was justified as these areas have not been modified to a degree which would affect our ability to accurately produce contours and carry out viewshed analysis [18]. Upland areas represented with the LIDAR data include terrestrial areas landward of our HWL shoreline not including salt marshes and other tidelands. These areas were clearly delineated on the Coast Survey maps and digitized as an "Upland" feature class for the base map. The Upland polygon feature class was used to clip the 2002 LIDAR data. The clipped LIDAR-derived DEM covered only upland areas of the study site and would later be integrated with the single value raster grids to provide full coverage of the historical topography.

Constant value raster grids contain the same single value within each of the raster cells and can be employed as a DEM. We developed 1 m by 1 m constant value raster grids that matched the resolution and registration of the LIDAR dataset to represent the areas of the study site where LIDAR could not be utilized. These included salt marsh and marine areas that have been heavily modified since 1775. The extensive filling of tidelands that occurred within the study site did not allow for the use of the LIDAR data in those areas because of the significant elevation changes that occurred, most notably the wharfing out and filling of salt marshes and other tidal lands.

We created a constant value raster grid and used it as a DEM to represent the salt marshes. To estimate the elevation value above sea-level of the historical salt marshes, we calculated the current salt marsh elevation. An elevation of 1.71 m above sea-level relative to the North American Vertical Datum of 1998 was obtained from the averaged elevation values from the unclipped 2002 LIDAR DEM in the area of the Belle Isle Saltmarsh Reserve. The use of this area as a proxy was based on our comparison of the Coast Survey maps and

the 2008 orthophotographs, which showed little change between the 1846 and 2008 tidal landscapes in the vicinity of Belle Isle Creek.

We assumed the only major vertical elevation change occurring in this area since 1775 was relative sea-level rise. Relative sea-level is a factor of both land surface changes and eustatic sea-level rise. Donnelly (2006) reconstructed a late Holocene sea-level history for the region based on tide gauge records and the radiocarbon dating of basal marsh sediments. The change in relative sea-level during the period between 1775 and 2002 was approximated based on the Donnelly (2006) results. Using tide gauge records, Donnelly (2006) calculated that sea-levels have risen in Boston Harbor at rate of 2.8 mm per year between 1922 and 2002. Donnelly (2006) calculated that prior to this the rate of rise was significantly lower at approximately 0.52 mm per year [23]. Using these numbers we determined that relative sea-level had risen approximately 0.30 meters between 1775 and 2002. This value was then subtracted from the previously determined 1.71 m value (current salt marsh elevation) resulting in a historical salt marsh elevation value of 1.41 m relative to the LIDAR dataset. A raster grid was then created using the “Saltmarshes” polygon shapefile we previously digitized, and all cells were assigned the 1.41 value. Similar methods were used to create a DEM to represent the water bodies within the study site, setting the value of each 1 m by 1 m cell to zero.

Despite the simplicity and likely vertical errors associated with the methods used to create the historical DEM, they nonetheless proved adequate for the purposes of this study. The integration of a LIDAR derived DEM and constant value raster grids provided a simple yet adequate method for developing a DEM to represent the historical terrain. Any vertical uncertainties associated with the model were well within the accuracy needed to carry out viewshed analysis and develop topographical contours.

2.2.5. KOCO military terrain analysis

The National Park Service ABPP utilizes a standard method of military terrain analysis, called the KOCO approach, to define the limits of historical battlefields. KOCO is an acronym that stands for: **K**ey or Decisive Terrain; **O**bservation and Fields of Fire; **C**over and Concealment; **O**bstacles; **A**venues of Advance and Withdrawal [24]. The KOCO approach correlates significant natural and cultural terrain features recorded in historical accounts and maps of the battle with terrain features that can be identified on the modern landscape. These terrain features are then organized and cataloged under the appropriate KOCO components. This enables for the identification of important areas of the landscape containing defining features and their associated cultural resources. The identification of the defining features of the battle serves as an aid in interpreting primary historical accounts and permits a reconstruction of the spatial and temporal aspects of the battle.

A KOCO analysis was carried out to identify and map defining features and visualize and assess battle events through space and time. Features identified as fitting into the KOCO schema were obtained through the historical and cartographic sources. A geodatabase was created to organize and integrate the data within the CDM. An individual map was created for each KOCO component as well as an inclusive map of all defining features. Our use of the KOCO approach to military terrain analysis provided a framework and methodology needed to document and map the complicated series of events taking place during the Battle of Chelsea Creek. The results from our application of the KOCO methodologies will be presented within the *Experimental data and results* section.

2.2.6. Time series maps

Eight time series maps were produced to enhance our ability to convey and understand battlefield events. One of these maps is included as an example within the results section. Each map portrays a temporal phase of the battle. The basis for the maps

was a timeline of events derived from the historical record. These series of events were divided into eight phases based on their spatial and temporal relationship and portrayed on an individual map. Individual feature classes were created to display a time series of events occurring during each phase. These data were overlaid on the historical base map.

2.2.7. Identification of areas exhibiting potential for preservation of historic resources and sites

Areas containing defining features of the battle were identified through the deciphering of primary historical sources, and geospatial analysis, and KOCO analysis. Walk over surveys and visual inspection was undertaken at those locations. Marine and terrestrial areas that had not been dredged or heavily developed were considered to exhibit the potential for preservation of cultural resources. Sites having preservation potential may contain archeological and cultural resources associated with the battle.

2.3. Experimental data and results

2.3.1. Base map

The high-resolution base map was the most critical data created for this project (Fig. 4). The meticulously digitized shoreline provided the foundation for the entire data set and contributed toward the registration of historical maps. It also served as a guide for the digitization of all other base map features.

Limiting the uncertainties associated with the shoreline and other coastal features was crucial for the creation of an accurate base map. There are many sources of potential uncertainty in the recreation of historical landscapes. Following the general principles of error propagation theory, one can budget these sources of potential error and calculate an overall uncertainty for coastal features. This calculation reflects generally accepted estimates for uncertainties including those associated with survey and mapping methods applied during the creation of the historical cartographic source, the registration and digitization of the historical cartographic sources taking into account media distortions, and accepted feature digitization uncertainties [14]. The sources of potential error were budgeted and overall horizontal uncertainty calculated to less than 9.7 m for the shoreline feature displayed on the base map [14]. This relatively low level of uncertainty compared with digitized representation of the historical environment made during this time period is primarily due to the high degree of accuracy achieved by the Mass-CZM Mapping Project when initially digitizing and georeferencing the historical Coast Survey maps.

By limiting the uncertainties associated with the base map, the location of critical defining features of the Battle of Chelsea Creek could be accurately identified on the current landscape, assessment of preservation potential performed, and, when overlaid on modern datasets, the historical layers can provide a clear visualization of landscape changes through time (Fig. 5). The base map also provides the backdrop for the KOCO and time series maps. According to our research, the base map currently exists as the most accurate geospatial representation of the 1775 landscape of Boston's Inner Harbor.

2.3.2. Historical Digital Elevation Model

The historical DEM provided a simplified representation of the 1775 topography within the study site (Fig. 6). The historical DEM allowed for the development of contours on the base map and the viewshed analysis of key observation positions on the battlefield. The LIDAR derived upland areas of the historical DEM provided a high-resolution depiction of these locations. However, the use of the 2002 LIDAR dataset had its drawbacks. These included some inaccuracies due to landscape changes that had occurred in the upland areas of the study site since 1846 including the leveling

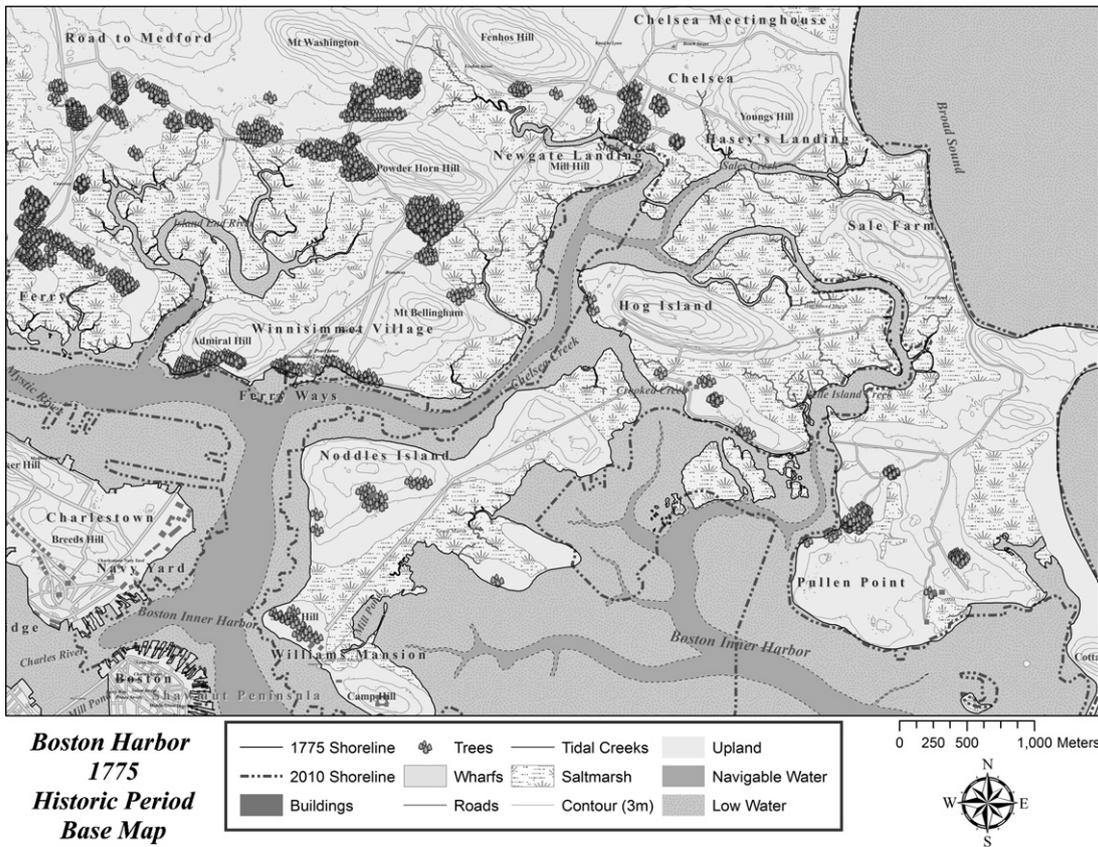


Fig. 4. Base map representing the historical 1775 landscape. The current shoreline is shown with a dashed line. Many of the features shown were digitally delineated using the Coast Survey raster imagery as the source data. The base map provided the foundation for the KOCO analysis and yielded a baseline dataset for future research.

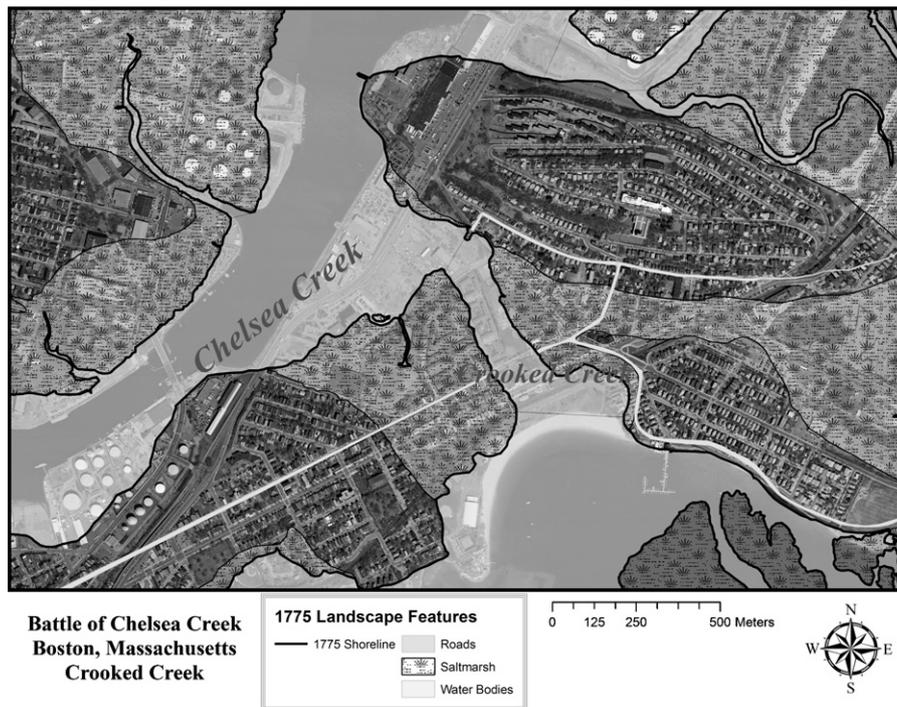


Fig. 5. Map of historical landscape features in the area of Crooked Creek overlaid on a 2008 orthophotograph. This map provides a visualization of the dramatic landscape changes that have occurred since 1775. Crooked Creek was the location of a significant battle event in which two British Marines were wounded. Due to the dramatic modifications at this location, it is doubtful whether the site will have preservation potential or contain cultural resources.

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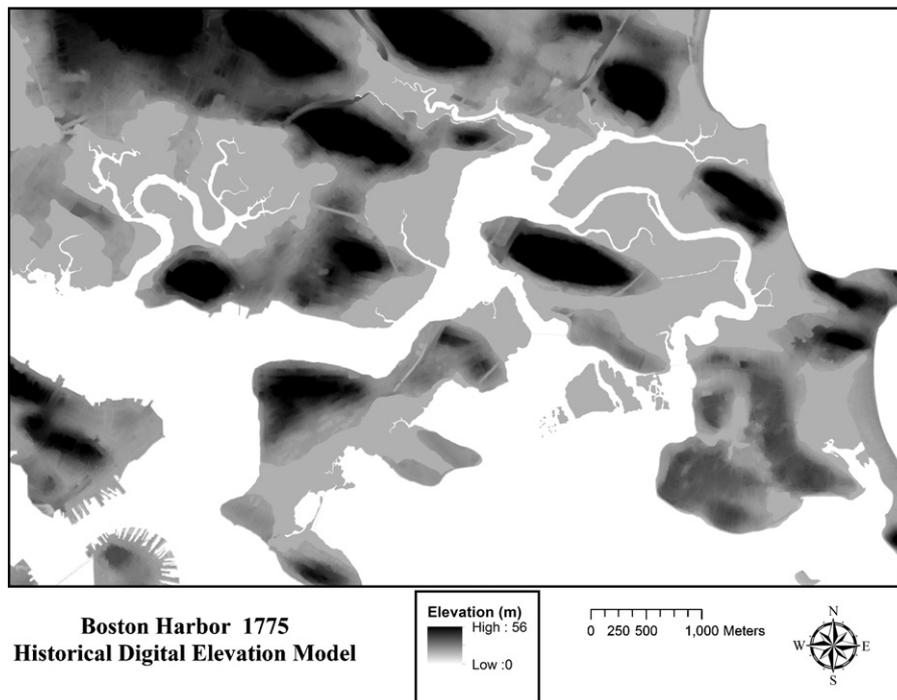


Fig. 6. Historical DEM representing the 1775 topography of the study site. Upland areas were derived by a LIDAR DEM, while tideland and marine areas were assigned a constant elevation value. Darker areas correspond to higher elevations of the uplands. The solid light gray areas represent the salt marshes and were assigned a constant value of 1.41 m. White areas represent the marine areas and were assigned a constant value of zero. The historical DEM allowed for viewshed analysis and contour production.

of some hills. For example, Smith Hill, positioned on the west side of Noddles Island, was leveled in 1922 to facilitate the filling of tidelands and construction of Logan International Airport [15]. Therefore, the LIDAR derived upland portion of the historical DEM is not accurate in this location and no contours are shown on the base map (Fig. 4). Other modifications included railroad and highway cuts made through existing hills. Areas on the historical DEM where modifications occurred do not therefore accurately represent the historical topography. However, modified lands located within the battlefield boundary were limited.

In addition to landscape modifications in the upland areas, the creation of constant value raster grids to serve as DEM's representing saltmarshes and waterbodies within the study site also simplified the actual 1775 terrain, but was adequate for the purposes of this study. Despite the uncertainties associated with the DEM, it nonetheless enabled us to fulfill our goals of carrying out viewshed analysis and creating contours for the base map.

The use of LIDAR data to derive contours for the upland areas of the study site was successful with a surprising degree of accuracy when overlaid on contours shown on the Coast Survey maps (Fig. 7). The close alignment between the contours we developed and those depicted on the Coast Survey map allowed us to validate our methods in employing modern LIDAR data to develop an historical DEM. As the purpose of these contours was to simply portray the topography of the battlefield, they served their purpose well.

The historical DEM was also successfully used to perform viewshed analysis. A viewshed map was produced for each of the key observation locations identified in the KOCO analysis and greatly enhanced the ability to understand what could have been seen during the battle. For example, based on this viewshed analysis we infer the British clearly had a tactical advantage holding the heights of Noddles Island and could observe the majority of the battlefield (Fig. 8). Despite this advantage, there were some areas that could not be observed, including the routes of approach and withdrawal of Provincial forces and areas directly below their observation position. Viewshed analysis was an efficient method to aid in the

interpretation of the battle that was significantly enhanced by the application of GIS.

2.3.3. KOCO analysis

A map was produced for each of the KOCO components. Two of these maps are included in this paper including fields of fire (Fig. 9) and defining features (Fig. 10). KOCO features were created based on historical sources and overlaid on the base map. Symbology was selected based on simplicity in order to accurately convey the location of key components on the map in a visually accessible format. All components are linked to their sources within the CDM and assembled as a feature dataset within the larger project geodatabase. Two examples will be used to review the results achieved through this assessment including fields of fire and defining features.

Fields of fire include all areas of the battlefield where artillery or small arms were used during the temporal extent of the battle (Fig. 9). Provincial artillery positions at Winnisimmet Village and Newgate Landing commanded the main channel and headwaters of Chelsea Creek, respectively. The largest British artillery position was located on the highest point on Noddles Island. In addition, the HMS *Diana* and other naval vessels were used at various locations throughout the battle as floating artillery positions. Provincial small arms fire came from several positions during the battle. The crew of the HMS *Diana* reported coming under musket fire from “the Houses behind Walls and other Covers” as they made their way past Winnisimmet Village [6]. We also displayed the approximate range of artillery and small arms fire on the map. The field of fire map was useful to identify areas where skirmishes and fighting took place and provided an important visualization of the battle occurring through space and time. It also provided a general location of potential archeological resources related to the battle such as cannon and musket balls.

Each component of the KOCO analysis helps to elucidate the defining features of the battlefield. The defining features provide a summary of the results achieved through KOCO analysis. Twelve

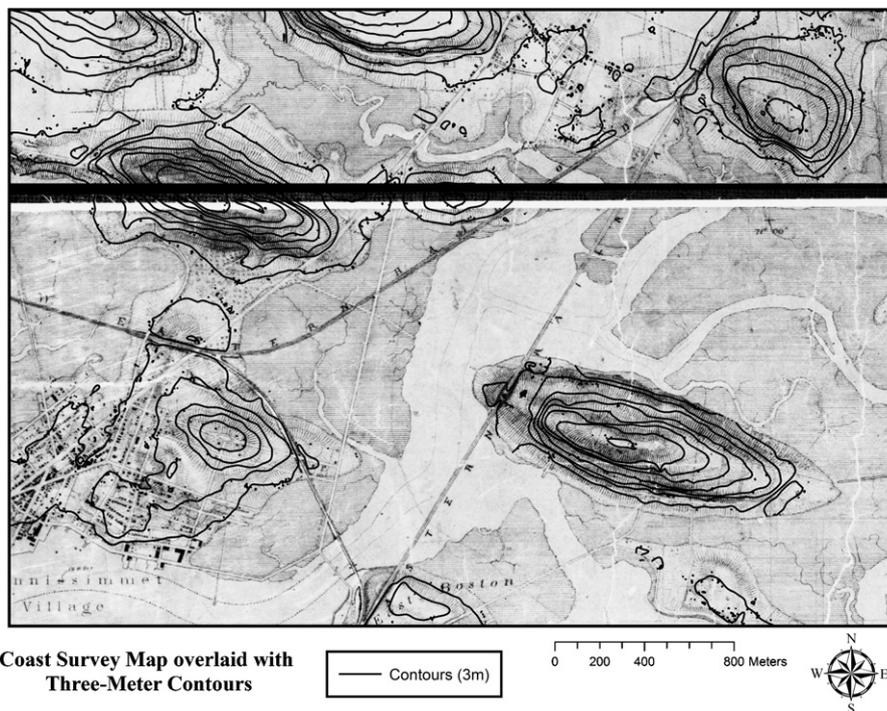


Fig. 7. LIDAR derived three-meter contours overlaid on 1847 Coast Survey map. The LIDAR derived contours match those shown on the historic map quite well and attest to the validity of incorporating LIDAR data in the creation of the historical DEM. The horizontal black line marks the boundary between the upper and lower sections of the historical paper map series shown layered within the GIS.

defining features identified and mapped are those locations where events took place that were significant to the outcome of the battle (Fig. 10). All defining features have the potential of having archeological resources associated with their location and also yield a geospatial summary of the Battle of Chelsea Creek. In addition, their

location also helped to define and delineate the boundaries of the battlefield which was another goal of the KOCO analysis.

For example, the Ferry Ways, located on the waterfront of Winnisimmet Village, was identified as “Key Terrain” in the KOCO analysis. This was also the site of a major engagement and the

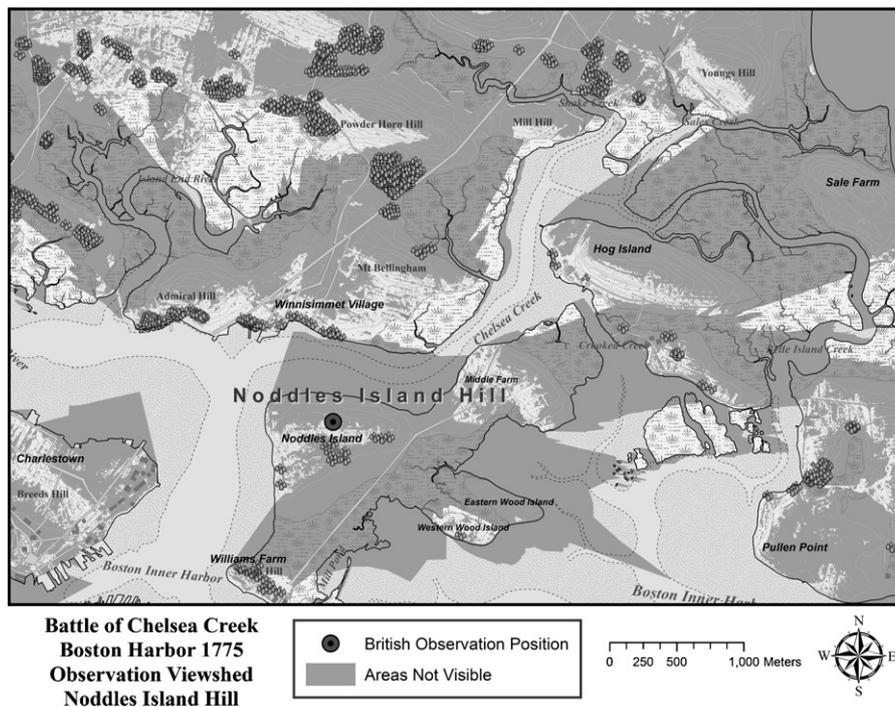


Fig. 8. Map displaying the results of the viewshed analysis on the British observation position located on Noddles Island shown with dark circle. Darker gray areas were not visible from the British position. According to this analysis, there were large areas of the landscape where Provincial troops could move unnoticed from British observation including the main routes of advancement and withdrawal. The element of surprise achieved by this cover proved crucial for the Provincial success of removing hundreds of livestock from Hogs and Noddles Islands before the British could adequately respond.

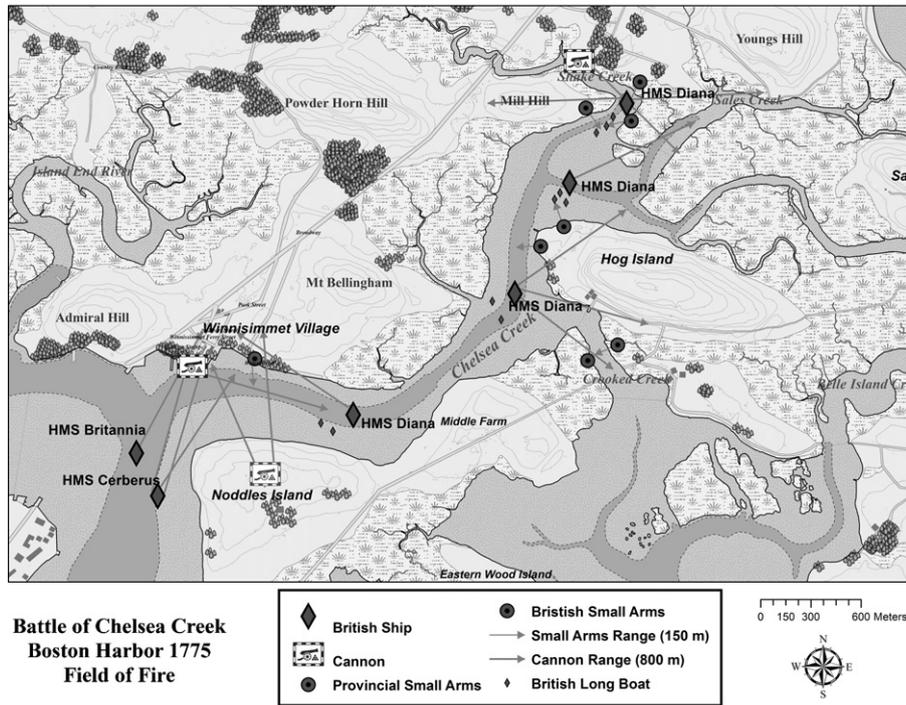


Fig. 9. Map depicting the field of fire component of the KOCO analysis. This map contains all of the firing positions documented throughout the duration of the battle and includes the locations of troops firing small arms and cannons. Also included are the various positions taken by the British ships including the HMS Diana, Cerberus, and Britannia. The HMS Diana is shown at several locations to represent the various positions she fired from.

subsequent grounding, looting, and burning of the HMS Diana [25]. The Ferry Ways was one of the most important locations of the battle and was identified as a defining feature. Other defining features include the Chelsea Meetinghouse used to muster and feed Provincial troops as they made their way to and from battle engagements,

and the small saltmarsh channels in the vicinity of Crooked Creek used effectively as cover in a successful Provincial rear guard attack of advancing British marines [26].

Based on the location of defining features, a battlefield boundary was delineated. The battlefield boundary contains all of the

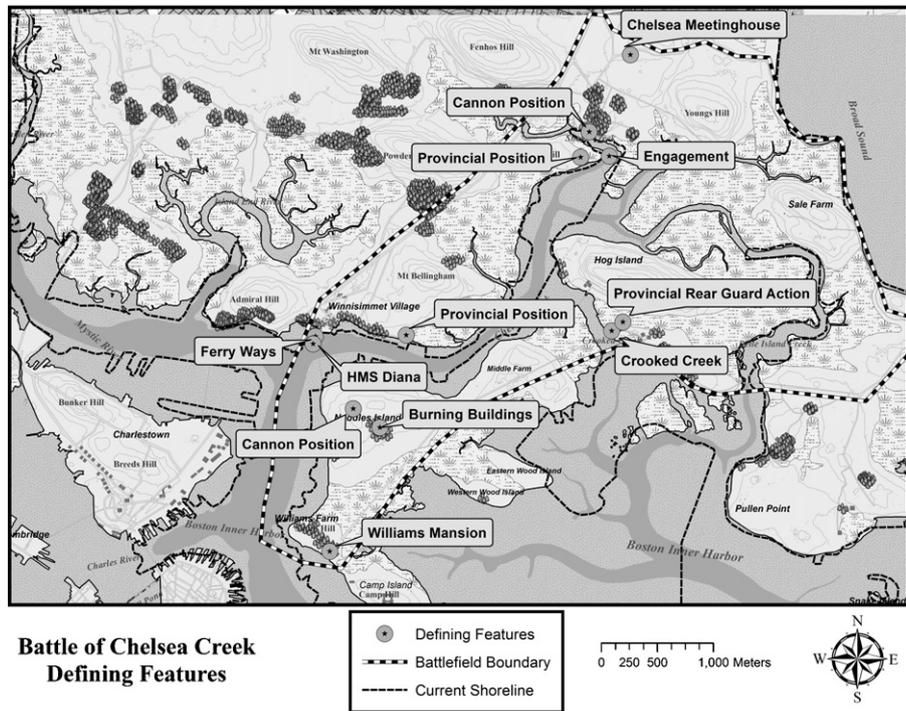


Fig. 10. Map showing the location of the critical defining features identified through the KOCO analysis. The features are displayed on the historical base map. Defining features of the battle include areas where events took place that had a significant impact on the battle such as the Ferry Ways in Winnisimmet Village, the Chelsea Meetinghouse, and Crooked Creek. Also shown with the dashed black-white line is the battlefield boundary derived from the general location of the defining features. The battlefield boundary enabled us to limit the spatial areas that may contain cultural resources associated with the battle.

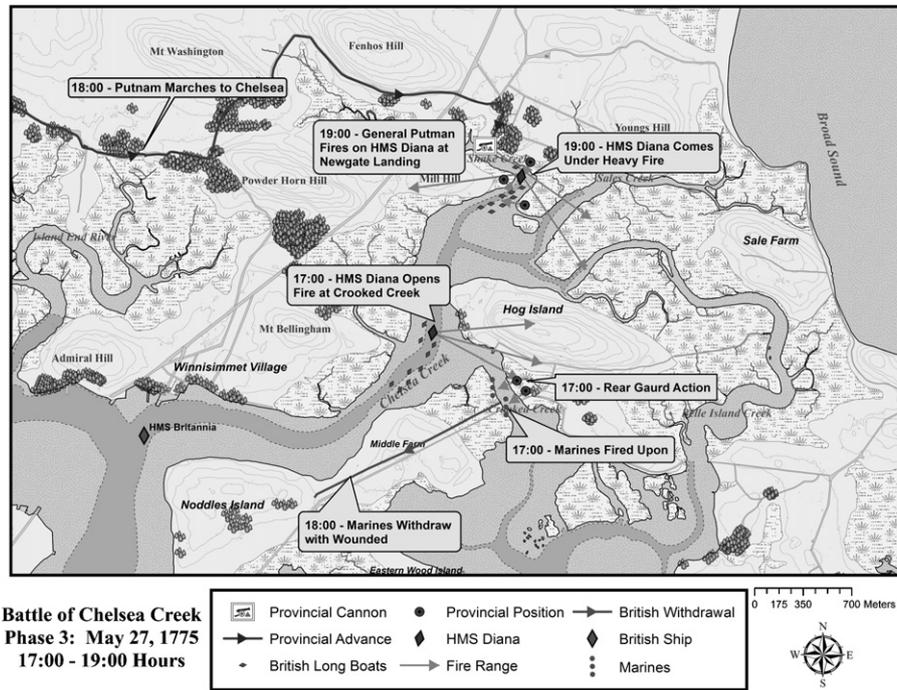


Fig. 11. Phase 3 time series map showing the battle events occurring between 17:00–19:00 hours on May 27th 1775. In this dramatic phase of the battle, the *HMS Diana*, seeking to cutoff the Provincial retreat, fired upon the Provincials at Crooked Creek. At the same time, the rear guard of the retreating Provincials then successfully defended against British Marines pursuing them on foot utilizing salt marsh ditches in the vicinity of Crooked Creek as cover. Later, continuing her pursuit of Provincial troops up into the headwaters of Chelsea Creek, the *HMS Diana* became heavily engaged within the narrows of Snake Creek. Having difficulty maneuvering, due to the incoming tide and lack of wind, the *HMS Diana* nearly ran aground and needed to be towed out of its predicament by the accompanying long boats. Provincial troops, now reinforced by 200 troops and artillery brought by General Israel Putman, quickly took advantage of the *HMS Diana*'s distress. The distressed ship in tow of twelve longboats was pounded by a cannon positioned at Newgate Landing and with small arms fire from several other surrounding locations.

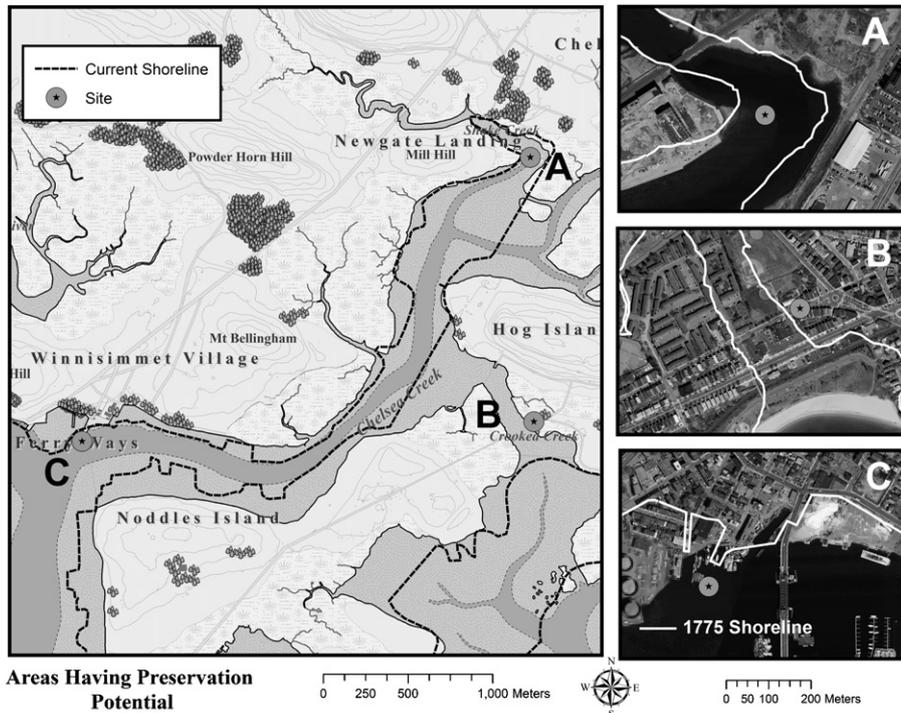


Fig. 12. Three locations have preservation potential within the study site. The sites are displayed on the larger historical base map and in the accompanying larger scale insets where each site is displayed overlaid on recent orthophotographs. The sites having preservation potential include, (A) Snake Creek Engagement, (B) Crooked Creek Engagement, and (C) the Ferry Ways at Winnisimmet Village. Further research is required to definitively identify cultural resources associated with the battle.

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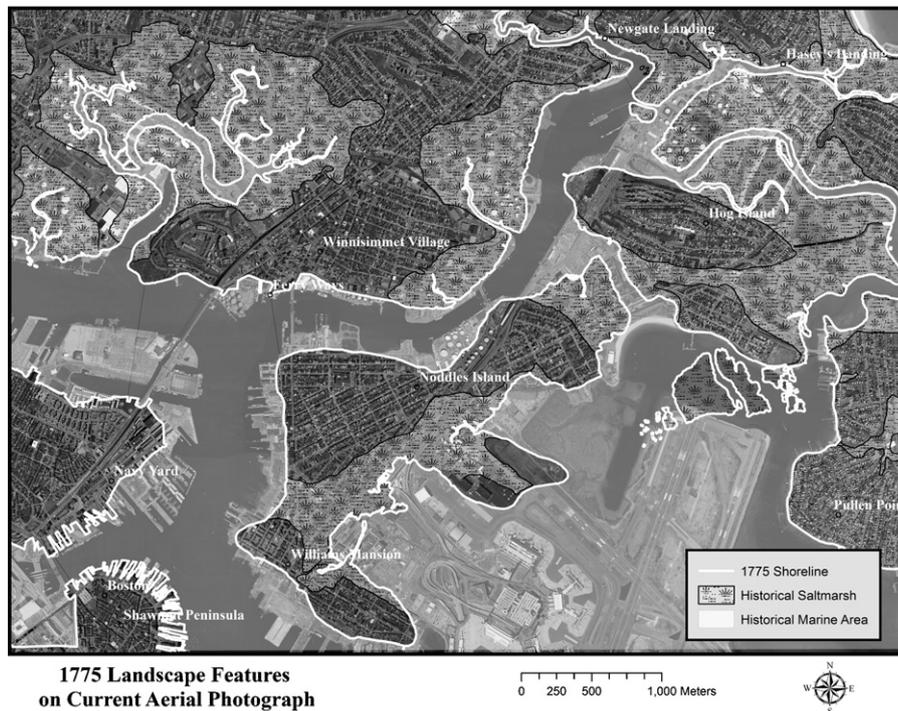


Fig. 13. 2008 orthophotograph shown overlaid with historical landscape features. This figure provides a clear visualization of the dramatic urbanization which occurred in Boston during the past two centuries. Also demonstrated with the figure is the effectiveness of comparing historical and current geospatial datasets to document coastal change. This provides a tool for understanding landscape change through time and is valuable to the research and management of cultural landscapes.

defining features and allows for a more confined estimate of areas of the historical landscape which played a significant role in the Battle of Chelsea Creek. By limiting the areas included within the designation of “battlefield,” a realistic management plan can be devised for future conservation and education activities.

2.3.4. Time series maps

The Phase 3 map depicts battle events that occurred between 17:00–21:00 hours on May 27, 1775 and will serve as an example of the results obtained from the Time Series analysis (Fig. 11). During this phase of the battle, there were two separate military engagements, one at Crooked Creek and the other in the vicinity of the Newgate Landing along the north shore of Snake Creek. This map was useful to the investigation because it provided a visualization of the interactions between battle events and the landscape upon which they occurred.

In our research, we found the time series maps important for the successful integration of the spatial and temporal aspects of the battle. They were critical to our ability to understand how the landscape impacted the sequential series of battle events. On several occasions, their development forced us to rethink our initial interpretation of the vague historical narrative as the physical landscape sometimes contradicted the historical accounts. Many of the primary sources of the battle were recorded in the journals of Provincial troops who were not familiar with the landscape [24]. This resulted in some discrepancies between the firsthand accounts recorded in the journals and the actual physical landscape we sought to map.

An example of these types of contradiction was the conflicting accounts of the cannon position put in place by Provincial troops led by General Israel Putnam. Based on some historical accounts, we initially identified a single cannon position on Mt. Bellingham, overlooking the Ferry Ways [25]. This location matched some of the historical records, but was beyond the cannons accurate range to fire on the HMS *Diana*. Based on the sequence of battle events and corroborating historical accounts of a cannon firing upon the HMS

Diana at close range on two separate occasions, we later determined that the cannon was first placed on Newgate Landing and then later moved to the Ferry Ways wharf. We therefore eliminated the Mt. Bellingham position all together. This demonstrates the effectiveness of using historical GIS and interdisciplinary research for the purposes of understanding the interactions between landscape and event during the Battle of Chelsea Creek.

2.3.5. Preservation and archeological potential

The majority of the “battlefield” within the study area has been heavily impacted by development. In some cases, potential archeological sites may remain preserved and accessible under fill and or beneath open space areas. Other areas that have been dredged or heavily developed may be inaccessible. We have identified three locations where cultural resources may be preserved either on the active harbor floor or under several meters of fill (Fig. 12). More detailed topographic and landuse analyses, integrated with archeological ground-truthing and geophysical surveys, will be necessary to conclusively determine the preservation potential of archeological and cultural resources associated with the Battle of Chelsea Creek.

3. Discussion

The abundance of cartographic sources for the Boston area provided a rich source of resources that proved crucial for the accurate depiction of the historical landscape and topography. This interdisciplinary investigation utilized the most accurate historical maps depicting the Boston area. The numerous Coast Survey maps dating from the early 19th century were most important as they provided accurate base-level information. The accurate depiction of the historical landscape could likely not have been achieved in other parts of the world with less extensive cartographic and historic sources.

Modeling a little known and complicated historical event through time and space demanded an interdisciplinary approach. The close collaboration among the project historian, archeologist,

GIS analyst, and outside consultants was also a key component of the project's success. The project also benefited from contributions made by local historical societies and community groups. The synergistic approach used in this study is applicable to a broad array of investigations which requires expertise in more than one discipline to achieve success.

Achieving an accurate representation of the spatial and temporal aspects of the Battle of Chelsea Creek had many challenges. For example, it was difficult to limit the features on the base map to only those that existed in 1775. Clearly by the necessity of relying on the 19th Century Coast Survey maps, some of the wharfs and roads depicted on our base map may not have been present in those precise locations in 1775. This was especially the case in the rapidly growing areas of Boston and Charlestown. In addition, due to the vague nature of the historical accounts, the exact (less than 10 m) location of defining features could not always be precisely derived. Their position on the map only provides a general location which likely has some degree of uncertainty associated with it. The final resting place of the burned wreck of the HMS *Diana* remains unclear while other locations were more accurately mapped. For example, the historic Chelsea Meetinghouse, though heavily modified, still exists at the same location as in 1775 and currently houses a health clinic. It was very difficult to positively identify the location of the defining features unless the feature still existed as was the case with the Chelsea Meetinghouse.

The development of the DEM also presented many challenges. Despite the simplicity of the methods used to develop the DEM, and the likely vertical uncertainties associated with it, they nonetheless were adequate for the purposes of this study. Clearly, a more accurate representation of the saltmarsh and intertidal areas of the study site could have been achieved, but was beyond the scope of this project.

Further research and analysis could dramatically improve the accuracy of the historical DEM. A more detailed and accurate historical DEM could then be used for a variety of purposes, including the assessment of vertical modifications to the historical landscape. Improvements would include the processing of the LIDAR derived portions to remove landscape modifications that occurred after 1775, including railroad cuts and highways. In addition, a bathymetric representation of marine areas could be achieved through the use of the extensive Coast Survey soundings depicted on hydrographic sheets. The integration of bathymetric and terrestrial DEM's would provide a seamless dataset representing the topography of the historical landscape.

We found that one of the greatest benefits to recreating an historical landscape within a GIS is the ability to visualize and understand the dramatic landscape changes which have taken place through time. By displaying the digitized 1775 landscape features overlain on a current orthophotograph, these coastal changes are clearly apparent (Fig. 13). Few cities in the world have experienced the anthropogenic coastal landscape changes that occurred in Boston. Further geospatial and geo-statistical analysis can now be carried out to quantify these changes.

4. Conclusions

This study embraced an interdisciplinary research approach to successfully create an accurate digital representation of the 1775 landscape and topography of Boston's Inner Harbor and enabled for the mapping and visualization of a complicated set of events taking place in time and space. A KOCOA assessment was carried out and defining features have been identified and mapped. Further, time series maps were created to visualize key battle events. Areas of the battlefield having preservation potential have also been identified.

A high-resolution GIS dataset and Citation Data Model (CDM) of the temporal and spatial features associated with the Battle of Chelsea Creek and the 1775 Boston landscape have been developed. Base-level and battlefield maps were produced within the GIS through the integration of multiple data sources including primary and secondary historical accounts, maps, high resolution orthophotographs, and LIDAR data. The final dataset will aid in the development of long-range management strategies and facilitate the assessment of threats posed by anthropogenic activities and environmental change.

This relatively little known but significant historical event provided a unique opportunity to apply GIS technologies. In conjunction with traditional historical research, the application of GIS methodologies have resulted in the completion and success of what we believe to be the most comprehensive and detailed interdisciplinary research study ever undertaken in regard to the Battle of Chelsea Creek. Its application has provided a clearer understanding of how the physical landscape influenced the Battle of Chelsea Creek and has provided valuable insights into battlefield events and preservation.

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