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Status, Evolution, and Storm Vulnerability Assessments of the Shoreline at George Washington Birthplace National Monument

Technical Report

ON THE COVER
Eroding high banks along the Potomac River at the George Washington Birthplace National Monument on 18 September 2008.
Photography by: Shoreline Studies Program, Virginia Institute of Marine Science.

Status, Evolution, and Storm Vulnerability Assessments of the Shoreline at George Washington Birthplace National Monument

Technical Report

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Abstract

The shoreline at George Washington Birthplace National Monument (GEWA) is eroding and vulnerable to storms. Recent storms, such as Hurricane Isabel and Tropical Storm Ernesto impacted the region in 2003 and 2006, respectively. Large losses of the Potomac River shoreline along GEWA prompted the National Park Service to assess the vulnerability of the shoreline and its associated cultural, natural and archeological resources to erosive forces. This project maps the existing shoreline along the Potomac River and at the Memorial House on Popes Creek, provides an assessment of shoreline and bank dynamics, determines the rate of shoreline change between 1937 and 2007, and presents an analysis of vulnerability for the park. The shoreline at GEWA is varied, with high, vertical eroding banks and low, swampy drainage areas, with fronting beaches along the Potomac River, which are eroding at an average rate of 0.3 m/yr (1 ft/yr). However, storm-induced losses can be greater; as much as 9 m (30 ft) of bank were lost along sections of the park between 2002 and 2007. In Popes Creek, extensive and fringing marshes are eroding at lower rates, 0.1–0.2 m/yr(0.3–0.7 ft/yr). Coastal vulnerability, from a management perspective, took into account, bank height, shore type, erosion rates, proximity to infrastructure, and potential loss of archaeological resources. Three areas (1,200 m [3,800 ft]) of shoreline were rated as most vulnerable and two areas (300 m [1,000 ft]) were rated as vulnerable.

Executive Summary

George Washington Birthplace National Monument (GEWA) is located on the southern shore of the Potomac River on its tributary, Popes Creek, in Westmoreland County, Virginia. It preserves ancestral lands occupied by the Washington family from 1657 through 1779. The current cultural landscapes are a combination of relicts of early colonial activities and archaeology and a built environment comprised of colonial revival architecture and interpretive props associated with early efforts in historic preservation and landscape architecture.

The shoreline at GEWA is eroding and is vulnerable to storms. Recent storms, such as Hurricane Isabel and Tropical Storm Ernesto, impacted the region in 2003 and 2006, respectively. Large losses of the bank prompted the National Park Service to assess the vulnerability of the shoreline and its associated cultural, natural, and archeological resources. The goal of this study is to document and provide a representation of the present shoreline and banks, as well as provide an assessment of shore and bank dynamics at GEWA. The report couples analyses of shoreline dynamics with modern technologies to estimate rates of change and to document storm wave-driven change at the site. The report also evaluates the feasibility of using Light Detection and Ranging (LIDAR) data in shoreline management along GEWA's steep, high banks. The report provides an analysis of shoreline vulnerability due to future erosion, particularly during storms, and can be used to assist in developing a strategy for managing erosion at GEWA.

In order to estimate the long-term rate of shoreline change, shorelines digitized from orthorectified images of GEWA from 1937, 1953, 1969, 1987, 1994, 2002, and 2007 were used. The rate of change between shorelines was estimated. A physical shoreline and nearshore topographic survey was performed in 2008 along 2.7 km (1.7 mi) of Potomac River shoreline and 0.3 km (0.2 mi) of Popes Creek shoreline to evaluate the present status of the shoreline. A real-time kinematic global positioning system and a Total Station were used to set site control and acquire data. These systems provide sub-decimeter horizontal and vertical accuracy. LIDAR data were collected on March 26, 2008, by National Aeronautics and Space Administration (NASA), Wallops Flight Facility in Virginia, for the National Park Service Northeast Coastal and Barrier Network monitoring program. USGS provided both the LIDAR bare earth ASCII files and 1 m (3 ft) gridded geotiffs. There was no additional processing of the LIDAR data for this project. These data were compared to the physical survey in order to consider the feasibility of using LIDAR for shore zone management. Hydrodynamic modeling of the GEWA shoreline characterized wave power along the shore.

The winds and water levels of two recent storms were analyzed for their impact on GEWA's shoreline. Hurricane Isabel and Tropical Storm Ernesto impacted the region in 2003 and 2006, respectively. Isabel was the most significant storm to impact Chesapeake Bay since the "storm of the century" in 1933. Analysis of sea-level records by Boon (2003) shows that Isabel's coastal flooding matched that of the August 1933 storm due to the long-term increase in sea level in the lower Chesapeake Bay. Sea level is rising at 4.8 mm/yr (0.19 in/yr) or 0.5 m (1.57 ft) per100 years.

While individual rates of change are highly variable, the overall net rate of change (1937–2007) is −0.3 m (−1 ft) per year, which is consistent with the overall reach rate, but the easternmost section of GEWA's shoreline had the maximum rate of −1.2 m (−4 ft) per year. However, between 2002 and 2007, the regions of maximum change of the top of bank were the westernmost section of the park associated with the pond and the easternmost section of the park nearer the spit where the shoreline is oriented more to the northeast. About half of the bank shoreline (excluding the low, sandy areas) had little or no change between 2002 and 2007, while about nine percent eroded up to 9 m (30 ft).

In Popes Creek, what was once a fairly contiguous marsh occupying the flood delta has disintegrated to marsh islands. The loss of marsh within the creek has converted the area to open water. At the Memorial House, shoreline change has been slow. Between 1953 and 2007, the rate of change on the Memorial House peninsula ranged from −0.1 to −0.2 m (−0.3 to −0.7 ft) per year.

The comparison between the survey and the LIDAR show both agreement and differences relative to the survey. The land behind the banks is fairly flat, which LIDAR is accurate at capturing. However, in the data received from the USGS, along many sections of the shoreline LIDAR data points do not exist immediately adjacent to the top of the bank, and in areas that do have data, the top of bank is not well modeled. The average difference in elevation along the top of bank on the Potomac River between the LIDAR data and the physical survey was 0.1 m (0.3 ft), while the average location of the top of bank was 4 m (13 ft) landward of the surveyed top of bank. The range between the two methods was large, 1.7 m (5.5 ft) in elevation and 19.8 m (65 ft) in distance. It is possible that reprocessing the raw data may more accurately predict the location of the top of bank.

Cultural resources include not only archaeological sites but also landscape features and structures. Natural resources, such as native floral species, paleontology, and habitat also are being lost to erosion. Vulnerability from a management perspective took into account bank height, shore type, erosion rates, proximity to infrastructure, and potential loss of archaeological resources. While most of GEWA's shoreline is eroding, three areas (1,200 m [3,800 ft]) of shoreline were rated as most vulnerable and two areas (300 m [1,000 ft]) were rated as vulnerable.

Acknowledgments

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Introduction

George Washington Birthplace National Monument (GEWA) (Figure 1) preserves ancestral lands occupied by the Washington family from 1657 through 1779. Over 5,000 years of human history have been documented at the park, dating to the late Archaic Period. Although interpretive and managerial programs include a wide span of natural resources (including paleontological) and human histories, the main periods of significance include the time of George Washington's 1732 birth and early 20th Century commemorative efforts. Interpretive programs tend to concentrate on these two periods and include associated natural resources when they support interpretive themes. The current cultural landscapes are a combination of relicts of early colonial activities and archaeology and a built environment comprised of colonial revival architecture and interpretive props associated with early efforts in historic preservation and landscape architecture.

Erosion of the banks at the park has resulted in the loss of archaeological resources and in landscape changes. Between 1862 and 1942, the shoreline eroded at an average rate of 1 m (3.5 ft) per year (Byrne and Anderson 1978). According to Blank et al. (2007), the site of George Washington's baptism reportedly eroded away prior to the establishment of the park. In light of erosion that occurred along sections of the shoreline during Hurricane Isabel (September 18, 2003) and Tropical Storm Ernesto (September 1, 2006), the National Park Service wanted to assess the vulnerability of the shoreline at GEWA to storms due to concerns about the potential loss of important natural and cultural resources. This report can be used to formulate a plan for documenting losses, evaluate controls for beach and shore dynamics, and educating the public about shoreline erosion at the park.

The goal of this study is to document and provide a representation of the present shoreline and banks, as well as provide an assessment of shore and bank dynamics at GEWA. The report couples analyses of shoreline dynamics with modern technologies to estimate rates of change and to document storm wave-driven change at the site. The report also evaluates the feasibility of using Light Detection and Ranging (LIDAR) data in shoreline management along GEWA's steep, high banks. The report provides an analysis of shoreline vulnerability to future erosion, particularly during storms, and it can be used to assist in developing a strategy for managing erosion at GEWA.

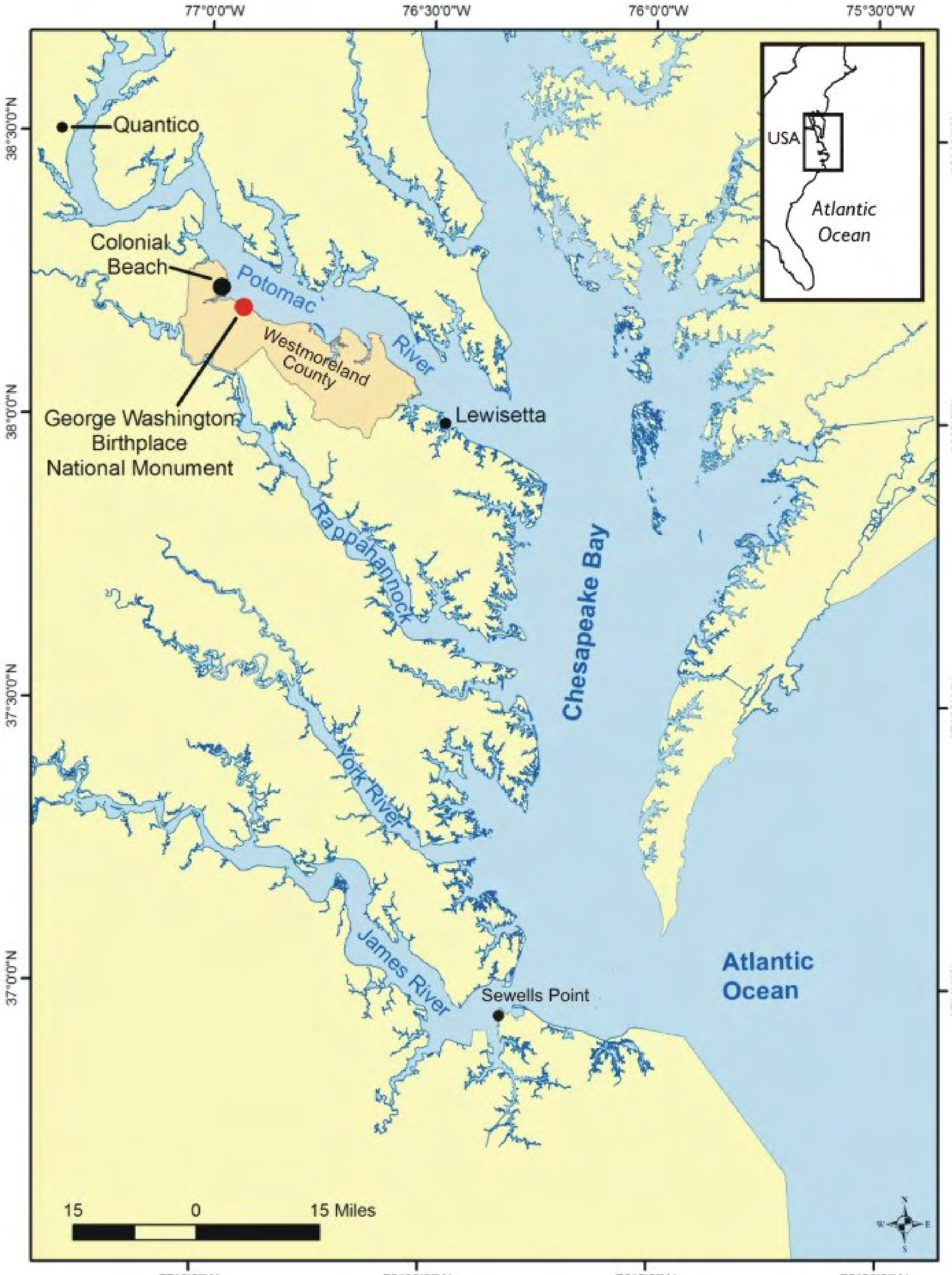


Figure 1. Location of George Washington Birthplace National Monument within the Chesapeake Bay estuarine system on the Potomac River in Westmoreland County, Virginia.

Study Area

GEWA is located along the Potomac River and Popes Creek, a tidal tributary of the Potomac River, in Westmoreland County, Virginia (Figure 2). Part of the federal system of national parks, GEWA has 223 ha (551 ac) of various habitats including beach, dune, marsh, estuary, open grassland, forest, and developed areas. Along the Potomac River, GEWA has about 2,910 m (9,550 ft) of shoreline, including inholdings. Several morphologic areas have been defined for discussion purposes and are shown on Figure 2A. Bridges Creek, Digwood Swamp, and Longwood Swamp are low drainage areas along the shores of the Potomac River and Popes Creek. The pond on the western section of the park has a low bank which transitions from the low Bridges Creek drainage to the high bank along the field. Digwood Swamp separates the field from the area that is being actively farmed. The headlands on either side of the swamp transition slightly from the higher field and farm, but there is still an abrupt change in elevation from the headlands to the swamp. The forested embayment represents a change in shoreline orientation that has ramifications for the response to storm wave approach. This embayment is completely wooded and has the highest, steepest shoreline in the park. This area transitions to the beach and spit that fronts Longwood Swamp. The low, backshore areas, or swamps, account for 1,151 m (3,775 ft) of Potomac River shoreline while the higher bluffs account for 1,760 m (5,775 ft). The park also includes about 762 m (2,500 ft) of shoreline along Popes Creek, including the present Longwood Swamp behind the sandy barrier and inholdings. This linear shoreline measure excludes the remnants of the marsh islands in Popes Creek

GEWA's shoreline is part of a larger reach along the Potomac River between Mattox Creek and Nomini Bay (Figure 2B). This reach also consists of high upland banks with infrequent low drainages. This region is relatively rural with pockets of residential development.

Figure 2. (A) An aerial photo of George Washington Birthplace National Monument indicating boundaries and location of selected features within the park; (B) An aerial photo showing the setting of the park within the regional shore zone.

Methods

Photo Rectification

In order to understand the suite of processes that work to alter a shoreline, knowledge of the history of shoreline change is essential. Often, analysis of aerial photographs provides the historical data. Images of GEWA from 1937, 1953, 1969, 1987, 1994, 2002, and 2007 were used in the analysis. The 1969, 1987, and some of the 1937 images were orthorectified for a previous project (Hardaway et al. 2006). Using the same procedure, the rest of 1937 and 1953 photos were rectified. The 1994, 2002, and 2007 images were available from other sources. The 1994 imagery was orthorectified by the U.S. Geological Survey (USGS) and the 2002 and 2007 imagery was orthorectified by the Virginia Base Mapping Program (VBMP). An 1879 map of the area was scanned and georectified for this project.

The 1937, 1953, 1969, and 1987 images were scanned as tiffs at 600 dpi and converted to ERDAS IMAGINE (.img) format. They were orthorectified to a reference mosaic, the 1994 Digital Orthophoto Quarter Quadrangles (DOQQ) from the USGS. The original DOQQs were in MrSid format and were converted into .img format. ERDAS Orthobase image processing software was used to orthographically correct the individual flightlines using a bundle block solution. Camera lens calibration data were matched to the image location of fiducial points to define the interior camera model. Control points from 1994 USGS DOQQ images provide the exterior control, which is enhanced by a large number of image-matching tie points produced automatically by the software. A minimum of four ground control points were used per image, allowing two points per overlap area. The exterior and interior models were combined with a digital elevation model (DEM) from the USGS National Elevation Dataset to produce an orthophoto for each aerial photograph. The orthophotographs that cover each USGS 7.5 minute quadrangle area were adjusted to approximately uniform brightness and contrast and were mosaicked together using the ERDAS Imagine mosaic tool to produce a one-meter resolution mosaic also in .img format. To maintain an accurate match with the reference images, it was necessary to distribute the control points evenly. This can be challenging in areas with little development. Good examples of control points were manmade features, such as corners of buildings or road intersections, and stable natural landmarks, such as easily recognized isolated trees. With a limited number of control points available on the 1879 map, particularly along the shoreline, the positional accuracy of the shore lacks certainty. However, farther away from the shoreline there is good visual agreement between the location of Bridges Creek Road and several points of land in Popes Creek.

Once the aerial photos were orthorectified and mosaicked the shorelines were digitized in ArcMap with the mosaics in the background. The toe of the narrow beaches, which can indicate the position of mean low water (MLW), was delineated as the shoreline. Mean high water (MHW) in many areas was on the bank, making it impossible to digitize. GEWA has a generally north-facing shoreline with narrow beaches and steep banks—some heavily forested. These factors, along with photo quality, combine to increase the difficulty of delineating the shore. In areas where the shoreline was not clearly identifiable on the aerial photography, the location was estimated based on the experience of the digitizer. The MLW shorelines are in shapefile format. One shapefile was produced for each year that was mosaicked.

In order to estimate the changes that occurred during Hurricane Isabel and Tropical Storm Ernesto the location of the top of bank was digitized on the 2002 and 2007 images. Hurricane Isabel is the largest storm to impact the bay since the hurricane in 1933. Ernesto also had significant impacts around the bay. In addition, these storms are recent enough that accurate photos are available. This methodology is not particularly accurate due to tree cover and shadows at the top of bank. However, it is the best means of estimating shore change in lieu of a physical survey.

Horizontal positional accuracy is based upon orthorectification of scanned aerial photography using USGS DOQQs. Vertical control is the USGS 30 m (100 ft) DEM. The 1994 USGS reference images were developed in accordance with National Map Accuracy Standards (NMAS) for Spatial Data Accuracy at the 1:12,000 scale. The 2002 and 2007 Virginia Base Mapping Program's orthophotography were developed in accordance with the National Standard for Spatial Data Accuracy (NSSDA). Horizontal root mean square error (RMSE) for historical mosaics was held to less than 6 m (20 ft).

Using methodology reported in Morton et al. (2004) and National Spatial Data Infrastructure (1998), estimates of error in orthorectification, control source, DEM, and digitizing were combined to provide an estimate of total maximum shoreline position error. The data sets that were orthorectified (1937, 1953, 1969, and 1987) have an estimated total maximum shoreline position error of 6.1 m (20.0 ft), while the total shoreline error for the three existing datasets are estimated at 5.6 m (18.3 ft) for USGS, and 3.1 m (10.2 ft) for VBMP. The maximum annualized error for the shoreline data is ±0.2 m (±0.7 ft) per year.

In order to calculate the change rate, the distance of each shoreline from an arbitrary baseline was measured along transects spaced 150 m (500 ft) apart. The transect number is the distance along the baseline. These data were exported to Microsoft Excel so that end point rates of change could be calculated between the photo dates and over the long-term (1937–2007). The 1879 shoreline was not included in rates of change because the datum was not indicated on the map. The 2002–2007 rates of change along the top of the bank are presented in ranges due to reduced confidence in the digitized location of top of bank in areas where there is tree cover. The long-term rate of change along the reach from Mattox Creek to Nomini Bay was calculated from 1937 and 2002 digitized shorelines at 305 m (1,000 ft) transects.

Site Surveying

A physical shoreline and nearshore topographic survey was performed along 2.7 km (1.7 mi) of Potomac River shoreline and 0.3 km (0.2 mi) of Popes Creek shoreline. The Potomac River shoreline was surveyed on April 7–8, June 16, July 8, and September 18, 2008. The shoreline along Popes Creek near the Memorial House was surveyed on on April 7–8, 2008. The data points for the entire survey are shown in Figure 3. A Trimble "R8 GNSS" real-time kinematic global positioning system (RTK-GPS) was used to set site control and acquire shore data. In addition, a Trimble 5600 Robotic Total Station was used to acquire data in the nearshore and in areas where tree cover did not allow satellite acquisition for the RTK-GPS. These systems provide sub-decimeter horizontal and vertical accuracy.

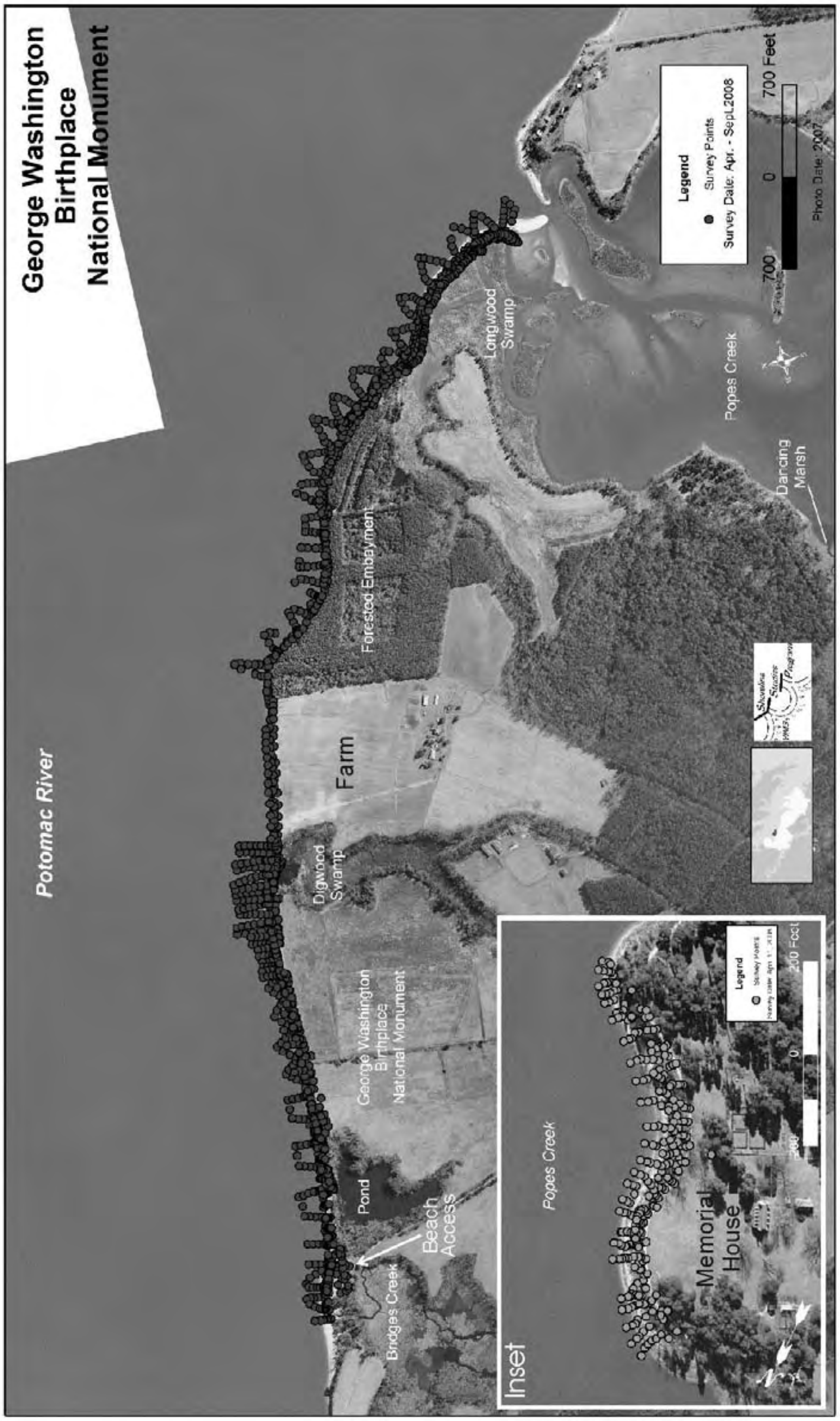


Figure 3. Locations of Real-Time Kinematic GPS and robotic total station survey points taken along the Potomac River shoreline between April and September 2008 (and inset) at the Memorial House on Popes Creek in April 2008.

Base station benchmarks were established with 2-hour occupations. These data were processed through the National Geodetic Survey's On-line Positioning User Service (OPUS) (http://www.ngs.noaa.gov/OPUS/). All survey data were referenced to these benchmarks. In addition, 3-minute occupations were taken at secondary benchmarks in order to determine survey error.

The project's horizontal datum is UTM, Zone 18 North, NAD83, international feet. The vertical datum is feet mean lower low water (MLLW), geoid03. Data were collected in NAVD88 and converted to MLLW using accepted datums as published by NOAA for the 1983–2001 tidal epoch at Colonial Beach. NAVD88 is 0.30 m (0.99 ft) above MLLW. (http://tidesandcurrents.noaa.gov/data_menu.shtml?stn=8635150%20Colonial%20Beach,%20VA&type=Datums). Tidal datums are used in Chesapeake Bay particularly when determining storm-surge levels. In addition, MLLW is a natural break between the beach and nearshore and is the jurisdictional boundary between private and state lands in Virginia. Generally, the survey extended to approximately the −3 ft MLLW contour and included the base of bank and top of bank. In order to analyze the profile data, arbitrary baselines with cross-sectional profiles were established along the Potomac River shoreline (Figure 4) and along the Popes Creek shoreline at the Memorial House (Figure 5). These baselines have 87 transects spaced 33 m (100 ft) apart and are different than those used in the long-term shoreline change analysis.

LIDAR data were collected on April 14, 2005 and March 26, 2008 by National Aeronautics and Space Administration (NASA), Wallops Flight Facility in Virginia, for the National Park Service Northeast Coastal and Barrier Network monitoring program. Elevation measurements were collected over George Washington Birthplace National Monument using the NASA Experimental Advanced Airborne Research LIDAR (EAARL), a pulsed laser ranging system mounted onboard an aircraft to measure ground elevation and coastal topography. The system uses high frequency laser beams directed at the Earth's surface through an opening in the bottom of the aircraft's fuselage. The laser system records the time difference between emission of the laser beam and the reception of the reflected laser signal back at the aircraft. The EAARL measures ground elevation with a vertical resolution of 15 cm (6 in). A sampling rate of 3 kHz or higher results in an extremely dense set of spatial elevation data. The data were reduced, and maps were produced by the USGS. The 2008 LIDAR map is shown in Figure 6. For the 2005 and 2008 data, the USGS provided 1 m (3 ft) gridded geotiffs as well as bare earth ASCII files. However, the 2005 geotiff was cropped along the shoreline, and the ASCII data were 1.8 million overlapping points. As such, the 2005 data was deemed to be of limited use for our analysis. There was no additional processing of the LIDAR data for this project; the data that was provided was used in the analyses.

The areas of interest along the Potomac River (in 2005 and 2008 data) and Popes Creek (2008 only) were clipped from the 1 m (3 ft) gridded geotiffs provided by the USGS and the x, y, and z data were exported. These data were input to Terramodel, converted to MLLW to match the physical survey data, exported along the same 87 profile cross-sections as the survey data, and plotted for comparison. For the 2008 data, the distance from the baseline and elevation of the top of bank were exported from the data for both the ground survey and LIDAR data. In the ground survey, the top of bank was delineated. In the LIDAR data, the top of bank was assumed

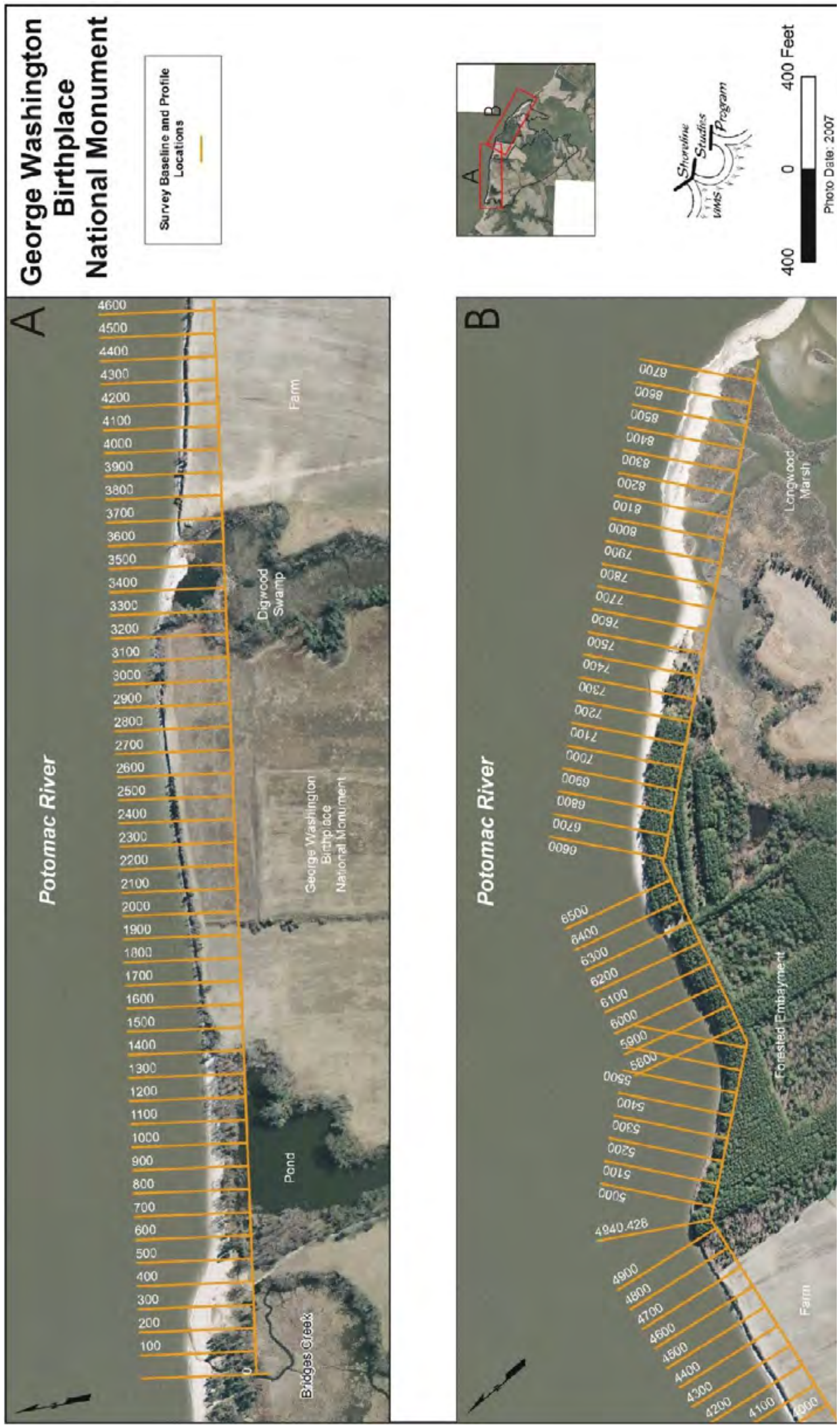


Figure 4. Location of profile cross-sections along the Potomac River coast.

Figure 5. Location of profile cross-sections along Popes Creek.

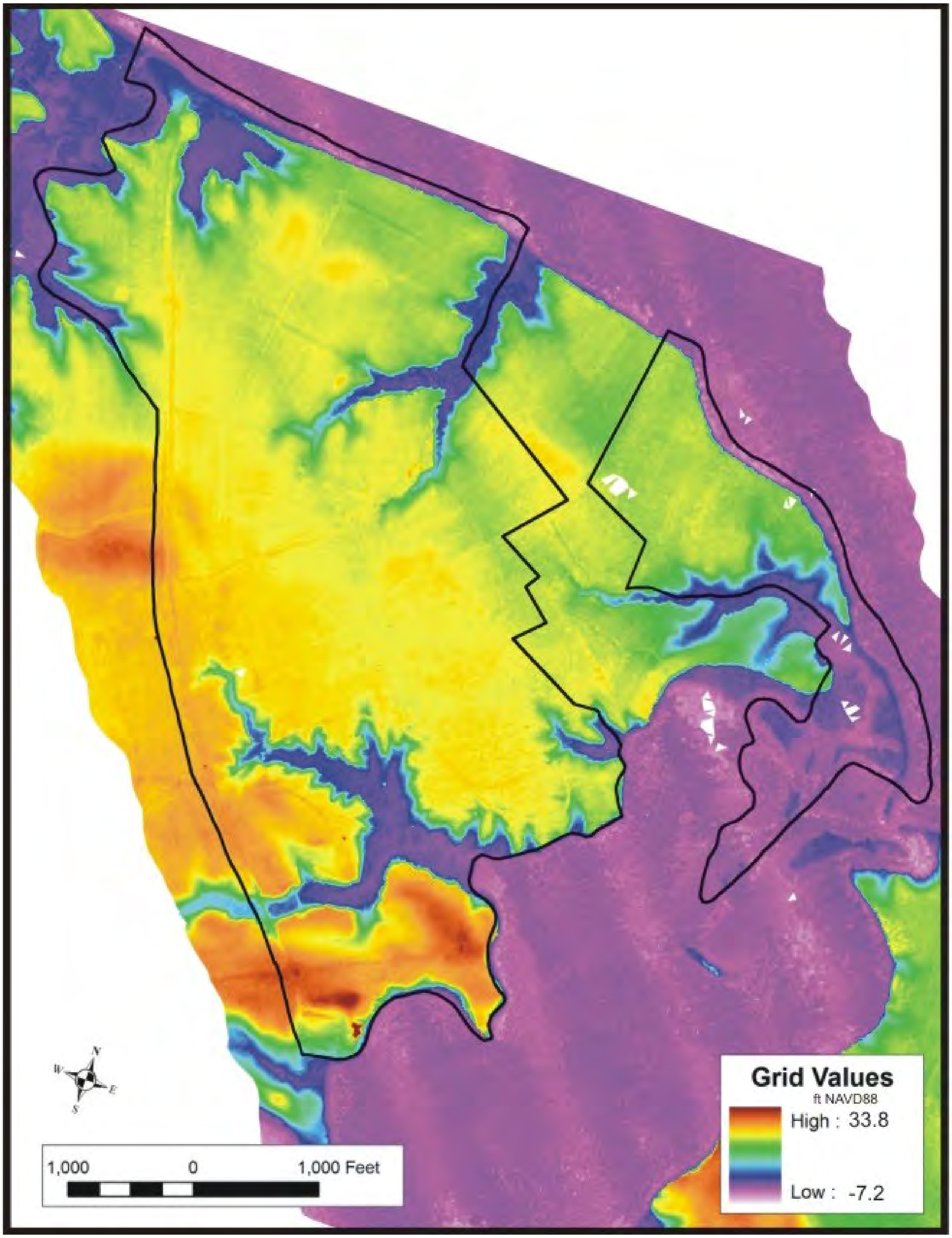


Figure 6. Digital Elevation Model of the 2008 LIDAR data.

to be the most riverward point at the height of the bank. In addition, the distance to MLLW was estimated for the two sets of data. These were compared and the differences were calculated. Estimating the average and median as well as the maximum and minimum differences provided a ground-truthing of the LIDAR as it pertains to quantifying vertical banks and narrow beaches along the Potomac River and the less steep, vegetated marsh fringe shoreline along Popes Creek.

Hydrodynamic Modeling

In order to model the wave height and period associated with specific storms, the Nearshore Evolution MOdeling System (NEMOS) was used. NEMOS is a set of codes that operates as a system to simulate the long-term planform evolution of the beach in response to imposed wave conditions, coastal structures, and other engineering activities. NEMOS is part of the Coastal Engineering Design and Analysis System (CEDAS) (Veri-Tech, Inc. 2009). Specifically, the grid generator was used to develop a bathymetric grid over which wave conditions were modeled.

In order to model storm impacts, georeferenced soundings and depth contour information were obtained from NOAA's Electronic Navigational Charts (NOAA ENC) online database (http://www.nauticalcharts.noaa.gov/csdl/ctp/encdirect_new.htm). These data were used to create a grid of the Potomac River near GEWA (Figure 7A). STeady state spectral WAVE (STWAVE) was used to model storm waves across this grid. STWAVE simulates depth-induced wave refraction and shoaling, current-induced refraction and shoaling, depth- and steepness-induced wave breaking, diffraction, parametric wave growth because of wind input, and wave-wave interaction and white capping that redistribute and dissipate energy in a growing wave field. In order to estimate the likely impact of different storms on GEWA's Potomac River shoreline, wave simulations were generated for several sets of conditions. The model simulations were for wind-driven storm waves from the northwest, north, northeast, and east resulting only from persistent high winds during four different storm conditions (Table 1). The storm surges are based on the predicted levels in FEMA (1987) with the exception of the 100-year event. The storm surge level for the 100-year event was based on a maximum water level surveyed at Colonial Beach by Shoreline Studies personnel following Hurricane Isabel.

The wave height, period, and direction output from the larger Potomac River grid was used as input conditions to STWAVE on the smaller, local grid (Figure 7B) in order to model the impact of the storms on the GEWA shoreline. The wave output from the larger grid would interact with the ongoing storm conditions (wind and surge) across the smaller local grid. The modeled wave conditions were exported from STWAVE at 13 stations along GEWA's shoreline. These data were converted to wave power using the Coastal Engineering Manual (Veri-Tech, Inc. 2004) wave parameter formula calculator in "Wave Energy and Power" (section II-1-2-c-9) which used the following equation where P = wave power, E=energy density, C=wave celerity:

$$P = EC$$

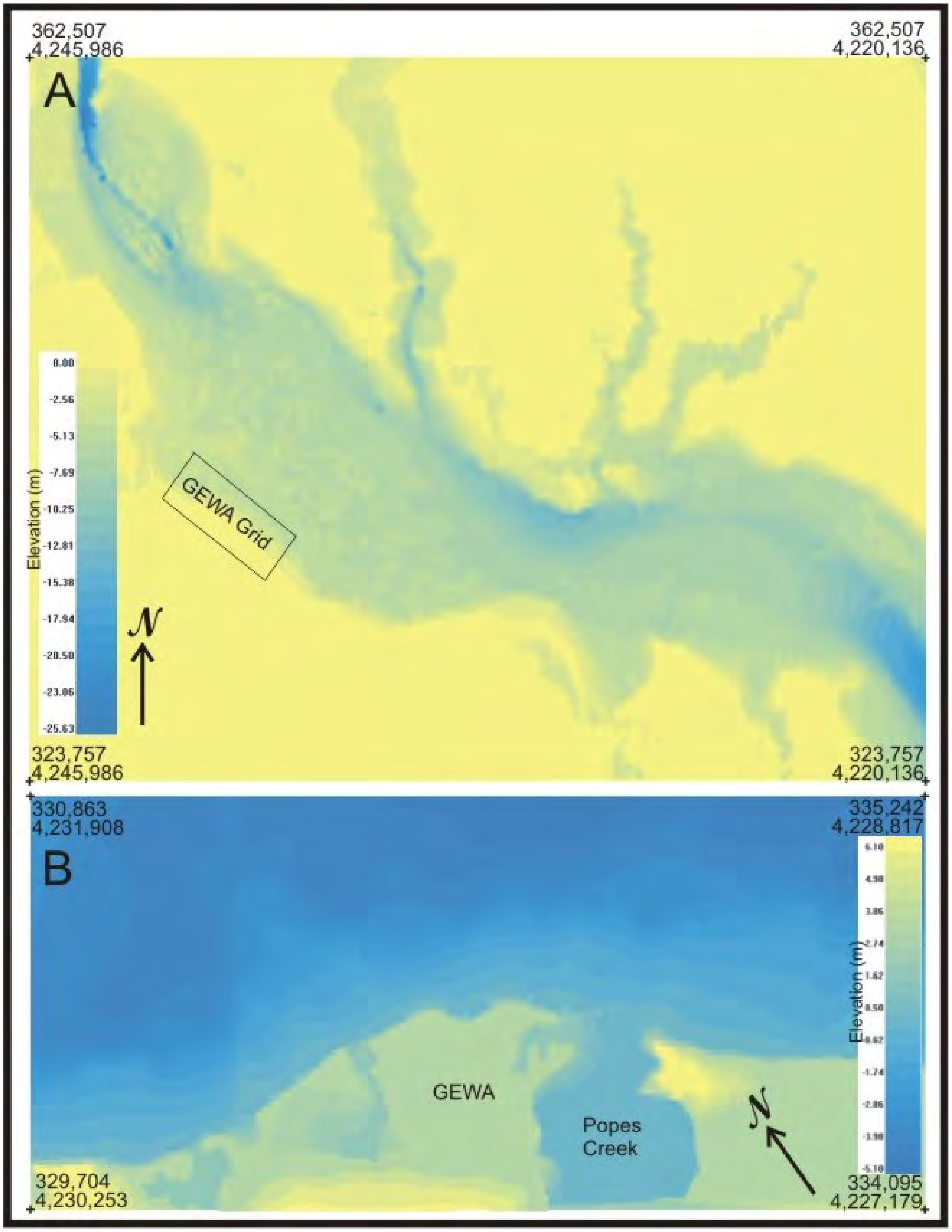


Figure 7. (A) Large Potomac River grid and (B) smaller scale GEWA grid used in NEMOS hydrodynamic modeling. Horizontal datum UTM zone 18N, NAD83, meters; vertical datum NAVD88, meters.

Table 1. Storm event parameters modeled in STWAVE. The 100 year event represents the maximum surge during Hurricane Isabel in 2003.

Storm Event		Wind Speed	Surge
Year	Frequency	mph (m/s)	ft (m) MLLW
10	10%	35 (16)	4.8 (1.5)
25	4%	45 (20)	5.5 (1.7)
50	2%	55 (25)	6.5 (2.0)
100	1%	69 (31)	8.8 (2.7)

Vulnerability Analysis

In order to estimate the areas of the shore that are most vulnerable to erosion, bank height, shore type, erosion rates, proximity to infrastructure, and potential loss of archaeological resources were taken into consideration when sections of shoreline were assessed as vulnerable or highly vulnerable. Generally, archaeological resources were given the highest priority since their loss is irrevocable. Conversion or loss of significant habitats was also a high priority.

Coastal Setting

Hydrodynamic Setting

The wave climate in the Chesapeake Bay estuarine system is both fetch limited and depth limited. The main forces operating along the study area are the waves resulting from storms. The assessment of hydrodynamic conditions is based on analysis of the winds and hydrodynamic modeling. The mean tide range at Colonial Beach, VA, just up river from GEWA, is 0.5 m (1.63 ft) with a spring range of 0.59 m (1.94 ft). Effective fetch (the over-water distance across which the wind blows) is an important indicator of the size of the waves that might be generated. GEWA has effective fetches of 10.5 km (6.5 mi) to the northwest, 11.7 km (7.3 mi) to the north, 10.3 km (6.4 mi) the northeast, and 16.6 km (10.3 mi) to the east.

Data collected at Quantico between 1973 and 2001 (Table 2) show that at wind speeds of 4–9 m/s (10–20 mph), north and northwest winds dominate; and, during higher wind events or storms, winds from the northwest, north, and west dominant. Two types of storms impact the area. Tropical systems, while relatively infrequent, can cause substantial damage to a shoreline with high water levels, large waves, high winds, and saturating rains. Nor'easters, or extra-tropical storms, have lower winds and, typically, a smaller storm surge than hurricanes, but they often last through several tidal cycles. Table 3 presents the estimated recurrence intervals of storm surge elevations as developed by the Federal Emergency Management Administration (FEMA) for Colonial Beach, Virginia.

Storm Characteristics

Hurricane Isabel, which had reached Category 5 on the Saffir Simpson scale in the open Atlantic, made landfall on September 18, 2003 along the southeastern coast of North Carolina as a Category 2 storm. By the time Isabel reached the Chesapeake Bay it was a minimal Category 1 hurricane. The storm path put southeastern Virginia and lower Chesapeake in the "right front" quadrant of the storm. This was the ideal situation for transporting seawater into the Bay and tributaries in the form of a substantial storm surge. At Lewisetta (Figure 1), about 55 km (35 mi) southeast and downstream from GEWA, winds were in the tropical storm range of about 24 m/s (54 mph) with gusts to 31 m/s (69 mph) (Figure 8A).

NOAA analyzed tide data obtained from all over the Chesapeake Bay during the passage of Hurricane Isabel. Hovis et al. (2004) stated that storm surge was generally lower and more variable in the lower Chesapeake Bay (Virginia) than the upper Bay (Maryland). Also, surges at open bay sites were lower than those located in more restricted rivers. Data show that Isabel's tide levels exceeded historical maximum water levels at Lewisetta, which has been in operation since 1970 (Hovis et al. 2004). The tide gauge at Colonial Beach, about 8 km (5 mi) upstream from GEWA, failed about 6:00 p.m. on September 28, 2003. At time of failure, recorded water level was 1.7 m (5.5 ft) above MLLW; normal low and high tide predictions were 2:19 p.m. and 8:47 p.m. The tide gauge at Lewisetta, about 55 km (35 mi) downstream, reached 1.7 m (5.5 ft) MLLW about 4:30 p.m. (Figure 9A). Predicted (no storm) times of high and low tide at Lewisetta were 1:12 p.m. and 7:52 p.m.—each roughly an hour before Colonial Beach.

Table 2. Summary wind conditions at Quantico from 1973–2001.

Wind Speed (mph)	Mid Range (mph)	Wind Direction: North	North East	East	South East	South	South West	West	North West	Total
< 5	3	35670[*]	3282	3798	4725	12120	4194	6813	15305	85907
		18.1[+]	1.7	1.9	2.4	6.1	2.1	3.5	7.8	43.5
5-10	8	12522	7785	5461	6772	18480	6720	10506	13811	82027
		6.3	3.9	2.8	3.4	9.3	3.4	5.3	7.0	41.5
10-20	15	6790	2984	1050	1287	4400	2175	2151	7434	28271
		3.4	1.5	0.5	0.7	2.2	1.1	1.1	3.8	14.3
20-30	25	293	95	47	35	93	79	109	439	1190
		0.1	0.0	0.0	0.0	0.0	0.0	0.1	0.2	0.6
30-40	35	15	3	3	2	3	3	7	9	45
		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
40-60	50	1	0	1	1	2	0	1	2	8
		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total		55291	14149	10360	12822	35068	13171	19587	37000	197448
		28.0	7.2	5.2	6.5	17.8	6.7	9.9	18.7	100.0

[*]Number of occurrences
[+]Percent

Table 3. Storm surge levels at Colonial Beach (FEMA 1987) converted from NGVD to MLLW.

Frequency (years)	Exceedance Frequency in any one year (%)	Elevation ft NGVD (m)	Elevation ft MLLW (m)
500	0.2	8.9 (2.7)	9.4 (2.9)
100	1	7.0 (2.1)	7.5 (2.3)
50	2	5.9 (1.8)	6.4 (2.0)
10	10	4.2 (1.3)	4.7 (1.6)

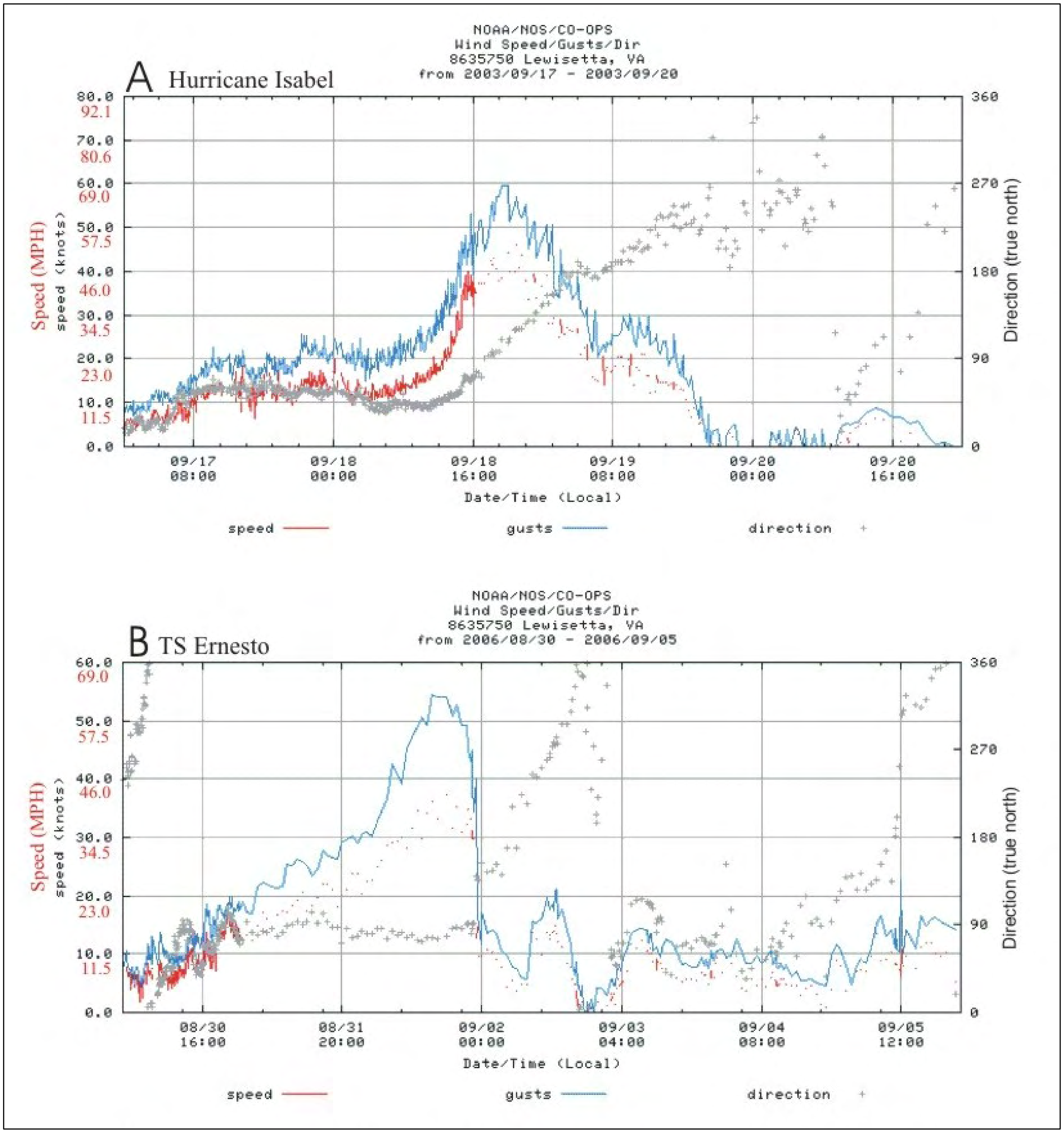


Figure 8. Wind speeds and directions at Lewisetta during (A) Hurricane Isabel; (B) Tropical Storm Ernesto.

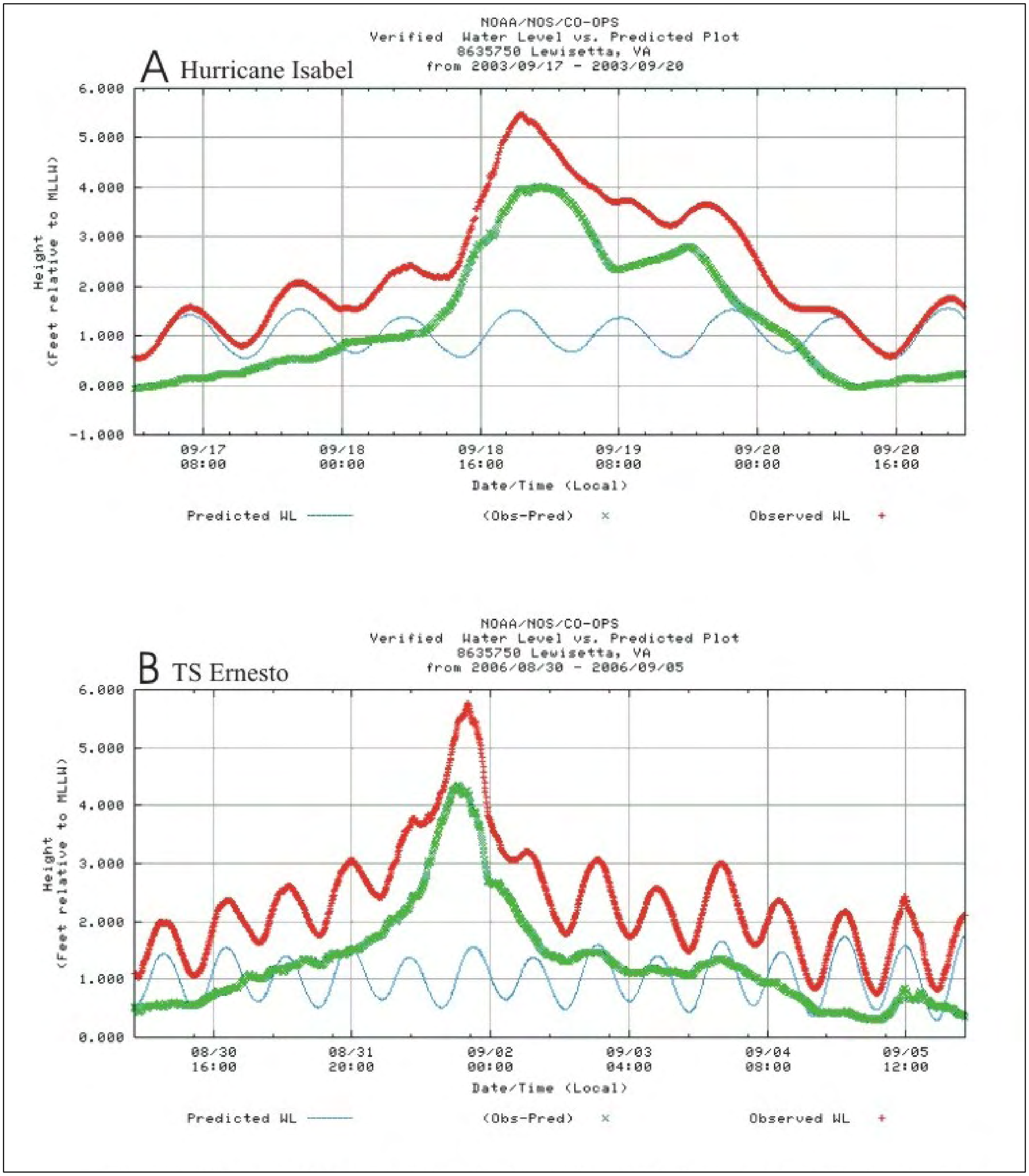


Figure 9. Tide gauge data at Lewisetta, Virginia, during (A) Hurricane Isabel and (B) Tropical Storm Ernesto. The red line shows the measured water level in feet relative to MLLW; the blue line represents the predicted tide; the green line shows the difference between the observed and predicted water levels and is commonly referred to as the storm surge.

During the day of the storm (Isabel), the water level reached 0.9 m (3 ft) MLLW at about 3:00 p.m. at Lewisetta and about 4:00 p.m. at Colonial Beach. Winds at Lewisetta were 5–8 m/s (12–17 mph) with gusts to 10 m/s (23 mph) from the northeast. The water level at the two gauges was 1.2 m above (4 ft) MLLW at 5:00 p.m. (Lewisetta) and 6 p.m. (Colonial Beach) and the winds at Lewisetta were 18–21 m/s (40–46 mph) with gusts to 26 m/s (58 mph) from the east. The maximum water level at Lewisetta, 1.7 m (5.5 ft) MLLW occurred at about 8:00 p.m. with winds of 21–23 m/s (46–52 mph) and gusts of 31 m/s (69 mph) from the east southeast. As noted above, the tide gauge at Colonial Beach failed at 6:00 p.m. The water level continued to rise above 1.7 m (5.5 ft) and, assuming the same relationship with Lewisetta, should have peaked about three hours later at about 9:00 p.m. Post-storm surveys at Colonial Beach indicated that the water level reached 2.7 m (8.8 ft) MLLW. The storm impacts at GEWA accompanied the rising storm surge as the winds veered from north to east southeast. Water levels receded as the winds continued to veer to the south and eventually southwest, blowing from the land to the river.

Ernesto was the first hurricane of the 2006 Atlantic hurricane season and made landfall at Plantation Key in the upper Florida Keys on August 30. The storm moved northward and reached the North Carolina/Virginia border on September 1. The storm evolved into an extratropical cyclone and, by September 2, was centered near Washington, DC. The strongest sustained wind measured by an official surface-based anemometer in North Carolina was 26 m/s (58 mph) at the National Ocean Service (NOS) station at Wrightsville Beach, where a gust of 33 m/s (74 mph) was reported (Knabb and Mainelli 2006). A large area of high pressure was centered over southeastern Canada as Ernesto advanced northward. The combined pressure system produced sustained gale-force winds near the coasts of Virginia, Maryland, Delaware, and New Jersey. The sustained wind measured at Lewisetta was 20 m/s (44 mph) with gusts of 28 m/s (62 mph) (Figure 8B). The storm generated about a 1.8 m (5.9 ft) MLLW water level at Lewisetta (Figure 9B).

Sea Level Rise

Sea level is rising around Chesapeake Bay. NOAA has calculated the rate of change based on long-term tide gauge data. At Colonial Beach, the monthly mean sea level was plotted with the variability due to regular seasonal fluctuations (due to coastal ocean temperatures, salinities, winds, atmospheric pressures, and ocean currents) removed (Figure 10A). These data indicate 4.8 mm (0.19 in) per year or 0.5 m (1.57 ft) per 100 years. This is more than double the global sea level rise rate of 1.84 mm (0.08 in) per year and is due to interdecadal fluctuations of ocean density and circulation, continuing isostatic adjustment of the land level from the last deglaciation, and subsidence due to the extraction of ground water (Church and White 2006). However, since tide gauges are a relative measure of sea level, it is impossible to discern sea level rise from land subsidence at Lewisetta without additional data (NOAA website 2009).

Average seasonal cycle of mean sea level, caused by regular fluctuations in coastal temperatures, salinities, winds, atmospheric pressures, and ocean currents, is shown in Figure 10B along with each month's 95% confidence interval. These data indicate a higher mean sea level in the summer and fall; these months correspond to the highest risk of extratropical activity along the

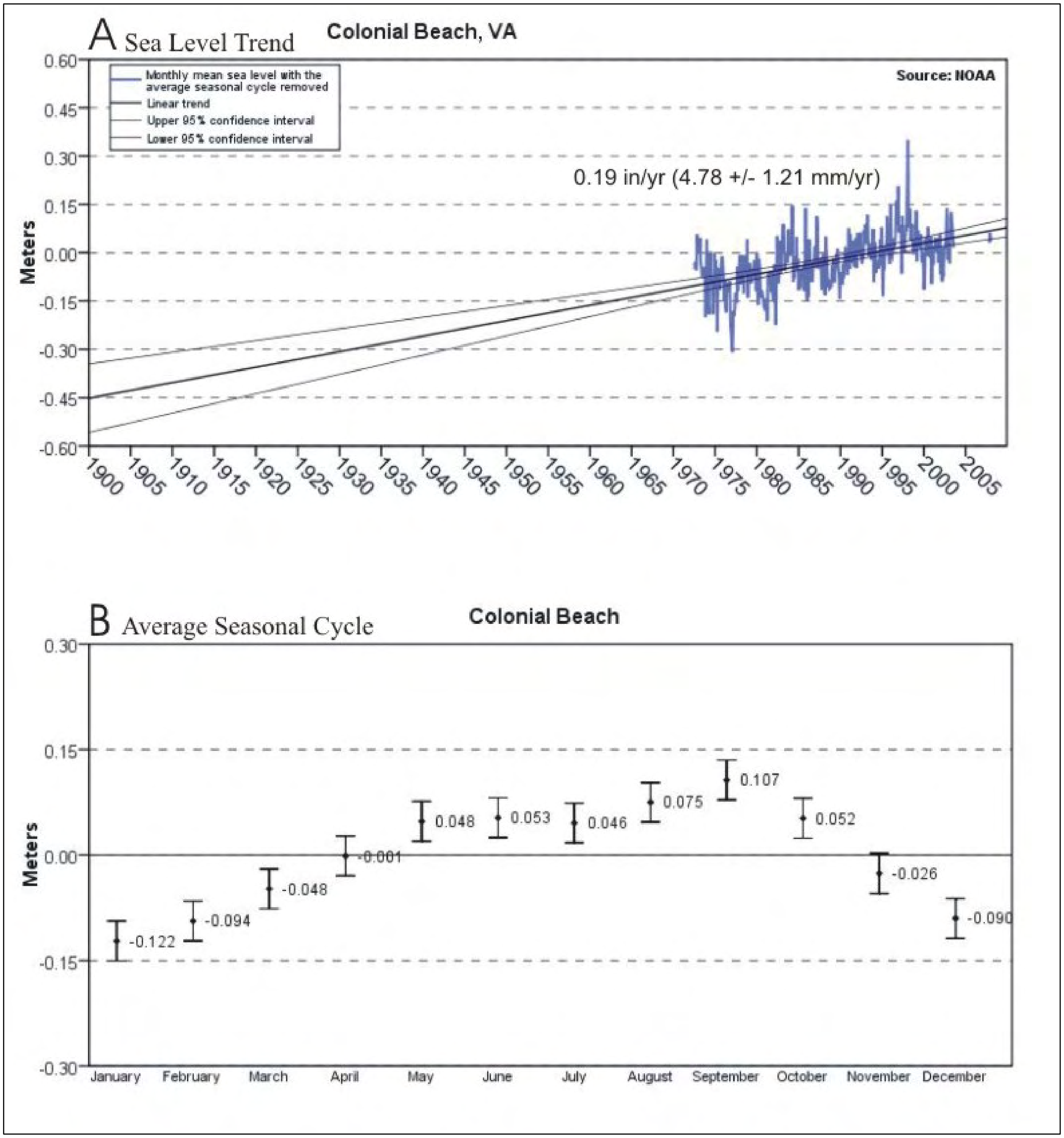


Figure 10. (A) The long-term linear sea level trend and its 95% confidence interval at Colonial Beach and (B) the Average Seasonal Cycle in mean sea level. The plotted values are relative to the most recent mean sea level datum established by CO-OPS (1983–2001).

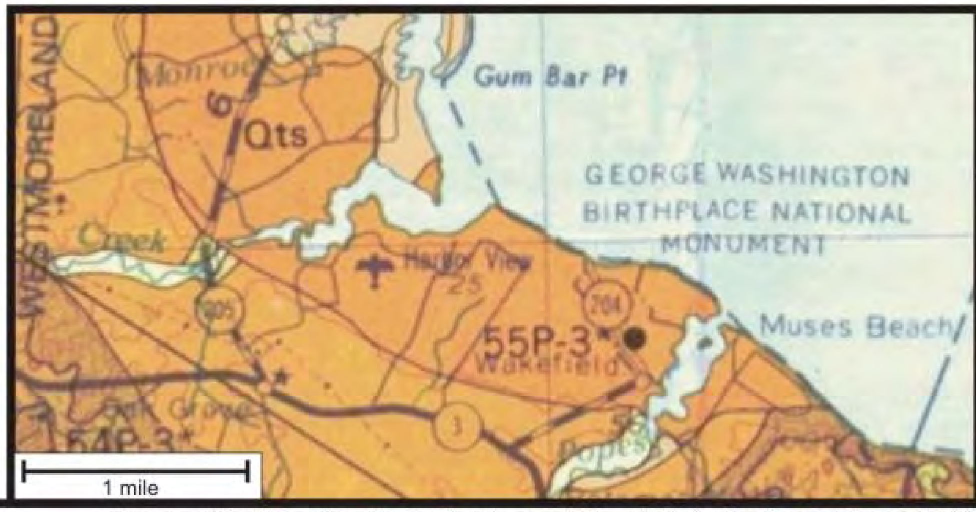
East Coast and Chesapeake Bay. Superimposed on the storm surge and astronomical tide, long-term sea level change can significantly increase the reach of storm waters (Boon 2003).

Prior to Hurricane Isabel, the hurricane of 1933, widely known as the "storm of the century" for Chesapeake Bay, generated a storm surge in lower Chesapeake Bay of 1.8 m (5.84 ft), more than a foot higher than the 1.5 m (4.76 ft) storm surge recorded for Hurricane Isabel. Yet many long-time residents say that the high-water marks left by Isabel equaled or exceeded those of the 1933 storm (Boon 2003). Analysis of sea-level records shows that Isabel's coastal flooding matched that of the August 1933 storm due to the long-term increase in sea level in lower Chesapeake Bay (Boon 2003). Data from the NOAA tide guage at Sewells Point show that sea level in the lower Bay rose 0.4 m (1.35 ft) between August 1933 and September 2003. The 1933 storm surge also occurred at the beginning of spring tides, while Isabel's surge occurred in the middle of a neap tide. However, the increase in sea level in the lower Chesapeake Bay in the seventy years between the two storms was enough to boost Isabel's storm tide to within an inch and a half of the level experienced during the 1933 storm (Boon 2003).

Physical Setting

The upland and nearshore morphology is a function of GEWA's underlying geology which is the history of the ancestral Potomac River and Chesapeake Bay. The Late Tertiary and Quaternary strata of the mid-Atlantic Coastal Plain were deposited in a series of major, glacially driven, marine transgressions. During high stands of sea level, marine processes cut into the shore, eroding older sediments and depositing them in the nearshore. During the subsequent marine regression, the terraces were incised by rivers and streams. This has resulted in a terrace-and-scarp geomorphology in which each terrace is the upper surface of a stratum that has been reworked and exposed by a regressing sea and each scarp essentially marks the landward limit of a marine transgression. This process continues with the ongoing marine transgression (i.e. sea level rise). As sea level rises, the shore erodes and the material is deposited elsewhere. At GEWA, the banks are the exposed Upper Pleistocene, Sedgefield Member of the Tabb Formation (Figure 11) which overlies older strata (Mixon et al. 1989). These Formations consist of fine to coarse-grained sand and pebbles at the base and fine upward into silt and clay. This material is eroded and deposited in the nearshore and downdrift where it is differentially separated by waves with the coarse material deposited along the beach and bars and the finer silts and clays carried offshore. More detailed geologic information is available in Belval et al. (1997)

GEWA is set within the Potomac River reach between Mattox Creek and Nomini Bay (Figure 2B). Generally, longshore sediment transport along this reach is to the east and erosion of the banks provides the material to the system. However, this system has relatively little sand as evidenced by the small beaches that exist in front of the banks. The exceptions are the inlet barriers and the area along the shoreline that has been managed with groins. Hardaway et al. (1992) sampled sediments from representative banks along the southern shore of the Potomac River. Their analysis, along with results of sediment samples from Ibison et al. (1990), indicated that the weighted mean sand/silt/clay ratio is 54/15/31 or a sand/mud ratio of 54/46. More specifically, a sampling of the bank just upriver of Bridges Creek had a weighted mean sand/silt/clay ratio of



Qcc	Charles City Formation (lower Pleistocene(?)) – Light- to Medium-gray and light-to dark-yellowish and reddish-brown sand, silt and clay composing surficial deposits of riverine terraces and coast-parallel plains at altitudes of 70-80 ft. Unit is adjacent to, and inset below, the Windsor Formation and older deposits. Fluvial-esturine facies in terrace remnants along major rivers consists of crossbedded gravelly sand and clayey silt. Unit is 0-55 ft, or more in thickness.
Qts	Sedgefield Member - Pebbly to bouldery, clayey sand and fine to medium, shelly sand grading upward to sandy and clayey silt; locally, channel fill at base of unit includes as much as 50 ft of fine to coarse, crossbedded sand and clayey silt and peat containing in situ tree stumps. Sandy bay facies commonly contains Crassostrea biostromes, Mercenaria, Anadara, Polynices, Ensis, and other mollusks. Specimens of the coral Astrangia have yielded estimated uranium-series ages averaging 71,000 +/- 7,000 yrs B.P.. Unit constitutes surficial deposit of river- and coast-parallel plains (alt. 20-30 ft)

System	Series		Mixon and others (1989)	
Quaternary	Holocene		Coastal barriers, lagoons, alluvial, swamp, eolian	
	Pleistocene	U	Tabb Fm.	Poquoson Mem.
				Lynnhaven Mem.
				Sedgefield Mem.
			Shirley Fm.	
		M	Chuckatuck Fm.	
		L	Charles City Fm.	
			Windsor Fm.	
Tertiary	Pliocene	U	Moorings Unit	
			Bacons Castle Fm.	
			Chesapeake Group	Yorktown Fm.
		L		
	Miocene			Eastover Fm.

Regional stratigraphic column of formations and members.

Figure 11. Geologic map of GEWA in Westmoreland County and regional stratigraphic column of formations and members (from Mixon et al. 1989).

58/23/19. In addition, about a third of the shoreline updrift of GEWA has revetments along the shoreline, which tend to impound sediments and remove them from the longshore transport system.

The GEWA coast is between the geomorphic boundaries of Popes Creek and Bridges Creek. Popes Creek inlet has changed dramatically over the years as the southward (and landward) moving spit has forced the channel southward causing it to narrow against the opposite bank. Bridges Creek has a much smaller mouth that becomes blocked during periods of low rainfall. Blank et al. (2007) suggested that the lower half of Bridges Creek has been gradually filling in with fine-grained sediments, creating an extensive marsh, since 1950 when a road was constructed across the Creek. Rain events flood the watershed and force a channel out to the Potomac River, and the channel moves up or down river depending on the direction, frequency, and power of the impinging waves. However, the creek maintains a relatively persistent ebb shoal that modestly bounds the GEWA reach on the upriver end.

Sand has accumulated in the low areas associated with both park boundaries and Digwood Swamp creating wider beaches. During storms, wind-driven waves overtop these beaches causing sand to washover into the adjacent low drainages/marsh. These three beach zones occupy three different drainage/watershed stages in shore evolution and sea level rise. The upland regions between the low areas are the intefluves that erode and provide the sediment for beach, sand bars, and, in places, the substrate for fringing marshes. The upland regions transition to the beach areas. Three upland headlands occur within the reach at Digwood Swamp and the two upland headlands within the forested embayment (Figure 2A).

Results

Shoreline Change

Knowledge of the rates and patterns of shoreline change through time is essential for shoreline management. Previous research showed significant coastal erosion dating back as far as 1,000 years ago and the measurements dating from 1650 indicate sea level rise and coastal erosion has resulted in 122 m (400 ft) of shoreline loss along the Potomac River (Ellsworth 2003). The results of this study show that erosion is continuing along this shoreline. From Mattox Creek to GEWA, the average rate of change was −0.5 m (−1.6 ft) per year between 1937 and 2002. Since the 1980s, revetments have been constructed along this shore. Today, about a third of the reach is hardened. From GEWA to Nomini Bay, the average rate of change depends on the shoreline orientation. Shorelines facing northeast and north-northeast eroded at a rate of about 0.4 m (1.4 ft) per year. Shorelines facing north eroded at about 0.2 m (0.8 ft) per year, while shorelines facing north-northwest had relatively little change. Also in this reach, the bank heights rise significantly, some to 46 m (150 ft). Overall, the entire reach is eroding at about 0.3 m (1 ft) per year.

This study presents a detailed analysis of the rates of change of GEWA's shoreline. Figures 12–15 show a map from 1879 and the photos with the digitized shoreline from 1937, 1953, 1969, 1987, 1994, 2002, and 2007 and the common baseline. Figure 16 shows just the shorelines superimposed on one another, and Figure 17 plots the rates of change at each transect for the different time intervals. The long-term rate (1937–2007) is shown on both plots. While individual rates of change are highly variable, the overall net rate of change is −0.3 m (−1 ft) per year, which is consistent with the overall reach rate, but Longwood Swamp barrier had the maximum rate of −1.2 m (−4 ft) per year. Some part of the shoreline at Bridges Creek and in front of the pond has accreted through time except between 1994 and 2002 (Figures 16 and 17). The greatest rates of erosion are along the shoreline in front of Longwood Marsh particularly near the end of the barrier which retreated 2.7 m (9 ft) per year between 2002 and 2007. It also is important to note the attempts at erosion control at the down river end of the forested embayment (Appendix A, photos 19 and 20). Although the old wooden bulkhead and groins (probably installed in the 1960s) have deteriorated severely, they have influenced the long-term rate of erosion by providing some shore protection. These structures, located between transects 6800 and 8200, have likely slowed the long-term erosion rate.

Generally, the erosion rate tends to increase toward the eastern end of the park, particularly where the shore orientation changes from north facing to northeast facing. Between 2002 and 2007, the regions of maximum change of the top of bank were the westernmost section of the park associated with the pond and on the easternmost section of the park nearer the spit where the shoreline is oriented more to the northeast (Figure 18). Many sections of bank, over 1,000 m (3,300 ft) or 49% of the bank shoreline (not including the lower elevation areas of the shoreline), had low rates of

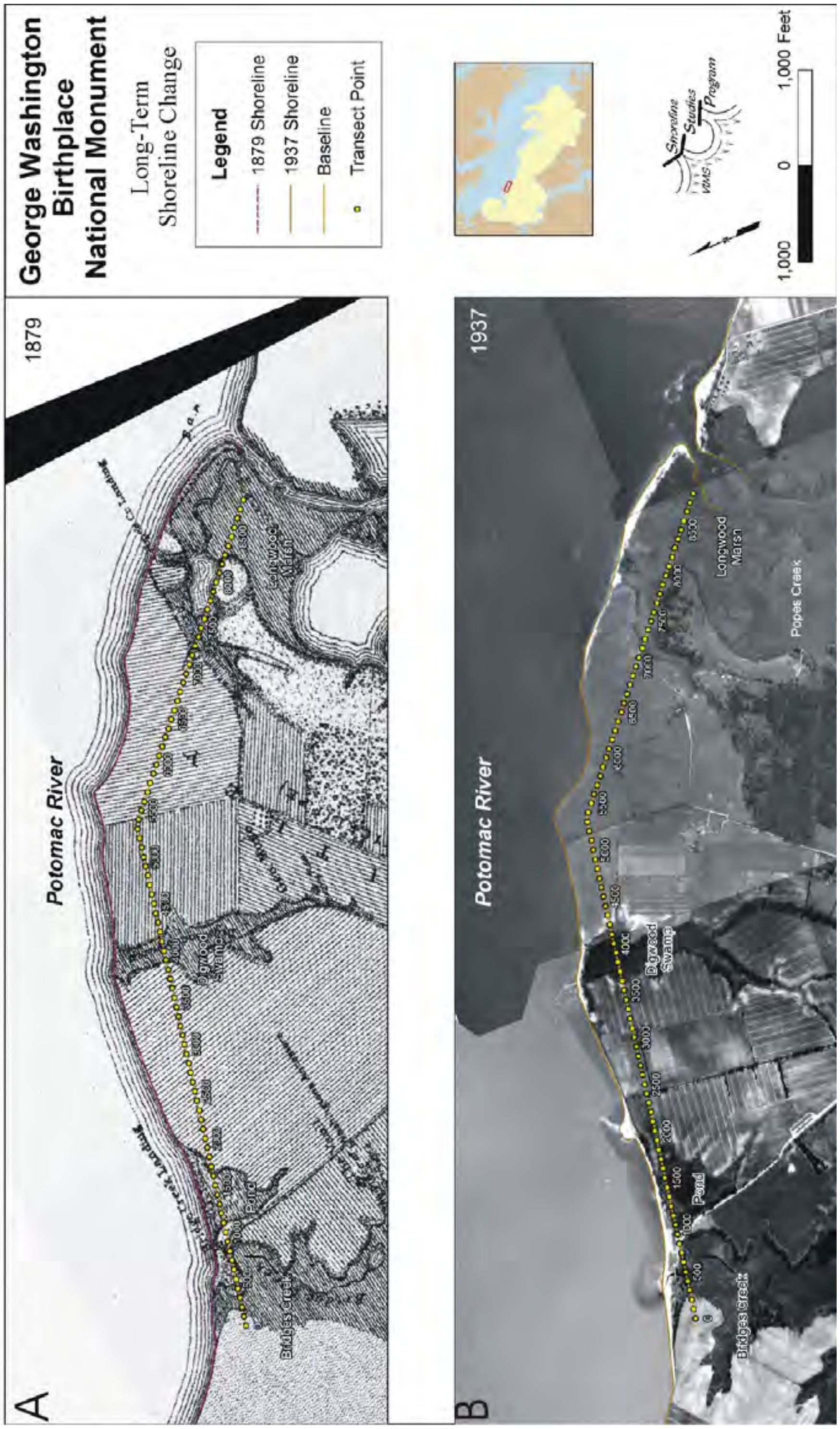


Figure 12. (A) Geo-rectified 1879 map and (B) 1937 orthorectified historic photos with digitized shoreline and the baseline used for rate of change analysis.

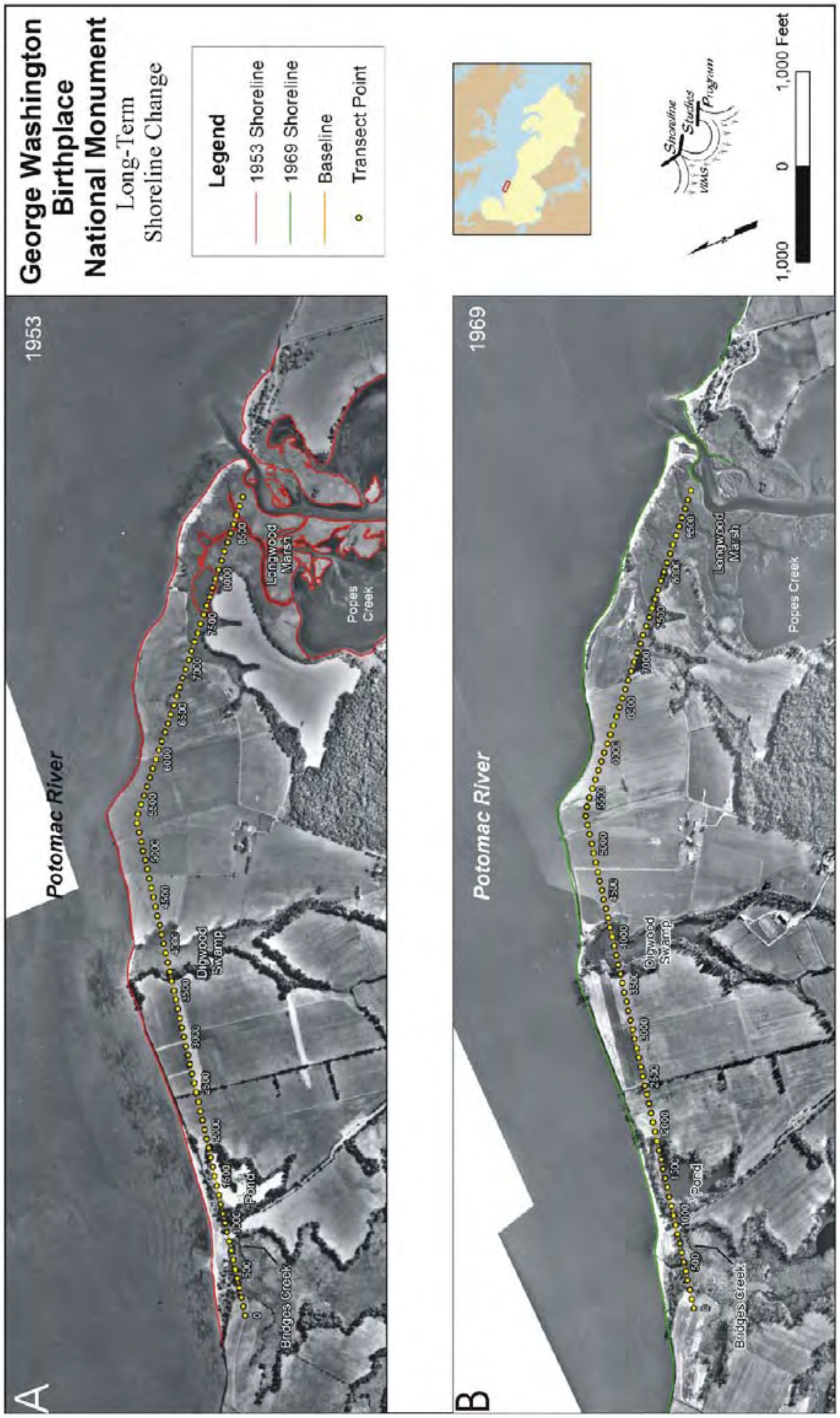


Figure 13. (A) 1953 and (B) 1969 orthorectified historic aerial photos with digitized shoreline and the baseline used for rate of change analysis.

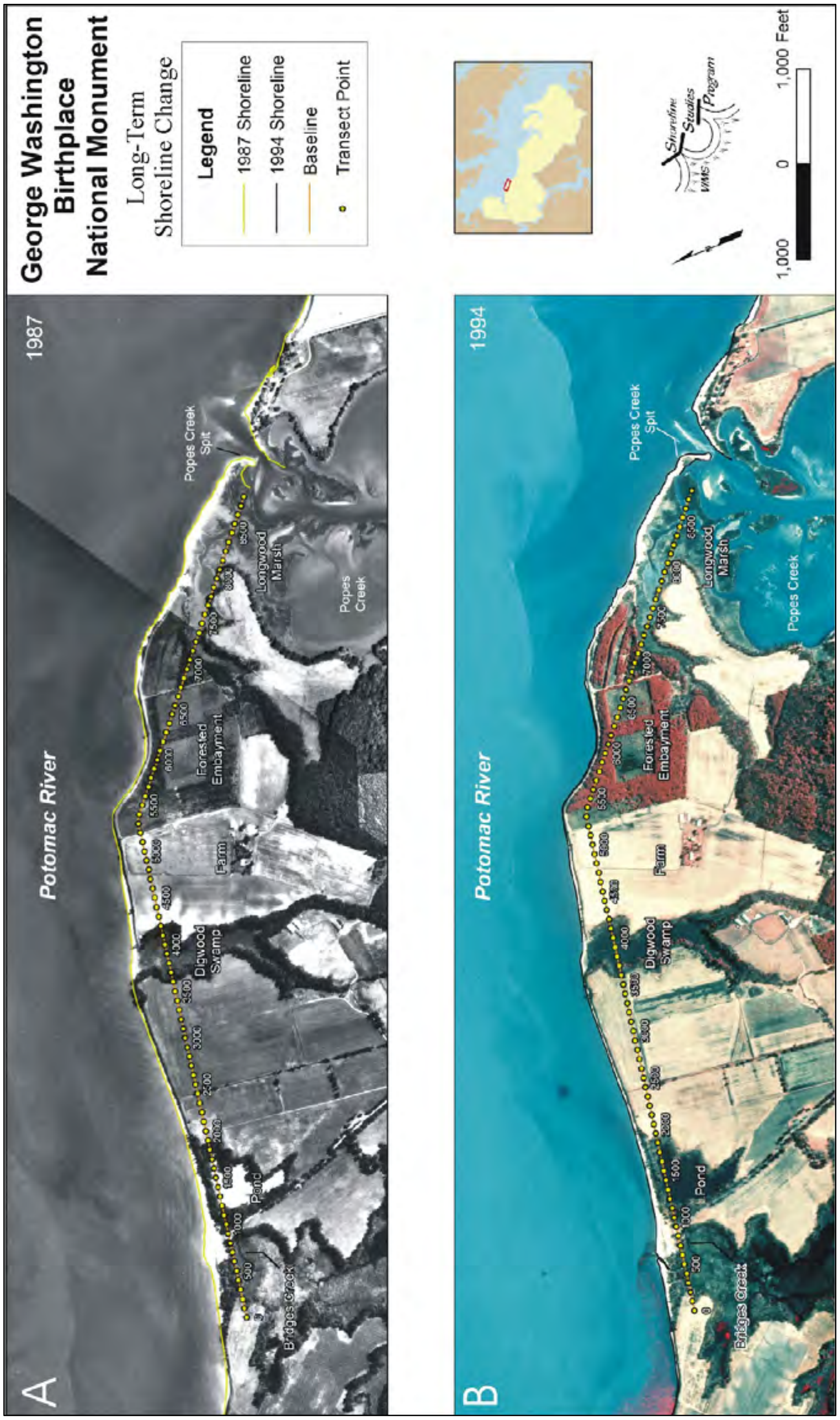


Figure 14. (A) 1987 and (B) 1994 orthorectified historic aerial photos with digitized shoreline and the baseline used for rate of change analysis.

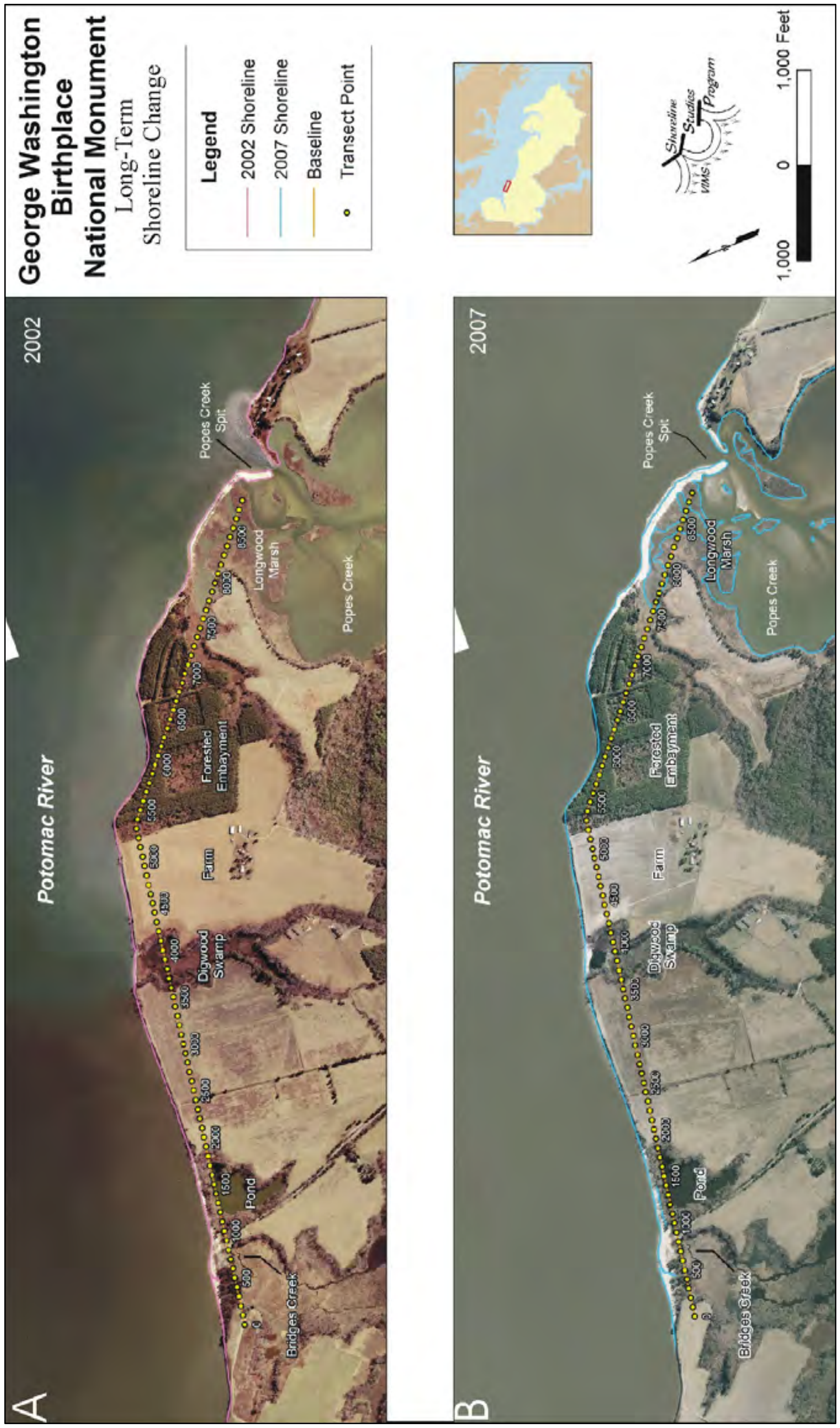


Figure 15. (A) 2002 and (B) 2007 orthorectified recent aerial photos with digitized shoreline and the baseline used for rate of change analysis.

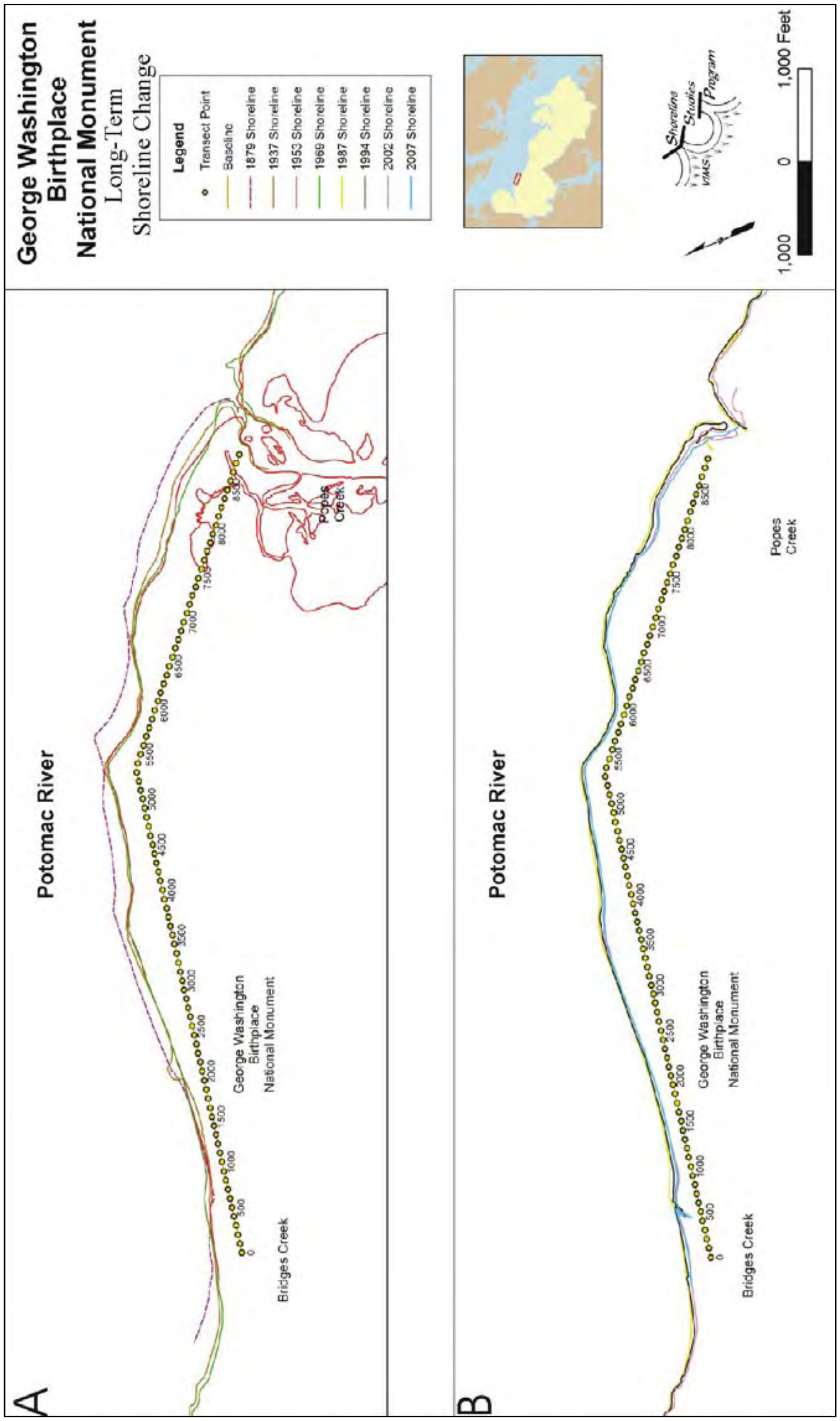


Figure 16. Comparison of digitized shorelines in (A) 1897, 1937, 1695, 1969, and (B) 1987, 1994, 2002, and 2007.

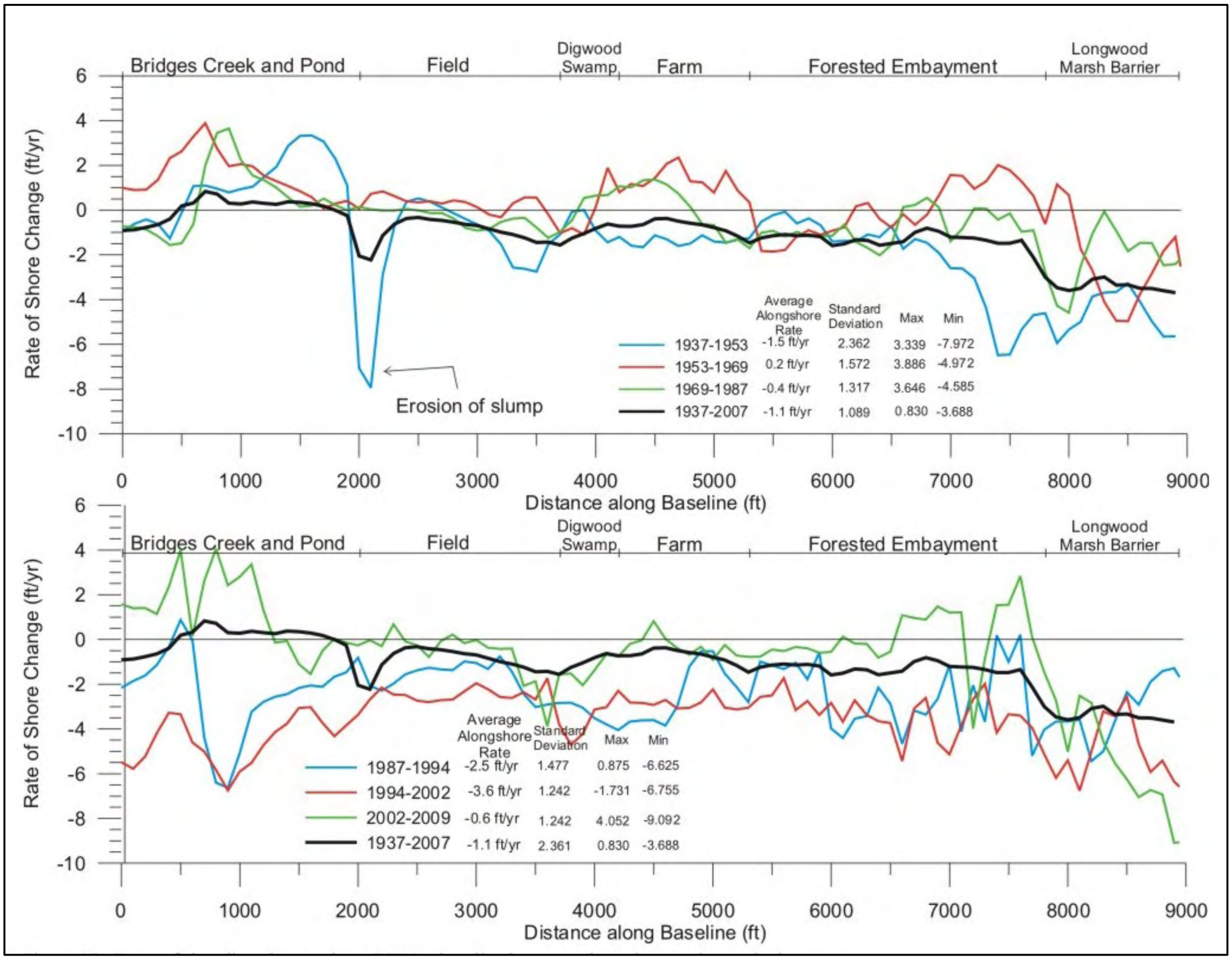


Figure 17. Rates of shoreline change along GEWA shoreline between photo dates and over the long term.

Figure 18. Top of bank digitized from 2002 and 2007 orthorectified aerial photos showing the cumulative impact to the shoreline of Hurricane Isabel and Tropical Storm Ernesto. Also shown on th eimages are the calculated rate of change averaged along the shore at MLW for areas that do not have banks (see Figure 17 for detailed rates in these areas).

change (0 to −0.3 m [0 to −1 ft] per year). Just over 610 m (2,000 ft) of bank (29%) had medium rates of change at the top (−0.3 to −0.9 m [−1 to −3 ft] per year) and 270 m (880 ft) of bank (13%) had high rates (−0.9 to −1.2 m [−3 to −4 ft] per year). About 183 m (600 ft) or 9% had the highest erosion rates of 1.2 to 1.8 m (4 to 6 ft) per year, which relates to 6–9 m (20–30 ft) of change over the five years most likely due to Isabel and Ernesto. At the pond, the bank lost about 8 m (26 ft).

At the entrance to Popes Creek, the spit has changed in configuration and the loss of marsh has been pronounced (Figure 19). What was once a fairly contiguous marsh has disintegrated to marsh islands. In 1879, Longwood Swamp was much more extensive with only a small creek channel (Figure 12A). The loss of marsh within the creek has converted the area to open water. At the Memorial House, shoreline change has been slow. Between 1953 and 2007, the rate of change on the Memorial House peninsula ranged from −0.1 to −0.2 m (−0.3 to −0.7 ft) per year (Figure 19, inset).

Topographic Data

Figures 20 and 21 show the elevation contours from the survey made in the spring and summer of 2008. Figures 22 and 23 show the surveyed locations of the top of the bank, base of the bank, mean high water, and MLLW. Along most of the shoreline, the bank face is vertical, the beach is narrow, and the nearshore is shallow and wide. The spit at Popes Creek shortened significantly during the time between when the photo was taken in 2007 and 2008, as indicated by the surveyed MHW line (Figure 23B). The average elevation of the bank along the field at the western end of the GEWA property is about 5.5 m (18 ft) MLLW (Figure 24). The elevation drops slightly at the eastern end of the field. Elevations are slightly higher, 5.5–5.8 m (18–19 ft) MLLW along the farm section (Figures 20B and 21A). In the forested embayment (Figure 21A), the top of the bank varies between 4.6 and 7 m (15 and 23 ft) above MLLW. The top of the nearly vertical bank erodes due to secondary causes of bank erosion (such as upland runoff, freeze-thaw cycles, etc.) with a resulting decrease of the elevation (Appendix A, Photos 14 and 15). The general 5.5 m (18 ft) elevation continues eastward but drops to about 4.3 m (14 ft) where the bank ends at the barrier in front of Longwood Swamp (Figure 24, Appendix A, photo 22). At Bridges Creek (Figure 20A), the maximum beach elevation is 0.9 m (3 ft) MLLW and the backshore area as measured in the area at the beach access is about 1.5 m (5 ft) MLLW. Digwood Swamp (Figure 20B) has a maximum sand level of 1.3 m (4.2 ft) MLLW and the sand barrier fronting Longwood Swamp (Figure 21B) has a maximum berm elevation of 1.3 m (4.2 ft) MLLW.

Figure 25A presents the surveyed elevations and Figure 25B the locations of the tops and base of the bank and tidal datums along Popes Creek in front of Memorial House. The shore along Popes Creek is not nearly as steep as along the Potomac and has a vegetative marsh fringe (Appendix A, photos 25–28). The elevations immediately inland are higher (maximum 8.2 m [27 ft] MLLW) than along the Potomac.

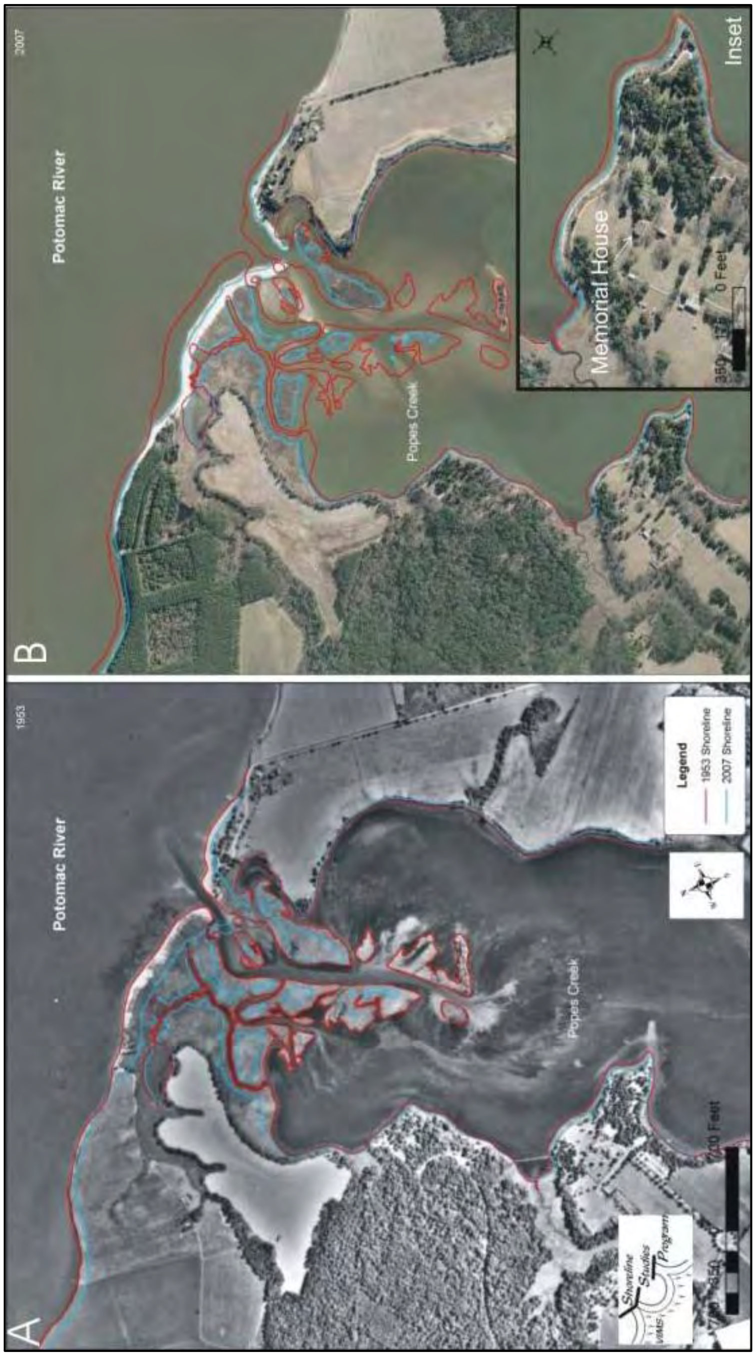


Figure 19. Orthorectified aerial photography showing the change in marsh within Popes Creek in (A) 1953 and (B) 2007.

Figure 20. RTK-GPS elevation contours along GEWA's western Potomac River shoreline.

Figure 21. RTK-GPS elevation contours along GEWA's eastern Potomac River shoreline.

Figure 22. RTK-GPS survey results showing the top of bank, base of bank, mean high water, and mean lower low water along GEWA's western Potomac River shoreline.

Figure 23. RTK-GPS survey results showing the top of bank, base of bank, mean high water, and mean lower low water along GEWA's eastern Potomac River shoreline.

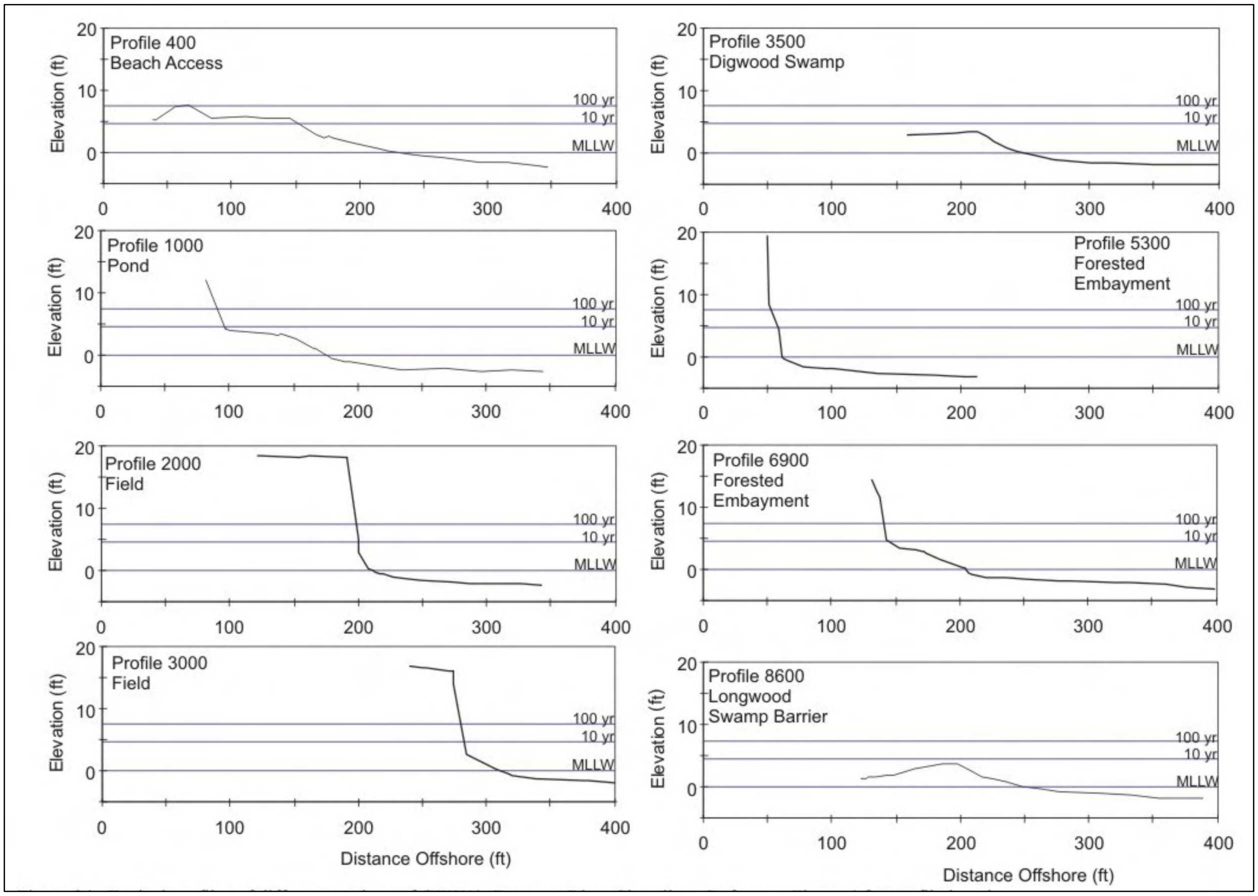


Figure 24. Typical profiles of different sections of GEWA's Potomac River shoreline (feference Figure for profile locations).

Figure 25. Survey results along GEWA's Popes Creek shoreline at the Memorial House showing (A) elevation contours and (B) topographic and vegetative features.

The comparison between the survey and the LIDAR show both agreement and differences relative to the survey (Table 4). In order to compare the LIDAR collected in 2008 to the survey data, eighty-seven 30 m (100 ft) profiles were exported from both data sets. Representative cross-sections are shown in Figures 26 and 27. Figure 26 shows representative comparison profiles for the Potomac River shoreline. In the lower elevation, less steep areas of the shoreline, there was good agreement between the physical survey and LIDAR data, particularly along the Bridges Creek beach/backshore region (profile 400), Digwood Swamp (profile 3400), and along the southern spit at Popes Creek (profile 8600). However, there were significant differences in data derived by the two methods along the eroding upland bank areas. The average distance to top of bank difference along the Potomac River was −4 m (−13 ft), meaning that, on average, LIDAR placed the top of bank −4 m (−13 ft) landward of the surveyed top of bank. The maxi-minimum discrepancies were that the LIDAR profiles placed the top of bank as much as 15 m (50 ft) landward and 5 m (15 ft) riverward of the surveyed surface. On average, LIDAR over predicts the elevation only about 0.1 m (0.3 ft). The land behind the banks is fairly flat, which LIDAR is accurate at capturing. Figure 28 shows the locations of selected data points, both LIDAR and survey. In many sections of the shoreline, LIDAR data points do not exist immediately adjacent to the top of the bank (Figure 28A). In areas that do have data, the top of bank is not well modeled (Figure 28B). Having top of bank delineated in the survey data allows the creation of a breakline at the top of bank when the data is processed, creating a good representation of the bank. While an in depth analysis of the 2005 data was not completed for this project, the profiles that were compared to the physical survey exhibited similar traits to the 2008 data (Appendix B).

The Memorial House shore surveys generally match, except in a few instances, regarding the position of the bank (Figure 27). The LIDAR data depict top of bank as being about 1 m (3 ft) riverward of the actual feature. This positive match may reflect the more gradual slope of the upland banks compared to the near vertical bank typical of the Potomac River eroding upland. The average difference in elevation of top of bank along Popes Creek was larger than along the Potomac River, but the range of error was smaller.

Table 4. Statistics for the differences between the ground survey and LIDAR.

		Top of Bank		MLLW
	Difference	Elevation m (ft)	Distance m (ft)	Distance m (ft)
Potomac	Average	0.1 (0.3)	−4 (−13)	1 (4)
	Median	0.1 (0.5)	−3 (−10)	0 (0)
	Maximum	0.8 (2.5)	5 (15)	26 (85)
	Minimum	−0.9 (−3.0)	−15 (−50)	−6 (−20)
Popes Creek	Average	−0.2 (−0.7)	1 (3)	−2 (−5)
	Median	−0.1 (−0.5)	1 (4)	−2 (−8)
	Maximum	0.1 (0.5)	7 (22)	3 (9)
	Minimum	−0.9 (−3.0)	−3 (−9)	−5 (−17)

positive elevation difference means LIDAR over predicts as measured by the physical survey;
positive distance difference means LIDAR is riverward of the physical survey;
negative distance difference means LIDAR places the feature landward of the physical survey.

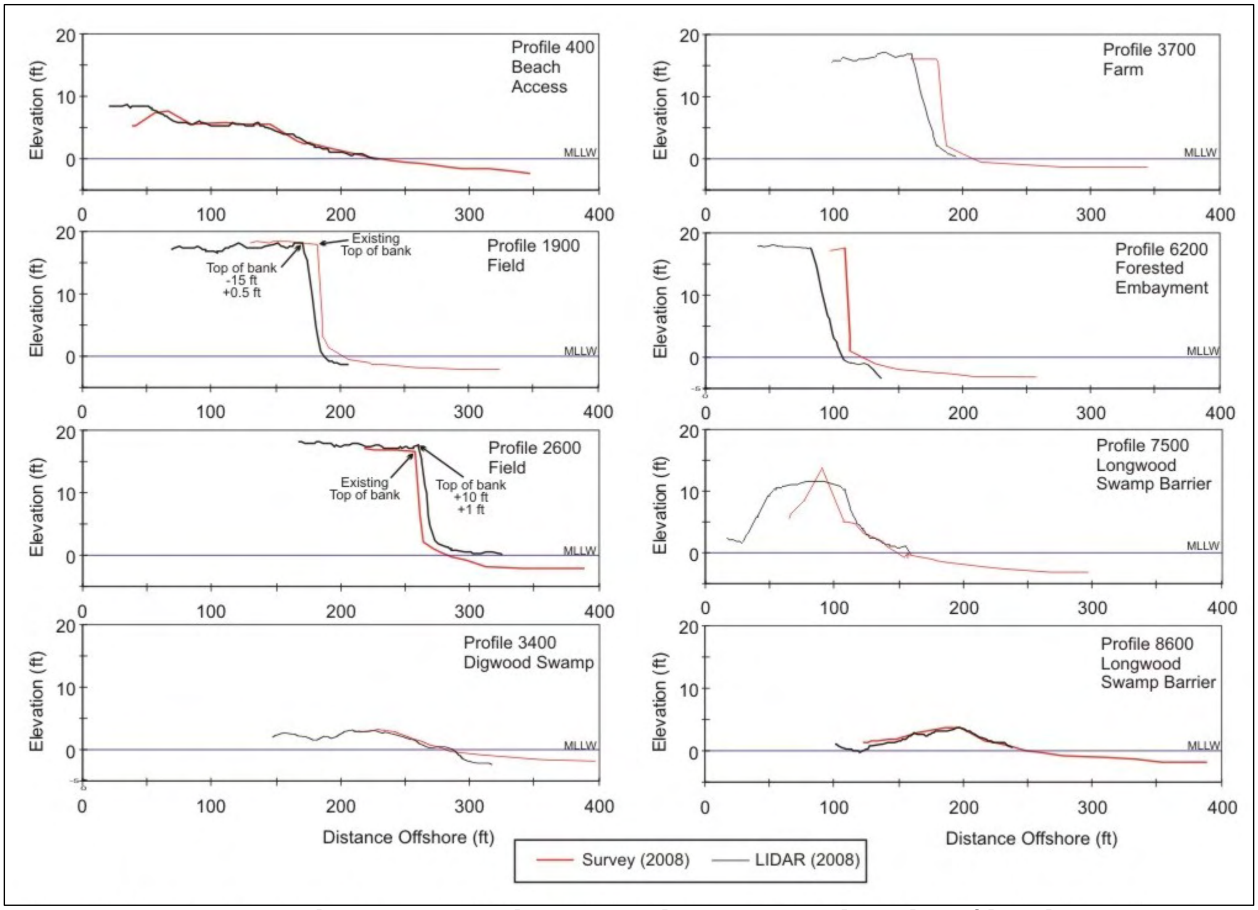


Figure 26. Comparison between ground survey and LIDAR at selected profiles along GEWA's Potomac River shoreline (locations as shown on Figure 4).

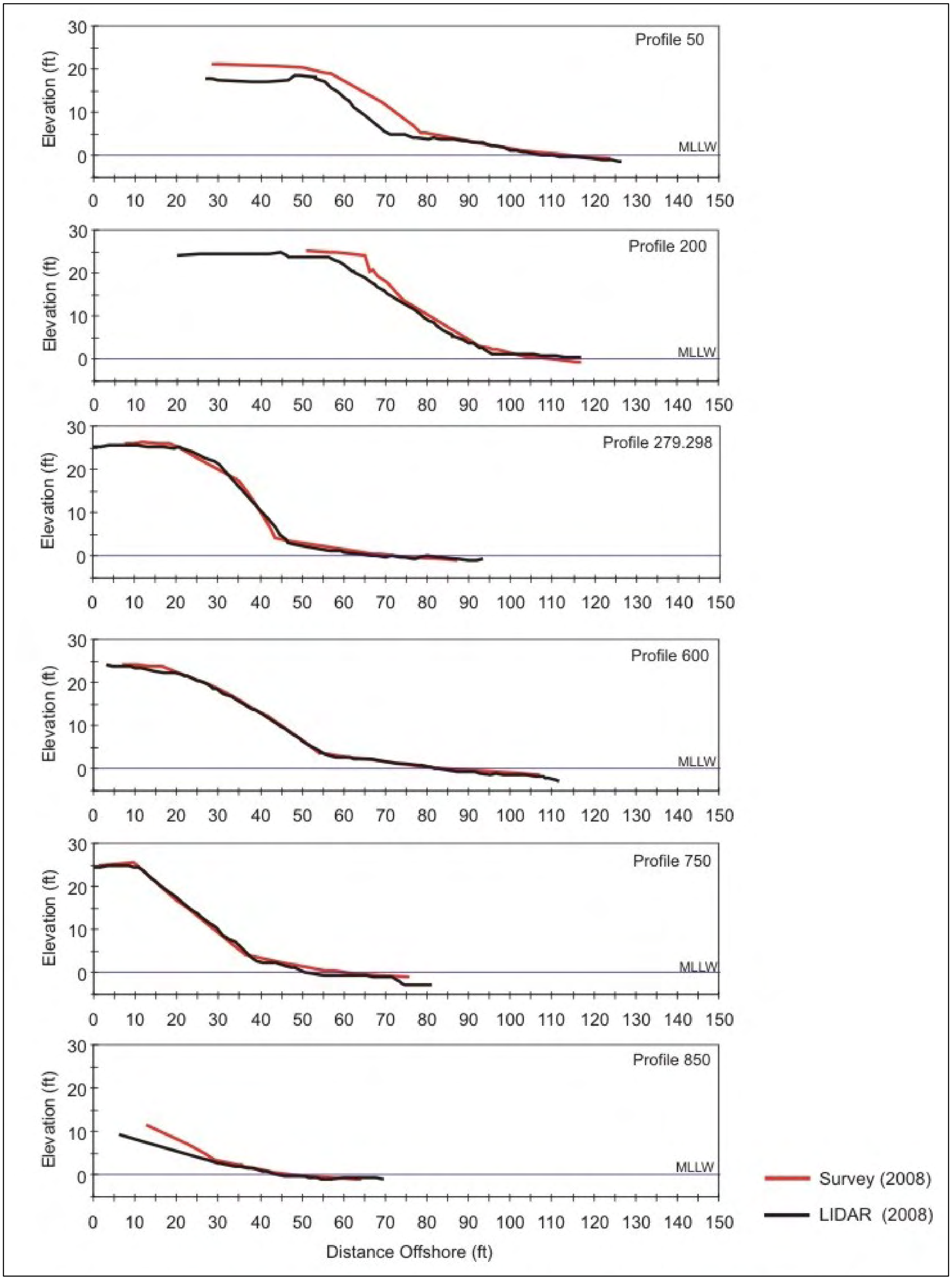


Figure 27. Comparison between ground survey and LIDAR at selected profiles along Popes Creek (locations as shown on Figure 5).

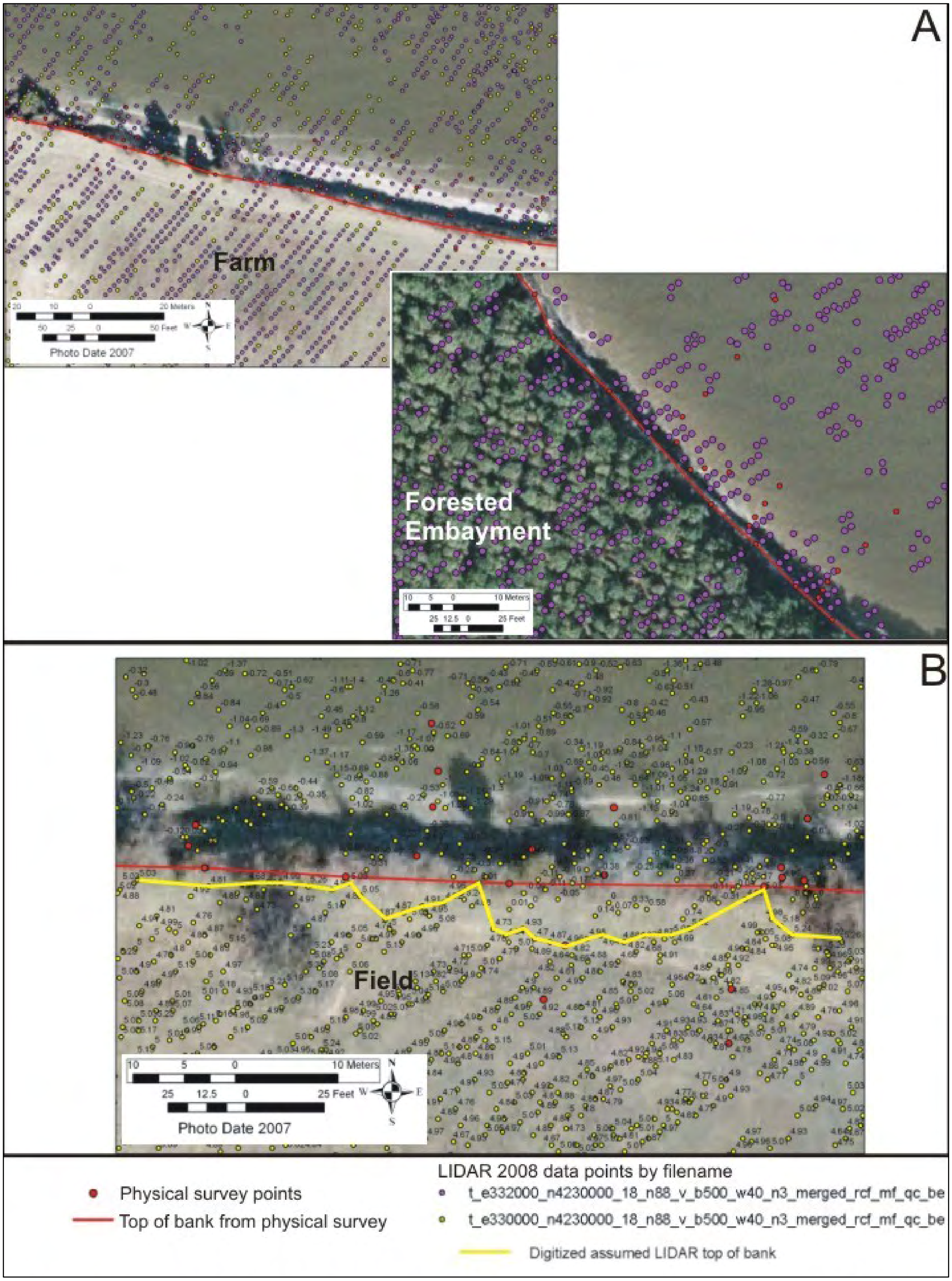


Figure 28. Comparison of the 2008 LIDAR data points with the surveyed top of bank showing (A) the dearth of points along sections of the shoreline and (B) areas where data points exist but do not accurately represent the position of the top of bank.

Hydrodynamic Modeling

Table 5 presents the calculated data for each of the 16 distinct scenarios (four wind directions for each of four storm frequencies) at each of 13 locations. Figures 29 and 30 depict the variations in wave power along the shoreline. Wave heights and, consequently, wave power are variable along the shore due, in part, to differences in shelter and fetch. As would be expected, the waves generated by stronger storms, which have greater storm surges, have higher energy. Wave power was selected to depict energy expended along the coast because during storms, the high water and increased wave heights directly impact the upland bank face. This can cause erosion along the base coupled with subsequent slumping of the upper bank.

Table 5. Wave conditions output from STWAVE at the alongshore stations and the wave power calculated from the data for each direction and storm frequency.

		10-year Event				25-year Event				50-year Event				100-year Event			
	Station	Height (m)	Period (s)	Direction °TN	Wave Power Nm/s	Height (m)	Period (s)	Direction °TN	Wave Power Nm/s	Height (m)	Period (s)	Direction °TN	Wave Power Nm/s	Height (m)	Period (s)	Direction °TN	Wave Power Nm/s
Northwest	1	0.45	4.2	181	920	0.5	4.3	186	1203	1	5	181	5264	1.275	5	175	9744
	2	0.45	4.2	169	920	0.5	4.2	169	1199	1	5	169	5264	1.25	5	169	9366
	3	0.58	4.3	169	1532	0.625	4.3	169	1880	1.125	5	169	6662	1.45	5	169	12603
	4	0.5	4.2	169	1136	0.55	4.2	163	1451	1.1	5	169	6370	1.35	5	166	10925
	5	0.65	4.3	169	1925	0.68	4.2	166	2218	1.125	5	169	6662	1.45	5	166	12603
	6	0.525	4.2	175	1252	0.55	4.2	169	1451	1.125	5	175	6662	1.4	5	169	11749
	7	0.65	4.3	175	1925	0.675	4.3	169	2192	1.125	5	175	6662	1.45	5	169	12603
	8	0.45	4.2	181	920	0.45	4.2	178	971	1.05	5	181	5804	1.325	5	178	10524
	9	0.4	4.2	181	727	0.4	4.2	181	767	0.95	5	186	4751	1.175	5	181	8276
	10	0.5	4.2	181	1136	0.5	4.2	175	1199	1.1	5	181	6370	1.35	5	175	10925
	11	0.49	4.2	186	1091	0.5	4.2	181	1199	1.1	5	186	6370	1.35	5	178	10925
	12	0.45	4.2	181	920	0.45	4.2	181	971	1.05	5	186	5804	1.3	5	181	10130
	13	0.45	4.2	192	920	0.45	4.2	186	971	1.05	5	186	5804	1.3	5	183	10130
North	1	0.84	4.25	192	3210	0.95	4.25	192	4336	1.14	5.3	92	6884	1.49	5.25	192	13405
	2	0.82	4.25	181	3059	0.93	4.25	181	4155	1.12	5.3	181	6645	1.47	5.25	181	13048
	3	0.84	4.25	186	3210	0.95	4.25	186	4336	1.15	5.3	186	7006	1.49	5.25	181	13405
	4	0.84	4.25	181	3210	0.95	4.25	181	4336	1.14	5.3	181	6884	1.48	5.25	181	13226
	5	0.84	4.25	181	3210	0.94	4.25	181	4235	1.14	5.3	181	6884	1.48	5.25	181	13226
	6	0.84	4.25	186	3210	0.95	4.25	186	4336	1.14	5.3	186	6884	1.49	5.25	181	13405
	7	0.85	4.25	186	3287	0.95	4.25	186	4336	1.15	5.3	186	7006	1.49	5.25	186	13405
	8	0.89	4.25	198	3603	1	4.25	192	4804	1.18	5	192	7330	1.53	5.25	192	14135
	9	0.84	4.25	196	3210	0.96	4.25	192	4428	1.16	5.3	192	7128	1.5	5.25	192	13586
	10	0.84	4.25	192	3210	0.94	4.25	192	4245	1.14	5.3	192	6884	1.48	5.25	192	13226
	11	0.87	4.25	198	3443	0.98	4.25	198	4614	1.17	5.3	198	7251	1.52	5.25	192	13950
	12	0.85	4.25	198	3287	0.95	4.25	198	4336	1.15	5.3	198	7006	1.49	5.25	192	13405
	13	0.82	4.25	204	3059	0.93	4.25	204	4155	1.12	5.3	204	6645	1.47	5.25	198	13048
Northeast	1	0.7	4.25	204	2229	0.975	5	204	4653	1.13	5	204	6722	1.49	5.25	209	13405
	2	0.825	4.25	204	3096	0.96	5	198	4511	1.12	5.3	204	6645	1.47	5.25	204	13048
	3	0.775	4.25	204	2732	0.95	5.3	204	4441	1.11	5.3	204	6527	1.45	5.25	209	12695
	4	0.85	4.25	198	3287	0.975	5.3	198	4678	1.14	5.3	198	6884	1.47	5.25	204	13048
	5	0.8	4.25	204	2911	0.975	5	204	4653	1.13	5.3	204	6764	1.46	5.25	209	12871
	6	0.825	4.25	209	3096	0.975	5	204	4653	1.14	5.3	209	6884	1.49	5.25	209	13405
	7	0.75	4.25	209	2559	0.98	5	209	4701	1.13	5	209	6722	1.48	5.25	215	13226
	8	0.825	4.25	215	3096	1.025	5	215	5143	1.18	5	215	7330	1.53	5.25	215	14135
	9	0.8	4.25	215	2911	1	5	215	4895	1.16	5.3	215	7128	1.5	5.25	215	13586
	10	0.825	4.25	209	3096	0.975	5	209	4653	1.14	5.3	209	6884	1.48	5.25	215	13226
	11	0.8	4.25	221	2911	1	5	221	4895	1.17	5.3	221	7251	1.52	5.25	221	13950
	12	0.85	4.25	221	3287	0.975	5	221	4653	1.15	5.3	221	7006	1.49	5.25	221	13405
	13	0.825	4.25	221	3096	0.96	5	221	4511	1.12	5.3	221	6645	1.47	5.25	221	13048

	Station	10-year Event				25-year Event				50-year Event				100-year Event			
		Height (m)	Period (s)	Direction °TN	Wave Power Nm/s	Height (m)	Period (s)	Direction °TN	Wave Power Nm/s	Height (m)	Period (s)	Direction °TN	Wave Power Nm/s	Height (m)	Period (s)	Direction °TN	Wave Power Nm/s
East	1	0.5	5	209	1156	0.725	5	209	2573	0.9	5	215	4264	1.25	6.25	215	9631
	2	0.7	5	209	2266	0.95	5	209	4418	1.1	5	215	6370	1.525	6.25	215	14335
	3	0.625	5	209	1806	0.85	5	209	3537	1.025	5	215	5531	1.45	6.25	215	12960
	4	0.7	5	204	2266	0.95	5	209	4418	1.1	5	209	6370	1.5	6.25	215	13869
	5	0.625	5	209	1806	0.85	5	209	3537	1	5	215	6140	1.4	6.25	215	12081
	6	0.65	5	215	1954	0.9	5	215	3965	1.08	5	221	5531	1.475	6.25	221	13410
	7	0.6	5	215	1665	0.825	5	215	3332	1.025	5	221	5531	1.4	6.25	221	13081
	8	0.625	5	226	1806	0.9	5	226	3965	1.1	5	226	6370	1.475	6.25	226	13410
	9	0.65	5	221	1954	0.9	5	226	3965	1.1	5	226	6370	1.5	6.25	224	13869
	10	0.7	5	215	2266	0.95	5	221	4418	1.1	5	226	6370	1.525	6.25	224	14335
	11	0.65	5	226	1954	0.825	5	232	4188	1.125	5	232	6662	1.525	6.25	232	14335
	12	0.75	5	232	2601	0.95	5	232	4418	1.125	5	232	6662	1.525	6.25	232	14335
	13	0.7	5	232	2266	0.95	5	232	4418	1.1	5	232	6370	1.525	6.25	232	14335

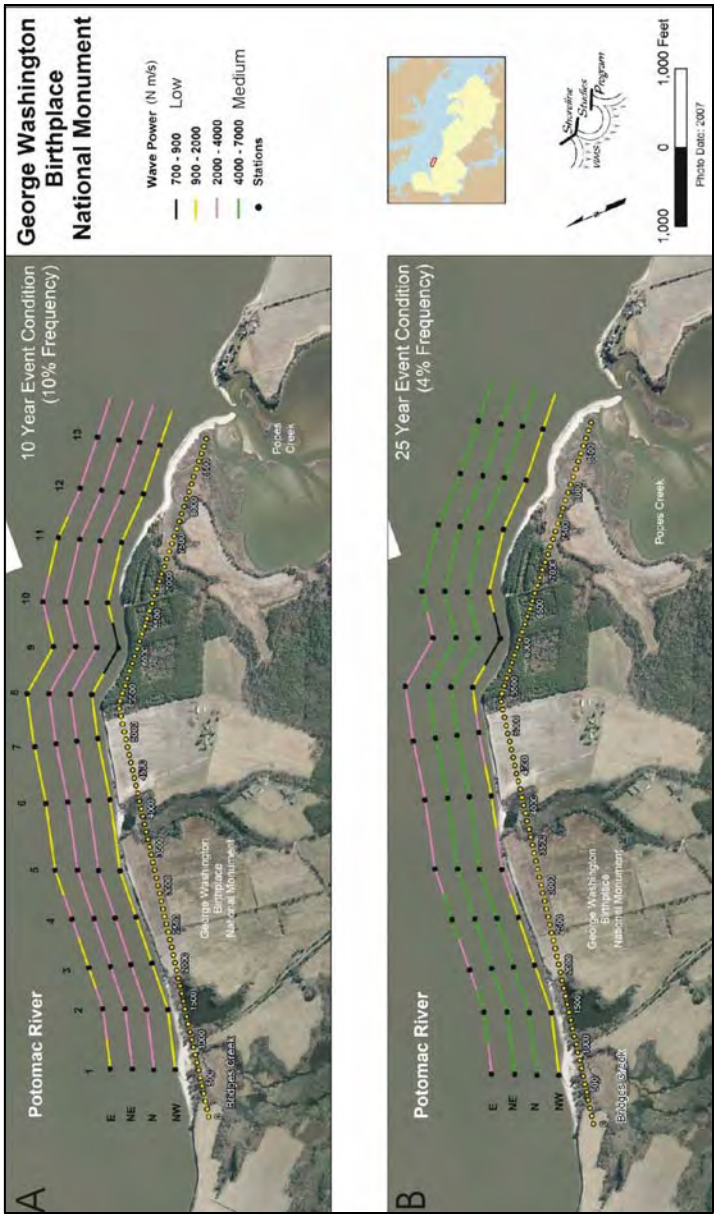


Figure 29. Wave power at 13 alongshore stations for the (A) 10-year and (B) 250year storm condition with different directions.

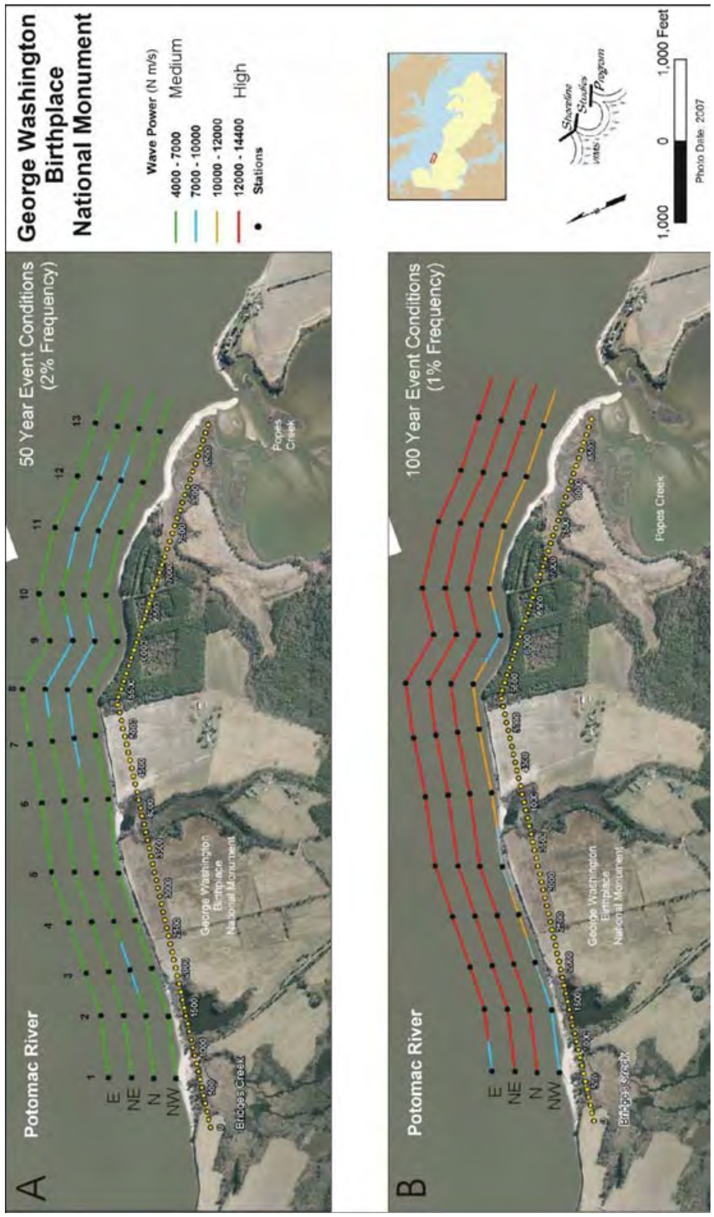


Figure 30. Wave power at 13 alongshore stations for the (A) 50-year and (B) 100-year storm condition with different directions.

Discussion

Potomac River Shoreline

The coastlines of Chesapeake Bay are quite variable, and GEWA is no exception. It has high, vertical banks, low sandy areas along the higher energy Potomac River and extensive marsh, and fringing marsh in lower energy Popes Creek. GEWA's Potomac River coast is very vulnerable to storms during which two separate processes, shoreline change and bank erosion, occur. Shoreline change, either erosion or accretion, typically is measured by the change in the position of the beach or marsh edge; however, change also occurs in the position of the top of the bank due to erosion. Typically, erosion of the banks puts material into the littoral system, potentially causing accretion of the shoreline. At GEWA, only the low drainage areas allow storage of the eroded material; in other areas, most of the material is transported along the shoreline or offshore.

While most of the shoreline is eroding, the area near Bridges Creek has a slight net accretion. Along the rest of the shoreline, long-term recession rates increase toward the east. When the shoreline changes to a more northeasterly orientation, there is a longer fetch, and it is exposed to the most intense wind-waves and highest storm surges during storms such as Isabel and Ernesto. In fact, the movement of the headlands at the forested embayment to the southwest through time indicate that the shoreline is eroding due to the northeast hydrodynamic processes. When banks erode to where they are unstable, slumping of material may occur along the shore. The result of this process may be seen in the 1937 photo (Figure 12B). The slumps represent a short-term "accretion" on the shoreline and provide material to the beaches downdrift. Little subaerial sands reside along the face of the vertically exposed and reflective upland banks.

The rate of bank change from 2002 and 2007 (Figure 18) reflects the storm impact of Hurricane Isabel, Tropical Storm Ernesto, and the northeast storms of October 6 and November 22, 2006. While an individual storm may have a peak 50-year return frequency, the hydrodynamics or wave power actually go through the 10- and 25-year events on each side of the peak for each storm. The top of the bank showed the highest rates of loss in front of the pond and along the shore with the deteriorated bulkhead. These sections of the shore have lower banks that likely were not overtopped by storm surge, but the waves were breaking on them. The low bank in front of the pond has a narrow beach, but it apparently did little to attenuate wave action from these storms. Bank losses on either side of Digwood Swamp were modest but most occurred where the high bank transitions to a lower bank.

Effective shore management requires documentation of the extent and nature of shoreline change. The advantage of LIDAR is that large areas can be surveyed quickly. However, the vertical shorelines at GEWA are particularly challenging to this methodology. When estimating the impact of storms on a shoreline, the location of the top and bottom of the bank are critical in calculating change. During a physical survey, these features can be noted in the data, whereas they are interpolated from LIDAR data such that sharp breaks in slope are smoothed. In LIDAR, a large number of points are collected and gridded to generate a Digital Elevation Model (DEM). Other potential concerns are the timing of the LIDAR flight to coincide with low tide (the 2008

LIDAR was flown at about low tide) since high water levels will cover the lower portion of the bank and the LIDAR does not penetrate the turbid waters of the Potomac estuary.

The differences between the ground survey and LIDAR are most pronounced along the Potomac River shore and the eroding upland banks. These banks are nearly vertical from the top to the base and might be difficult for LIDAR to "mark" the land with its lasers. While most often, LIDAR data showed the top of bank 3 m (10 ft) behind the true top of bank, it could have been as much as 15 m (50 ft) landward or 5 m (15 ft) riverward. LIDAR does better at capturing the beaches and spits where more open and gentle gradients occur. It is possible that the raw LIDAR data could be reprocessed to better capture the sharp break in slope; however, that is outside the scope of this project. As with any type of remote sensing, unless LIDAR data are ground-truthed, one is not sure of its accuracy, especially along those vertical steep banks. The data might not accurately represent the change due to a particular storm. One solution might be to ground survey the top of bank position in conjunction with future LIDAR flights. Burton and Malone (2009) presented a method for accurately determining the top of the bank along the banks of Lake Erie. Their method involves digitizing the top of the bank from rectified aerial photos taken at the same time as the LIDAR. This created a break which could be applied to the data when the DEM is created.

LIDAR data taken at GEWA in 2005 also were reviewed for this project but not extensively analyzed (Appendix B). Since the review of the 2008 LIDAR revealed differences between the GIS survey and the airborne data, we did not feel that the comparison of the LIDAR datasets would accurately represent bank change through time, which was the main goal of this project. If the raw LIDAR data can be reprocessed to depict the bank accurately, they may suffice for monitoring.

Cultural resources include not only archaeological sites but also landscape features and structures. Natural resources, such as native floral species, paleontology, and habitat also are being lost to erosion. In order to assess the vulnerability of the park's resources, the position of archaeological sites were plotted against the local erosion trends (Figure 31). In terms of archaeological resources, the areas at the pond and the bulkheaded shore downriver are highly vulnerable. From a natural resources perspective, the barrier at Longwood Swamp will continue to erode, overwash, and threaten the marsh. Continued erosion may soon open the pond. As the breach widens, sand will enter the pond and create a washover situation somewhat similar to the Digwood Swamp coast. However, Bridges Creek inlet and the associated ebb shoal influence the shoreline rate of change as the adjacent beaches migrate. The frequency of future storms will play an important role as well. Because of the archaeological resources located in the pond area, it is categorized as highly vulnerable. Since there are no known archaeological resources at Digwood Swamp, but it is subject to the same physical processes, it is designated as vulnerable. The low drainage areas also are subject to sea level rise. Given the current rate, in 50 years, sea level will be about 0.23 m (0.75 ft) higher. This increase generally will not affect the high banks, but Longshore transport rate and direction often can be gleaned from the geomorphic change. However, calculation of transport rates generally is more meaningful along more open, sandy coasts, not GEWA's near vertical banks with very little subaerial beach. The strong net movement of sandy material downriver is apparent along the Popes Creek shoreline complex in the form of the changing spit. The waves pounding against the upland banks cause undercutting and erosion.

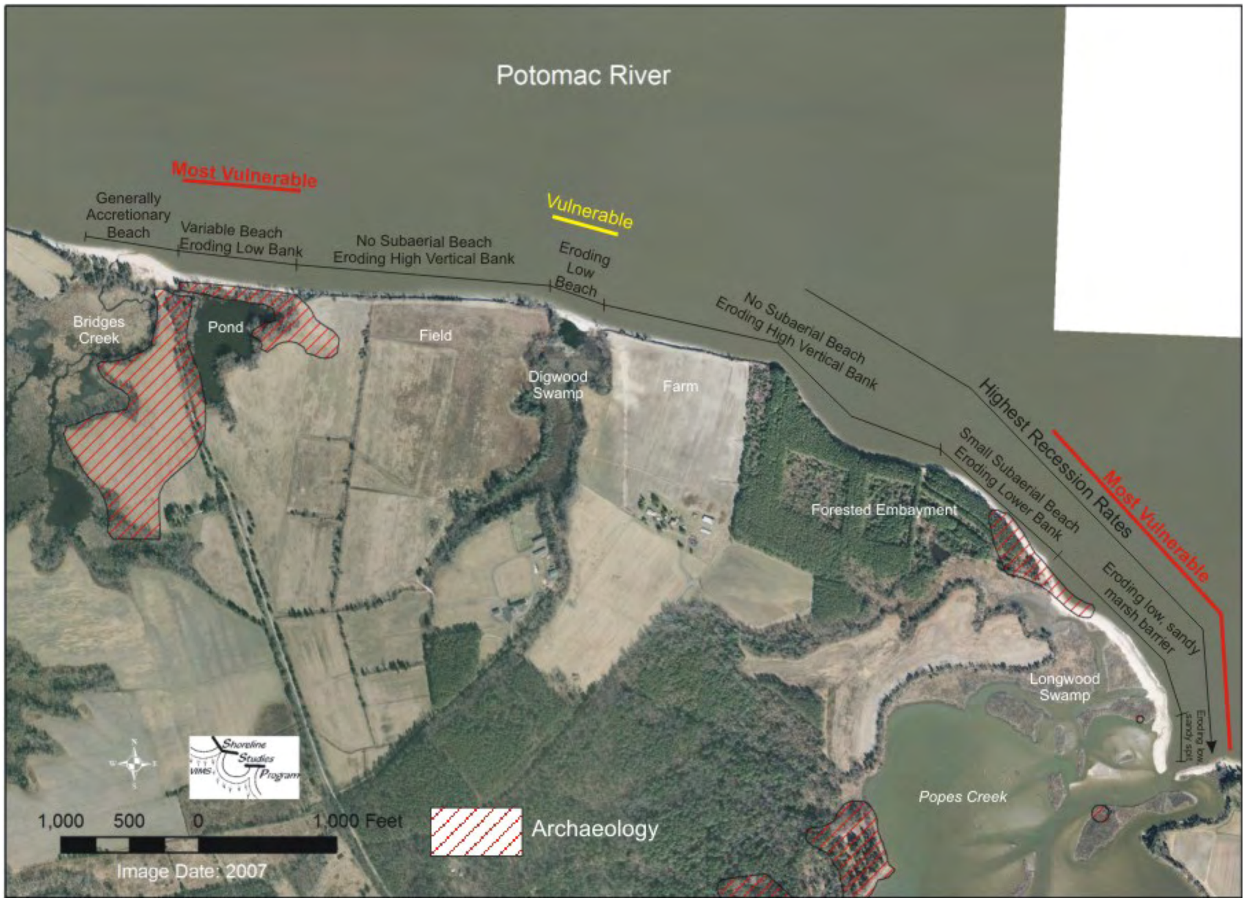


Figure 31. Summary of major findings and vulnerability map for GEWA's Potomac River shoreline.

Longshore transport rate and direction often can be gleaned from the geomorphic change. However, calculation of transport rates generally is more meaningful along more open, sandy coasts, not GEWA's near vertical banks with very little subaerial beach. The strong net movement of sandy material downriver is apparent along the Popes Creek shoreline complex in the form of the changing spit. The waves pounding against the upland banks cause undercutting and erosion.

The direction of wave approach is important from a sediment transport perspective. Waves approaching the shoreline, normally, with wave crests parallel to the shore, will be reflected back into the oncoming wave train, creating a counter wave going back into the river. Sediment transport would be mostly offshore. Waves approaching obliquely to the coast also will be reflected, but as progressive standing waves moving in the direction of the wave bearing. Sediment transport would be mostly alongshore. The physical impact to the eroding uplands is difficult to measure between onshore and alongshore, as a storm may impact the shoreline from different directions, water levels, and wave heights.

The retreat of the top edge of the bluff is not fully dependent upon shoreline erosion. Waves, often abetted by storm surge, attack and erode the base of a bluff with the result that the face of the bluff can collapse onto the beach. This process maintains the steep face of the bluff and provides sediment to the littoral system. Indeed, if the location of the shoreline is surveyed so soon after the bluff failed that the bolus of sediment has not been redistributed, it would appear that the shoreline has advanced and not retreated. However, even in the absence of erosion at the base of the bluff, the top of the bluff will retreat. Clark et al. (2004) document the evolution of coastal bluffs elsewhere in the Chesapeake Bay system. Over a span of 35 to 40 years after the toe of the bluff was protected from erosion, the slope decreased to between 25° and 37° before becoming stable.

The situation where the top of the bluff continues to retreat after the bottom is protected can be difficult for managers who might be concerned with the loss of the area at the top of the bluff. The engineering techniques for stabilizing a steep bluff are unrelated to standard shoreline control practices. The loss at the top of the bluff would extend almost twice as far inland as the bluff is tall before stabilizing. Also the protection of the toe of the bluff would decrease and eventually stop the influx of sediment to the beach system and result in a potential increase in the rate of erosion downdrift from the engineering works.

Popes Creek

Deposition at the mouth of Popes Creek created an ecologically important delta marsh (Blank et al. 2007). Continued erosion of the spit/upland interface on Popes Creek might breach the barrier into Longwood Swamp causing washover sands to enter the tidal channel in the spit's lee. This breach might cause two tidal inlets, thereby reducing efficient tidal flow. This process has already begun as evidenced by the washovers seen in 2007 imagery. The shoreline complex within the entrance to Popes Creek has undergone significant change. The net change between 1953 and 2007 is seen in Figure 19 where tidal marsh islands have been reduced by over 75 percent. Belval et al. (1997) suggested the reasons for loss are selective loss of areas dominated by saltbush, tidal and wave effects, abundance of parasitic plants, and plant community age structure. The USGS (2004) stated that sediment in the estuary is derived from three primary sources: cleared land in the watershed, the Potomac River, and shoreline erosion along Popes Creek. Sediment supply to the Popes Creek basin could be decreasing as a result of the change from in land use from farming to preservation.

While Wilcox (1989) found that the average marsh vertical accretion rate was keeping pace with sea level rise, a lot can change in 20 years. Wilcox (1989) cited the sea level rise rate as 2.5 mm (0.10 in) per year (based on data from Davis 1987). Newer NOAA data (Figure 10) reveals a much higher rate of 4.8 mm (0.19 in) per year. As a result, marsh loss is likely a result of a combination of these factors including sea level rise. As the small island that has archaeological resources is very likely to disappear, it is considered highly vulnerable (Figure 32). The shoreline at the Memorial House has a small rate of change that is within the error of our method of measurement; however, the shoreline is clearly eroding since there is a wave-cut scarp. The shoreline is mostly marsh fringe. Because the infrastructure along this stretch of shore is at least 50 m (150 ft) back from the shore at a high elevation, it was not rated as vulnerable at this time.

While not directly part of this study, shore erosion is occurring at the Visitor Center which is placed close to the shore. In addition, the height of the bank is lower in this region. For these reasons, it was considered vulnerable (Figure 32). Overall, about 1,200 m (3,800 ft) of shoreline was rated as “most vulnerable” and 300 m (1,000 ft) was rated as “vulnerable” along Potomac River and Popes Creek.

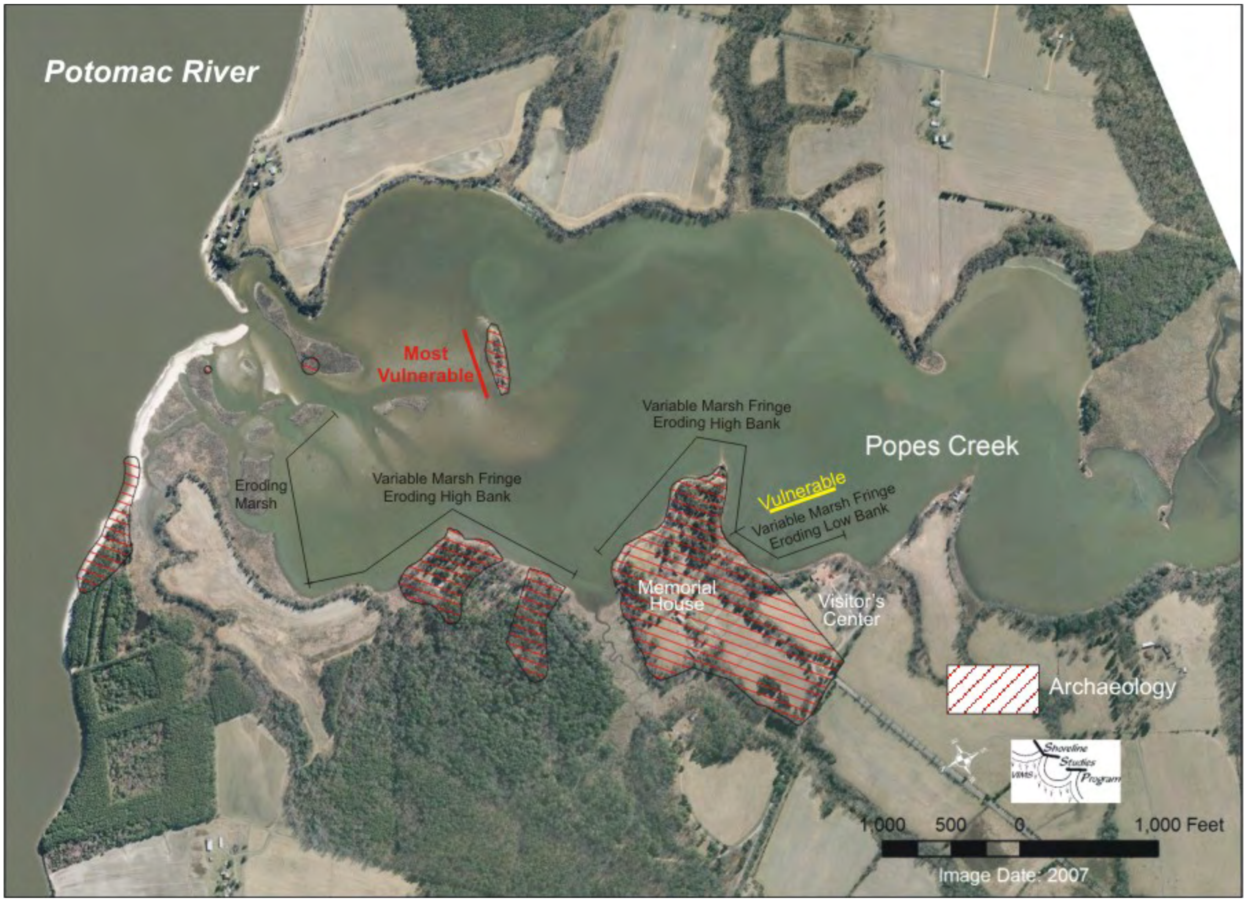


Figure 32. Summary of major findings and vulnerability map for GEWA's Popes Creek shoreline.

Recommendations

Vulnerability

- While the entire Potomac River reach will continue to erode with very few exceptions, the vulnerable and highly vulnerable areas indicated in this report are at the highest risk during future storms. If a “do nothing” management strategy is adopted, the banks likely will continue to look as they do today, only they will migrate landward, particularly during storms. In addition, the nature of the low, drainage areas may change if they are breached.
- Rate of change is minimal at the Memorial House, and the vegetative edge maintains a relatively stable shoreline. The limited fetch means there is little wave action, even under flood conditions. As a result, although the bank may have a scarp, it is not unstable.
- In all, GEWA has about 1,250 m (4,100 ft) of most vulnerable shoreline and 230 m (750 ft) of vulnerable shoreline.

Monitoring

- A monitoring program should be established to assess the impacts of storms on GEWA’s Potomac River shoreline. A program of annual surveys plus a survey after each major storm would measure GEWA’s coastal response. A lower-cost alternative that could be performed by park personnel would be to establish permanent benchmarks back from the top of the bank and regularly measure the distance from the benchmarks to the top of bank. This alternative will not map the entire shoreline, but it will provide an estimate of the amount of bank lost. While LIDAR data is useful in the less steep areas of the park, the dataset provided for this analysis does not provide a close enough representation to measure storm changes. However, should the park develop a methodology that accurately represents the top of bank, LIDAR would be an effective means of measuring storm or longer-term changes over larger areas.
- Annually and after major storms, the monitoring of the shoreline through low-level rectified aerial photography can provide data to quantify shoreline and bank change.

Management

- Along Popes Creek at the Memorial House, the shoreline can be monitored visually for increases in erosion by resource managers. They can, if necessary, trim trees to avoid shading the marsh and plant marsh vegetation in existing substrate where necessary.
- A shoreline management plan would make specific recommendations for effective erosion mitigation if the park’s intent is to preserve land area and the archaeological resources along the shoreline. Beyond the “do nothing” approach, other management strategies include both structural and non-structural elements. These recommendations would merge park goals, such as erosion control and archeological site preservation, with habitat-friendly, cost-effective management strategies that minimize adverse impacts.
- In the areas rated as highly vulnerable to storms, action will be needed soon if the archaeological resources are to be preserved.

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Appendix A. Ground Photos taken along GEWA's shoreline by Shoreline Studies Program during the physical survey.

Figure A1. Entrance to Bridges Creek -Westernmost boundary of GEWA. Inlet is blocked at this time.

Figure A2. In front of parking loop near Bridges Creek.


Figure A3. Shoreline in front of the pond.


Figure A4. Shoreline in front of the pond.


Figure A5. Bank erosion in front of the pond.

Figure A6. Eroding shoreline at the field.

Figure A7. The shoreline in front of the field.

Figure A8. Along the field.

Figure A9. Erosional headland west of Digwood Swamp.


Figure A10. Erosional headland west of Digswood Swamp.

Figure A11. At the headland where the bank ends at Digwood Swamp.


Figure A12. Sandy shore in front of Digwood Swamp.

Figure A13. Looking west from NPS property toward the private property that splits GEWA's Potomac River shoreline.

Figure A14. Vertical banks with no beach at high water in forested embayment.

Figure A15. Vertical banks with no beach at high water along forested embayment -Top of bank elevation varies due to erosion at the top.


Figure A16. Vertical bank face.


Figure A17. At the headland where the shoreline turns from northeast facing to north facing.


Figure A18. Eroding banks along the northeast facing shoreline.

Figure A19. Along the northeast facing shoreline north of the sandy spit -Remnants of an old bulkhead are evident.

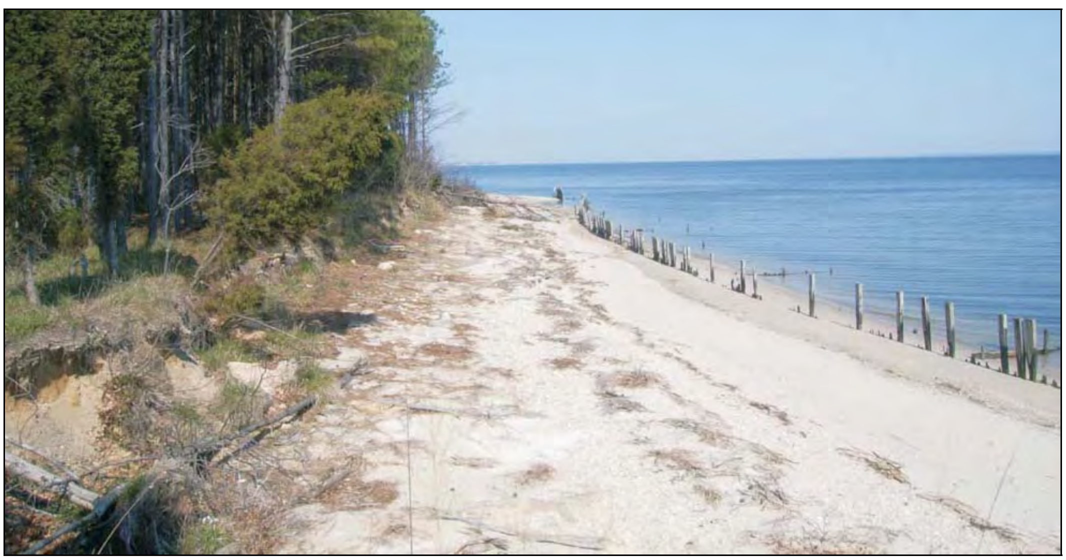

Figure A20. Shoreline where the sandy spit that fronts Longwood Swamp attaches to the upland - Remnants of an old bulkhead are evident.

Figure A21. Longwood Swamp from the sandy spit.

Figure A22. Along the sandy spit in front of Longwood Swamp near where the spit attaches to the upland.

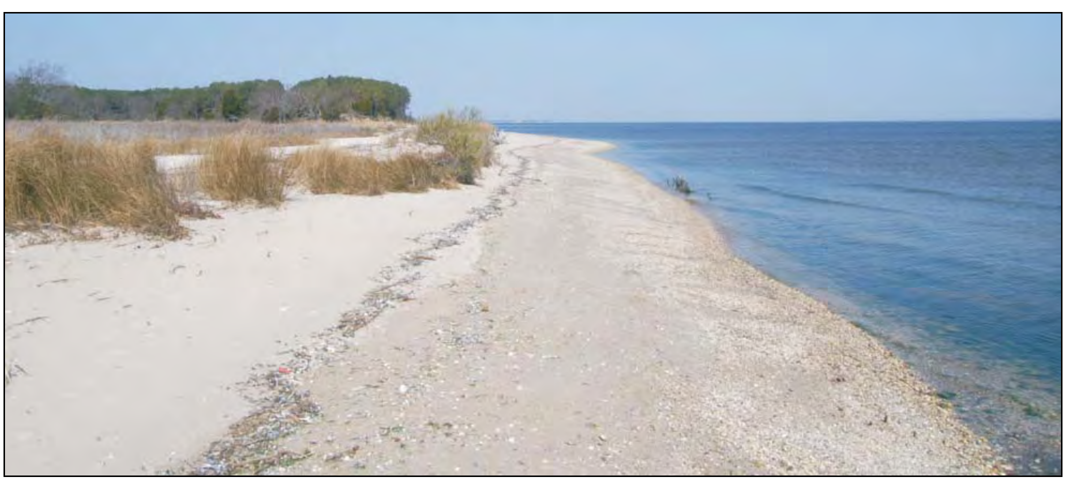

Figure A23. Midway along the sandy spit in front of Longwood Swamp.


Figure A24. At the distal end of the Popes Creek spit in front of Longwood Swamp.


Figure A25. Marsh along Popes Creek at the Memorial House.


Figure A26. From the top of the bank at the Memorial House.


Figure A27. From the top of the bank at the Memorial House.


Figure A28. From the top of the bank at the Memorial House looking south.


Figure A29. Looking toward the Visitor's Center.


Figure A30. Eroding point of land near the Visitor's Center.

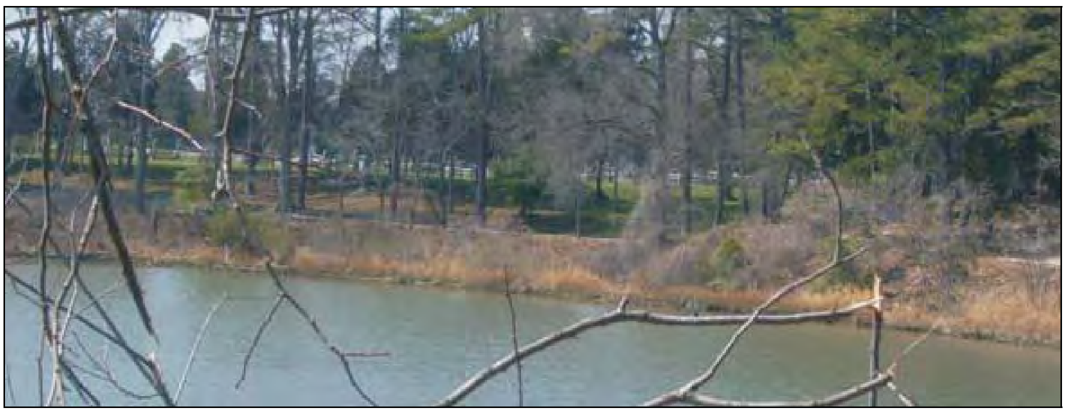
Figure A31. Low shore near the Visitor's Center.

Appendix B. Comparison between the 2008 physical survey and the geotiff produced by USGS from LIDAR data taken in 2005

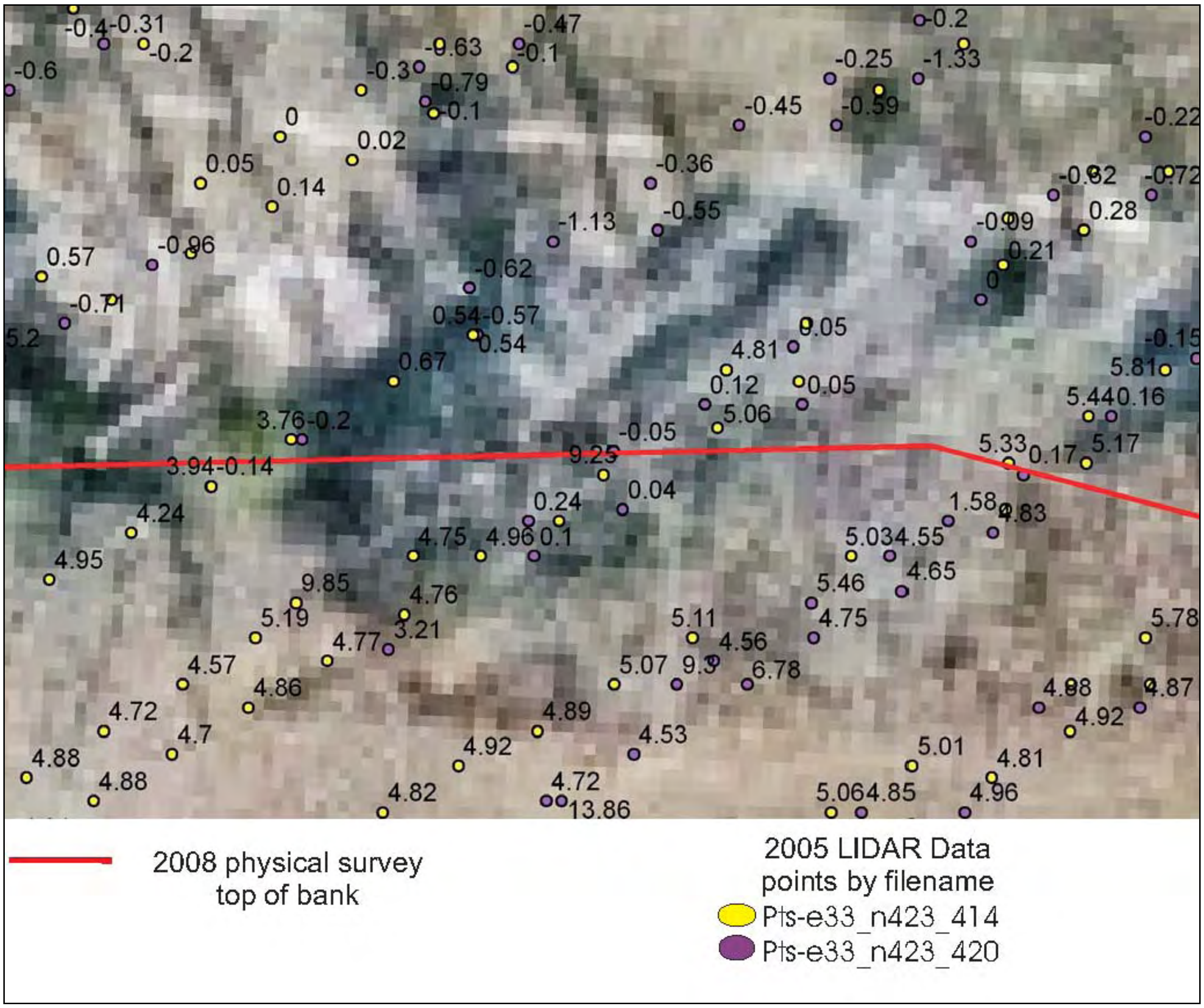

Figure B1. Close up of the 2005 LIDAR data showing the USGS ASCII points for one area along the shoreline. In this particular area, two separate files overlap indicating a wide variation in the elevations measured. Also shown is the measured top of bank on the 2007 photo. In addition to the large amount of data, the variability in elevation where files overlapped made the ASCII data unsuitable for our analyses.

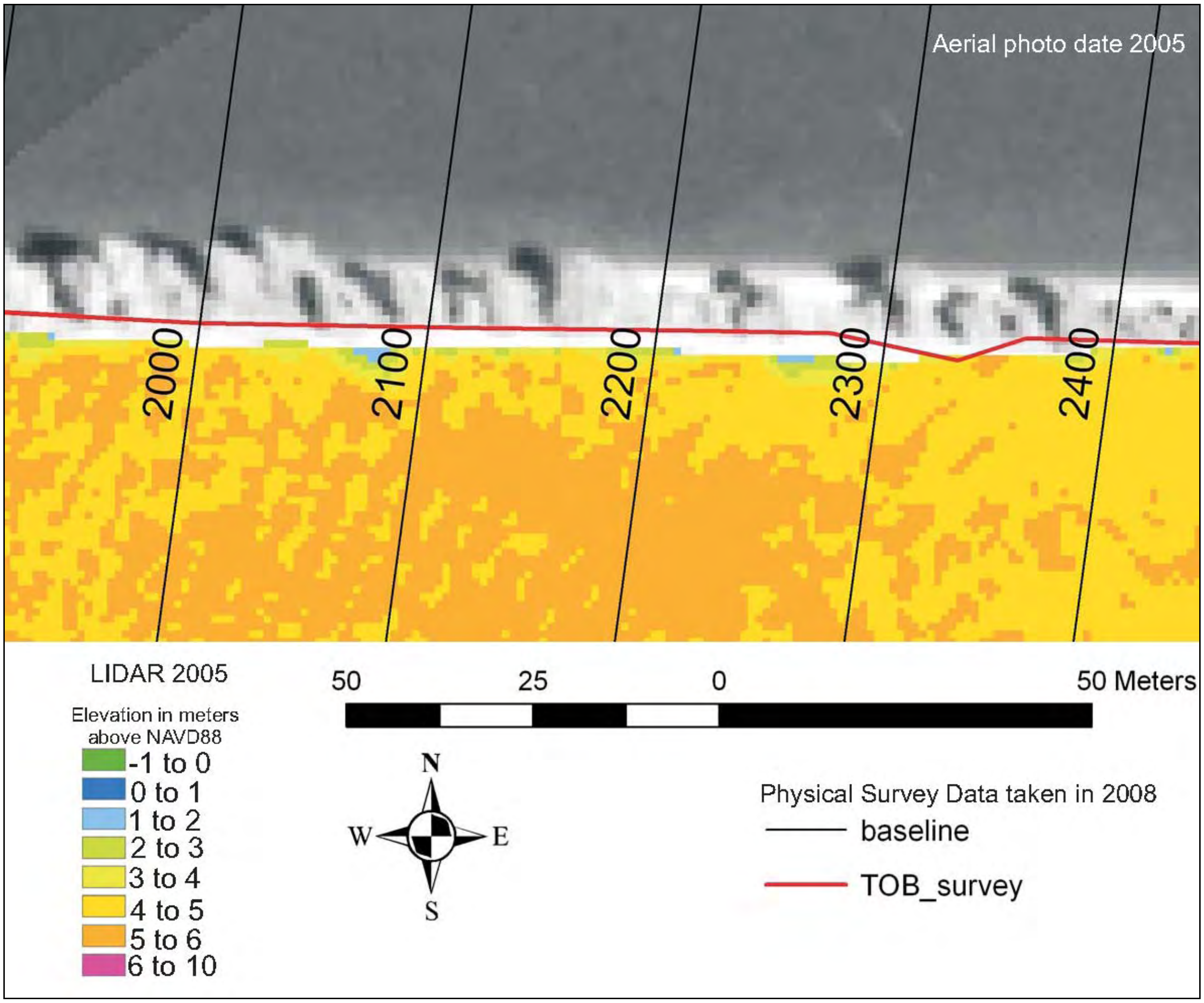

Figure B2. USGS's gridded geotiff of LIDAR data taken in 2005 overlain on a rectified 2005 serial photo. Also shown is the profile cross-sections and the surveyed top of bank in 2008. The geotiff is cropped landward of the existing top of bank, and elevations indicate similar issues that were encountered with the 2008 data as described in the results and discussion sections of this report. In addition, the geotiff did not include the inholding's shoreline on the Potomac River. Following methodology used to analyze the 2008 LIDAR data, this geotiff was used to generate the cross-sections that are compared to the 2008 physical survey on the following page. The selected cross-sections indicate that the data do not accurately represent the bank at GEWA.

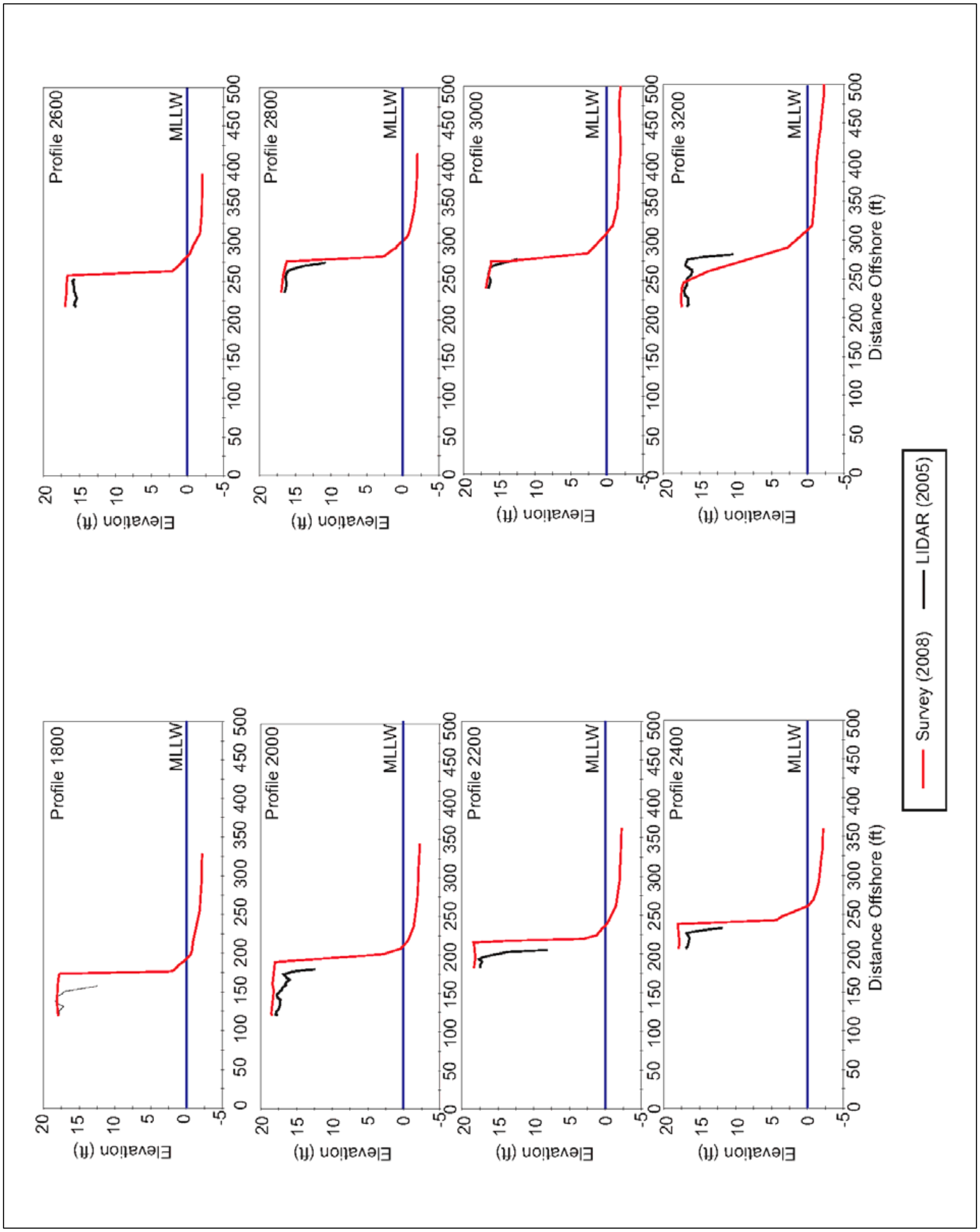

Figure B3. Selected top of bank LiDAR and VIMS field measured data for comparison.

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