SPATIAL ANALYSES AND REPLETION OF GARGATHY COASTAL LAGOON

By

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ABSTRACT

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Coastal lagoons and bays vary in shape and size in response to antecedent topography, geologic processes and sea level rise. Variations in shape and environmental conditions of coastal basins are believed to influence the distribution of benthic sub-environments and the exchange of water with the ocean and other adjacent coastal systems. Gargathy Inlet and its coastal lagoon vary spatially from the inlet, where the greatest depths are observed, to the mainland, dominated by shallow intertidal areas, colonized by marsh. *Hypsographic* and *hydro-hypsographic* analyses of Gargathy's coastal lagoon were the primary techniques applied to understand the relative distribution of the benthic and pelagic surface areas at different elevations. Using these techniques, four benthic sub-environments, upper intertidal benthic environment, lower intertidal flats, shallow sub-tidal lagoons and sub-tidal channels were differentiated. The *Hypsographic* curve of Gargathy Lagoon illustrated that 80.81 % of the total surface area is colonized by marsh; however, only 27% of the basin volume occurs over the marsh.

Water exchange and flushing characteristics of this marsh-dominated system were associated with *volume-hypsography*, the hydraulic turn-over time and the repletion footprint. The *volume-hypsographic curve* for Gargathy lagoon, illustrated that about

77.3% of the basin capacity is completely exchanged with coastal oceanic waters with each tidal cycle. If repletion water completely mixed with residual water between tidal cycles, then, hydraulic turn-over time (HTT) could be as low as 1.29 tidal cycles. Mixing between residual water and repletion water is strongly influenced by hypsometry. Repletion patterns are strongly influenced by the presence of marsh during the last stages of the tidal cycle when water spreads over the marsh surfaces after filling the tidal channels. This study provides spatial techniques and methods that allow for a better understanding and characterization of coastal basins.

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I am very grateful to Dr. George F. Oertel for his support and guidance during my Master's degree. His advice, patience and hours of dedication deserve special recognition. Special thanks are also extended to the other members of my thesis committee, Dr. Zimmerman and Dr. Whittecar for their guidance and advice. I would like to thank the Virginia Coast Reserve LTER Program for logistically supporting this project and the National Science Foundation (DEB 621014) for sponsoring it. I would also like to thank Kathleen Overman and Chris Buck for their assistance in the field during the data collection surveys. I extend many, many thanks to George McLeod for sharing his knowledge about GIS and for always been there for me when I needed help. Finally, I would like to thank and dedicate this work to my family and boyfriend for always believing in me and encouraging me to become better at what I love.

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INTRODUCTION

1.1 Background on Subject/ Previous Work

1.1.1 Coastal lagoons Water Exchange

Coastal lagoons are water bodies associated with coastal drainage basins. They are characterized by having restricted water exchange and complex hydrodynamics. Water exchange and flushing properties of coastal lagoons are affected by local factors such as wind, tides, runoff, weather, waves and density gradients (Kjerfve and Magill, 1989).

Circulation at coastal lagoons varies according to local factors affected by the spatial and environmental characteristics of the lagoon. Kjerfve and Magill (1989) studied leaky, restricted and choked lagoons to determine the dominant forces affecting circulation and water exchange. Strong tidal currents dominated leaky lagoons, allowing non-restricted water exchange with the ocean along salinity and turbidity fronts. Circulation in restricted lagoons is caused by a combination of tides, winds and runoff. Wind was a major factor affecting circulation in the choked lagoons they studied.

Concepts such as residence time or hydraulic turnover time (HTT) have been used to understand water circulation and exchange in coastal lagoons (Takeoka, 1984; Kjerfve and Magill, 1989 and Oertel, 2001).

OERTEL, G.F., KRAFT, J. C., KEARNEY, M.S., AND WOO, H.J., 1992, A rational theory for barrier lagoon development: SEPM Special Publication No. 48, p. 77-87.

Residence time and HTT provide information on water exchange time scales. HTT at coastal lagoons is an estimate of the number of tidal cycles required for the complete exchange of a certain volume of water with the ocean or other mixed waters in a system. Residence time is an estimate of how long a specific parcel of water remains within a coastal lagoon.

Whereas water circulation and exchange in estuaries are generally well known (Pritchard, 1955), little is known about how the bathymetry or shape affect water circulation and exchange. Oertel (2001) analyzed the bathymetry of an open-water lagoon, The Great Machipongo Bay, and determined the flushing and exchange properties of the system. Oertel (2001) used *hypsometry* to study exchange characteristics and suggested *hydro-hypsographs* could be used to estimate exchange.

However, many coastal lagoons do not have vast open water areas, but are filled with extensive marsh surfaces. These coastal lagoons are tidally expandable to greater relative volumes than their open-water counterparts. Circulation in marsh surfaces occur as non-canalized water flows. Marsh topography and *hypsographic* methods are especially important for the estimation of water budgets in marsh dominated systems (Eiser and Kjerfve, 1986).

For this project, I wanted to determine how the *hypsometric* relationship of marsh-filled systems differed from the open water lagoon studied by Oertel. A marsh dominated coastal lagoon in the Virginia Coast of the Mid-Atlantic was selected for this project.

1.1.2 Marsh

Marsh dominated coastal systems have marsh along the mainland and barrier areas. The community of plants found in the tidal areas of coastal lagoons, is dominated by *Spartina alterniflora*. This grass tolerates salt spray, periodic submergence, high-light intensities, strong winds, and can tolerate reduced or soft soils. *Spartina alterniflora*, Smooth Cordgrass, dominates the barrier island salt marshes off the Virginia coast. Two forms of *Spartina alterniflora* have been distinguished, the tall form reaching 2 to 3 meters high colonizes the creekbank and the dwarf form, usually found in flat areas, reaches 10 to 40 cm high (Valiela et al., 1978; Osgood et al., 1993 and Tyler et al., 1999).

Marsh colonization and development in coastal systems is strongly dependant on local elevation and topographic relief; mature marsh develops closer to creeks while younger marsh is usually found at higher elevations relative to sea level. Marsh development is strongly affected by regional landscape which is directly related to hydrology, which in turn controls the chemistry and biota in marshes (Tyler et al., 1999). Marshes in Virginia occur between mean sea level (MSL) and highest high water (HHW) (Oertel and Woo, 1994).

1.2 Purpose and Objectives

The main purpose of this study was to describe the environment of a marsh dominated coastal lagoon based on *hypsometry* and *hydro-hypsometry* and to determine how elevation and depth influence repletion.

Gargathy coastal lagoon is the tidally dominated barrier lagoon selected for this project. As part of a shallow, non-navigational system, bathymetric data for Gargathy lagoon was limited. To obtain and analyze the bathymetry at Gargathy lagoon, echo-sounding depth readings were collected throughout the area and a digital elevation model (DEM) was created as a basis for three dimensional spatial analysis using GIS techniques.

Determination of the flushing characteristics of the system involved several objectives. The first objective was to determine the total, tidal and residual prisms in the system from a DEM. Determination of the total, tidal and residual prisms provided information about how much water is present in the system at high tide, how much remains at low tide and much water is exchanged with every tidal cycle. The second objective involved the computation of the hydraulic turn-over time (HTT). Knowledge about the HTT gave us information about the number of tidal cycles required for the complete exchange of the system's water prism. The third objective was to create a *volume-hypsometric curve* to determine the distribution of different water masses in the lagoon. The fourth objective was to determine an exchange "footprint" representing the maximum extent to which a volume of water equivalent to the tidal prism reaches into the lagoon after tidal flooding.

1.3 Study Site Location

1.3.1 Regional Setting of the Delmarva Peninsula

The study site is a barrier lagoon located on the Virginia section of the Delmarva Peninsula. The Delmarva Peninsula is located in the Mid Atlantic region of the east coast of the United States. The Delmarva Peninsula is bordered by the Chesapeake Bay to the West, the Atlantic Ocean to the East and the Delaware Bay to the North. The coastline extends for over 200 km and forms a chain of barrier islands, between Cape Henlopen, Delaware and Cape Charles, Virginia (Figure 1).

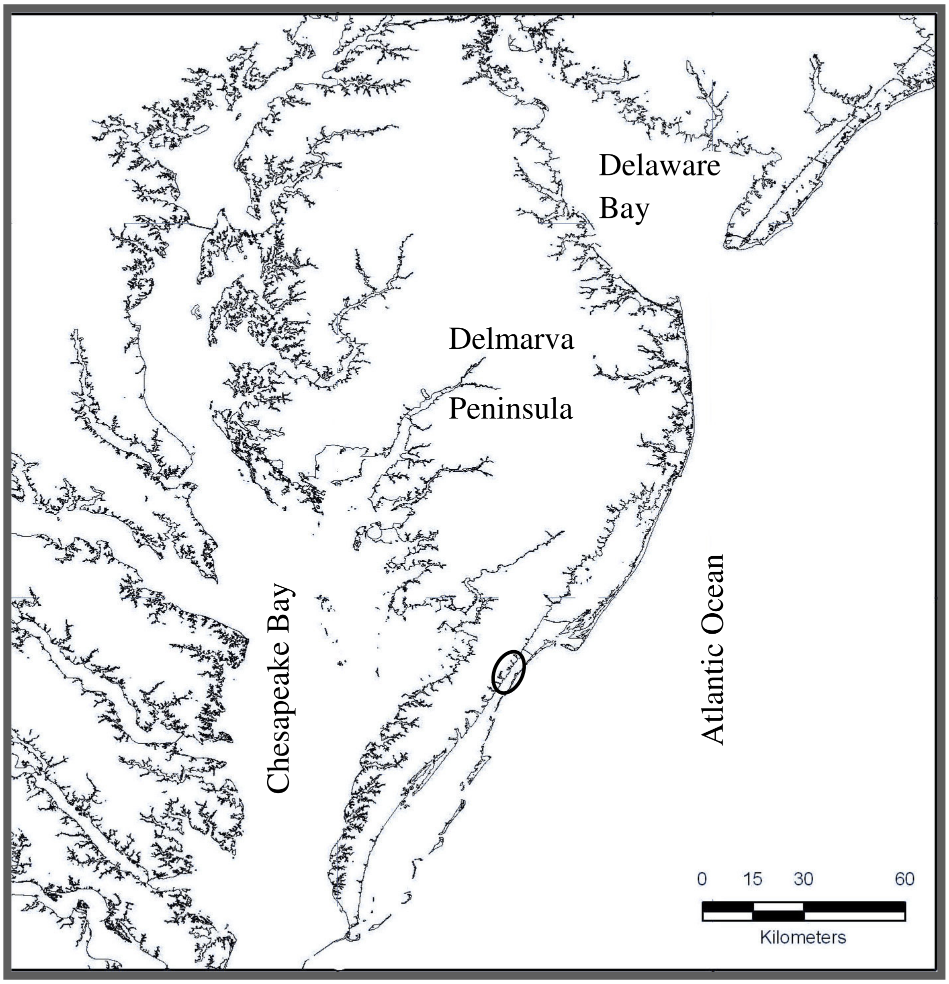


Figure 1. Location of the Delmarva Peninsula. The Delmarva Peninsula is located in the Mid Atlantic region of the east coast of the United States. It is bordered by the Chesapeake Bay to the East, the Atlantic Ocean to the West and the Delaware Bay to the North. The study site, Gargathy, is located on a barrier lagoon off the Virginia coast, located within the ellipsoid label.

Oertel et al. (2004) described the Delmarva Peninsula as a five-element coastal compartment with a headland, a right hand spit, a left hand spit, wave-dominated barrier islands and tide-dominated barrier islands.

The Virginia section of the coast of the Delmarva Peninsula is the Southern Delmarva Peninsula and it is locally called "The Eastern Shore". The landscape, dominated by agriculture, shrub-lands, grasslands, salt-marsh, brackish and fresh water ponds and beaches, serves as a refuge for numerous migratory and endangered species (U.S fish and Wildlife Service, 2005).

1.3.2 Gargathy Location, Setting and Characteristics

Gargathy Creek is located in the northern portion of the Southern Delmarva Peninsula (Figure 2). It drains into a coastal lagoon before exiting into the Atlantic Ocean. The lagoon is about 2 km wide between the mainland shoreline and the barrier Islands. The shoreline is about 10 km long between Wallops Island and Metompkin Bay.

Gargathy lagoon system has channels 1.5 to 5 meters deep, shallow bays 0.5 to 1.5 meters deep and extensive marsh areas located in the upper intertidal zone, influenced by tidal inundation. Gargathy inlet and its coastal lagoon form part of a tidal-dominated system with a tidal range of 1.04 meters.

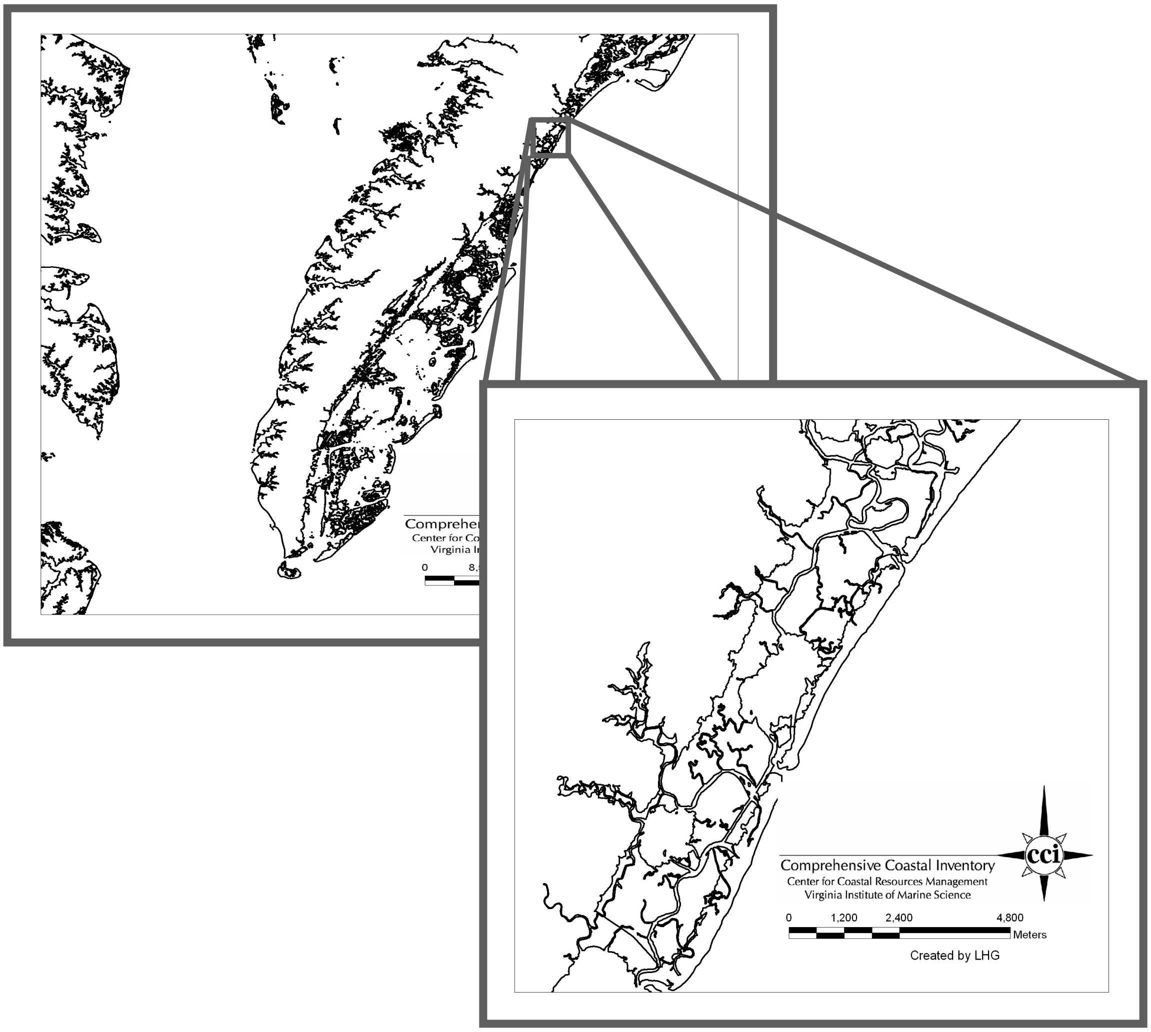


Figure 2. Gargathy system Location. Gargathy is located in the northern portion of the Southern Delmarva Peninsula. It extends for about 10 km, from Metompking bay in the South to Wallops Island in the North. Gargathy inlet and its coastal lagoon form part of a tidal-dominated system.

1.4 The Barrier Island system

Barrier lagoons, such as Gargathy lagoon, are coastal water bodies backed by barrier islands. The lagoon is one part of a barrier island system. A Barrier Island System is formed by six different interactive environments or elements (Oertel, 1985): The mainland, the inlet, the barrier platform, the shoreface, the barrier lagoon and the barrier island. Although this study focuses on the lagoon, each of the five elements influences the character of the lagoon.

The mainland slope and topography are important to the lagoon shape and size. As sea level rises, inundation of the shore or mainland increases the lagoon size by expanding the lagoon boundaries. Inundation of the mainland topography affects the bathymetry and shape of the lagoon. Bathymetry spatial variation results from the inundation of a valley or drainage basin; deep channels are the result of drowned thalwegs and elevated marshes and flats surfaces occur from inundation of interfluves.

The inlet serves as a channel for water and sediment exchange between the open water and the barrier lagoon. Inlet width and cross-sectional area directly affect the tidal prism entering and leaving the lagoon (O'Brien, M.P., 1969 and Jarrett, J.T., 1976). Qiaomin et al. (1992) studied the evolution of Gargathy tidal inlet and determined the effect inlet migration had in basin capacity. They focused and identified geomorphic changes in the inlet between 1851 and 1989 with the use of charts, maps and photos of the system. Main geomorphic changes resulted in a 72% inlet narrowing which caused a decrease of the tidal prism and discharge. Sediment deposition and accumulation can occur on the seaward and landward sides of inlets forming ebb tidal-deltas or flood tidal-deltas respectively (Oertel, 1985). Inlet migration often occurs in the presence of strong longshore currents.

The barrier shoreface and platform are other necessary elements in a barrier island system. The composition of these two elements varies in sediment size and material according to geological and physical processes. Accumulation or erosion of material in these areas affect basin size as the barrier island regresses or transgresses.

Barrier lagoons vary in shape, size and location according to the antecedent topography, inlet size and tidal conditions of the area. Two types of lagoons have been described in the past based on the amount of sediment input and the rate of sea-level rise, surplus lagoons (Lucke, 1934) and deficit lagoons (Oertel and Woo, 1994). Surplus lagoons are marsh dominated lagoons in which the rate of sediment filling exceeds that of lagoon expansion due to sea level rise. The other “end-member state” is known as deficit lagoon or open water lagoon. These lagoons have large open water areas (bays and channels) due to higher rates of inundation than sediment input.

The Barrier Island is the sixth element defining a barrier island system, and its presence creates the lagoon. Barrier Islands dominate about ten to twenty percent of the world’s coasts, covering eighty-five percent of the East coast of the United States (Stauble, 1989). Barrier islands are of extreme importance to lagoons since, without the barrier island, the lagoon waters would just be part of coastal oceanic waters, subject to waves and wind action, and the lagoon as such would not exist. Several hypothesis of barrier island formation have been suggested. De Beaumont (1845) described the process of barrier island formation by emergence of offshore bars. Formation of barrier islands by spit breaching was described by Gilbert (1885). McGee (1890) described the process of barrier island formation by inundation of topographic lows.

Because of the importance of these coastal systems to geologists, ecologists, biologists and inhabitants of the coast, many studies have been conducted on different elements of barrier Island systems to understand their unique geology, morphology, and dynamics. Swift (1975) attempted to understand the origin and formation of barrier islands by examining the relief and slope of the continental shelf in the Atlantic Ocean. He observed flat surfaces and terraces composed of lagoonal deposits and covered by thin layers of sand. As a result of the flat continental shelf surface, mainland beach detachment was determined the primary method for barrier island formation in the area. Slingerland (1983) focused on temporal morphologic variations at Assawoman Inlet, VA. He budgeted sediment volume along the different elements of this mesotidal system to determine the effect constructive and destructive waves have in barrier island systems. Byrnes et al. (1989), examined changes in shoreline migration rates in Metompkin Island. This study allowed him to understand the processes affecting island and inlet migration and the appearance and closure of inlets.

1.5 Hypsometry

Hypsometry, a concept first introduced by Langbein et. al (1947), describes the relationship between surface area and elevation. The first applications of the concept of *hypsometry* were used to describe the relationship between surface area and elevation above sea level in a drainage basin (Strahler, 1952). In these basins, the base area is the maximum area and land surface area decreases in elevation to the rim of the basin as a result of landmass erosion. Barrier lagoons are tidal basins with characteristics similar to terrestrial drainage basins. *Hypsometric* conditions in barrier lagoons describe the distribution of different land-surfaces associated with elevation such as marsh, tidal flats or deep tidal channels (Oertel and Woo, 1994). My interest is not on the landmass but on the void areas that get filled with water. *Hypsometric* concepts can be applied to hydrologic modeling (Luo, 1998) and these concepts are valuable tools used to understand the hydrodynamic characteristics affecting flushing in coastal lagoons and tidal inlets (Boon and Byrne, 1981, Kjerfve and Magill, 1989).

The concept of *Hydro-hypsometry* was introduced by Oertel (2000) to represent the capacity of a lagoon. *Hydro-hypsometry* relates fractions of water surface areas, a/A, (where a is the area at a specific elevation and A is the maximum water surface area in the basin) to fractions of the basin height, h/H, (partial height at a specific elevation over the total elevation or depth of the basin). In studying water distribution, the surface area is minimum at the bottom and it increases as coastal basins get flooded. This relationship can be illustrated in *Hydro-hypsographic curves* showing the areas in a basin submerged by water at different elevations. The idea of *hypsography* and *hydro-hypsography* in coastal lagoons varies slightly from the initial concept of *hypsography.*

Volume-hypsometry, another application of *hypsometric* concepts, was used by Oertel (2001) to understand flushing characteristics at coastal bay environments. *Volume- hypsographic curves* illustrate the relationship between fractions of water volumes to fractions of basin height. The shape of the *volume hypsographic curve* and the location of the flushing point (F-point) along the curve can be used to determine flushing characteristics.

SECTION 2

METHODS

Field and laboratory methods were designed for accomplishing the above tasks. Field methods involved initial observations of the area, establishing a vertical datum plane across the study area and measuring depths in the intertidal and open-water areas. Laboratory analysis included data correction, creation of an elevation model, volume determination and hypsometric calculations.

2.1 Field Methods

2.1.1 Temporary benchmarks establishment in Gargathy lagoon.

A 1979 U.S.G.S Bloxom Quadrangle sheet (N3745-W7530/7.5, Virginia-Accomac co., 7.5 min series, Commonwealth of VA, division of mineral resources), was used to locate benchmarks on the mainland margin of Gargathy lagoon. A bench mark, designated as BM 4 in the Bloxom Quadrangle, was identified along the lagoon edge on Gargathy Neck. On May the 20th, 2007, “Sutton” was located using a hand held GPS (Garmin) at -75.5621° longitude and 37.773917° latitude on Gargathy Neck (Figure 3). The benchmark was buried under about 30 cm of organic rich soil.

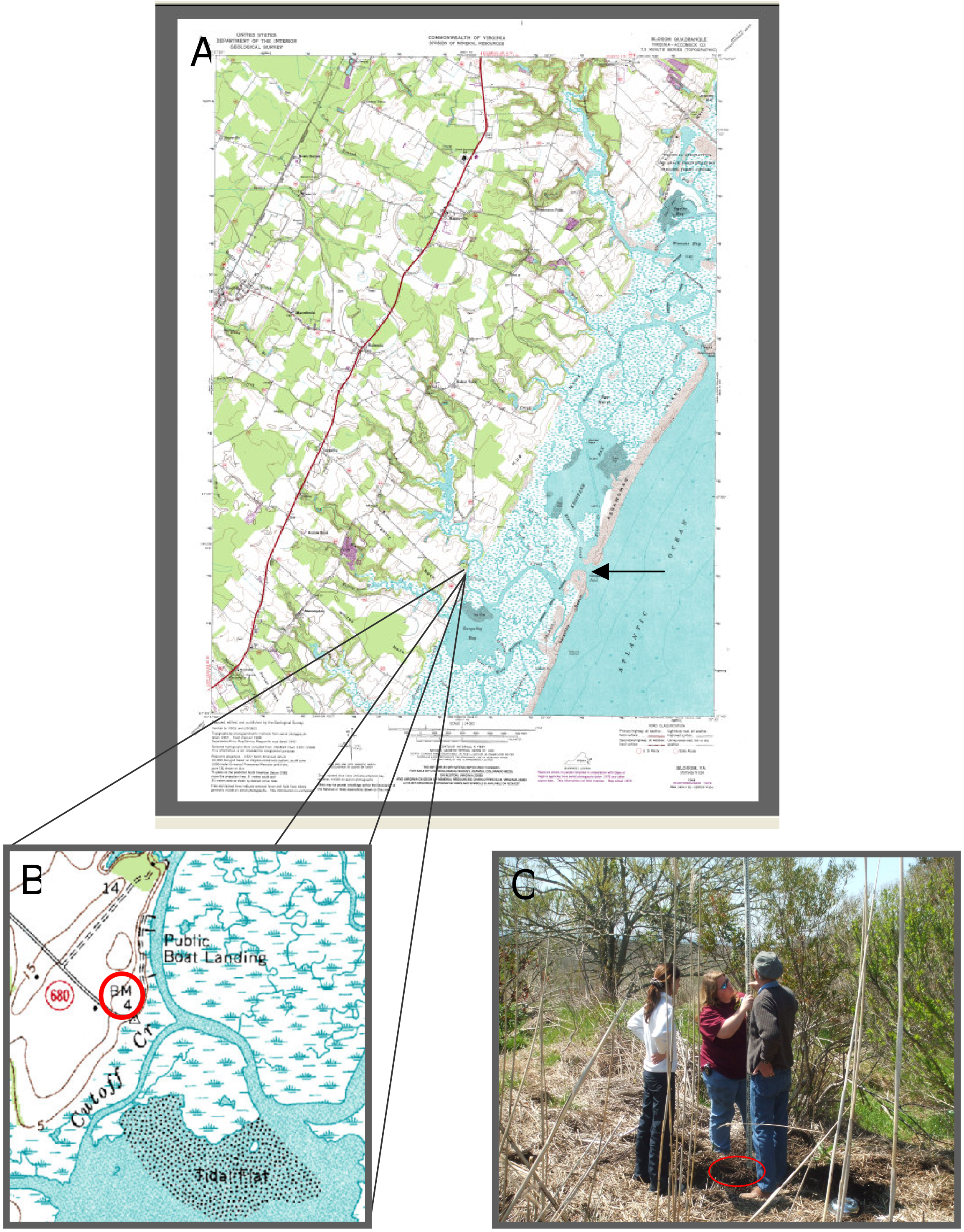


Figure 3. 1979 Bloxom Quadrangle. (A) Digital Raster of Bloxom, VA Quadrangle showing Gargathy inlet (arrow) and its coastal lagoon. Used to locate a NOS-NOAA/USGS benchmark (BM4) along the edge. (b) Blown up image of selected BM (Sutton). (c) Location of Sutton BM buried under 30 cm of orgnic rich soil, Overman, Dr. Oertel and Herraiz-Gomez setting survey rod over benchmark.

The elevation from Sutton benchmark (NAVD88 Datum) was carried to a dock (37° 46.505' latitude and -75° 33.683' longitude) on Gargathy Neck using a Pentax auto level PAL-2C, and a graduated survey rod. A bolt in the dock was used to establish a temporary benchmark (TBM-GC) that could be accessed from a small boat (Figure 4).

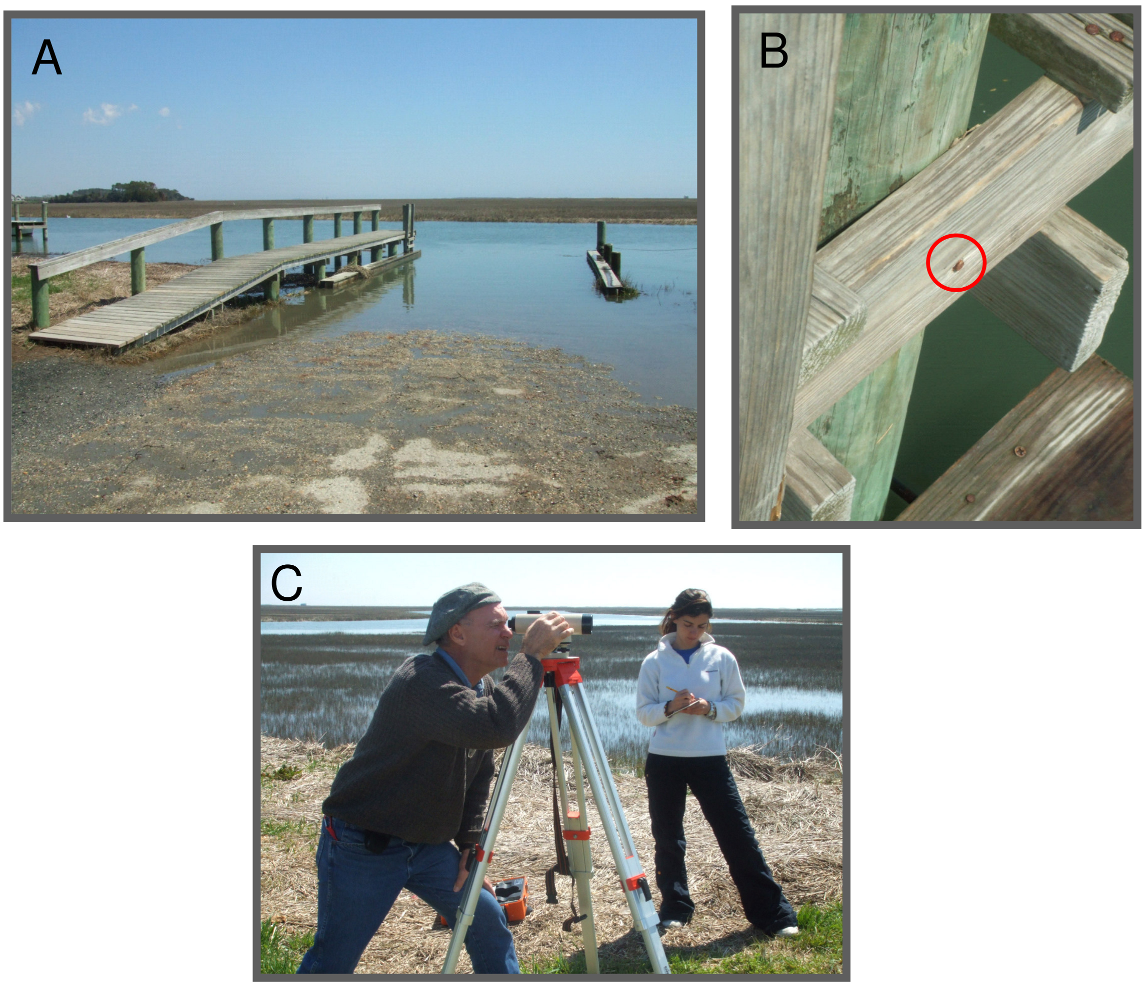


Figure 4. TBM-GC. The top pictures show the (A) dock used to establish Temporary benchmark GargathyCreek (TBM-GC) and (B) TBM-GC. The bottom picture (C) shows the Pentax auto level PAL-2C used to carry out the elevation from "Sutton" Benchmark to the dock.

To build an elevation model of the marsh-lagoon system, it was necessary to obtain depths in the intertidal and open-water areas. This was done by surveying the area at or close to high tide when most surfaces were submerged. However, even at high tide, marsh surfaces were generally too shallow for echo-sounding surveys and another technique (described below) was used.

Since depth data obtained from echo-sounding is relative to rising and falling water surfaces, it was necessary to adjust all field data to a constant datum.

NAVD88 at TBM-GC was carried to other locations in the Gargathy system using a water surface leveling technique. The water surface leveling technique consisted of going back and forth between “known” and “new” TBMs. New TBMs were created by screwing a yellow tag or bolt to a fixed pole (Figure 5), and recording the change in water level over the period of time spent to go from one “known” TBM to a “new” TBM and back to the “known” TBM. Change in water level over the time interval allowed us to readjust the effect of water level change on the new TBM and therefore to determine the relationship between the “new” TBM and the “known” TBM.

On March 23rd of 2007, a survey was conducted using a skiff obtained from the Anheuser-Busch Coastal Research Center, during which 11 TBMs were established throughout the system (Figure 6), following the procedure described above. Locations and elevations of the TBMs are described in Appendix A.

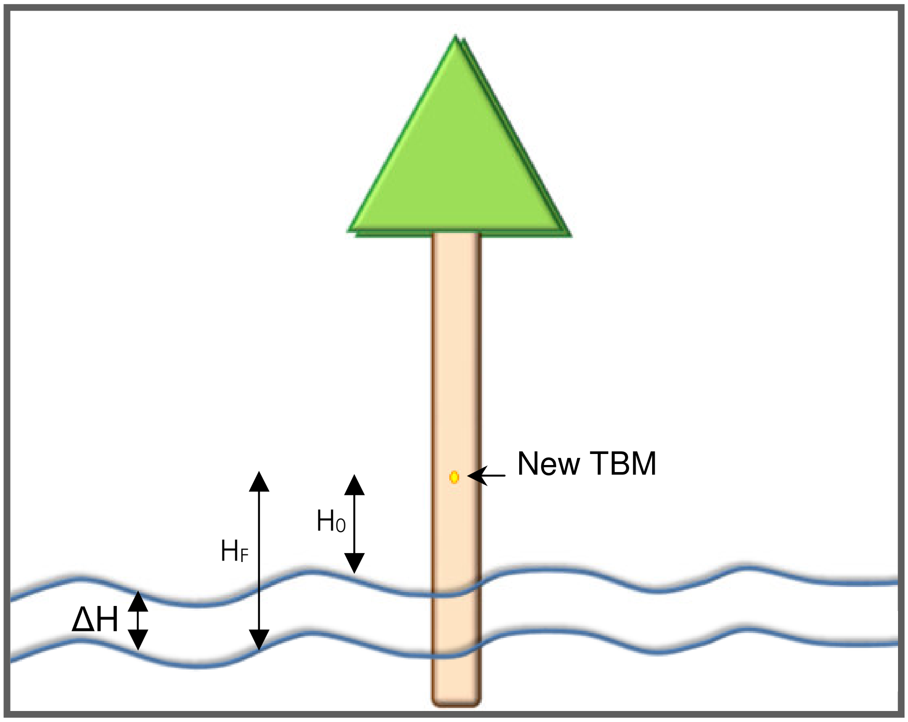


Figure 5. New TBM. This figure shows a newly established TBM. New TBMs were created by screwing a bolt or a yellow tag to a pole and determining the relationship to TBM-GC. H_0 represents the distance from the established TBM to the water surface at the beginning of the transect. H_F represents the distance from the TBM to the water surface at the end of the transect. ΔH represents the change in water elevation between the initial and final water levels. ΔH and the time spent to go from known TBM to new TBM and back to Known TBM were used to determine the relationship between TBM-GC and the newly established TBM.

2.1.2 Echo-sounding

After establishing the TBMs throughout the area of interest, the main goal of the field surveys was to record water depths and locations in intertidal and open-water areas in the Gargathy lagoon. Nine bathymetric surveys were conducted in June, July and August 2007 and March 2008. A high-resolution echo-sounder (Innerspace™ Digital Fathometer, Model 448) mounted in the hull of the boat was linked to a Trimble ™ 4000

SE global positioning system (GPS) and navigation software (Figure 7). Simultaneous collection of location, time and echo-sounding depths were obtained and recorded in a laptop computer with two communication ports.

Figure 6. Location of TBMs created along Gargathy system. Eleven TBMs were created in the system to monitor changes in water levels during Echo-sounding surveys.

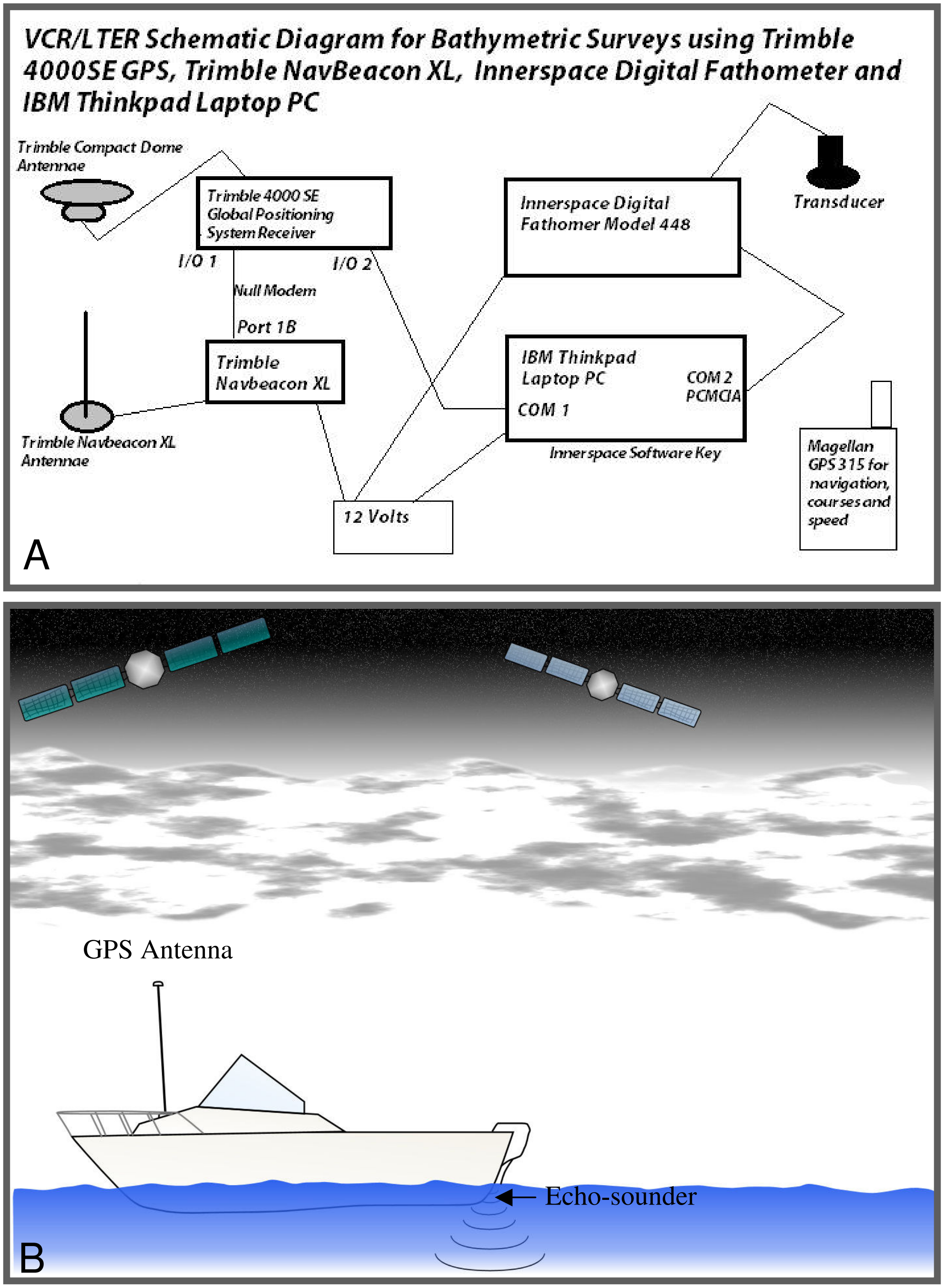


Figure 7. Equipment used for bathymetric surveys. (A)The top image shows the Equipment set-up and connections necessary for the collection of echo-sounding depth, location coordinates and time (After Carlson 2001). (B)The lower image shows the equipment on the boat (echo-sounder, antenna, GPS).

Water levels fluctuated tidally during echo-sounding surveys. In order to account for tide-induced water level fluctuations during the surveys, the process of data collection involved the “opening” and “closing” of transects at known TBMs. Opening a transect involved a measurement (to the nearest 2 cm) of the distance between the TBM and the surface of the water. Time was recorded and a computer file was opened to record the echo-sounding depths. A transect was run for about 20 to 30 minutes and the vessel returned to the TBM to close the transect by measuring the distance from the TBM to the water and recording the closing time (Figure 8). Opening and closing times and distances to the water surface for all surveys are located in Appendix B. The change in water level over the period of time spent in a transect allowed the integration of the data so that every depth is related to the same (initial) water level. A total of 23,000 points were collected during the echo-sounding surveys. Data were collected in UTM coordinates in a Zone 18, WGS 84 datum.

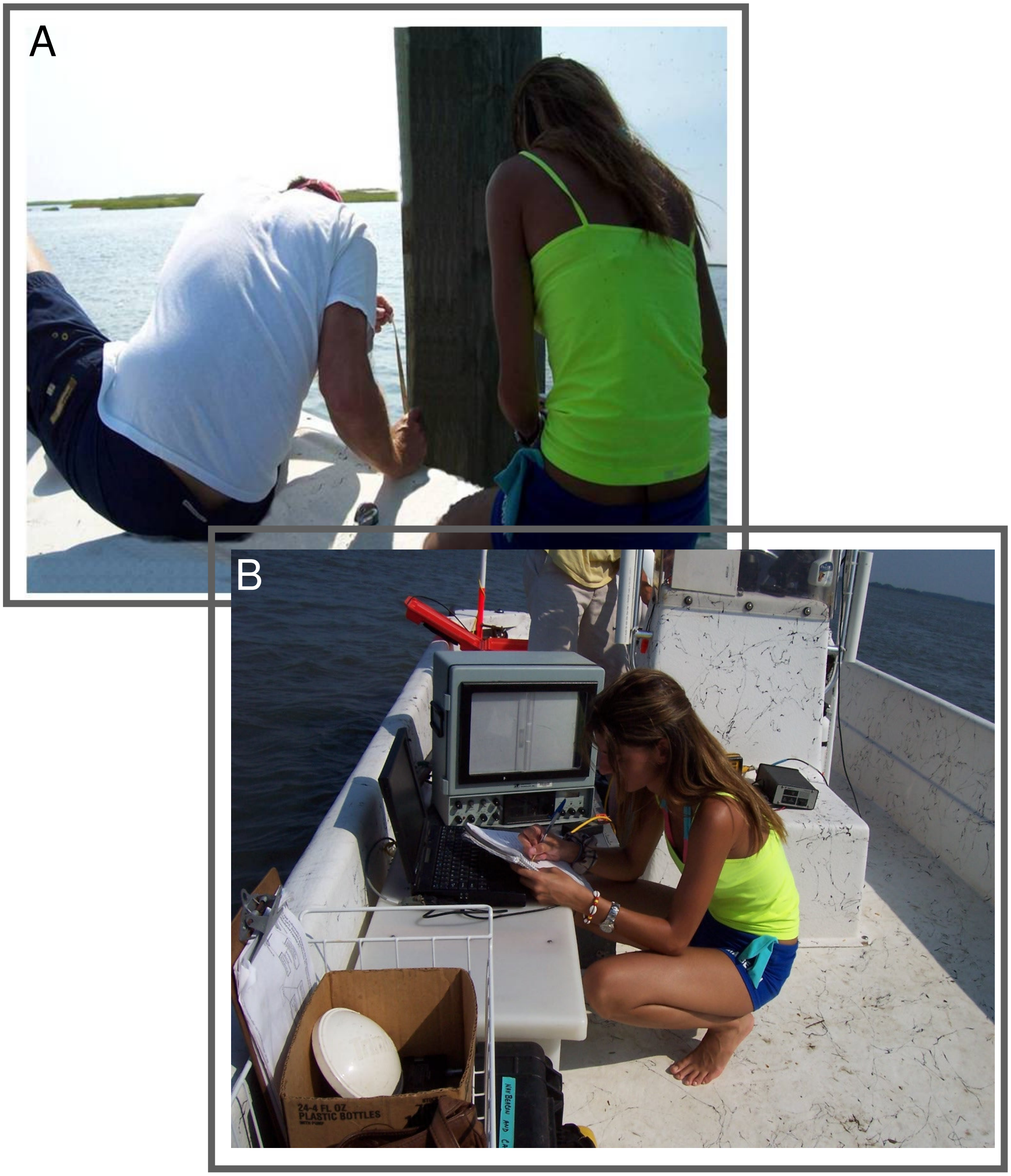


Figure 8. Bathymetric Survey. During echo-sounding surveys, depth data were collected in transects or sections. Each transect was opened and closed at a TBM. Starting and closing time and distance from the TBM to the water surface were recorded for each transect. (A) In the top picture George McLeod is measuring the distance from TBM to water surface and I am recording it. (B) In the lower picture, I am writing down the opening time from the computer.

2.2 Laboratory Methods

2.2.1 Data Correction

2.2.1.1 NAVD88/MHW Relationship

The Gargathy Inlet/coastal lagoon is a tidally dominated system where significant changes in water levels occur. Because of the high tidal influence in the system, the depth data acquired during the echo-sounding surveys needed to be corrected to account for these tidal oscillations. As described above, a level plane was established throughout the system, which allowed us to adjust echo-sounding data to a specific vertical horizon (datum).

For this study, we were interested in correcting the data to mean high water (MHW). To relate all the depth points to mean high water, the relationship between NAVD88 and MHW needed to be estimated.

The tidal range at Gargathy Neck was determined and used to obtain the relationship between NAVD88 and MHW. The tidal range was estimated by taking an average of 5 different stations close to Gargathy Neck. Tidal ranges at stations located in Gargathy inlet, Chincoteague, Metompkin, Wachapreague and Wallops Island's (www.co-ops.nos.noaa.gov/station-retrieve.shtml?type=bench+mark+data+sheets) were used to compute an average tidal range at Gargathy Neck. The tidal range at Gargathy Neck was determined to be 1.04 m $\pm$ 0.18 m.

Next, the relationship between NAVD88 and MHW was determined for Wallops Island and two stations at Chincoteague (www.co-ops.nos.noaa.gov/station-retrieve.shtml?type=bench+mark+data+sheets). About 40% of the tidal range was above NAVD88 datum and about 60% of the tidal range was below NAVD 88 datum.

Based on these distributions around NAVD 88 datum, mean high water at Gargathy Neck, was determined 0.43 m above NAVD 88 and mean low water is 0.64 m below NAVD88 (Figure 9). The relationship between NAVD 88 datum and mean high water was used to adjust the bathymetric data to mean high water level.

2.2.1.2 Echo-sounding data correction for tidal fluctuation

Time, location coordinates and depth data were collected in the field and recorded as notepad text files on the computer hard drive. The files were insets of seven coupled data packets. Each file contained data point, time, latitude, longitude, Eastings (X), Northings (Y) and relative depth (in feet).

The raw data were initially culled by Kathleen Overman, the laboratory and Research Specialist at the UVA LTER who supervised field work in summer of 2007. The culling process involved the elimination of invalid data points that were acoustic multiples or a result of erroneous echo-sounder operation.

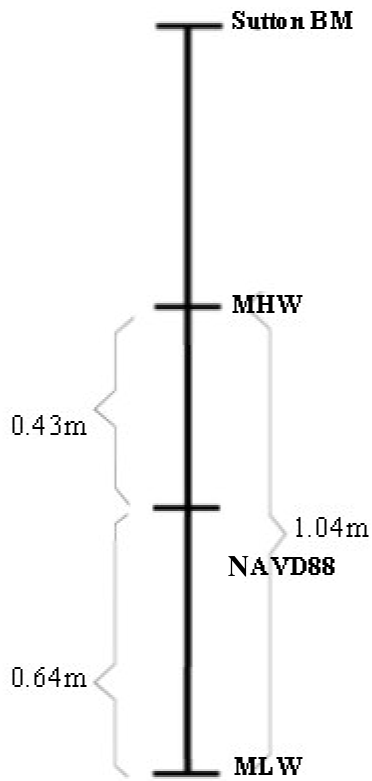


Figure 9. Relationship between NAVD88, MHW and MLW. This figure shows the relationship between mean high water, mean low water and NAVD88. The vertical distance between NAVD88 and MLW represents 60% of the tidal range and MLW is 0.64 meter below NAVD88. The vertical distance between NADVD88 and MHW represents 40% of the tidal range and MHW is 0.43m above NADV88.

Since water levels rose or fell during field surveys, it was necessary to adjust all data in a survey leg to the initial water level at the beginning of each leg. Data were organized in a spreadsheet (Excel ™) to correct for tidal adjustments. Each file was divided into transects that initiated at a TBM and closed at the same TBM. This allowed the water level change to be associated to time gates. A total of forty-six transects, with more than 20,000 data points, were time-gated and adjusted to the initial water level (at the beginning of the transect).

Correcting the echo-sounding depth data for tidal fluctuations involved several steps. The first step in correcting raw data was to convert the time, recorded as hours, minutes and seconds into decimal hours. Conversion of time from hours, minutes and second to decimal hours was computed using equation1.

Equation 1

Time (decimal hours) = hours+ (minutes/60) + (seconds/3600).

Next, the surveying time or duration spent between the opening and closing of a transect was determined. This was used to determine the rate of water level change with respect to time ($R=\Delta d/ \Delta T$). Each echo-sounding depth in a survey was time-gated using increments of the elapsed time between the opening of the transect and each echo-sounding depth.

The rate of water level change with time and the elapsed time for each collected depth were used to determine the "height adjustment" that needed to be added or subtracted to each depth (to be adjusted to the initial water level). "Height adjustment" for each echo-sounding depth was computed by multiplying the elapsed time at each depth point by the change in water elevation per time (decimal hours).

The final step in the process of tidal adjustment was to add or subtract the height adjustment to/from the original, collected depths. Height adjustments were subtracted from initial depths when tides rose during the transect. During falling tide the height adjustment was added to the initial depths.

2.2.1.3 Data adjustment to MHW

After data were corrected for tidal fluctuations, depths contained within each transect were related to the water level at the starting of the transect. Water levels varied according to the rise and fall of tides. These temporal fluctuations in water level cause the starting water level to be different for each transect performed.

To build an elevation model, it is important to relate all the depth data within the system to the same water level. For this project, depths were adjusted to Mean High Water (MHW) to determine the maximum capacity of the lagoon.

Data correction to MHW required previous adjustment of the data to NAVD88 level. Each of the TBMs that were established had different elevations. Therefore, surveys using different TBMs had different adjustments to NAVD88. The relationship between each of the TBMs used and NAVD88 are summarized in Appendix A.

Next, data were adjusted to MHW. Mean high water was estimated to be 0.43 meters above NAVD 88, following the procedures described in the first section of “methods”. Adjusting the water surface to MHW was achieved by adding 0.43 meters to the water depths adjusted to NAVD 88 (Figure 10).

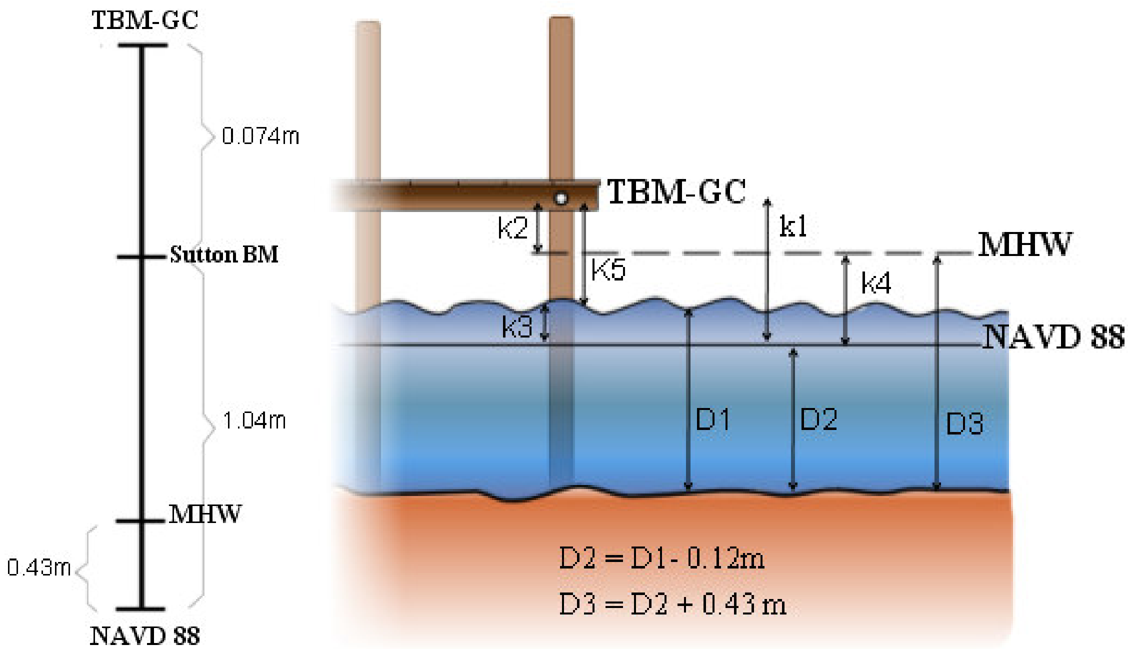


Figure 10. Data Adjustment to MHW using TGM-GC. On the left, the relationship between TBM-GC, Sutton NAVD88 and MHW is illustrated. The relationship between TBM-CG and Sutton BM was first determined using leveling techniques described in methods section. That relationship and the known relationship between Sutton BM and NAVD88 were used to determine the relationship between TBM-GC and NAVD88. On the right, echo-sounding data adjustment to MHW is illustrated. Distance from the TBM to the water surface (k5) and echo-sounding depths (D1) were collected in the field during surveys. Relationship between the TBMs and NAVD88 (K1) was previously determined and is located in Apendix A. K4, the relationship between NAVD 88 and MHW is 0.43m. With these known parameters (D1, K1, K5 and K4) the other parameters (K2, K3, D2 and D4) can be determined. D2 represents the water depth adjusted to NAVD88 and D3 represents the final water depth adjusted to MHW.

2.2.2 Data Processing

Data processing involved the integration of GIS techniques using ArcGIS 9.3 (ESRI) software. ArcGIS software along with a 2002 aerial image from the Virginia Base Mapping Program (VBMP) were used to create a Digital elevation model of the system

(DEM), to delineate the marsh boundary or to calculate the volume of water present in the system.

2.2.2.1 Inserting data into ArcGIS and shapefile creation

To manipulate and process the corrected data using ArcGIS software, files created in .xls Excel format were converted into .csv Excel format. The .csv file was added as XY data to ArcMap 9.2. Data were collected and projected in WGS84 (World Geodetic System 1984).

Next, the data layer was converted to a shapefile to ease the manipulation process. This process was done by exporting the data to a shapefile (Figure 11).

2.2.2.2 Creation of a Marsh Boundary.

Due to vessel inaccessibility to shallow areas, we were unable to get depth readings for the entire system. However *Spartina alterniflora* at the water-marsh boundary was used as a substitute for MSL elevation. *Spartina alterniflora*, the salt marsh cord grass dominating Gargathy system, colonizes the muddy surfaces between Mean sea level (MSL) and highest high water (HHW) (Oertel, Kraft, Kearny and Woo, 1992).

In "data correction" section, the tidal range at Gargathy Neck was determined to be 1.04 m $\pm$ 0.18. Based on this tidal range, MSL was estimated to be 0.52 meters below high water.

The lower marsh boundary was used as a surrogate for 0.52 meters elevation. The boundaries of marsh were modeled by creating a new point shapefile in ArcCatalog. The point shapefile was added to ArcMap, as well as a one meter resolution, 2002 aerial image of Gargathy system, obtained from the Virginia Base Mapping Program (VBMP). Approximately 18,600 points delineating the water-marsh boundary were manually drawn using the sketch toolbar in ArcMap and the 1m resolution aerial image as background (Figure 12). Depth values of 0.5m (0.5 meters below HW) were assigned to points delineating the marsh-water boundary.

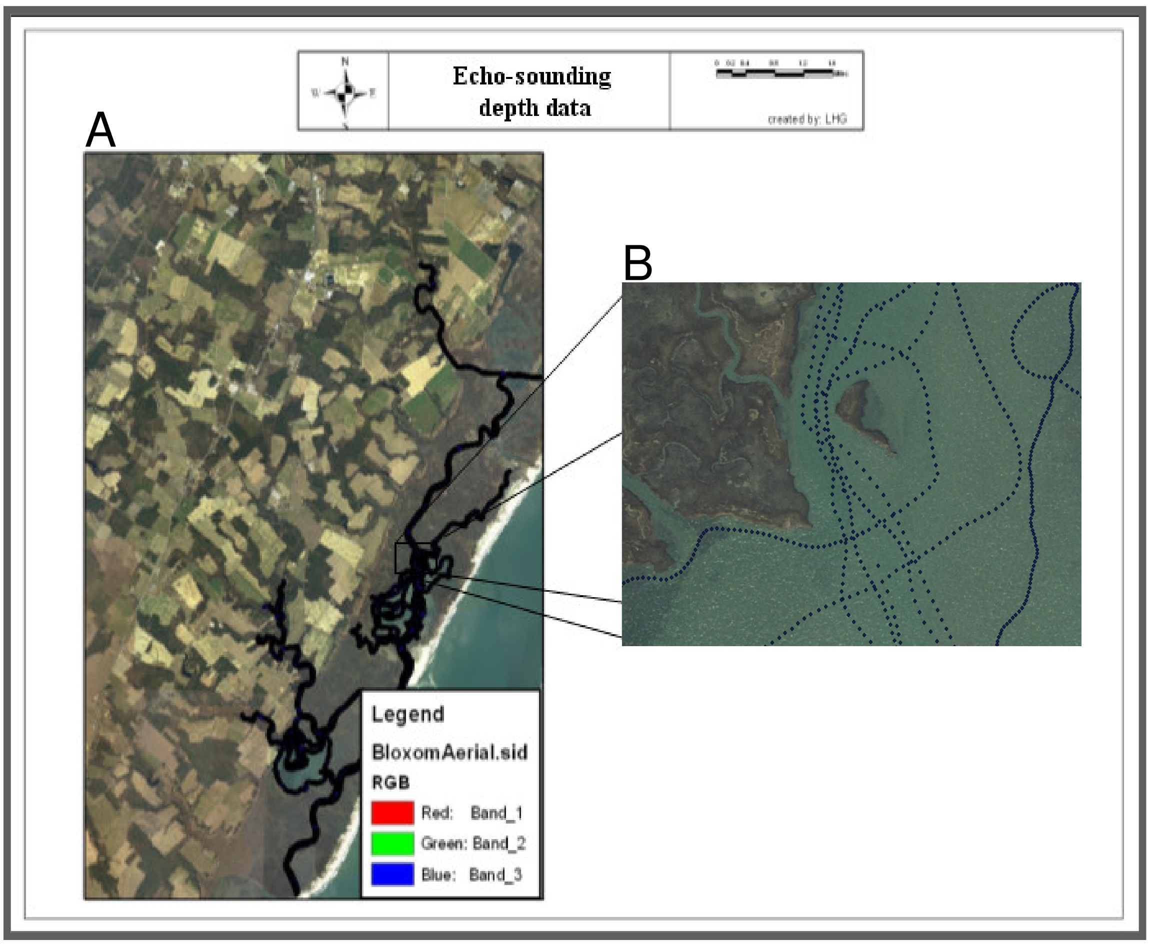


Figure 11. Echo-sounding depth data. This figure illustrates the echo-sounding depth data collected in field. Before the data were added to ArcMap, correction of the data to MHW was performed. (A) Approximately 23000 depth points were corrected and displayed. The data was added to ArcMap as XY data. (B) Blown up image of shapefile containing collected and corrected depth data points.

2.2.2.3 Interpolation

Interpolation is an important tool available in the ArcDesktop interface that allows the user to create a continuous surface of known values. Interpolation techniques were used in this project to create a digital elevation model (DEM) throughout the study area. Depth values for un-sampled points with unknown depth were estimated based on the surrounding sampled points, of known depth values.

Several interpolation techniques were tested and analyzed in this project to select the most accurate elevation model for Gargathy system. Simple kriging, ordinary kriging or IDW (inverse distance weighting) were some of the interpolation methods used.

Before, executing the interpolation, a set of analysis tools for ArcGIS 9.3 (© ESRI), "Hawth's tools," were downloaded from the web and added to ArcMap. A sampling tool available under Hawth's toolbar was used to randomly select 2% of the known elevation points.

From the 23,059 depths recorded in the field and displayed on ArcMap, 2%, (461 points) were randomly extracted from the file. These extracted points were later used to determine the accuracy of each interpolation method by comparing the estimated value to the true value.

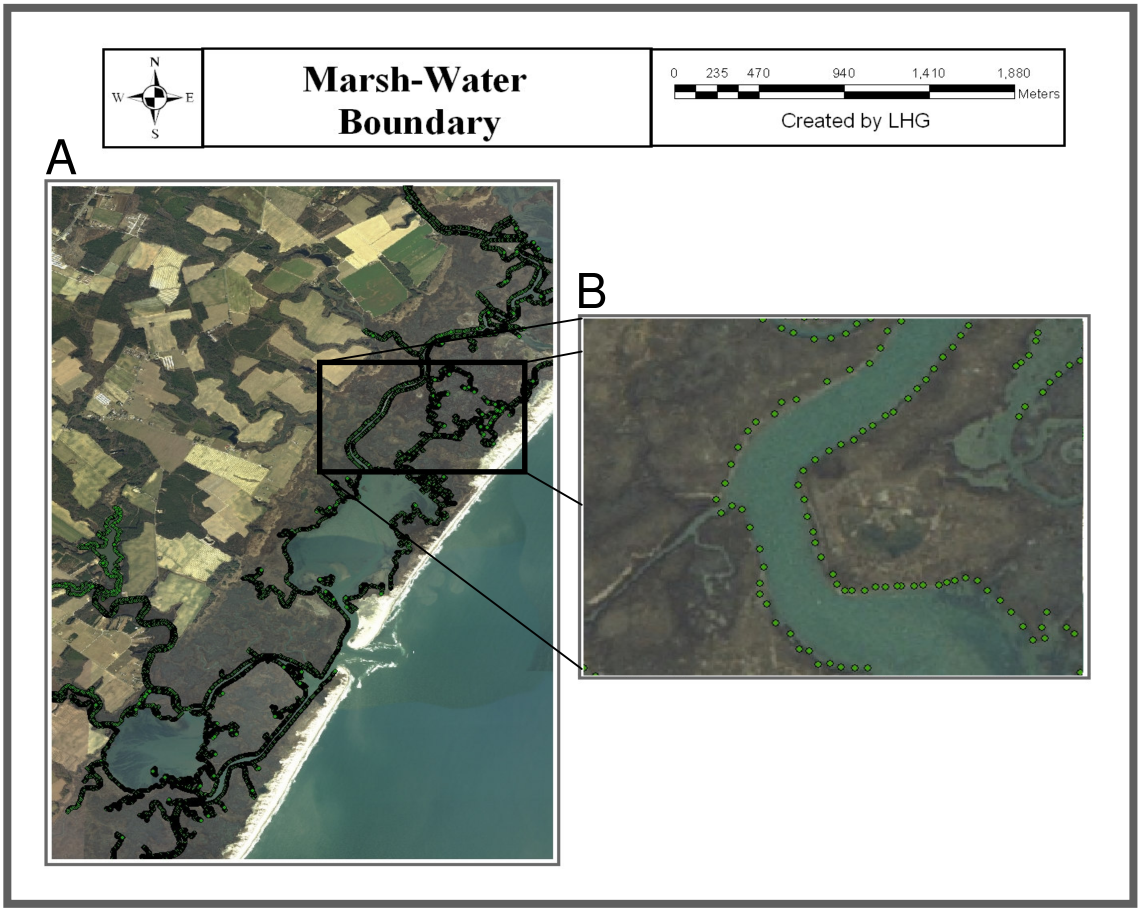


Figure 12. Marsh-water boundary. (A)This figure illustrates the shapefile containing 18,600 created points delineating the marsh-water boundary. (B) Blown up image of Marsh-water boundary. A 2002 aerial image of Gargathy system was used as background and reference for the delineation of the marsh boundary. A depth value of 0.5 meters was assigned to each of the created points. This shapefile was later merged with the field echo-sounding data corrected to MHW and used to run the interpolation process.

A total of 40,476 elevation points (22,598 depth points from the total collected in the field plus 18,613 points created in ArcMap representing the marsh-water boundary), were used for the interpolation process to estimate the elevation (depth) values at the un-sampled locations in the system.

Two different tools (Geostatistical Analyst and spatial analyst tools) in ArcMap were used to run interpolations. The shapefile containing 40,476 elevation points was used as the input layer for the interpolation process. Parameters such as number of neighbors used to estimate unknown points or maximum distance to the known points were entered. Different parameter options were selected to determine the ones that best represented the elevations in Gargathy system.

A one meter resolution raster file, representing Gargathy's DEM (Digital Elevation Model) was obtained as the output and added to ArcMap.

Several steps were followed to determine which of the created DEMs was the most accurate. A shapefile was created containing only the 461 extracted points from the echo-sounding corrected depths. This shapefile was used to extract the interpolated (estimated) elevation values from the DEM. After the extraction, a new shapefile was created containing the known and estimated values at the 461 points (Figure 13).

Under the attributes table, a new column, "PercentError", was created and the cell values were calculated using the following formula:

Equation 2

% Error = (abs [Observed Depth – Interpolated Depth]/Observed Depth)x100

The cell values obtained for that column were used to determine the accuracy of each method used.

IDW was determined to be the most accurate interpolation method for Gargathy system. The best interpolation obtained had an average % error of 3.15 %, with 437 points of 461 having an average error of 0.85% $\pm$ 2.29.

Parameters selected for the most accurate IDW method performed included a maximum distance to the known points of 5 meters and the use of 5 known neighbors to estimate the unknown depths. Comparison of the true and estimated elevation (depth) values is present in Table 1 of Appendix C.

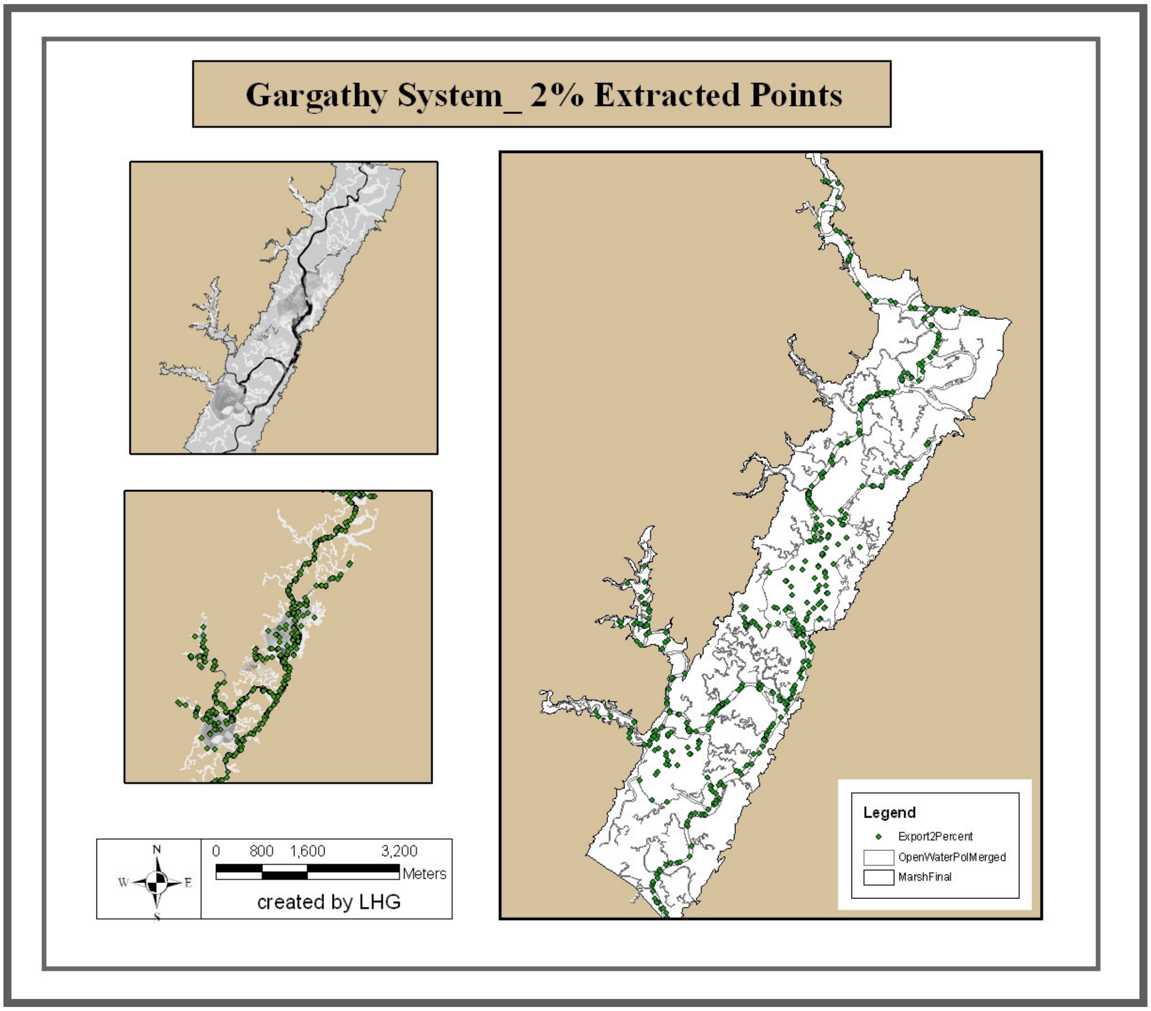


Figure13. Extracted depth points. 461 depth points were randomly selected and extracted from the approximately 23,000 echo-sounding depths adjusted to mean high water. These 461 depth points were used to extract the depth value estimated at each of those points from the DEM. The top left figure shows the DEM used to extract the estimated depth values. Lower left figure shows the extraction of estimated depth values from DEM using the randomly selected points. Figure on right shows, depth points, each containing the new estimated depth value.

2.2.2.4 Creation of Open water areas

The interpolation process produced a rectangular output layer, reaching out beyond the surveyed points. However for this study we were only interested in having the DEM cover the open water areas. To extract the open water areas from the rectangular layer produced in the interpolation, a polygon covering just the open water areas in the system was created. This was done by creating a new polygon shape-file using ArcCatalog and manipulating it in ArcMap. Three hundred forty five polygons, covering the open water areas, were manually created using the sketch toolbar in ArcMap. The three hundred forty five polygons were then merged into a single polygon, using the dissolve tool in ArcMap (Figure 14)

2.2.2.5 Extraction of open water areas to the DEM

The shape of the open-water polygon showed in Figure 14, was used to extract the open water areas from the rectangular shaped DEM. Reshaping the DEM was achieved using the “extract by mask” tool in ArcMap. The DEM raster layer was used as the input and the open water areas polygon served as the mask shapefile used to extract the open water areas from the DEM. The DEM for the open water areas at Gargathy system is illustrated in Figure 15.

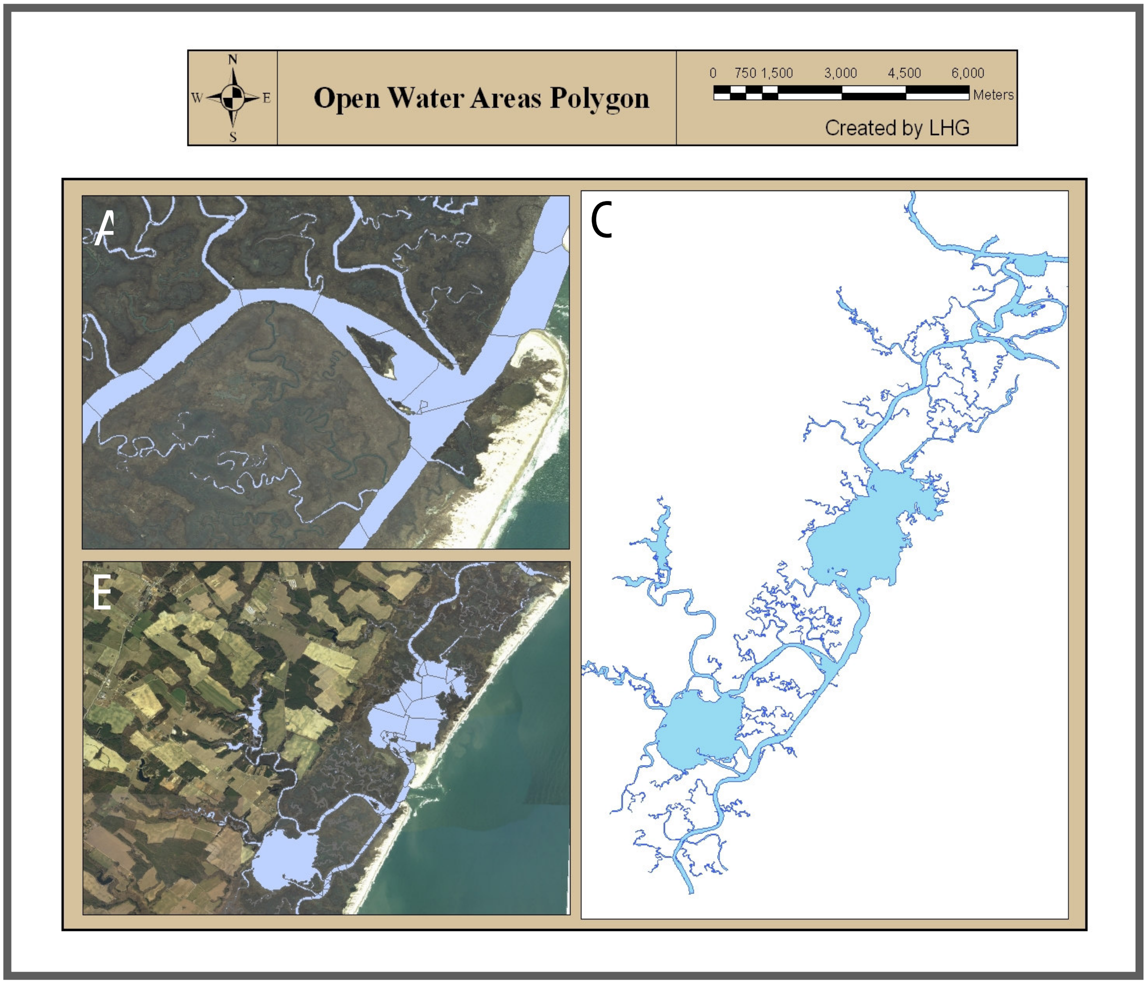


Figure 14. Open Water Areas Polygon. (B)The bottom left image illustrates the shapefile containing 345 polygons created to represent the open water areas in Gargathy system. (A) Top left picture gives a closer look at some of these created polygons. (C) The figure on the right illustrates the final open water polygon, after all 345 polygons were dissolved. This polygon was created using the sketch tool in ArcMap and a 2002 aerial image as background. The open water areas polygon illustrated in this figure was used to obtain a DEM for the open water areas at Gargathy system.

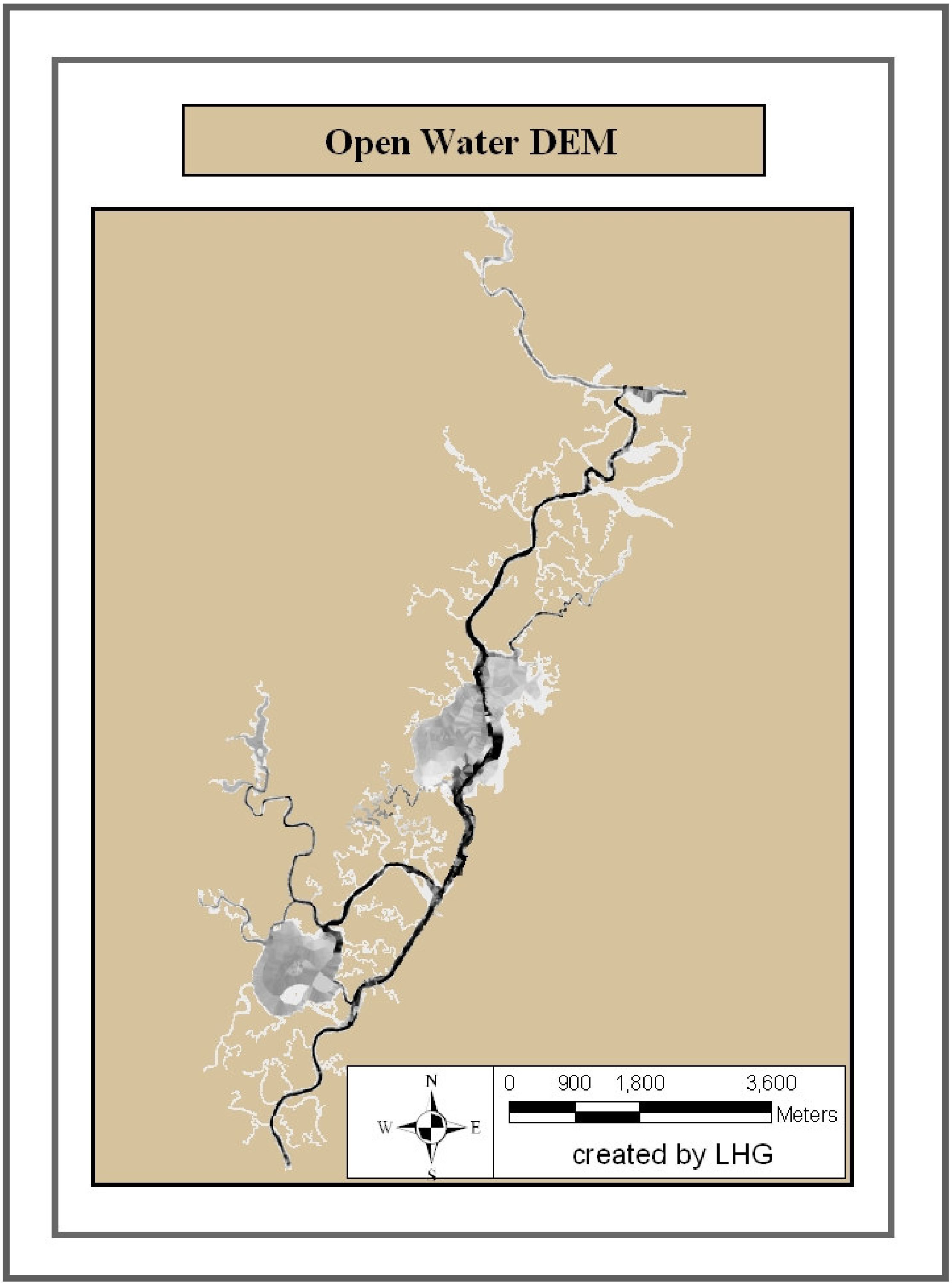


Figure 15. Open Water areas DEM. Figure shows DEM for the open water areas at Gargathy system. The open water DEM was obtained using the open water areas polygon (figure 16) and extracting those areas from the DEM obtained from interpolation output file.

2.2.2.6 Marsh DEM

An important goal of this study was to construct a *hypsographic curve* that describes the different benthic sub-environments in the system (i.e. tidal flats, marshes, intertidal channels, etc).

A *hydro-hypsometric* curve was also generated to determine the water-surface areas at different depths. Since Gargathy lagoon is dominated by extensive marsh areas, the generation of *hypsographic* and *hydro-hypsographic curves* required the creation of a DEM that included the open-water DEM and a DEM for the marsh areas.

The marsh DEM was created in several steps. First, a polygon covering the entire lagoon (marsh and open-water), "LagoonPolygon," was created. This polygon included the areas from the mainland shoreline to the back barrier shoreline (Figure 16A). Second, the "lagoon polygon" was re-shaped to cover just the marsh areas. Reshaping of the lagoon polygon was achieved by deleting the open water areas from the entire lagoon polygon. The open-water area polygon was used as input in the erase tool, and a new polygon covering just the marsh areas was created as the output (Figure 16C).

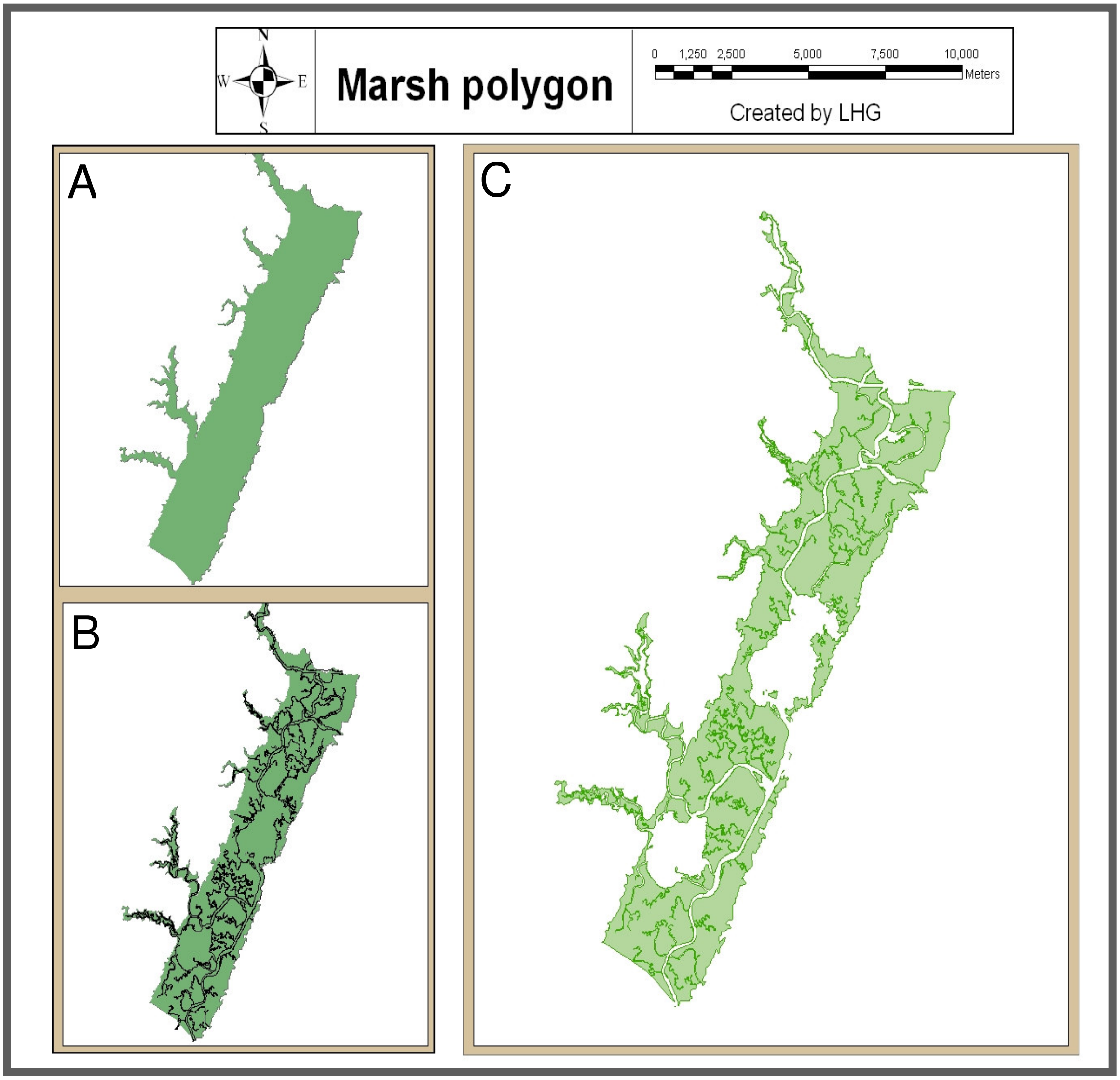


Figure 16. Marsh polygon. (A) Figure illustrating the entire lagoon polygon. This polygon was formed from 38 smaller polygons covering the lagoon from the mainland to the back-barrier shoreline. (B) Figure showing the open-water area polygon over lagoon polygon. The open-water areas were deleted from the lagoon polygon using ArcMap. (C) Figure illustrating the final marsh polygon, covering just the marsh areas.

Next, elevation values were assigned to the marsh polygon. Since, *Spartina alterniflora* dominates the marsh in the Gargathy system, elevations could be assigned based on tidal characteristics. Using a tidal range of 1.04m, we estimated that marsh colonizes the area between 0.5 meters below high water and goes up to high water.

Assuming a constant slope in the marsh areas, the average depth over the marsh would be 0.25 meters. However, field observations suggest the marsh areas do not have a constant slope but it was steep close to the creeks and flattened away from them. Based on these observations, the marsh was assigned an average elevation of about 0.15 meters below high water. To assign this elevation value (0.15m), a new attribute column called "depth" was added to the marsh polygon attribute table and given a value of 0.15m.

Finally, the marsh polygon shapefile was converted to a 1 meter resolution raster file using the "polygon to raster conversion tool" in ArcMap. This tool allowed us to have a continuous surface over the marsh areas with elevation values assigned to each 1m pixel.

2.2.2.7 Gargathy System Digital Elevation Model

Creation of a digital elevation model (DEM) for Gargathy system was performed by merging the previously created 1meter resolution DEMs for both the open water areas and the marsh areas in the system. Combining the two raster layers together was accomplished using the mosaic tool and inserting both raster files as inputs to create a new raster file covering the areas at Gargathy system that get flooded at high tide (Figure 17).

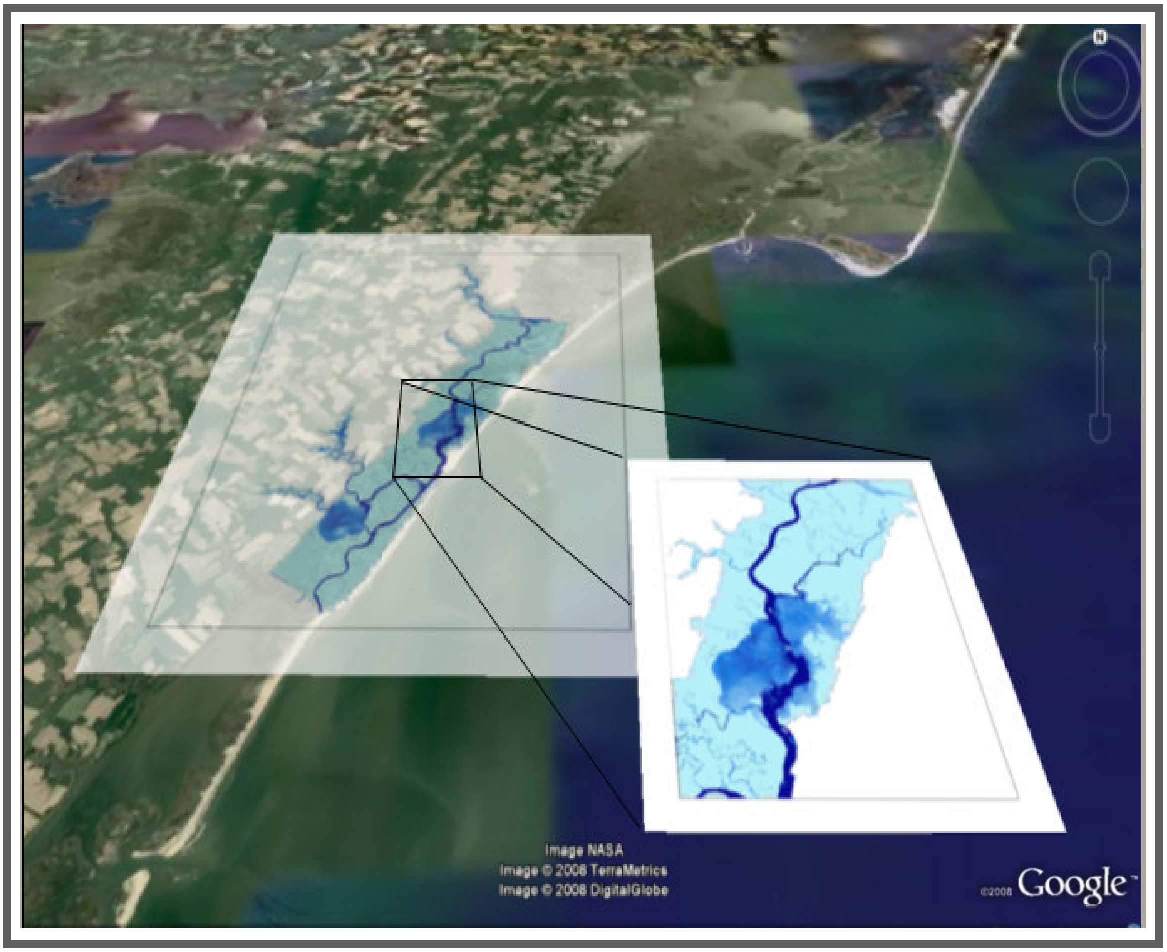


Figure 17. Gargathy DEM. This figure illustrates the final DEM for Gargathy. The darker color represents the deeper areas in the system and the ligher colored areas represent the shallower areas in the system. Depths range from – 13.4 meters at the inlet to -0.15 in the marsh areas. This DEM was used to calculate partial and total surface areas and volumes.

2.2.2.8 Volume/Area calculations

The Gargathy DEM was used to compute partial and total areas/volumes at different depths in the system. Total and partial volumes in the system were obtained using the surface analysis tool in ArcMap. Volumes of water covered by each pixel are calculated by determining the product of pixel areas ($1m^2$) and pixel depth. The surface analysis tool computes partial and total volumes of water below a specified level or depth. The volume of water below 0m (HW) represents the total volume of water present in the system at high water and volumes decrease as the input level or depth decreases from 0 (HW) to -13.4 (the maximum depth in the system). Volumes relative to depth were used to calculate the total volume of water present in the system at high tide as well as the tidal and residual prisms.

Areas relative to elevation in the system are also determined using the surface analysis tool available in ArcMap. The area at a certain depth is computed by adding the areas of each pixel present at that specific depth. Areas and Volumes relative to depth were used for the creation of *hypsographic*, *hydro-hypsometric* and *volume-hypsographic* curves.

The maximum basin height (H) is the sum of all increments of height (h) between the basin floor and the surface. The height at the basin floor (h_0) is assumed to be zero and it increases to the water surface. Minimum values of h occur at the greatest depths (d). The maximum benthic surface area (A) occurs at the basin floor, at h_0, and decreases towards the water surface, reaching a value of zero where basin height is the maximum, (H), (Figure 18).

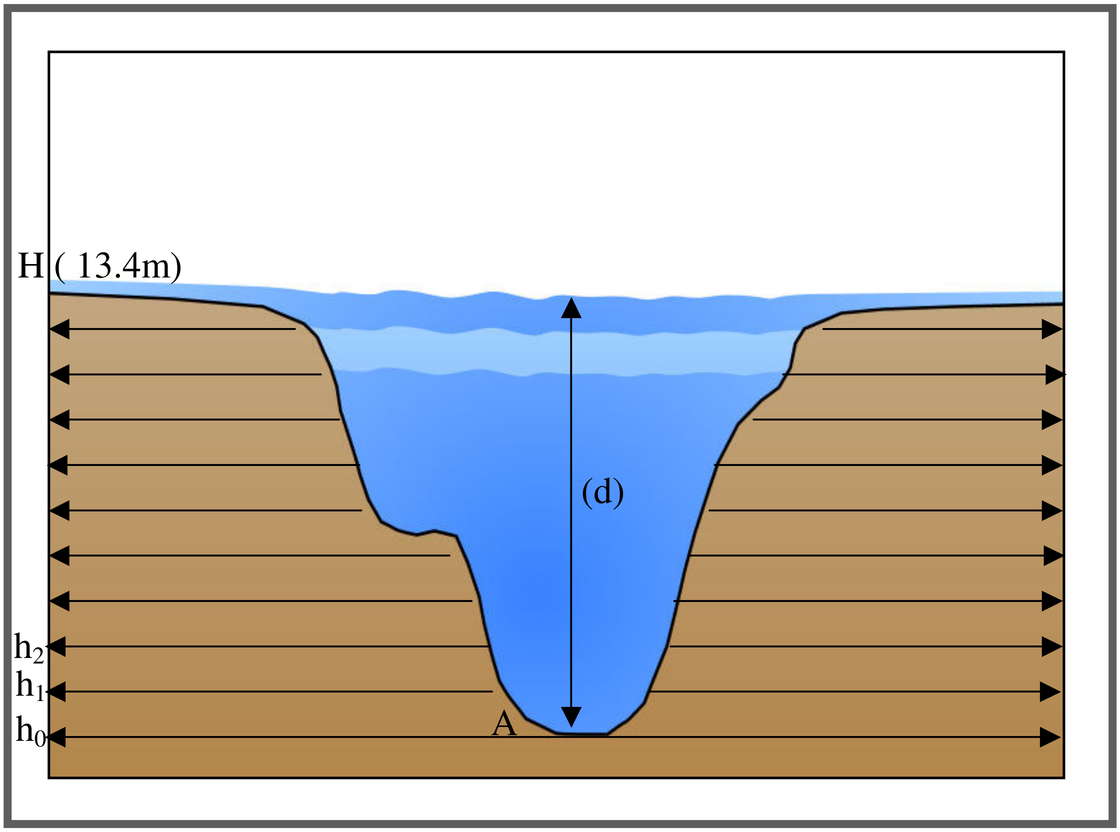


Figure 18. ***Hypsographic*** **Areas/heights**. This figure illustrates the relationship between areas and heights in a basin. The height at the basin floor (h_0) is zero and it increases to the water surface. Minimum values of h occur at the greatest depths (d). The maximum benthic surface area (A) occurs at the basin floor, at h_0, and decreases towards the water surface, reaching a value of zero where basin height is the maximum, (H).

SECTION 3
RESULTS

3.1 Hypsography, Hydro-hypsography and Volume-hypsography Analysis

3.1.1 Bathymetric spatial variation and benthic sub-environments and water-surfaces distributions.

Bathymetric analysis was used to investigate the hydrological characteristics of the Gargathy lagoon system and to describe the benthic and pelagic environments. Depth varied spatially throughout the system; the larger depths, reaching up to13.4 meters below mean high water, occurred near the inlet, while the shallower areas occurred on intertidal areas dominated by marsh (Figure 19). These depth variations were used to describe/understand the different benthic sub-environments.

A *hypsographic curve* for Gargathy system was created to describe the benthic areas based on elevation above the basin floor. The *hypsographic* curve (Figure 20) illustrates the spatial distribution of 4 benthic sub-environments, upper intertidal benthic environment, intertidal flats, sub-tidal flats and sub-tidal channels. The upper intertidal benthic sub-environment covers about 80 % of the total surface area of the basin but only the upper 3.7 % of the basin height. While this surface has been colonized by the smooth cordgrass *Spartina alterniflora*, most of the marsh occurs on the upper 1 % of the basin height.

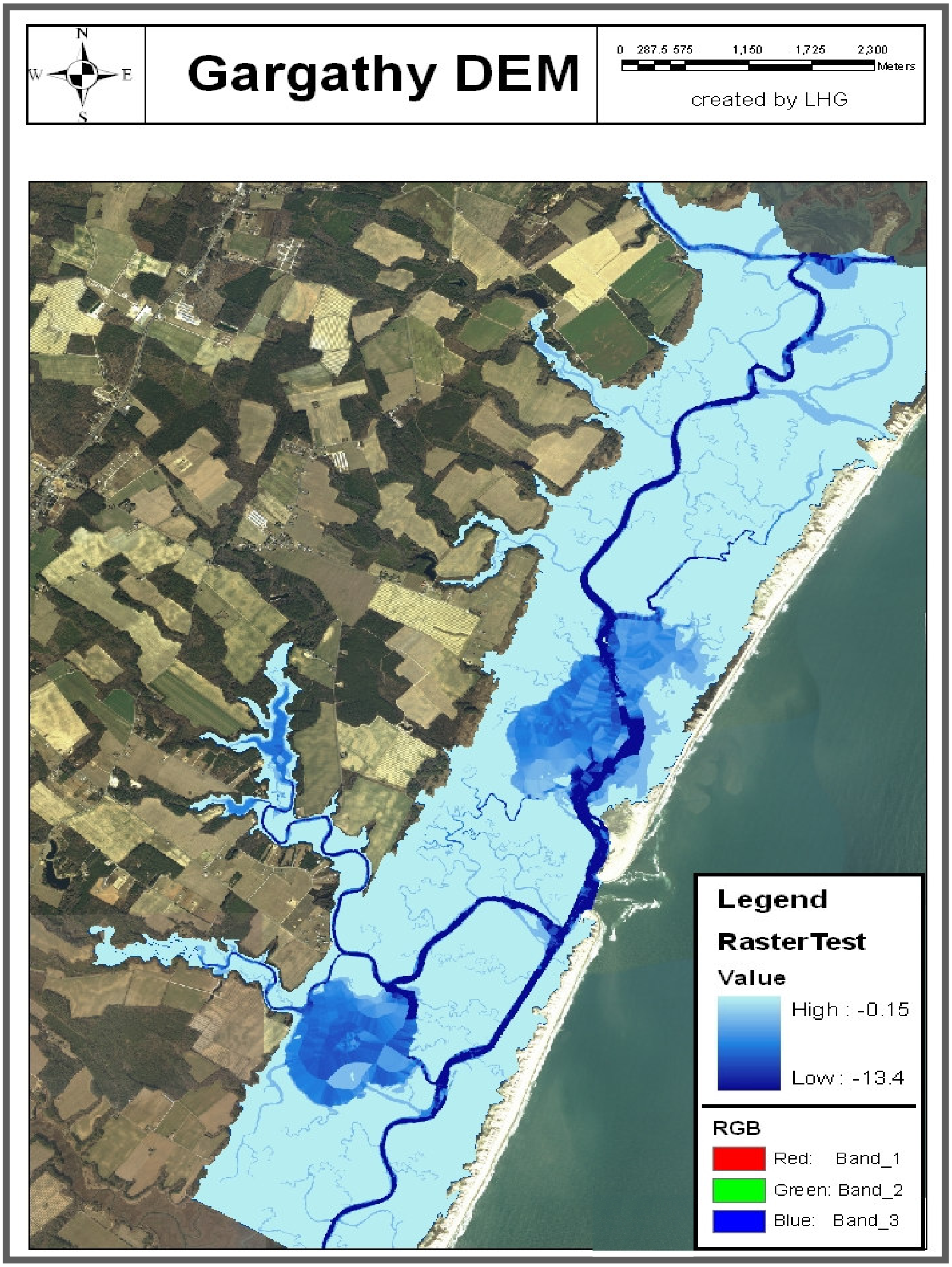


Figure 19. Spatial depth variation. Depth varies spatially throughout the system; the larger depths in the system, reaching up to13.4 meters below mean high water occurred at the inlet section while the shallower areas predominate in the intertidal areas dominated by marsh

Marsh develops on elevated flat surfaces in the upper intertidal benthic environment. Much of this surface is dissected by a network of tidal channels for marshes that Oertel and Woo (1984) have classified as fringe marshes and marsh islands. Marsh islands dominate the upper 1 % of the basin height and the upper intertidal areas, developing in antecedent highs or highly sedimented platforms. Distribution of these marsh surfaces is associated with recent submergence of topography on areas with a history of fine-grain sedimentation (Oertel, 2001). Tidal channel edge marshes occur on steep surfaces along the margin of the channels. Tall form *Spartina alterniflora* occur at these margins between 0.5 and 0.25 of the tidal range on the channel berms.

The lower intertidal benthic sub-environment (LIBSE) covers 9 % of the benthic surface area of the system. Ranging from about -0.5 to -1 meter deep, this benthic sub-environment also represents 4 % of the total height of the basin. The lower intertidal benthic sub-environment is present on two interior bays surrounded by marsh (Gargathy Bay and Kegotank Bay). Narrow bands of LIBSE occur along the margin of all tidal channels. LIBSE are optimal sites for Oyster reefs colonization. Together, the upper and lower intertidal areas cover about 90 % of the benthic surface area of the basin. However, these two environments (marsh and intertidal flats) represent only 7 % of the total basin height.

Sub-tidal environments occupy about10% of the benthic surface area and remain constantly submerged. Sub-tidal environments occur in two sub-classes. Flats occur at depths between 1 to 2 meters and channels occur at depths greater than 2 meters. Together, the sub-tidal flats and channels represent 93 % of the total basin height. The sub-tidal flats cover 9 % of the benthic surface areas and may be suitable to SAV

(Submerged Aquatic Vegetation) colonization. The Sub-tidal channels represent only 2% of the benthic surface and 78% of the basin height. Channels are bordered by higher marsh surfaces that confine flow and cause high velocity tidal currents. Tidal scour is present at the inlet channel where the maximum depths are about 13.5 meters.

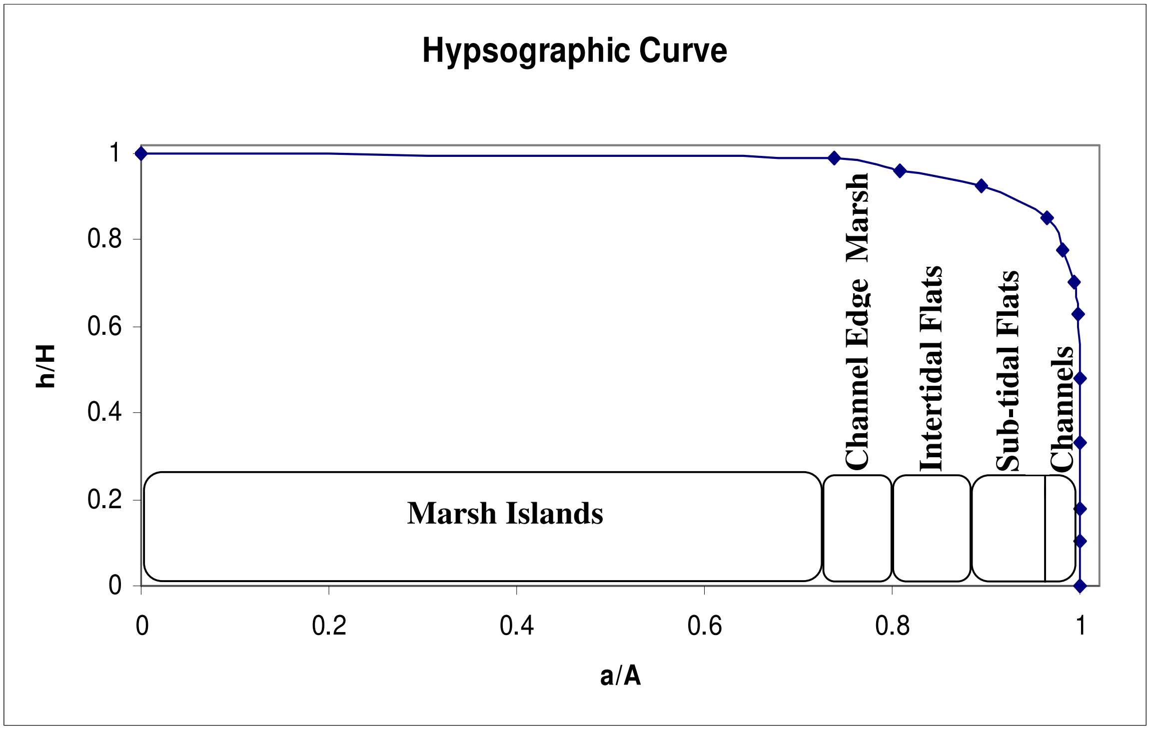


Figure 20. *Hypsographic* Curve. This figure illustrates the distribution of the benthic environments associated with basin heights. Four benthic sub-environments, upper intertidal benthic environment (Marsh islands and Channel edge marsh), intertidal flats, sub-tidal flats and sub-tidal channels were distinguished. The upper intertidal benthic sub-environment covers about 80 % of the total surface area, the lower intertidal benthic sub-environment covers about 9 % of the benthic surface area, the sub-tidal flats cover about 9 % of the benthic surface and about 2 % of the benthic surface occurs in sub-tidal flats and channels.

3.1.2 Hydrological Analysis

3.1.2.1 Hydro-hypsography

A *hydro-hypsographic* curve illustrates the relationship of water-surface areas between high tide and depth horizons to the deepest point of the system. Relative depths (d) were plotted versus relative water-areas (a) to illustrate the water-surface distribution in the Gargathy lagoon (Figure 21). By definition, 100% of the water surface area occurs at high tide when d/D=1 or d=D. At mid-tide (MSL), the water surface area is reduced to about 19 % of the maximum water surface area. Around MSL, a 0.02 m change in h produces a 6 % change in water surface area. The water surface area at low tide represents about 10 % of the total water surface. The water surface at the base of the sub-tidal flats (top of channels) was about 2 % of the total. If the water surface were at depths of 5 meters, the water surface would be reduced to 0.2 % of the total water-surface area present in the system at high tide. Finally, at depths greater than 13.4 m, the water surface area has shrunk to 0% of a/A.

3.1.2.2 Water Budgets. Total, tidal and residual prisms.

A total water prism of 10.6 x 10^6 cubic meters is present in the system at high water. This is considerably smaller than other nearby coastal lagoons described by Oertel et al. (2001) and Allen et al. (2007). The Hog Bay system described by Oertel et al. (2001) has a high water (HW) capacity of about 3.13 x 10^8 cubic meters. Chincoteague (Allen et al, 2007) has a HW capacity of 4.0 x 10^8 cubic meters. At high tide, water covers the upper and lower intertidal benthic sub-environments and the sub-tidal flats and channels.

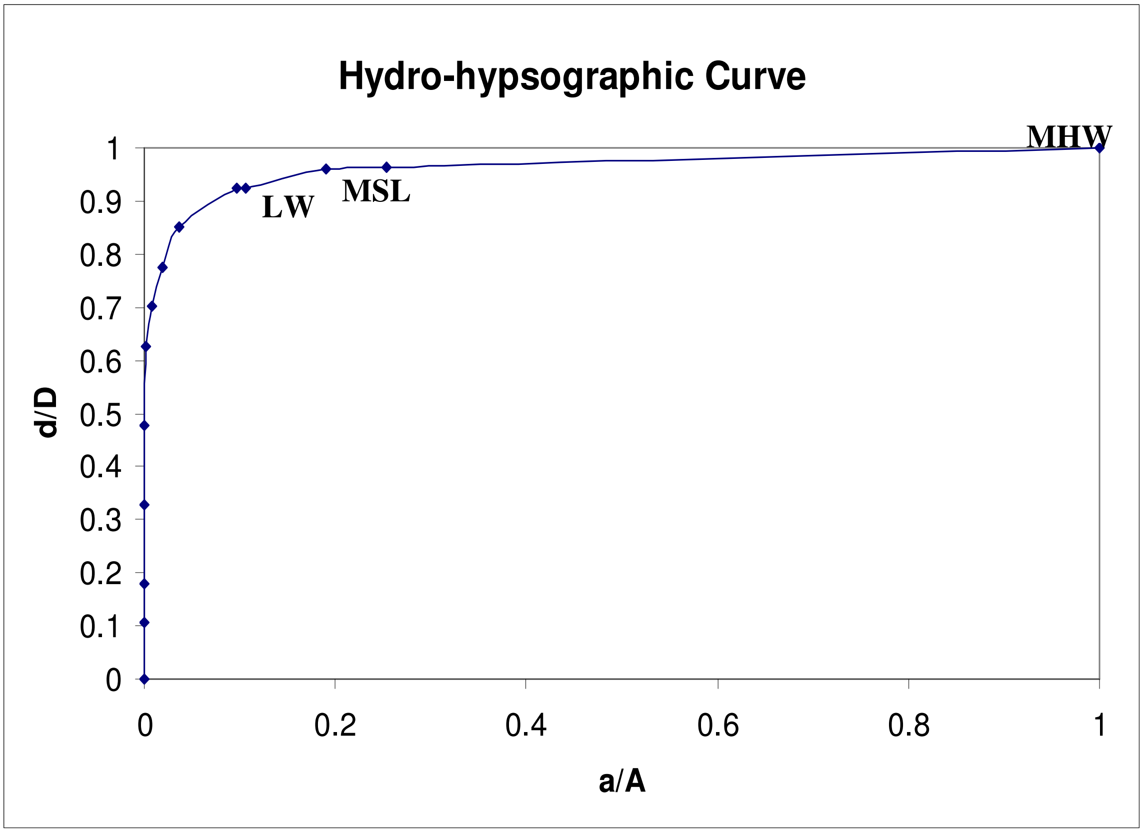


Figure 21. ***Hydro-hypsographic* curve**. The *hydro-hypsographic* curve illustrates the relationship of water-surface between high tide and the deepest point in the system. As illustrated, 100% of the water surface area occurs at high tide when d/D is a maximum. At mid-tide (MSL), the water surface area is reduced to about 19 % of the water surface area. At low tide (base of intertidal flats), the water surface area is 10 %.

The hydraulic character of the Gargathy system is driven by tides. A tidal prism of about 8.2×10^6 cubic meters was estimated by the difference between the total water prism at high tide and the residual prism (water volume below 1.04 meters).

The tidal prism represents 77 % of the total volume of water present in the system at high tide. Most of the tidal prism (76%) covers the shallower areas in the system where depths are less than 0.5 meters.

The residual prism (remaining at low tide) was about 2.4 x 10^6 cubic meters or 22.66 % of the total water volume at high tide. Residual water occupied the channels and the deeper lagoon areas that represented the lower 92 % of the basin height and about 10% of the surface area.

3.1.3 Hydraulic Flushing Characteristics of Gargathy Coastal Lagoon

3.1.3.1 Flushing and Hydraulic Turn-Over Time

Oertel et al. (2001) used an F-point (Flushing Point) on a *volume-hypsographic* curve to represent the amount of water vacated by the ebb tide. They used the F-point volume to estimate hydraulic turn-over time for the entire basin. Since *volume-hypsographic* curves only illustrate the relationship between water volume and basin height, they provide little insight into movement of flushing patterns within lagoons.

The F-point (Figure 22), representing the tidal prism, covered the upper 8 % of the system's total height and it exchanged about 77 % of the basin capacity within each tidal cycle. Hydraulic Turn-Over Time (HTT) is the inverse of F1 or HTT=1/F1. The HTT for Gargathy lagoon is 1.29 tidal cycles.

A HTT of 1.29 assumes all the water in Gargathy system is completely mixed in less than two tidal cycles between exchange with the ocean. This is probably not true, since water near the inlet may not mix with water in the "upper" reaches of the system. HTT for coastal lagoons is best used as a means for comparing turn-over time at different coastal lagoons but not for determining flushing. To determine flushing, some knowledge of water mass movement is required.

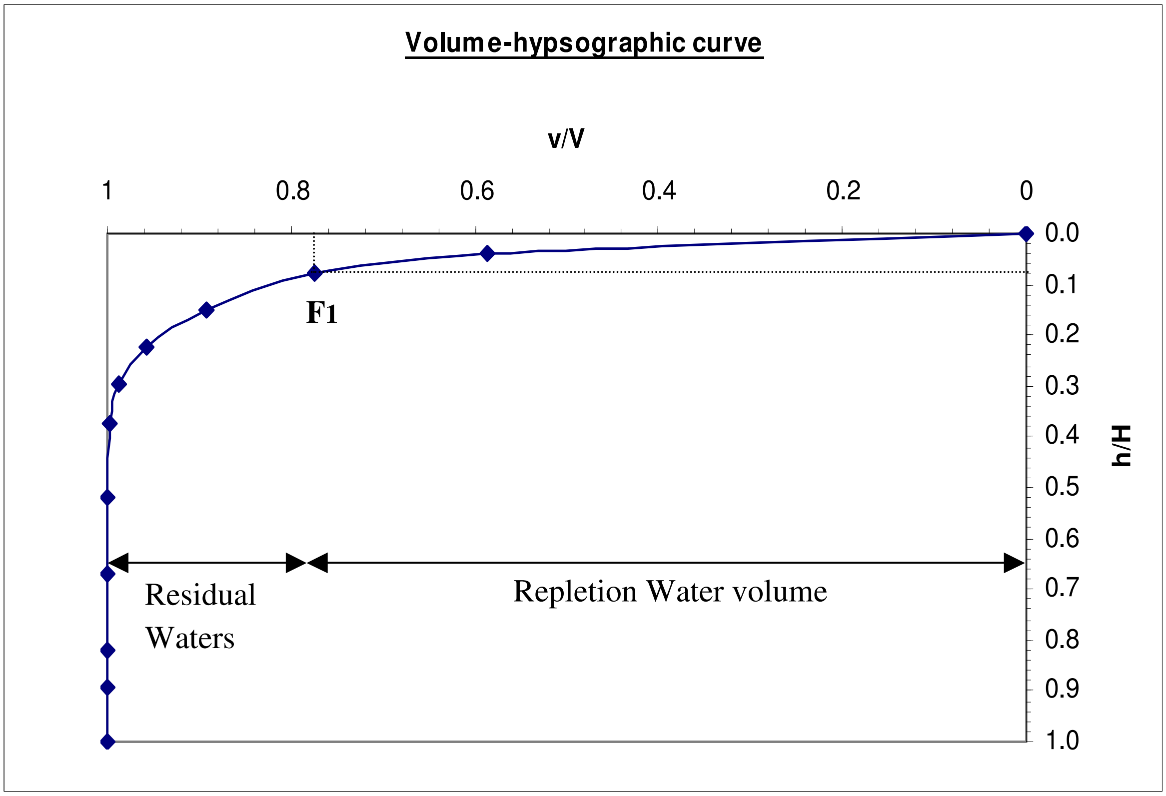


Figure 22. *Volume-Hypsographic Curve*. This Volume-hypsographic Curve illustrates the relationship between water volume and basin height. The F-point has a value of 0.77, indicating 77 % of the total water present in the system at high tide gets exchanged with the ocean with each tidal cycle.

3.1.3.2 Repletion Footprint

To further understand the flushing characteristics of Gargathy lagoon system, a volume of water equivalent to the tidal prism was used to identify the repletion footprint of water re-entering the basin. Repletion patterns/footprints refer to the maximum extent to which the repletion water mass expands into the void basin areas during flooding stages of the tidal cycle. Repletion water volume expands into a lagoon over the full water column height of tidal channels. As it moves into the lagoon it pushes the residual lagoon water landward (Oertel et al.,2007).

A first-order repletion model for Gargathy Lagoon was created (Figure 23A) by expanding a volume equal to the tidal prism into the volume of the voided basin. This model does not take into consideration flood-flow rates. This first-order repletion model assumes water spreads in all directions once it passes the inlet. Figure 23A, illustrates the repletion volume equal to 77 % of the basin capacity. The repletion water floods the bays, main channels and most of the marsh dominated areas. Of the 77% of the basin capacity (representing the repletion prism), 17 % floods the marsh-dominated surface and the remaining 60 % fills the deeper areas of the lagoon. Tables 1 and 2 in Appendix F illustrate the repletion distribution over the different benthic environments. About 23 % of the repletion volume floods the marsh surface, 32 % floods the intertidal flats (ITF), 22 % fills the sub-tidal flats (STF) and 24% of the repletion water floods the sub-tidal channels (STC) (Figure 24A). This model, however, is unlikely because it does not account for flow confinement to tidal channels during first stages of the tidal cycle. The first-order model spreads into the system as if no topography were present in the lagoon.

A second-order repletion model for Gargathy lagoon was created (Figure 23B) by confining repletion water to tidal channels. With this model, the total repletion volume filled the channel space up to the mainland. In this model, 37 % of the repletion volume occupied the channels, 53 % flooded the intertidal and sub-tidal flats and 11 % of the repletion prism inundates the marsh surfaces (Figure 24B). While more than 12 x 10^6 square meters of marsh were covered by repletion water in the first-order repletion model, only 6 x 10^6 squared meters of marsh were inundated in this second-order repletion model. Residual water in this second-order model occupied the prism over the marsh surfaces. This second-order model still left mechanical concerns of how residual water was pushed out of the channels and onto the marshes. To address this issue, a third model was created (Figure 25). This model allowed residual water to be pushed into the landward extremes of channels as the repletion water floods through the entire basin height. Residual water that was pressed laterally into these regions allowed for the vertical expansion of the residual water masses needed to flood interior marsh surfaces. In this model, 82 % of the repletion prism filled the channels and flats pushing the residual waters landward. When the channels and flats were filled, the remaining 18 % of the repletion prism inundated the marsh surface.

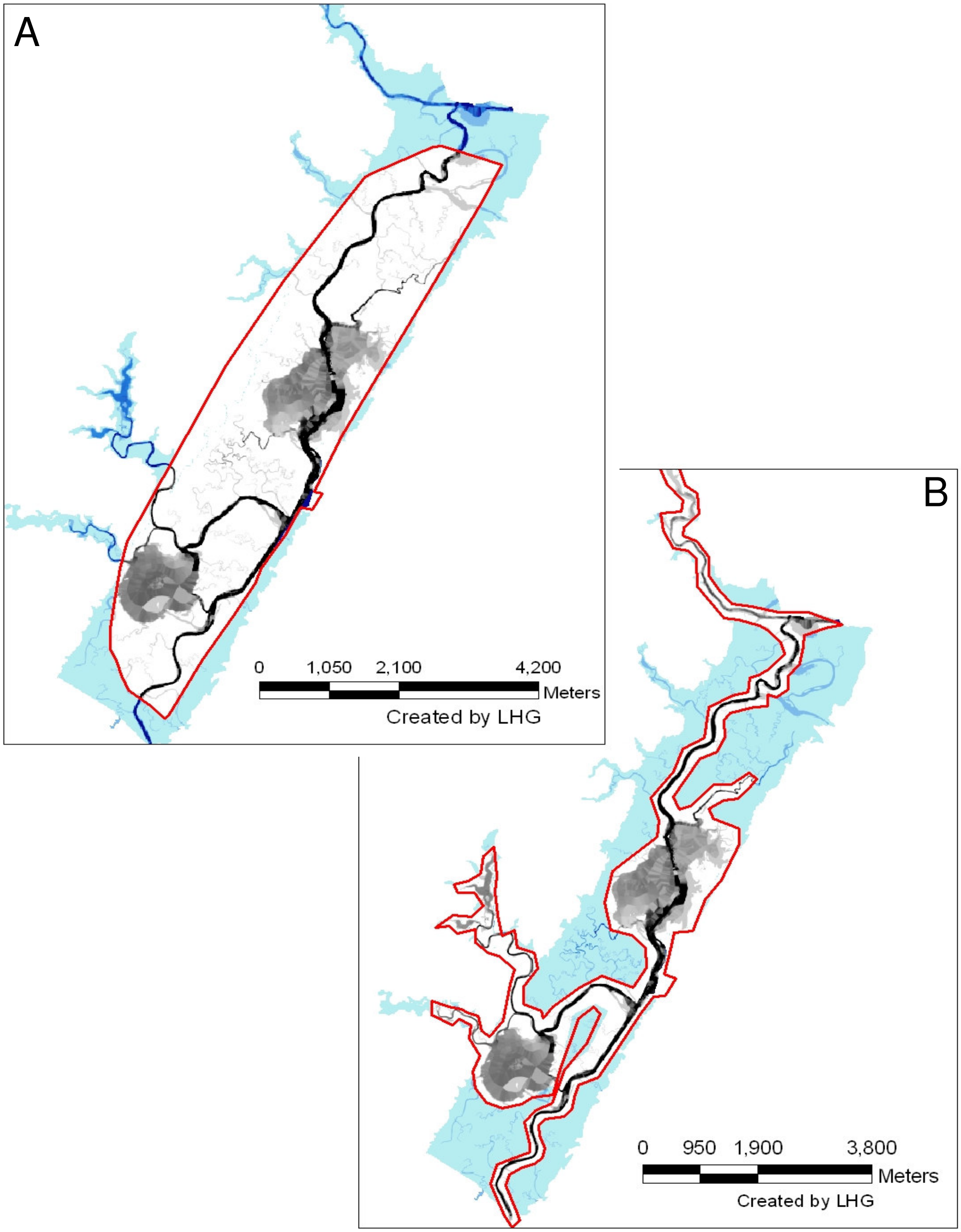
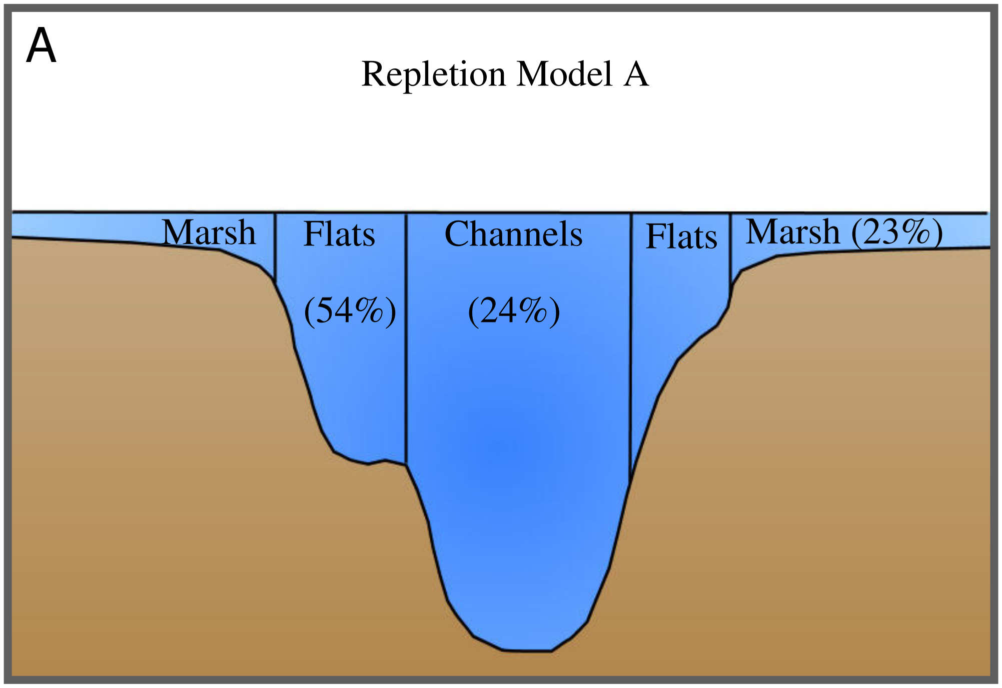


Figure 23. Repletion Pattern. Figure A shows a repletion pattern based on low speed plume expansion. This model does not take into consideration flood-flow rates. Figure B illustrates a second-order repletion footprint which allowed repletion water to spread into the channels. Are within red polygon represents repletion water and blue areas are residual waters.



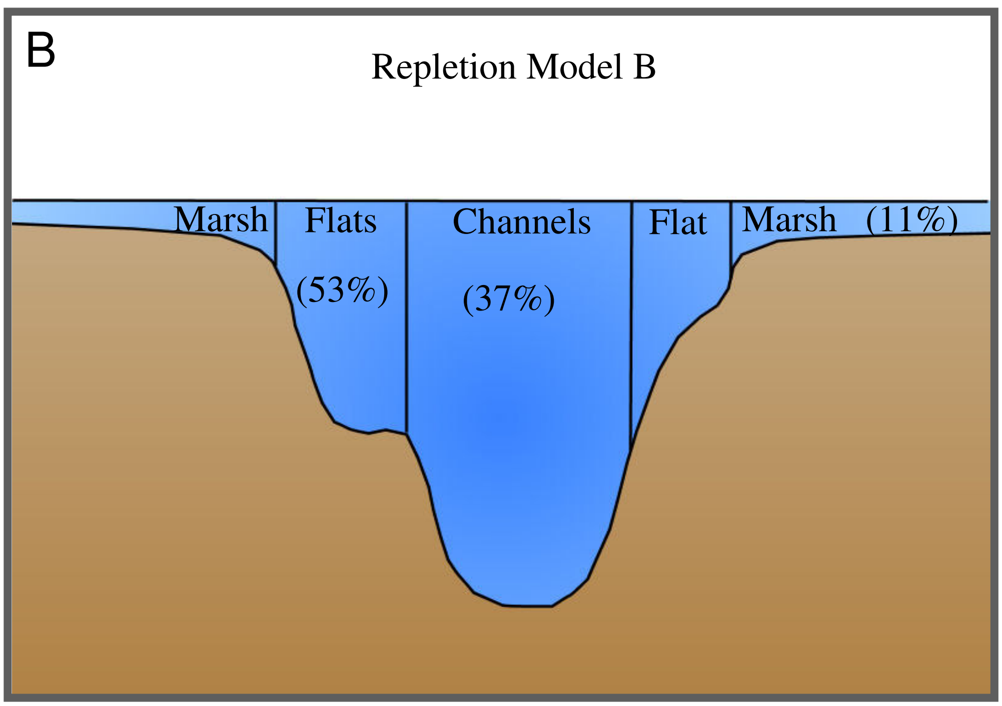


Figure 24. Repletion Water Distribution. Figure A shows the distribution of the repletion water over the benthic environments (in percentages) present at Gargathy using model A. In this model, most of the repletion water fills the flats (mostly present on Gargathy and Kegotank bays) and marsh areas. Figure B illustrates the repletion distribution in model B. Using this model, the volume over the marsh decreases by 10% and a higher percentage floods the channels.

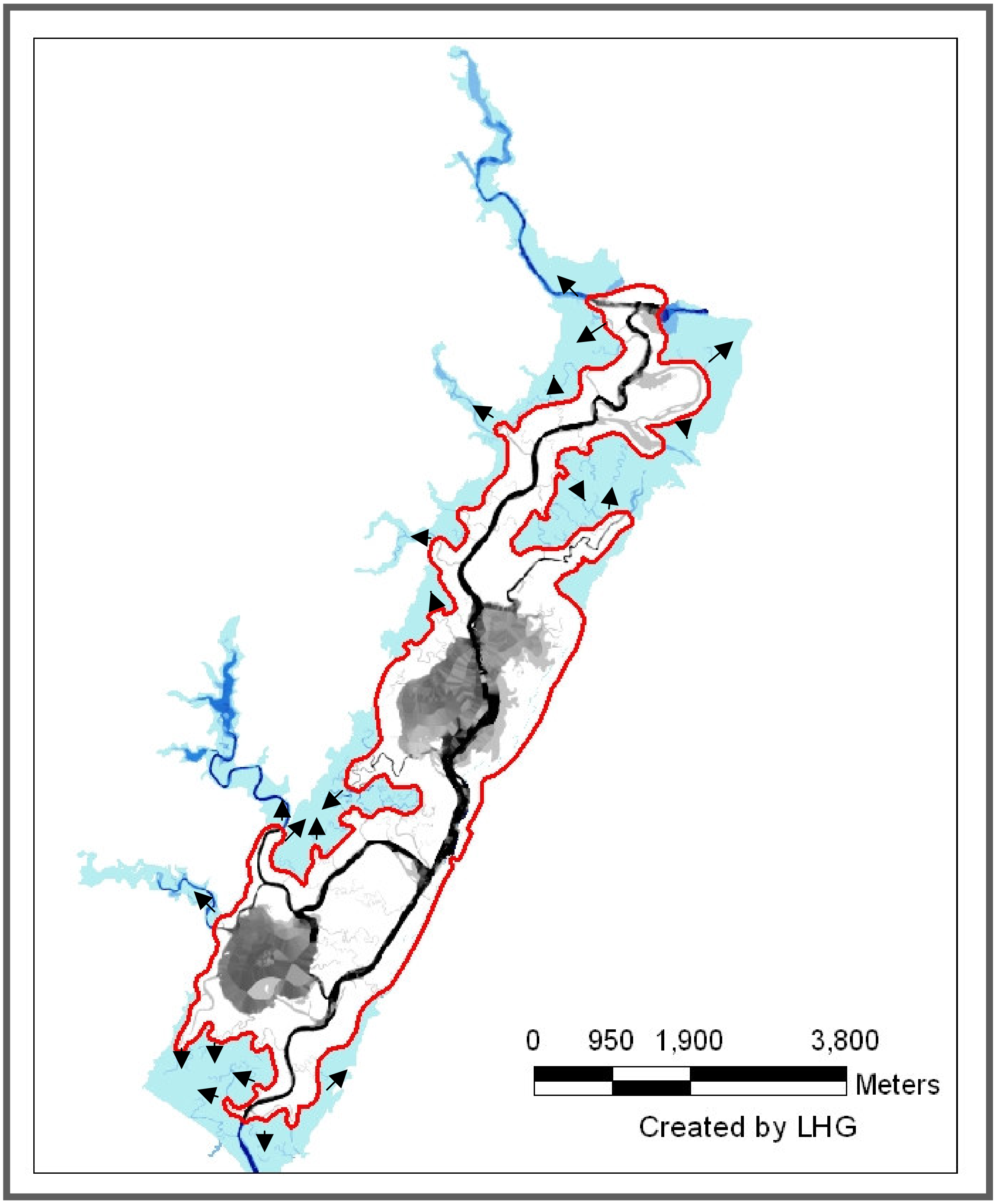


Figure 25. Gargathy Repletion Footprint. This model allowed residual water to be pushed into the landward extreme of channels as the repletion water floods through the entire basin height. Residual water compression into these regions allowed for the vertical expansion of the residual water masses needed to flood interior marsh surfaces.

SECTION 4
DISCUSSION

Benthic and pelagic distributions, and hydraulic characteristics of Gargathy barrier lagoon were studied to determine the effect of bathymetry on water exchange. Comparison of the hydraulic and flushing characteristics between a marsh dominated barrier lagoon (Gargathy) and an open water lagoon (The Great Machipongo Bay) are discussed below. The comparison of a marsh-dominated lagoon with an open water lagoon provided a better understanding of the effect landscape distribution and shape of coastal lagoons have on repletion.

4.1 Benthic environment spatial distribution

Gargathy and The Great Machipongo barrier lagoons, located in the Southern Delmarva Peninsula, exchange water with the coastal Atlantic Ocean through constricted tidal inlets. The systems have similar mean tidal ranges.

The two systems have different landscape characteristics and spatial distributions. Gargathy lagoon is about 2 km wide between the mainland shoreline and the barrier Islands. The system is composed of channels, shallow bays and extensive marsh areas. The marsh is the dominant class in the lagoon. Maximum depths of about 13.5 meters occur at the inlet; however, 74 % of the system does not have depths greater than 0.5m. The hydraulic depth of the basin is about 0.4 meters and it is significantly less than the tidal range of 1.04 meters. The Great Machipongo lagoon is six times wider than the Gargathy lagoon and is dominated by sub-tidal flats. The Great Machipongo Bay is an open water barrier lagoon where maximum depths reach 26.75 meters at the inlet. The dominance of the sub-tidal environment produces a hydraulic depth of about 2.1 meters.

The benthic distribution varies significantly between the two systems. Four benthic environments were distinguished for Gargathy Lagoon using hypsographic techniques; upper intertidal benthic environment, intertidal flats, sub-tidal flats and sub-tidal channels. The upper intertidal marsh sub-environment dominates the benthic areas at Gargathy covering about 81 % of the total surface area of the basin. Hypsographic analysis of The Great Machipongo Bay were classified into six different benthic sub-environments; marsh, intertidal flats, shallow flats, deep flats, shallow channels and deep channels (Oertel et al, 2001). The Great Machipongo Bay was dominated by shallow sub-tidal flats (ranging from MLW to -2m deep) which cover almost 50% of the benthic surface area. Different benthic distributions between these systems may be the result of different drainage histories; while the Great Machipongo Bay formation was influenced by the Machipongo River and its drainage basin, Gargathy lagoon is the product of partial inundation of five drainage basins (Muton Hunk Br. Creek, Gargathy Creek, Northam creek, Hog Neck creek and Assawoman creek). Flooding in lagoons is controlled by the topography of drainage basins; the lower elevation areas get flooded first and the higher elevation interfluves get flooded last. *Hypsography* at Gargathy lagoon showed the dominance of extensive high elevated areas colonized by marsh. These elevated areas formed on interfluves. As sea level rises, the creeks get inundated first, followed by flooding of the channels margins. During the last flooding stages, the interfluvial high elevated areas get inundated. Since these areas are still part of intertidal environments and have not yet been completely submerged, they are suitable places for marsh colonization.

Benthic differences in these two systems could also be explained by different sedimentation models (Lucke, 1934 and Oertel et al, 1994). Gargathy Lagoon, at its present stage of inundation, relates to Lucke's concept of surplus lagoons, as the system's rate of sediment filling exceeds the rate of expansion from sea level rise and marsh dominates the lagoon. On the other hand the great Machipongo bay is a "deficit" lagoon. Deficit lagoons start off as marsh dominated systems, but, because of inundation and sea level rise, marsh surfaces get submerged and evolve into an open water areas. The topography of the antecedent surface and the amount and rate of sedimentation in these systems could therefore be responsible for differences in benthic distributions.

4.2 Pelagic environment distribution and water prisms.

Differences in the benthic distribution affect water exchange and repletion within these lagoons. H*ydro-hypsographic* analyses for both, the marsh-dominated lagoon and the open-water lagoon, provided information about water-surface distribution with depth. Maximum water-surface occurs at high tide. Water surface area decreases from high tide to low tide and goes to zero at the basin floor. The water-surface distribution at MSL varies significantly between the two systems. At Great Machipongo Bay, the MSL water surface is 70% of its maximum surface area. At Gargathy lagoon, the MSL water surface is 19% of the maximum value observed at HW. These differences in the water surface distribution may affect water exchange and mixing. The large surface area of the Great Machipongo Bay produces large wind fetches that increase wave development and enhance mixing, whereas the relatively small surface area of the Gargathy Lagoon limits the potential for mixing to the late stages of the cycle.

Hydraulically, the Gargathy and the Great Machipongo systems are tide dominated. Of the total 10.63 x 10^6 cubic meters present in Gargathy lagoon at high tide, about 77 % (8.22 x 10^6 m^3) gets exchanged with the ocean in every tidal cycle. The Great Machipongo Lagoon capacity (3.13 x 10^8 m^3) is considerably greater than that of Gargathy Lagoon. However, the tidal prism at the Great Machipongo Lagoon is about 54% of the total volume. The higher percentage observed at Gargathy Lagoon suggests that tidal influence is greater in marsh dominated lagoons, indicating better flushing because a higher percentage of water exchanges with the ocean with every tidal cycle.

4.3 Flushing and Hydraulic Turn-Over Time.

To better understand and compare water exchange between the two systems, hydraulic turn-over times (HTT) were compared. The HTT of both systems are relatively short and would turn over all the basin water is less than two tidal cycles. The Great Machipongo Lagoon has a longer HTT than Gargathy Lagoon. Assuming complete mixing, The Great Machipongo Lagoon would take almost two complete tidal cycles to exchange the total prism with the ocean. Gargathy Lagoon, on the other hand, is smaller at 1.29 tidal cycles, suggesting that all the water in Gargathy system completely mixes in little over a tidal cycle. Comparison of the HTT however should not provide information about flushing, as knowledge of water mass movement is required to understand mixing in these coastal systems.

Residual water is the volume of water that remains in the basin at low tide. Residual volumes of 2.4 x 10^6 cubic meters for Gargathy Lagoon and 1.4 x 10^8 cubic meters for The Great Machipongo were estimated. These volumes suggest that about 23% and 46% of the total lagoon capacity at Gargathy and The Great Machipongo remain in the respective systems at low tide. Oertel et al (2007) determined the repletion pattern at Hog Bay Basin to further understand water exchange. They created a hybrid repletion pattern model based on variable flood-flow rates over tidal flats and through tidal channels. In their model, water was able to spread through channels and over lagoons without being confined by high-elevation marsh surfaces. Since Hog Bay had about 70% open water area (channels and tidal flats), repletion was not confined by marsh topography as it spreads into the lagoon. The Gargathy Lagoon has about 20% open water for repletion water to spread into the lagoon. Figure 26 shows the repletion patterns for both the Great Machipongo Bay and Gargathy Lagoon. In the Great Machipongo Bay, residual water appears to "slosh" back and forth in the upper reaches of the lagoon during flooding and ebbing stages, respectively (Oertel et al., in prep.). In Gargathy Lagoon, residual water migrates into numerous tidal channels before it spreads into interior marsh surfaces during late stages of the flood. Mixing in the Great Machipongo Lagoon occurs along water-water boundaries between the repletion and residual zones. Mixing in Gargathy Lagoon is more complex due to the presence of land-water boundaries. Since 80% of the benthic surface at Gargathy is dominated by marsh, water-water boundaries in this surplus lagoon are restricted to small tidal creeks and land-water boundaries dominate the system. Mixing at Gargathy Lagoon might be low during the first stages of the tidal cycle due to the dominance of land-water boundaries and enhanced during the last stages. Oertel et al. (In prep.) differentiated three distinctive zones, the footprint, the upper sloshing zone and the interior frontal boundary to further describe mixing in coastal lagoons. Repletion waters, present over the footprint zone, completely mix and exchange with the ocean with each tidal cycle. Mixing with residual waters, present in the upper sloshing zone, is laterally restricted and it can only occur at the boundary between repletion and sloshing zones (Oertel et al., in prep.). To further identify flushing and mixing at Gargathy Coastal Lagoons, the interior frontal boundary needs to be quantified.

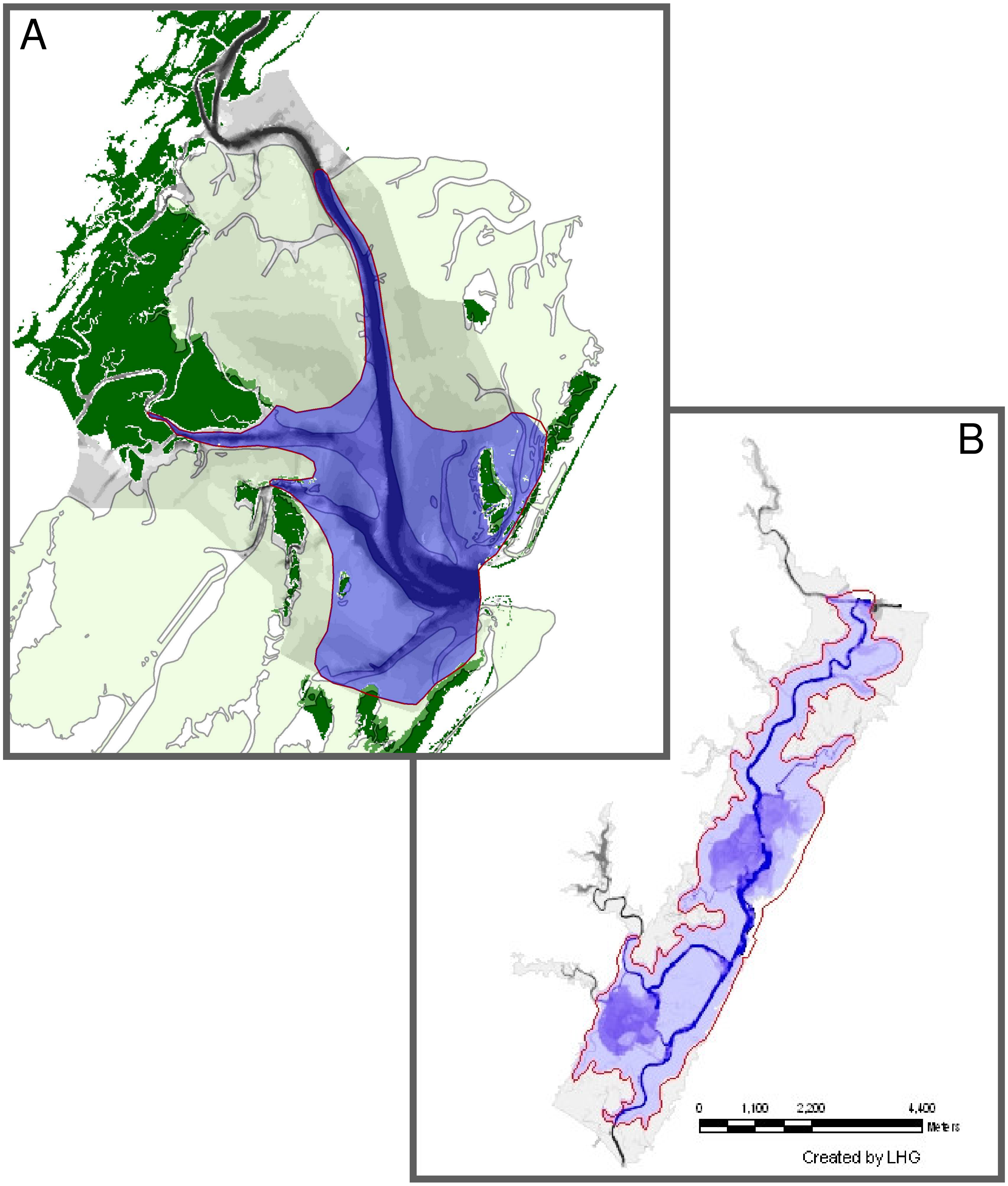


Figure 26. The Great Machipongo Bay and Gargathy Lagoon Repletion Footprints. Image A shows repletion at Hog Bay. Repletion here is not confined by marsh topography but to the open water areas (channels and tidal flats). Image B illustrates repletion at Gargathy lagoon. Repletion water here is confined to channels and flats until late stages of the tidal cycle, when water starts flooding the marsh.

SECTION 5
CONCLUSION

Coastal lagoons and bays vary in shape and size in response to antecedent topography, geologic processes and sea level rise. Numerous coastal lagoons are present along the Mid-Atlantic region of the United States. Many coastal systems have similar tidal ranges and surface areas, but bathymetry below surfaces may vary significantly. Spatial bathymetric distribution within coastal basins can strongly influence water exchange with the coastal ocean.

This project focused on Gargathy Coastal Lagoon, VA. The main purpose was to understand repletion characteristics of the system and to describe the environment based on *hypsometry* and *hydro-hypsometry*.

Gargathy is a shallow coastal lagoon where depths have significant spatial variation. The greatest depths occur in a small area around the inlet. However, the system is dominated by shallow intertidal areas, colonized by marsh. *Hypsometric* analysis showed that 80% of the benthic surface at Gargathy is dominated by marsh areas, colonized by *Spartina alterniflora*. During high stages of the tidal cycle, over 18,000,000 m^2 of marsh become inundated. Water capacity over the marsh surface is about 27% of the lagoon capacity.

As part of a marsh dominated system, Gargathy lagoon is tidally expandable. The tidal prism represents 77% of the lagoon capacity. At low tide, residual water remaining in the system represents 23% of the lagoon capacity. This residual water is pushed into numerous small tidal channels of the upper sloshing zone as repletion water floods into the lagoon. During the last stages of the tidal cycle, water spreads over the marsh surface.

Mixing and repletion in marsh-dominated systems differ from open water systems where water flow in confined to channels and flats. Although more knowledge about mixing and water circulation at Gargathy Coastal Lagoon is required to fully understand flushing, repletion analyses suggested that elevated marsh surfaces restrict mixing to late stages of the tidal cycle when water spreads over the marsh surfaces after filling the tidal channels.

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APPENDIX A

Table 1. Established TBMs location information.

TBM #	Coordinates	Description
TBM-GC	N 37.773917°/ W 75.5621°	Nail on Southern side of dock at Gargathy Neck
TBM 2	N 37° 46.286/ W 75°33.725	Ilegal Shelfish Haversting Signal
TBM 5	N 37° 45.174/ W 75°33.378	Day Marker # 67. Nail with yellow tag.
TBM 6	N 37° 45.566/W 75°33.084	Day Marker # 66. Nail with yellow tag
TBM 7	N 37° 46.516/W 75°32.248	Day Marker # 60. Nail with yellow tag
TBM 8	N 37° 47.197/ W 75°32.106	Day Marker # 53. Nail with yellow tag
TBM 9	N 37° 47.938/ W 75°31.843	Day Marker # 47. Bottom NW side crossbar
TBM 10	N 37° 48.499/ W 75°32.003	Day Marker # 41. Nail on side.
TBM 11	N 37° 49.418/ W 75°31.246	Day Marker # 37. New screw on side.
TBM 12	N 37° 47.541/ W 75°34.009	House dock. Measured from bottom of dock
TBM 13	N 37° 47.206/ W 75°33.709	House dock. 2nd of three located in vicinity.

Table 2. TBMs relationshipts to NAVD88 and MHW

	Relation to MHW (above MHW)		Relationship to NAVD 88	
TBM	**Feet**	**Meters**	**Feet**	**Meters**
TBM-GC	2.3	0.7	3.7	1.1
TBM-LHG (13)	0.7	0.2	2.1	0.6
TBM-GM (12)	2.3	0.7	3.7	1.1
TBM-DRO (2)	1.8	0.5	3.2	1.0
TBM-60	2.2	0.7	3.6	1.1
TBM-66	2.0	0.9	4.4	1.3
TBM-67	2.7	0.8	4.1	1.3

Table 2. Cont'd

	Relation to MHW (above MHW)		Relationship to NAVD 88	
TBM	**Feet**	**Meters**	**Feet**	**Meters**
TBM-53	3.0	0.9	4.4	1.3
TBM-47	1.6	0.5	3.0	0.9
TBM- 41	2.4	0.7	3.8	1.1
TBM-37	2.2	0.7	3.6	1.1

APENDIX B

Table 1. Survey 1 (June 6th, 2007)

	Opening	Closing
Time	9:50 a.m.	10:15 a.m.
Location	TBM-GC	TBM-GC
Distance to Water Sfc (inches)	39.25	37.75
File Name	G157003	
Time	10:22 a.m.	10:50 a.m.
Location	TBM-GC	TBM-GC
Distance to Water Sfc (inches)	37	33.75
File Name	G157004	
Time	10:50 a.m.	11:21 a.m.
Location	TBM-GC	TBM-GC
Distance to Water Sfc (inches)	33.75	31.5
File Name	G157004	
Time	11:28 a.m.	12:00 p.m.
Location	TBM-GC	TBM-GC
Distance to Water Sfc (inches)	31.5	30.5
File Name	G157005	
Time	12:00 p.m.	12:33 p.m.
Location	TBM-GC	TBM-GC
Distance to Water Sfc (inches)	30.5	30.5
File Name	G157005	

Table 1. Cont'd

	Opening	Closing
Time	12:33 p.m.	13:02 p.m
Location	TBM-GC	TBM-GC
Distance to Water Sfc (inches)	30.5	31.5
File Name	G157005	
Notes		
High tide: 1 p.m.		
Time recorded in Eastern time NOT daylight savings.		
No meter stick. Distance to water recorded in inches instead of meters.		

Table 2. Survey 2 (July 5th, 2007)

	Opening		Closing
Time	8.31 a.m.		9:12 am
Location (UTM)		TBM-60 (TBM7)	
Distance to Water Sfc (m)	1.29		1.13
File Name		G186001	
Time	9:12 a.m.		10:05 a.m.
Location (UTM)		TBM-60 (TBM7)	
Distance to Water Sfc (m)	1.13		0.97
File Name		G186001	
Time	10:29 a.m.		11:11 a.m.
Location (UTM)		TBM 13	
Distance to Water Sfc (m)	0.61		0.49
File Name		G186002	
Time	11:22 a.m.		11:56 a.m.
Location		TBM 12	
Distance to Water Sfc (m)	1.02		0.925
File Name		G186003	
Time	11:56 a.m.		12:30 p.m.
Location (UTM)		TBM 12	
Distance to Water Sfc (m)	0.925		0.89
File Name		G186003	
Time	12: 43 p.m.		1:36 p.m.
Location (UTM)		TBM 2	
Distance to Water Sfc (m)	0.85		0.93
File Name		G186004	

Table 3. Survey 3 (July 17th, 2007)

	Opening		Closing
Time	8:20 a.m.		8:58 am
Location (UTM)		TBM 60	
Distance to Water Sfc (m)	0.87		0.80
File Name		G199001	
Time	9:17 a.m.		9:52 a.m.
Location (UTM)		TBM 60	
Distance to Water Sfc (m)	0.75		0.68
File Name		G199001	
Time	10:02 a.m.		10:23 am
Location (UTM)		TBM 66	
Distance to Water Sfc (m)	1.02		0.963
File Name		G199002	
Time	10:23 a.m.		10:48 a.m.
Location (UTM)		TBM 66	
Distance to Water Sfc (m)	0.963		0.933
File Name		G199002	
Time	11:11 a.m.		11:56 a.m.
Location (UTM)		TBM 67	
Distance to Water Sfc (m)	0.855		0.922
File Name		G199003	

Table 3. Cont'd.

	Opening		Closing
Time	11:56 a.m.		12:40 p.m.
Location (UTM)		TBM 67	
Distance to Water Sfc (m)	0.922		1.03
File Name		G199003	
Time	12:40 p.m.		13:10 p.m.
Location (UTM)		TBM 67	
Distance to Water Sfc (m)	1.03		1.09
File Name		G199003	
Time	13:10 p.m.		13:34 p.m.
Location (UTM)		TBM 67	
Distance to Water Sfc (m)	1.09		1.162
File Name		G199003	

Table 4. Survey 4 (July 18th, 2007)

	Opening		Closing
Time	8:35 a.m.		9:13 am
Location (UTM)		TBM 60	
Distance to Water Sfc (m)	0.97		0.85
File Name		G200001	
Time	9:13 a.m.		9:56 a.m.
Location (UTM)		TBM 60	
Distance to Water Sfc (m)	0.85		0.75
File Name		G200001	
Time	9:56 a.m.		10:45 a.m.
Location (UTM)		TBM 60	
Distance to Water Sfc (m)	0.75		0.65
File Name		G200001	
Time	10:58 a.m.		11:31 a.m.
Location (UTM)		TBM 2	
Distance to Water Sfc (m)	0.6		0.56
File Name		G200002	
Time	11:31 a.m.		12:09 p.m.
Location (UTM)		TBM 2	
Distance to Water Sfc (m)	0.56		0.58
File Name		G200002	
Time	12:09 p.m.		12:40 p.m.
Location (UTM)		TBM 2	
Distance to Water Sfc (m)	0.58		0.61
File Name		G200002	

Table 4. Cont'd

	Opening		Closing
Time	12:55 p.m.		13:21 p.m.
Location (UTM)		TBM 66	
Distance to Water Sfc (m)	0.98		1.04
File Name		G200003	

Table 5. Survey 5 (July 19th, 2007)

	Opening		Closing
Time	8:21 a.m.		8:38 am
Location (UTM)		TBM 60	
Distance to Water Sfc (m)	1.21		1.18
File Name		G201001	
Time	8:47 a.m.		9:10 a.m.
Location (UTM)		TBM 53	
Distance to Water Sfc (m)	1.27		1.21
File Name		G201001	
Time	9:10 a.m.		9:33 a.m.
Location (UTM)		TBM 53	
Distance to Water Sfc (m)	1.21		1.04
File Name		G201001	

Table 6. Survey 6 (Aug. 01th, 2007)

	Opening		Closing
Time	8:29 a.m.		9:13 am
Location (UTM)		TBM 53	
Distance to Water Sfc (m)	0.73		0.65
File Name		G213001	
Time	9:13 a.m.		10:21 a.m.
Location (UTM)		TBM 53	
Distance to Water Sfc (m)	0.65		0.7
File Name		G213001	
Time	10:21 a.m.		11:15 a.m.
Location (UTM)		TBM 53	
Distance to Water Sfc (m)	0.7		0.84
File Name		G213001	
Time	11:35 a.m.		12:09 p.m.
Location (UTM)		TBM 53	
Distance to Water Sfc (m)	0.88		0.96
File Name		G213001	
Time	12:10 p.m.		13:37 p.m.
Location (UTM)		TBM 41	
Distance to Water Sfc (m)	0.74		0.91
File Name		G213002	

Table 7. Survey 7 (Aug. 02th, 2007)

	Opening		Closing
Time	8:46 a.m.		9:26 am
Location (UTM)		TBM 41	
Distance to Water Sfc (m)	0.74		0.63
File Name		G214001	
Time	9:26 a.m.		9:51 a.m.
Location (UTM)		TBM 41	
Distance to Water Sfc (m)	0.63		0.61
File Name		G214001	
Time	9:51 a.m.		10:18 a.m.
Location (UTM)		TBM 41	
Distance to Water Sfc (m)	0.61		0.556
File Name		G214001	
Time	10:18 a.m.		11:44 a.m.
Location (UTM)		TBM 41	
Distance to Water Sfc (m)	0.556		0.613
File Name		G214001	
Time	11:44 a.m.		12:43 a.m.
Location (UTM)		TBM 41	
Distance to Water Sfc (m)	0.613		0.73
File Name		G214001	

Table 8. Survey 8 (Aug. 03th, 2007)

	Opening		Closing
Time	8:24 a.m.		9:50 am
Location (UTM)		TBM 37	
Distance to Water Sfc (m)	0.99		0.81
File Name		G215001	
Time	9:50 a.m.		11:25 a.m.
Location (UTM)		TBM 37	
Distance to Water Sfc (m)	0.81		0.635
File Name		G215001	
Time	11:33 a.m.		12:16 p.m.
Location (UTM)		TBM 47	
Distance to Water Sfc (m)	0.34		0.43
File Name		G215001	
Time	12:16 p.m.		12:41 p.m.
Location (UTM)		TBM 47	
Distance to Water Sfc (m)	0.43		0.48
File Name		G215001	
Time	12:41 p.m.		13:03 p.m.
Location (UTM)		TBM 47	
Distance to Water Sfc (m)	0.48		0.52
File Name		G215001	

Table 9. Survey 9 (March, 12th, 2008)

	Opening	Closing
Time	9:55 a.m.	11:56 am
Location (UTM)	TBM 37	
Distance to Water Sfc (m)	1.16	0.85
File Name	GA71001a, GA71002a, GA71003a	

APPENDIX C

Table 1. Interpolation Results

True Value	Estimated Value
-3.24	-3.24
-3.04	-3.03
-4.29	-4.24
-4.75	-4.74
-1.09	-1.10
-4.19	-4.19
-4.71	-3.50
-2.93	-1.67
-2.83	-1.67
-2.93	-2.93
-2.07	-2.09
-2.86	-2.86
-3.80	-3.80
-3.65	-3.64
-0.96	-1.01
-2.91	-2.91
-0.99	-0.99
-1.02	-1.02
-1.27	-1.28
-1.08	-1.06
-0.99	-0.99
-3.16	-3.18
-2.89	-2.88
-1.88	-1.87
-1.60	-1.59
-2.92	-2.92
-2.71	-2.71
-1.09	-1.09
-1.25	-1.24
-1.28	-1.91
-0.85	-0.85
-0.82	-0.82
-1.06	-1.06

True Value	Estimated Value
-3.5	-3.49
-2.53	-2.53
-3.23	-2.09
-1.04	-1.06
-0.98	-1.00
-1.11	-1.12
-1.08	-1.07
-1.39	-1.22
-0.90	-0.90
-0.99	-0.99
-2.21	-2.17
-1.75	-1.75
-1.61	-1.61
-1.21	-1.21
-0.98	-0.98
-0.90	-0.90
-0.96	-0.95
-2.74	-2.74
-1.04	-1.05
-2.58	-2.58
-2.05	-2.05
-1.79	-1.78
-0.52	-0.52
-1.14	-1.14
-1.99	-1.99
-2.17	-2.18
-1.92	-1.91
-1.97	-1.97
-2.97	-3.00
-0.86	-1.41
-1.06	-1.06
-1.01	-1.01
-1.12	-1.12
-1.02	-1.02
-1.31	-1.31

Table 1. Cont'd

True Value	Estimated Value	True Value	Estimated Value
-1.65	-1.65	-3.13	-3.08
-1.03	-1.03	-1.12	-1.12
-1.58	-1.41	-1.14	-1.13
-0.90	-0.90	-3.13	-3.10
-0.87	-0.87	-0.84	-0.87
-0.90	-0.90	-4.38	-4.38
-3.30	-3.27	-0.71	-0.71
-1.96	-1.94	-0.76	-0.74
-2.29	-2.25	-1.00	-1.01
-0.98	-0.98	-1.12	-1.12
-1.72	-1.72	-1.12	-1.12
-1.15	-1.15	-0.92	-1.00
-1.10	-1.10	-0.93	-0.94
-1.16	-1.15	-2.76	-2.76
-1.98	-1.96	-5.17	-5.17
-1.70	-1.69	-4.51	-4.50
-1.43	-1.43	-5.27	-5.27
-1.31	-1.31	-3.35	-3.38
-1.41	-1.80	-3.45	-3.45
-1.45	-0.93	-2.51	-2.51
-1.59	-1.58	-4.66	-4.66
-2.38	-2.40	-3.78	-3.78
-3.12	-3.12	-2.99	-2.98
-2.60	-2.60	-6.10	-6.09
-1.83	-1.80	-1.35	-1.24
-1.91	-1.92	-2.38	-2.36
-3.21	-3.20	-1.32	-1.32
-2.89	-2.89	-1.05	-1.05
-3.93	-3.93	-0.93	-0.93
-0.85	-0.84	-1.68	-1.68
-2.37	-2.36	-0.86	-0.86
-2.43	-2.42	-1.01	-1.01
-2.58	-2.57	-0.76	-0.76
-2.52	-2.52	-0.98	-0.98
-0.74	-0.74	-0.83	-0.80

Table 1. Cont'd

True Value	Estimated Value
-0.87	-0.87
-2.00	-2.00
-2.51	-2.48
-0.85	-0.85
-0.88	-0.89
-1.20	-1.19
-4.25	-4.25
-4.13	-4.13
-4.50	-4.49
-5.27	-5.26
-4.99	-4.99
-1.16	-1.17
-3.84	-3.42
-3.96	-3.21
-0.83	-3.67
-2.93	-3.67
-2.90	-3.41
-3.61	-3.61
-3.15	-3.15
-3.51	-3.51
-2.07	-2.07
-2.79	-2.76
-2.69	-2.68
-0.89	-0.94
-4.26	-4.07
-3.22	-3.21
-1.94	-2.35
-4.70	-4.64
-4.03	-4.09
-2.73	-2.73
-3.31	-3.30
-3.49	-3.42
-2.47	-2.47
-1.46	-1.46
-1.66	-1.66

True Value	Estimated Value
-6.47	-6.47
-3.57	-3.49
-2.92	-2.8
-3.41	-3.41
-1.16	-1.16
-1.19	-1.19
-1.28	-1.28
-1.21	-1.21
-0.94	-0.94
-0.91	-0.91
-0.88	-1.39
-0.94	-0.94
-1.07	-1.07
-1.26	-1.26
-1.26	-1.26
-1.23	-1.23
-1.26	-1.26
-1.08	-1.08
-1.02	-1.02
-1.02	-1.02
-0.81	-0.81
-0.67	-0.67
-1.19	-1.19
-1.01	-1.01
-0.92	-0.92
-0.77	-0.77
-0.92	-0.92
-0.92	-0.92
-1.08	-1.08
-0.65	-0.65
-0.94	-0.94
-1.16	-1.19
-0.98	-0.99
-4.11	-4.08
-5.69	-5.68

Table 1. Cont'd

True Value	Estimated Value	True Value	Estimated Value
-1.95	-1.95	-0.83	-0.83
-1.59	-1.59	-1.01	-1.01
-1.04	-1.05	-1.07	-1.07
-3.42	-3.08	-0.87	-0.87
-4.45	-2.71	-0.60	-0.60
-2.94	-3.58	-0.57	-0.57
-1.95	-1.94	-0.58	-0.58
-4.12	-4.11	-0.68	-0.68
-3.79	-3.78	-0.59	-0.59
-3.71	-3.71	-1.29	-1.30
-2.95	-2.94	-0.62	-0.62
-1.36	-1.35	-0.71	-0.71
-0.53	-0.53	-0.63	-0.63
-3.17	-3.12	-0.88	-0.88
-3.19	-3.19	-0.70	-0.70
-3.79	-3.79	-2.37	-2.41
-2.47	-2.47	-2.37	-2.36
-2.46	-2.46	-4.42	-4.41
-2.40	-2.39	-4.57	-4.56
-3.62	-3.59	-5.24	-5.24
-0.67	-0.67	-4.79	-4.79
-1.16	-1.36	-6.89	-6.65
-0.70	-0.72	-0.95	-1.08
-1.10	-1.10	-5.77	-5.77
-0.49	-0.50	-5.29	-5.29
-0.89	-0.89	-4.32	-4.30
-0.81	-0.80	-0.92	-0.92
-0.59	-0.59	-1.04	-1.04
-0.75	-0.75	-1.33	-1.33
-1.33	-1.32	-0.76	-0.76
-1.09	-1.09	-0.95	-0.95
-0.39	-0.42	-0.96	-0.96
-2.04	-1.85	-0.82	-0.82
-0.73	-0.77	-3.94	-3.95
-0.40	-0.40	-0.95	-1.18

Table 1. Cont'd

True Value	Estimated Value	True Value	Estimated Value
-0.92	-0.91	-3.39	-3.39
-4.90	-4.77	-2.26	-2.26
-4.90	-4.89	-2.26	-2.27
-3.37	-3.37	-1.78	-1.76
-5.47	-5.47	-2.42	-2.42
-6.63	-6.63	-0.74	-0.74
-4.00	-4.00	-0.77	-0.77
-1.40	-1.40	-1.38	-1.38
-0.80	-0.80	-0.60	-0.60
-4.21	-4.21	-0.60	-0.55
-4.72	-4.72	-1.34	-1.34
-4.22	-4.22	-1.28	-1.28
-3.91	-3.91	-2.07	-2.05
-2.60	-2.59	-1.49	-1.49
-3.57	-3.55	-2.04	-2.05
-2.16	-2.16	-2.20	-2.21
-4.54	-4.54	-1.11	-1.11
-4.75	-4.75	-0.83	-0.83
-2.13	-2.06	-0.86	-0.86
-0.60	-0.63	-0.62	-0.62
-1.60	-1.60	-4.37	-4.39
-5.33	-5.33	-5.72	-5.72
-3.53	-3.53	-2.74	-2.77
-1.41	-1.41	-1.16	-1.16
-4.27	-4.26	-1.29	-1.29
-4.66	-4.67	-1.17	-1.17
-3.86	-3.83	-1.20	-1.20
-3.07	-3.09	-1.02	-1.02
-2.98	-2.98	-1.14	-1.14
-4.26	-4.23	-0.75	-0.75
-4.47	-4.47	-1.16	-1.16
-3.69	-3.69	-1.13	-1.13
-3.75	-3.75	-1.14	-1.14
-1.43	-1.43	-0.78	-0.78
-1.58	-1.58	-4.85	-4.85

Table 1. Cont'd

True Value	Estimated Value	True Value	Estimated Value
-3.54	-3.49	-0.71	-0.71
-4.55	-4.54	-0.74	-0.74
-0.62	-0.94	-3.42	-3.42
-1.85	-2.94	-0.69	-0.69
-0.96	-0.95	-7.30	-7.29
-4.09	-4.11	-2.00	-2.00
-4.05	-4.02	-3.25	-3.25
-3.81	-3.80	-3.67	-3.63
-2.37	-2.36	-2.84	-2.85
-0.93	-0.93	-0.86	-0.87
-4.94	-4.89	-3.50	-3.46
-2.08	-2.11	-3.40	-3.39
-1.05	-1.11	-3.85	-3.53
-1.06	-1.06	-4.00	-4.00
-0.97	-0.98	-0.69	-0.68
-1.31	-1.31	-1.01	-1.01
-1.11	-1.11	-0.66	-0.66
-0.89	-0.90	-0.81	-0.81
-1.37	-1.38	-0.87	-0.87
-2.95	-2.95	-0.79	-0.79
-5.60	-5.59	-0.83	-0.83
-3.12	-3.09	-0.86	-0.86
-4.76	-4.76	-0.72	-0.79
-4.15	-4.17	-1.20	-1.20
-0.94	-1.01	-0.76	-0.76
-4.43	-4.43	-0.82	-0.82
-6.86	-6.84	-0.65	-0.74
-2.85	-2.76	-1.30	-1.30
-5.50	-5.29	-0.69	-0.71
-3.36	-3.34	-1.18	-1.18
-4.52	-4.60	-1.06	-1.06
-1.68	-1.65	-1.03	-1.03
-2.21	-2.15	-1.80	-1.80
-2.00	-1.99	-5.28	-5.28
-1.93	-1.92	-3.78	-3.78

Table 1. Cont'd

True Value	Estimated Value
-7.77	-7.77
-2.31	-2.27
-4.00	-3.99
-4.08	-4.08
-3.69	-3.69
-2.67	-2.63
-4.35	-4.35
-4.38	-4.32
-3.46	-3.46
-1.59	-1.58
-1.90	-1.90
-2.85	-2.88
-3.94	-3.94
-1.96	-1.95
-1.39	-1.39
-1.54	-1.54
-2.29	-2.90
-4.05	-2.90
-3.55	-2.90
-2.25	-2.25
-1.60	-1.58
-1.33	-1.33
-1.20	-1.18
-1.34	-1.34
-2.14	-2.12
-1.25	-1.25
-1.92	-1.88
-0.74	-0.75
-0.74	-0.74
-0.79	-0.79
-0.67	-0.68
-0.71	-0.71
-0.95	-0.96
-1.22	-1.22
-1.15	-1.17

True Value	Estimated Value
-0.73	-0.73
-1.42	-1.42
-1.09	-1.09
-1.08	-1.19
-1.33	-1.33
-0.64	-0.64
-1.18	-1.18
-0.87	-0.86

APPENDIX D

Table 1. Hypsographic Curve Data

Water Depth (m)	h above base(m)	Sfc. Area (m^2)	h/H	a/A
0	13.42	0	1	0
0.5	12.92	20.7×10^6	0.96	0.80807
1	12.42	22.9×10^6	0.93	0.89368
2	11.42	24.7×10^6	0.85	0.96390
3	10.42	25.1×10^6	0.78	0.98032
4	9.42	25.4×10^6	0.70	0.99282
5	8.42	25.6×10^6	0.63	0.99829
7	6.42	25.6×10^6	0.48	0.99980
9	4.42	25.6×10^6	0.33	0.99994
11	2.42	25.6×10^6	0.18	0.99996
12	1.42	25.6×10^6	0.11	0.99998
13.42	0	25.6×10^6	0	1

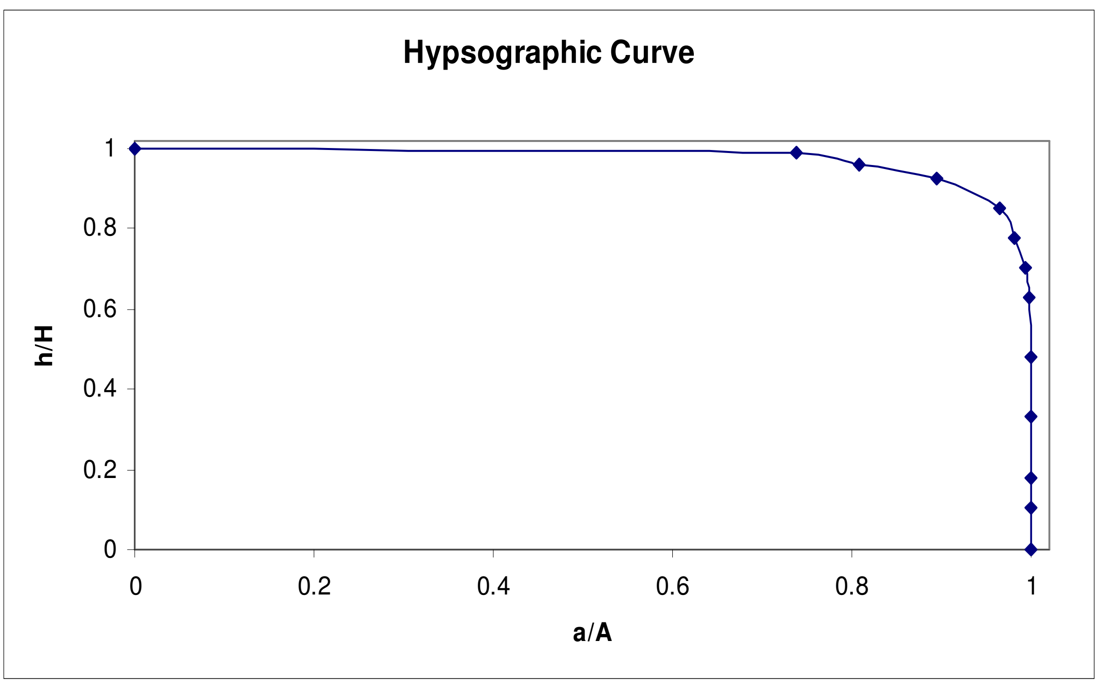


Table 2. Hydro-hypsographic Curve Data

Water Depth (m)	h above base(m)	Sfc. Area (m^2)	d/D	a/A
0	13.42	25,604,450	1	1
0.5	12.92	6,491,950	0.96	0.25355
0.52	12.9	4,858,400	0.96	0.18975
1	12.42	2,722,260	0.93	0.10632
1.04	12.38	2,456,900	0.92	0.09596
2	11.42	924,360	0.85	0.03610
3	10.42	503,850	0.78	0.01968
4	9.42	183,970	0.70	0.00719
5	8.42	43,890	0.63	0.00171
7	6.42	5,180	0.48	0.00020
9	4.42	1,650	0.33	6.43×10^{-5}
11	2.42	990	0.18	3.84×10^{-5}
12	1.42	600	0.11	2.30×10^{-5}
13.42	0	0	0	0

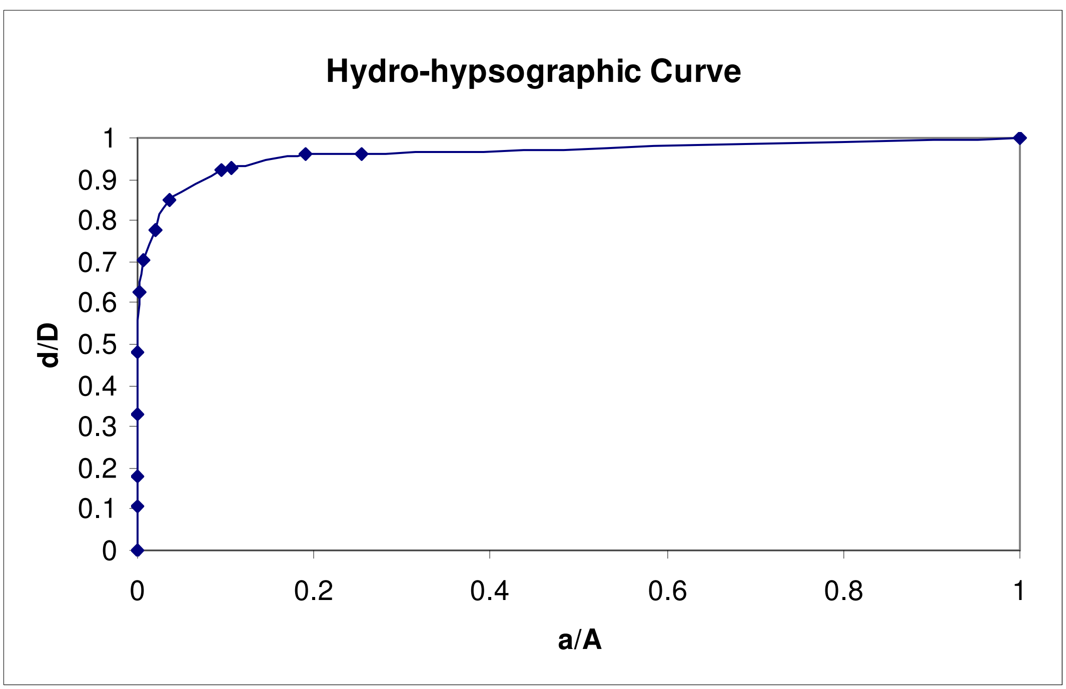
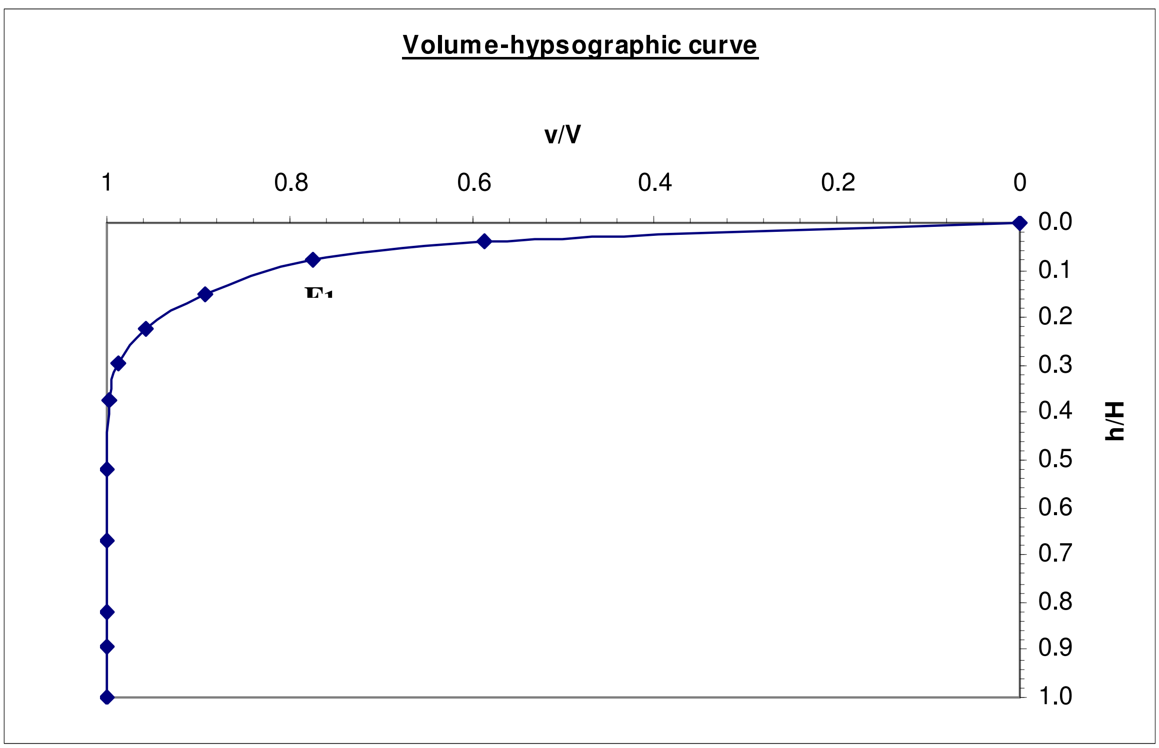


Table 3. Volume-Hypsographic Curve Data

Depth (m)	h above base(m)	Vol. (m^3)	Vol. below HW(m^3)	h/H	v/V
0	13.42	10,629,970	0	0	0
0.52	12.90	4,396,400	6,233,600	0.04	0.58641
1.04	12.38	2,409,210	8,220,800	0.08	0.77335
2	11.42	1,146,340	9,483,600	0.15	0.89216
3	10.42	453,480	10,176,500	0.22	0.95734
4	9.42	135,560	10,494,400	0.30	0.98725
5	8.42	39,370	10,590,600	0.37	0.99630
7	6.42	8,310	10,621,700	0.52	0.99922
9	4.42	3,500	10,626,500	0.67	0.99967
11	2.42	1,070	10,628,900	0.82	0.99990
12	1.42	280	10,629,700	0.89	0.99997
13.42	0	0	10,630,000	1	1



APPENDIX E

Table 1. Water Budgets

	Total Vol.(Ώtot.)	Tidal Vol.(Ώtidal)	Residual Vol. (Ώres.)
Volume (m^3)	10,600,000	8,221,00	2,409,000
% of total Vol.	100	77	23

APPENDIX F

Table 1. Repletion Distribution

	Model A		Model B		Model C	
	Area (m^2)	**Volume (m^3)**	**Area (m^2)**	**Volume(m^3)**	**Area (m^2)**	**Volume(m^3)**
Marsh	12,200,000	1,900,000	5,900,000	896,000	9,700,000	1,500,000
ITF	2,800,000	1,900,000	3,000,000	2,100,000	2,900,000	2,000,000
STF	1,500,000	1,800,000	1,800,000	2,200,000	1,500,000	1,900,000
STC	800,700	2,600,000	900,000	3,000,000	880,000	2,900,000

Table 2. Repletion Volume Percent.

	Model A	Model B	Model C
	Volume %	**Volume%**	**Volume%**
Marsh	23	11	18
ITF	32	26	25
STF	22	27	23
STC	24	37	35

APPENDIX G

Table 1. Gargathy/The Great Machipongo Bay Comparison.

	Gargathy Lagoon	The Great Machipongo Bay
Max. Depth (m)	13.4	26.75
HD (m)	0.4	2.1
Tidal Range (m)	1.04	1.25
Ω_{total} (m^3)	10.63×10^6	3.13×10^8
Ω_{tidal} (m^3)	8.22×10^6	1.7×10^8
HTT (tidal cycles)	1.29	1.85

VITA

Loreto Herraiz Gomez

EDUCATION:

Old Dominion University, Norfolk, VA

Master's of Science in Oceanography 2006-2008

- GPA: 3.80
- Certificate in spatial analysis of the coastal environment
- Golden Key international Honor Society-academic Honor Member

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- Minor: Chemistry
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FIELD WORK AND LABORATORY EXPERIENCE

Gargathy Coastal lagoon research project

Hoffler creek Wildlife Preserve research project

Photochemical oxidation of arsenic and antimony (III) research

Familiar and experienced with all basic laboratory procedures (gravimetric and volumetric methods; pH determinations, etc) and safety measures

Familiar and experienced with field work and procedures. More than 10 days of ship experience.

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