Characterization of Tidal Wetland Inundation in the Murderkill River Estuary

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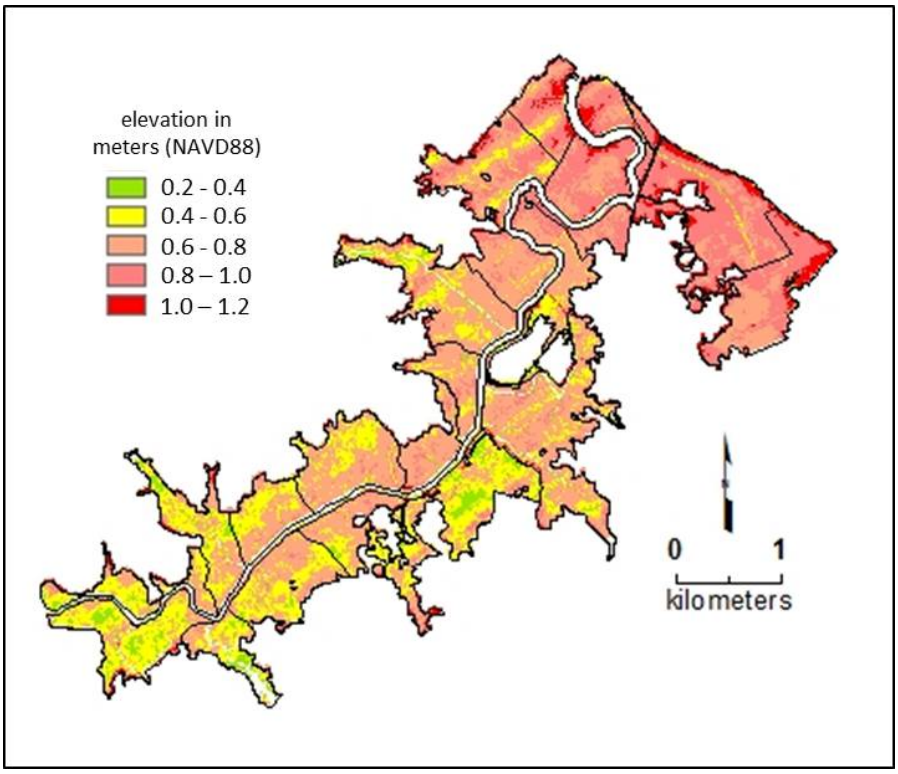

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Murderkill River Study Group

EXECUTIVE SUMMARY

The inundation of a salt marsh with tidal water is a simple concept, but quantifying this process in time and space is difficult due to the difficulty of adequately sampling a dynamic and spatially heterogeneous flow system on a vegetated surface having microtopography. This analysis is in support of a numerical hydrodynamic and water-quality model developed to investigate low dissolved oxygen in the tidal Murderkill River. A parameterization of inundation is developed for the 1,200 hectares of tidal marsh along the 12-kilometer reach of the tidal Murderkill River between Frederica and Bowers Beach. A parsimonious modeling approach is used to bridge the gap between the simple "bathtub model" of instantaneous inundation using only water elevations from Delaware Bay and the complexity of hydrodynamic modeling of overland flow in tidal wetlands. A more complex parameterization or process model is not warranted due to the lack of data to document inundated marsh areas along the extensive marsh platform of the 12-km river reach. Having a simple parameterization within a more complex hydrodynamic model provides flexibility in sensitivity testing of the extent of hydrologic and biogeochemical interactions between the marsh and the river. Project resources do not need to be committed to modeling a complex process that is unconstrained by observations. The parameterization can also be useful for understanding and evaluating anomalies in the conservation of water mass and phase offsets in tidal discharge that may result by not explicitly modeling the dynamic flow and storage of water in tidal wetlands.

In the parameterization, the marsh is divided into "marsh zones" (n=31) based on hydrologic character and position along the river. A cumulative probability distribution of wetland elevation is calculated from a digital elevation model for each marsh zone. These cumulative probability distributions serve as a simplification (parameterization) of the critical information contained in the raster data sets of marsh zones and elevation. Each marsh zone is related to an adjacent river reach and the area in the zone that is below the stage of its related reach is instantaneously inundated. Marsh zones are aggregated into two sets of marsh "groups" (n=22 and n=4). This methodology incorporates the spatial and temporal variation in water levels in the Murderkill River but the results are put into a structure more conducive to analysis and visualization.

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INTRODUCTION

The process of periodic inundation and exposure of tidal wetlands is a primary controlling variable in many physical, chemical, and biological processes in estuaries with extensive wetlands. The fate and transport of sediment and chemical compounds is one such process with scientific and practical relevance. Sediment and chemicals in dissolved and particulate form are primarily transported to and from the marsh platform by tidal water. The fate of chemicals in tidal water interacting with the marsh platform depends on biogeochemical reactions and rates that are functions of the timing of inundation and exposure (*Zafiriou, et al., 1984; Franklin and Forster, 1997; Canario et al., 2007; Crowell et al, 2011*). Due to the very low topographic relief on marsh platforms and the spatially dynamic nature of the shallow water flow, small variations in tidal stage can cause large changes in the areal extent of wetland inundation, making it challenging to accurately estimate temporal inundation areas and volumes (*Dyer, 2000; Crowell et al, 2011*). The details of shallow water flow on the marsh platform remain largely uncharacterized (Lawrence et al., 2004) and the capabilities of hydrodynamic models are outpacing the data collection required to validate the models (*French, 2010*). In this report, a parameterization of marsh inundation is presented that can be used in a coupled numerical model (*Thuman et al., 2011*) of the hydrodynamics and water quality of the Murderkill River. The parameterization uses a parsimonious approach as complexity is not always the most useful path to understanding and hydrologic data are not available to constrain more complex estimates of the inundation of the extensive marsh platform.

The issue driving this study is a better understanding of the causes of low dissolved oxygen in the tidal Murderkill River, a reach that does not meet State of Delaware water quality standards (*DNREC, 2005*). Biogeochemical processes associated with high loads of nutrients (nitrogen and phosphorous) and oxygen consuming compounds (BOD) in the river are the likely causes of low dissolved oxygen (DNREC, 2005). A number of sources may contribute to high nutrient loads including inputs from the watershed upstream of the estuary, net export of nutrients from the extensive tidal wetlands adjacent to the river, and effluent from the Kent County Wastewater Treatment Plant. A coupled numerical model of the hydrodynamics and water quality of the Murderkill River is being used to investigate the causes of low DO in the river (Thuman et al., 2011). The model explicitly represents hydrodynamic and biogeochemical processes in the river

and biogeochemical interactions between the river and subtidal sediments. Hydrodynamic and biogeochemical processes in intertidal wetlands are treated implicitly using parameterizations in model cells that represent intertidal wetlands. In support of the numerical model, the sediment-oxygen demand (SOD) of wetland sediments was quantified by laboratory measurements on sediment cores (*Chesapeake Biogeochemical Associates*, 2010) and the nutrient exchange between the river and a local intertidal wetland was estimated from a field study (*Hays and Ullman 2009; Hays, 2009.*). To upscale the results of these studies for implementation in the numerical model, they need to be normalized to a wetland area and coupled with a parameterization of marsh inundation. This report documents a parameterization that can be used for the Murderkill River Estuary. The parameterization can also be used to evaluate model hydrodynamics, particularly dealing with issues of conservation of water mass and phase offsets in tidal discharge due to the dynamic storage of water in intertidal areas.

Purpose and scope

The purpose of this study is to develop a model to quantify inundation of tidal wetlands (salt marsh) in the Murderkill River Estuary in Kent County, Delaware so that it can be used as a parameterization in a coupled numerical model of hydrodynamics and water quality. The scope is to parameterize marsh inundation along a 12-kilometer (km) reach of the river between Frederica and Bowers Beach.

Study area

The Murderkill River Estuary is located in eastern Kent County, Delaware and discharges into Delaware Bay at the Town of Bowers Beach (Figure 1). The physiographic setting of the estuary is a low-relief coastal plain. The estuary is comprised of approximately 35 km of main-stem river reaches of the Murderkill River and its tidal tributaries (Spring Creek, Hudson Branch, Browns Branch) and extensive tidal wetlands. About 16 km of the tidal reaches are considered salt-water reaches based on the vegetation communities in wetlands adjacent to the river (*DNREC, 1994*) and these extend about 14 km upstream from Delaware Bay. The estuary watershed has an area of 94.0 km^2 with the estuary comprising 19% of the watershed area (1,788 hectares; 13% salt-water tidal wetlands, 4% fresh-water tidal wetlands, and 2% tidal surface water).

The study area is the lower part of the Murderkill River Estuary defined by a 12-km river reach, its' tributaries, and adjacent tidal wetlands between Route 1 at Frederica and the Town of Bowers Beach (Figures 1 and 2). The upstream and downstream boundaries of the study area coincide with locations of tide gaging stations maintained by the United States Geological Survey (USGS; Figure 2; Table 1). The study area watershed has an area of 42.8 km^2 with the estuary comprising 30% of the area. Most of the estuary in the study area (90%) is salt-water tidal wetlands (1,143 hectares); 93% of all salt-water tidal wetlands in the estuary are within the study area. The tidal salt-water wetlands are salt marshes dominated by *Spartina alterniflora* with smaller areas characterized by *Spartina patens* and *Distichlis spicata* (*Daiber, et al., 1976*). Marshes in the downstream part of the estuary have extensive grids of ditches (Figure 2). Elevations of the salt marsh platform range from about 0.2 to 1.2 m NAVD88 (meters, relative to the North American Vertical Datum of 1988). Tides in the estuary are semidiurnal with a spring/neap cycle that is modulated by upstream freshwater discharge and subtidal forcing (*Kuo, et al., 2009*). The tide range decreases from about 1.5 m at Bowers Beach to 0.9 m at Frederica with the high tide taking about 1.5 hours to propagate upstream. The strong spring/neap component in the tide at Bowers is largely absent at Frederica (*Kuo et al, 2009*). In the study area, the Murderkill River ranges from about 20 to 90 m wide and has an average channel depth of about 4.5 m (*Kuo et al., 2009*).

The Murderkill River bisects the salt marshes in the study area as a large "pass-through" channel with flow in and out of the study area to and from Delaware Bay and from the upstream Murderkill River. Numerous "side" channels branch off from the Murderkill River into the salt marsh. At the downstream end of the estuary, many of the side channels are dense grids of man-made ditches (Figure 2). The majority of side channels are "blind channels" with their headwaters within the salt marsh, but some of the channels are "pass-through" channels with headwaters in the uplands. Based on limited visual and observations and aerial thermal imaging in the southeastern part of the study area, the dominant pathway for flooding of the salt marshes appears to be from small side channels rather than from larger side channels that connect them to the Murderkill River or from the Murderkill River itself. The larger channels and the Murderkill River likely serve as direct pathways to the marsh only during the highest tides.

Inundation modeling

Models of marsh inundation may range from simple estimates based on "bathtub" models to complex hydrodynamic models of coupled overland, channel, and groundwater flows, precipitation, and evapotranspiration. The parsimonious modeling approach is followed in this study to bridge the gap between the simple "bathtub model" of instantaneous inundation using only water elevations from Delaware Bay and the complexity of hydrodynamic modeling of overland flow in tidal wetlands. A parsimonious model has only enough features to represent key data and processes needed to answer the questions at hand. The parameters used in the model are limited to the fundamental components of marsh elevation, tidal stage in the Murderkill River, and a simple zonation of marsh areas based on hydrologic characteristics. Each marsh zone is related to an adjacent river reach and the area in the marsh zone that is below the stage of its related reach is instantaneously inundated. The calculation of inundation is driven by specified time series of river stage in defined reaches. The calculation is independent of the source of the water elevations so they can be from observations or a hydrodynamic model. In this report, output from a numerical model is used. A more complex parameterization or process model is not warranted due to the lack of data to document inundated marsh areas along the extensive marsh platform of the 12-km river reach. This goes beyond the bathtub model by incorporating tidal propagation in the river, but at the scale of a marsh zone, it is still a bathtub model.

Having a simple parameterization within a more complex hydrodynamic model provides flexibility in sensitivity testing of the extent of hydrologic and biogeochemical interactions between the marsh and the river. Project resources do not need to be committed to modeling a complex process that is not constrained by observations. The parameterization can also be useful for understanding and evaluating anomalies in the conservation of water mass and phase offsets in tidal discharge that may result by not explicitly modeling the dynamic flow and storage of water in tidal wetlands.

DATA AND METHODS

Watershed, river, and tidal-wetland boundaries

Existing digital boundaries for watersheds, tidal wetlands, and the Murderkill River are modified for the study. Existing digital data are in vector format and are modified using ESRI ArcGIS software. Watershed boundaries (Figures 1 and 2) are based on the DNREC HUC-12 boundaries for the Murderkill River (*DNREC, 2008*) as modified for the Murderkill River Study Group to be consistent with statewide 2007 LiDAR-derived elevation data (*Nardi, 2008*). Modifications to the boundaries include clipping the upstream boundary relative to the location of the USGS tide gage at Frederica (Figure 2), moving the eastern boundary to represent the topographic divide on coastal dunes, and moving part of the southeastern boundary within the marsh to coincide with Brockonbridge Gut. Brockonbridge Gut is chosen as a nominal boundary because the actual boundary in the marsh between the Murderkill River and the gut is dynamic and difficult to quantify.

The Murderkill River and tidal-wetland boundaries (Figure 2) are based on the digital vector layer produced by the DNREC State Wetland Mapping Program (SWMP; *DNREC, 1994*) and are reclassified and aggregated for this study (Table 2). A small fraction (< 2%) of tidal wetlands in the study area (upstream of the Kent County WWTP) is removed from the analysis because the digital elevation model (DEM) was not available for the area. The tidal-wetland boundaries are modified slightly during analysis to be consistent with an analysis of wetland elevations (see Results and Discussion).

Elevation surveys

A local vertical control network is established using survey-grade global positioning system (GPS) techniques and was used as the control for all other surveys. All positions are reported in meters in the UTM18N (Universal Transverse Mercator Zone 18 North) horizontal coordinate system using the NAD83 (North American Datum of 1983) datum and in meters using the NAVD88 vertical datum. The network (Table 3) is least-squares adjusted using one fixed control point using GNSS Solutions software. The fixed control point is a monument (855A) with good vertical control that was recently resurveyed by the National Geodetic Survey (NGS).

GPS and total-station surveys are done to obtain elevations of reference marks for three USGS tide gages (Figure 2; Table 1), the marsh surface and the crowns of several roads to compare to LiDAR-derived elevations. The GPS surveys are conducted to reference points established by the USGS for the three tide gages and to road crowns. Total station surveys are conducted from a control network monument to road crowns and the Bowers Beach and Unnamed Ditch tide gages.

A digital elevation model (DEM; raster format) and set of points (vector format) representing bare-earth elevations was supplied by the USGS (*Nardi, 2009*). USGS conducted an aerial Light Detection and Ranging (LiDAR) survey on January 23, 2008 (20:00 to 20:45 UTC) and February 5, 2008 (1811 to 2131 UTC) using the full-waveform EARRL LiDAR system. The data were supplied in the UTM18N coordinate system using the NAD83 datum and the NAVD88 vertical datum. The root-mean square error (RMSE) reported for elevations in the LiDAR survey is 0.17 m. The RMSE is based on a comparison of LiDAR-derived data points to 83 ground control points on roads in the eastern part of the study area that were less than 0.5 m away from LiDAR-derived data points. Reported DEM elevations are compared to road-crown elevations in an augmented set of ground-control points in the eastern and western parts of the LiDAR survey to investigate bias between the data sets. The comparison is done for LiDAR points less than 2 m from ground-control points. The DEM is adjusted to be consistent with the established vertical control network. A very-limited survey (n=69) of marsh platform elevations and vegetation (*Spartina alterniflora* and *Spartina patens*) heights is compared to LiDAR point elevations to examine potential bias due to the LiDAR beam not penetrating through the vegetation canopy.

Murderkill River stage

Water-surface elevations measured at the three tide gages on 6-minute intervals were obtained from the USGS along with descriptions of surveys used to establish elevations of the gages. Elevations were reported by the USGS in feet using the NGVD29 vertical datum. Elevations are converted to the NAVD88 vertical datum and units of meters using VERTCON software from the U.S. National Geodetic Survey (NGS). The reference monuments used by USGS for

vertical control were part of the established vertical control network. The USGS-reported values are adjusted to be on the same datum as the established vertical control network.

Tidal datums and descriptive statistics are calculated for the Murderkill River gages at Bowers Beach and Frederica using the methodology suggested by the US National Oceanic and Atmospheric Administration (NOAA) for gages with less than 18 years of record (*NOAA, 2003*). A NOAA tide gage at Lewes, Delaware (Station ID: 8557380) was used as the primary station in calculations of tidal datums at the secondary station at Bowers Beach. The calculated tidal datums for Bowers Beach were then used in calculations of tidal datums at Frederica. Using Bowers Beach tidal datums in the procedure for Frederica does not strictly follow NOAA suggested methodology but using Lewes datums gave unreasonable results. Tidal datums at Frederica should be used with caution as they are based on a very short period of record (2 years).

Hourly modeled elevations of the Murderkill River were supplied as output from a hydrodynamic model of the estuary prepared by Hydroqual for each model cell in the mainstem of the river for 2007 and 2008 (*Thuman, 2011*). These are the time series driving the inundation discussed in this report. The calibrated hydrodynamic model is constrained by measurements of water elevation, velocity, discharge, salinity, and temperature at the USGS gages at Bowers Beach and Frederica *(Thuman, 2011)*. Water elevations were reported by Hydroqual in units of meters relative to mean sea level (MSL). Water elevations are adjusted to be on the same datum as the established vertical control network by adding the mean tide level (MTL) at the Bowers Beach gage to all model-derived elevations.

Marsh Zones and groups

To facilitate evaluating spatial patterns in marsh platform elevations and calculating inundation as a function of local tidal stage, the SWMP vector layer of tidal wetlands is classified into zones based on hydrologic character resulting in a digital layer of marsh zones in vector format. Classification parameters are the geometric relationship with the Murderkill River and the existence of large tidal channels, ditches in a grid-pattern, and/or large impoundments. Each

marsh zone has a boundary contiguous with the Murderkill River (with one exception in the southeast part of the study area near Brockonbridge Gut). The classification is based on visual analysis of existing aerial photography obtained in 2007 (*Datamil, 2008*). Marsh elevations in the DEM are also considered in the classification but topographic highs are not strictly followed as boundaries; no data are available to truly know the boundaries of inundation and the boundaries most likely change with hydraulic conditions. Marsh zones are converted from vector to raster format to enable raster processing using the marsh zones and DEM. Marsh zone boundaries are modified during analysis to be consistent with an analysis of wetland elevations (described below). A marsh zone in raster format is the fundamental map unit used in the calculation of inundation.

Marsh "zones" are aggregated into larger marsh "groups" to facilitate analyses and visualization of results. A marsh group is an aggregate of one or more marsh zones. Two "sets" of marsh groups are defined. Set 100 (n =22) aggregates relatively small marsh zones with adjacent marsh zones. Set 200 (n =4) aggregates the marsh groups in Set 100 based on similar elevation distributions and position along the river (see Results and Discussion).

Elevation distributions and statistics are calculated from the DEM for each marsh zone and group. Areas are tabulated for marsh areas with elevations lower than a set of elevations representing expected water elevations.

Inundation calculation

The full parameterization of inundation requires the table relating inundation areas to sets of water-level elevations for each marsh zone and a one-to-one relationship between each marsh zone and a reach of the Murderkill River. A model using the parameterization must supply time series of water elevations in each river reach to drive the temporal inundation. The area in a marsh zone with an elevation below the water elevation in the related river reach is instantaneously inundated or drained. In this report, the time series of water elevations is from the output of a calibrated numerical model of hydrodynamic (*Thuman et al., 2011*). An algorithm is developed to step through hourly time series of water elevations and calculate areas

inundated for each marsh zone and group. This helps to visualize temporal results and enables analysis external to a direct implementation in a hydrodynamic model.

RESULTS AND DISCUSSION

Common vertical datum and elevation uncertainty

Due to very low topographic relief, small variations in tidal stage can cause large changes in estimates of inundation areas and volumes. Therefore, to have confidence in results, it is critical to convert all elevation data to a common vertical datum that is valid for the entire study area and to evaluate the uncertainty in elevation data sets. Data sets used in this analysis include water surface elevations from USGS tide gages, a DEM from a LiDAR survey, elevations of ground-control points for evaluating the LiDAR data, and water-level elevations output from a hydrodynamic model. The NAVD88 vertical datum is established as the common datum and the data sets are converted to this datum.

A local vertical control network is established and used as the control for all other surveys. Survey monuments in low-lying coastal plains like the study area are typically considered unstable monuments by NGS, especially in the study area where documented land subsidence is high (> 3mm/yr; *Holdahl and Morrison, 1974*). So even monuments documented as good vertical control by NGS when they were surveyed have uncertainty that increases with time due to subsidence and instability. For time periods of less than about 5-10 years and relatively small survey areas where all elevations can be referenced to one control monument, the relative elevation of that monument to elevations of surrounding monuments may not be important. In larger survey areas like the study area, elevation surveys use multiple reference monuments so it is critical to confirm and/or establish that all monuments are referenced to a common vertical datum, even if all are reported by data providers as NAVD88 elevations. The established local vertical control network consists of 5 monuments (Figure 3; Table 3) and includes the temporary monument (WWTP) used as control by the USGS for the LiDAR survey and the reference monuments used by USGS to determine elevations of the tide gages (2605, 855A, WRM1). The NGS monument used by USGS to establish the elevation of the Bowers Beach tide gage is used

as a fixed vertical control point in the least-squares adjustment. The estimated uncertainty in NAVD88 elevations in the network is 4 cm (centimeters).

USGS-reported water-level elevations from tide gages are adjusted (Table 1) to be consistent with the vertical control network. This adjustment was significant, especially for tide elevations at the Bowers and Webbs Slough gages where over 50% of the correction is due to the current study using the published NGS elevation of the reference monument. Tide data were reported by USGS with an implicit relative uncertainty of 0.2 cm (0.005 feet). An estimate of uncertainty for absolute water-level elevations used in the analysis is 4 cm (based on the accuracy of the control network).

LiDAR-derived elevations are analyzed to investigate bias relative to ground control. The root-mean square error reported for elevations in the LiDAR survey is 0.17 m. Comparison of GPS surveys of road crowns (Figure 3) to LiDAR bare-earth points indicates a global bias of -0.05 m in the LiDAR-derived elevations relative to ground control and no systematic bias between the east and west ends of the survey. The DEM is adjusted to remove the global bias by adding 0.05 m to all cells. The format of the delivered bare-earth data are not conducive to analyzing individual flight lines to calculate statistics on elevation measurements as suggested in the literature for low-relief terrain (*Rosso et al., 2006; Sadro et al., 2007*).

LiDAR-derived elevations are compared to a small GPS survey of the marsh platform under different types of vegetation to examine bias due to the potential for LiDAR beam not penetrating through the vegetation canopy. The analysis indicates a potential positive bias of up to 0.1 to 0.2 m in the LiDAR-derived elevations relative to ground control (i.e. LiDAR-derived elevations are too high). The data set is too small to put much confidence in specific results but is consistent with literature values indicating a 7 to 30 cm positive bias in salt-marsh environments (*Gibeaut, et al.,2003; Morris et al., 2005; Montane and Torres, 2006; Rosso et al., 2006; Sadro et al., 2007*). Based on comparisons to tidal datums at the Bowers and Frederica tide gages, a bias of 0.1 m appears to be the most reasonable. However, no adjustment is made to the DEM or data presented in the tables in Appendices A and B to account for this bias because of the limited amount of ground-control.

Model elevations of Murderkill River stage from *Thuman et al. (2011)* are adjusted to be on the same datum as the established vertical control network by adding the mean tide level (MTL) at the Bowers Beach gage (-0.08 m) to all model-derived elevations (see below for discussion of tidal datums). MTL was calculated to be equivalent to MSL at the Bowers gage.

Tidal datums

Tidal datums are calculated for the Bowers Beach and Frederica gages (Table 4). The MHW and MHHW tidal datums are the most important datums related to the inundation of the salt marsh platform. The tidal datums are used in comparing inundation results with the relationship between local tidal datums and vegetation types as often cited in the literature with the vast area of Spartina alterniflora in the Murderkill River Estuary being indicative of low marsh (*Silberhorn, 1982; Carey, 1997; Field and Phillip, 2002*). They are also compared to calculated percentile statistics for tides and marsh elevations. Tidal datums for a position in Delaware Bay less than 0.5 km from the Bowers Beach gage are also available (Table 4) as output from NOAA's VDatum product (*Yang et al., 2008).* There is a discrepancy of 8-9 cm for MHW and MHHW compared to those reported in the VDatum product. The discrepancy is likely due to the fact that NOAA results are based on a hydrodynamic model constrained by primary NOAA tidal stations that do not include the Bowers gage. The calculated tidal datums are used in all comparisons in this report because they are based on the actual data from Bowers Beach and they have been converted to be consistent with the local elevation control network.

Marsh elevation

The lower and upper ends of the elevation distribution of the DEM were investigated for spatial patterns to determine appropriate upper and lower limits for marsh elevations. Areas with elevations < 0.2 m NAVD88 occur in linear patterns coincident with tidal channels and represent 4% of the total area (Figure 4). In the inundation and statistical analyses, areas with elevations less than 0.2 m are considered tidal channels. Because bathymetric data do not exist for these tidal channels, volumes cannot be calculated for the channels but could be significant. Spatial patterns at the high end of the distribution indicate that elevations >1.2 m NAVD88 represent small regions near the marsh/upland boundary as defined in the SWMP data set and small areas of high elevation within the marsh (Figure 5). All inundation and statistical analyses exclude

areas with elevations > 1.2 m. The resultant marsh area (Figure 6) is 94% of the area defined as tidal wetlands in the SWMP layer.

Elevations have a normal distribution (t-test at 1% significance level) with a mean elevation of 0.72 m NAVD88 and standard deviation of 0.19 m. As noted above, these values have a potential positive bias of 0.1 to 0.2 m (i.e. LiDAR-derived elevations are too high) due to the potential for the LiDAR beam not penetrating through the vegetation canopy. A nominal relief on the marsh at the scale of the study area is about 0.6 m (0.4 to 1 m NAVD88), based on the difference between the 5th and 95th percentiles of the elevation distribution for the marsh platform. This is lower than the 0.8 to 1.1 m relief reported for a set of Delaware marshes in the Delaware Bay Estuary *(Carey, 1997)*.

The marsh was split into smaller areas defined as marsh "zones" and marsh "groups" (Table 5; Figures 7-9) to facilitate calculation, analysis, and visualization. A marsh zone (Figure 7) is the fundamental map unit used in the calculation of inundation. Using the small marsh zones for the inundation calculation takes advantage of the coupling to nearby water-level elevations in the Murderkill River. A marsh group is defined as a set of one or more marsh zones aggregated together to facilitate analysis and visualization. Two "sets" of marsh groups are defined. Set 100 (Figure 8) aggregates adjacent small marsh zones into marsh groups in order to minimize the difference in marsh area between groups. Set 200 (Figure 9) further aggregates groups in set 100 into four groups based on elevation distributions and position along the river.

Histograms and cumulative probability distributions of elevation were examined for all groups in sets 100 and 200. Set 100 consists of 22 marsh groups (Figure 8) with the area of each marsh group representing two to ten percent of the total marsh area (Figure 10). Anomalous elevation distributions were identified for groups 101, 105, and 120. Processing artifacts ("striping") are evident in marsh groups 101 and 105 and large areas of standing water mischaracterized as marsh is evident in marsh group 120 (Figure 6). To facilitate a consistent analysis of inundated area, elevation distributions of the marsh zones (1, 5, 20, and 22) within these three groups (101, 105, and 120) were replaced with pseudo-data representing the cumulative probability distributions of their associated group in set 200 (Table 5). These pseudo-data are used in all

subsequent analyses. Set 200 aggregates marsh groups from set 100 into four groups (Figure 9) based on similar elevation distributions (Figures 11 and 12) and their position along the river (Figures 8 and 9). Groups 202 and 203 have similar elevation distributions (Figures 11 and 12) but are kept as distinct groups due to a distinct difference in hydrologic character (group 202 has a dense grid of man-made ditches) and for increased spatial resolution during analysis.

Areas with elevations less than a set of NAVD88 elevations (0.25 to 1.4 m in 0.05 m increments) were tabulated for each marsh zone (Table A1) using raster overlay methods. Table A1 is a parameterization of the critical information contained in the raster data sets of marsh zones and elevation. Therefore, the raster datasets do not need to be used directly in the calculation of inundation. Table A1 is used for the inundation calculations discussed below. Results are then aggregated by groups in sets 100 and 200 (Tables A2 and A3). This methodology incorporates the spatial and temporal variation in water levels in the Murderkill River but the results are put into a structure more conducive to analysis and visualization.

There is clearly a decrease in marsh elevation upstream from Bowers to Frederica as quantified in Figures 11-13 with the median elevation decreasing from 0.85 m to 0.60 m NAVD88 (Table B1). As described above, it was confirmed that this elevation difference is not due to any systematic bias in measurement and processing of the LiDAR-derived elevations between the upstream (southwest) and downstream (northeast) parts of study area. Identifying this trend is clearly important for understanding salt-marsh inundation in the estuary and underscores the values of using a common vertical datum to improve confidence in the existence of the elevation trend and of having a tide gage at Frederica to better quantify tidal fluctuations in the upstream part of the study area. Examples of spatial trends in marsh-surface elevation are well-documented in the literature at the smaller length scale (from tidal channel to upland) of about two km with salt-marsh elevations typically decreasing with distance away from channels that act as the flooding source. The bulk of these studies are for tidal channels having their headwaters within the salt marsh (although the definition of a “tidal channel” is often not given explicitly [Green and Hancock, 2012]). No literature citations were found that document the observed spatial trend at the scale of the Murderkill Estuary (12 km from Delaware Bay to

Frederica). This is likely due to the difficulty and time-intensive nature of reducing uncertainty in elevation measurements and using a common vertical datum to clearly document such a trend.

Inundation Parameterization

The components used to analyze inundation are i) a table with the area in each marsh zone having an elevation less than a set of NAVD88 elevations (Table A1), ii) a one-to-many relationship between marsh zones and river reaches (i.e. one river reach may relate to many marsh zones but a marsh zone can only relate to one river reach) (Tables 5 and 6), and iii) a text file with time series of hourly tidal stage for reaches of the Murderkill River during 2007 and 2008. The latter was output from a calibrated numerical model (Thuman et al., 2011). In the results shown below, the area of each marsh zone that is below the stage of its related reach on an hourly time step is assumed to be instantaneously inundated for the next hour. As noted above, the relationships between marsh zones and groups (Table 5) are used to aggregate the results (Tables A2, A3, and B1).

The tables in Appendix A and B can be used directly as lookup tables in a parameterization of marsh inundation applied at boundaries between the marsh and river or in active cells representing the marsh. Using Table A1 as a lookup table requires the assumption of instantaneous flooding as discussed above. Use of Tables A2 or A3 as lookup tables provides a coarser spatial parameterization and would require assigning each marsh group to a river reach using the marsh zone to river reach relationships in Tables 5 and 6 as guides. Table B1 is simply a different representation of the same information given in Tables A2 and A3. Alternatively, the tables in Appendices A and B could be used as fundamental information to develop other parameterizations of marsh inundation that could also include biogeochemical loading.

While the elevations presented in the tables in Appendices A and B assume that there is no vegetation bias in the DEM as discussed above, a correction can be applied if desired. This requires the assumption that the correction is a zonal (same correction applied to all pixels in a marsh zone DEM) or global (same correction applied to all pixels in the entire DEM) correction. Therefore it will not account for any variable bias due to different vegetation (e.g.

vegetated/barren areas on the marsh platform, high/low marsh; short-form/tall-form *Spartina alterniflora*). If a global positive bias in elevation is assumed, simply subtract the assumed value from the elevation column in Tables A1, A2, and A3. For example, if the bias is assumed to be 0.1 m (i.e. elevations are 0.1 m too high), then the elevations in the tables would range from 0.15 to 1.0 m instead of from 0.25 to 1.2 m. For Table B1 and a global positive bias, subtract the assumed bias value from the elevation given in the body of the table. If a positive zonal bias in elevation is assumed, then subtract the assumed value from the elevation column in Table A1 for each distinct marsh zone. A zonal bias cannot be used on the aggregated information in Tables A2 and A3. The user would need to aggregate the results using information from Table 5 after calculating results for each marsh zone. A zonal bias cannot be used on the aggregated information in Table B1.

Hydroperiod

While the marsh elevation is lower upstream near Frederica than downstream near Bowers, the tidal characteristics (Table 4) are also different, so the hydroperiod (frequency and duration of inundation) is not readily apparent. The mean elevation of the marsh is 0.26 m lower upstream (0.6 m) than downstream (0.86 m). The mean high water (MHW) elevation is 0.17 m lower upstream (0.46 m) than downstream (0.63 m) and the tidal range (Mn) is 0.39 m lower upstream (1.01 m) than downstream (1.40 m). A number of calculations are done to evaluate the differences in hydroperiod between marsh groups. A 2-year time period (2007 and 2008) is evaluated to determine the frequency and duration of inundation events for the marsh groups in set 100. An inundation event is defined as inundation of an area larger than 50,900 m^2 during a single high tide. This is equivalent to 5 hectares or 12.6 acres and represents 10% of the mean area of marsh groups in Set 100. There are 1,402 high tides over the two year period; about 1,100 to 1,300 events (78 to 93%) occur in the upstream marshes but only 600 to 700 events (43 to 50%) occur in the downstream marshes (Figure 14). The mean duration of inundation events is longer upstream (Figure 15) with mean duration of 2.6 to 3.4 hours compared to mean duration of 1.6 to 1.8 hours in downstream marshes. Therefore, upstream marshes are flooded more frequently and for longer duration than downstream marshes (Figure 16) based on this model. The downstream marsh shown in Figure 16 is Webbs Marsh. The short duration and low frequency of inundation in this downstream marsh is consistent with field observations in 2007

and 2008. Unfortunately, there are no observations of inundation in the upstream marshes to test this model result. The most frequent duration of inundation downstream is one hour (the minimum time step) compared to three hours in upstream marshes (Figure 16).

A point of discussion is the assumption of instantaneous inundation and draining of marsh zones. As a first approximation, it seems reasonable to assume that any actual time lag in flooding is offset by a time lag in draining of the marsh. A more robust parameterization that includes a time lag ("time of concentration" method) could be used to theoretically assess this assumption but it would still be unconstrained by data. Another point to consider is the implicit assumption that the hydrologic processes of flooding and draining are similar in both upstream and downstream marshes. The downstream marshes have extensive grids of mosquito ditches and documentation of the changes in the hydrology of these systems is largely anecdotal, both at this site and within the literature.

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Hydraulic loading

Flooding of the marsh brings tidal water in contact with sediments and organic matter on the marsh platform, enabling biogeochemical reactions that ultimately alter the chemistry of the tidal water as it drains off the marsh back into a tidal river. The draining water draining water may be the same parcels of water that flooded the marsh or may be shallow groundwater that discharges to the channel due to the increased hydraulic head caused by the flooding and subsequent infiltration. Regardless of the mechanism, as a first approximation, we can assume that the wetted area of the marsh is proportional to specific changes in water chemistry. The other key factor to consider is the duration of a wetting event. A hydraulic load is a concept that combines these two factors. It is defined as the wetted area multiplied by the duration of wetting (units of $m^2 \cdot s$). Mean hydraulic loads for a tidal flooding event and the frequency distribution of hydraulic loads are shown in Figures 17 and 18, respectively. These were calculated for the two-year time period (2007-2008). The hydraulic load for each event can be multiplied by a mass loading rate (units of kg / [$m^2 \cdot s$]) and summed to determine mass loads (units of kg).

CONCLUSION

A parameterization of inundation is developed for the 1,200 hectares of tidal marsh along the 12-kilometer reach of the tidal Murderkill River between Frederica and Bowers Beach. In the parameterization, the marsh is divided into “marsh zones” (n=31) based on hydrologic character and position along the river. A cumulative probability distribution of wetland elevation is calculated from a digital elevation model for each marsh zone. Each marsh zone is related to an adjacent river reach and the area in the zone that is below the stage of its related reach is instantaneously inundated. Marsh zones are aggregated into two sets of marsh “groups” (n=22 and n=4). This methodology incorporates the spatial and temporal variation in water levels in the Murderkill River but the results are put into a structure more conducive to analysis and visualization.

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Table 1. USGS tide gage information

USGS Station Number	USGS Station Name	Alias	Period of Record for Gage Height	correction* (m)
01484080	Murderkill River at Frederica, DE	Frederica	6/2/2007-12/31/2008; 6/13/2010-present	-0.55
01484084	Unnamed Ditch at Webb Landing at South Bowers, DE	Webbs Slough	6/15/2007-12/16/2008	-0.55
01484085	Murderkill River at Bowers, DE	Bowers	2/5/1998-9/30/2002; 10/1/2003-present	-0.17

* correction to apply to USGS data to convert to least-squares adjusted NAVD88 datum

Table 2. Reclassification of DNREC SMWP codes

New Code	SWMP Code
tidal , salt water, regularly flooded (tswr)	
tswr	E2EM1/USNh
tswr	E2EM1Nh
tswr	E2EM1Nd
tswr	E2EM1N
tidal , salt water, irregularly flooded (tswi)	
tswi	E2EM1P
tswi	E2EM1Pd
tswi	E2EM1Ph
tswi	E2SS3/1P
tswi	E2SS4/3P
tidal , fresh water, seasonally or temporarily flooded (tfwi)	
tfwi	PEM1R
tfwi	PSS1/3R
tfwi	PSS1/EM1R
tfwi	PSS1/EM1R1
tfwi	PSS1/EM1Rh
tfwi	PSS3/1R
tfwi	PSS3/EM1R
tfwi	PSS3R
tfwi	PSS1R
tfwi	PFO1/SS3R
tfwi	PFO1R
tfwi	PFO2/1R
tfwi	PSS4S
tfwi	PFO1S
tidal, fresh water, riverine, permanently flooded (tfwriver)	
tfwriver	R1UBV
tidal, salt water, riverine, regularly flooded (tswriver)	
tswriver	R1EM2N

Table 3. Local survey control network

ID	easting* (m)	northing* (m)	ellipsoid height** (m)	elevation*** (m)
WWTP	461873.4	4316223.0	-24.981	10.05
103m	466153.1	4322458.5	-33.843	1.06
2605	460155.7	4319581.3	-26.780	8.14
855A	465591.9	4323347.5	-33.647	1.22
WRM1	466148.2	4322423.4	-33.290	1.61

* UTM Zone 18N datum

** NAD83 datum

*** NAVD88 datum

Table 4. Tidal datums

	elevation (m NAVD88*)		
Datum**	**Bowers*****	**Frederica*****	**Bowers (VDatum)******
MHHW	0.74	0.47	0.83
MHW	0.63	0.43	0.71
MTL	-0.08	0.01	-0.08
MSL	-0.08	0.01	-0.08
DTL	-0.04	0	-0.03
MLW	-0.78	-0.41	-0.86
MLLW	-0.82	-0.48	-0.90
Mn	1.40	0.84	1.56
Gt	1.55	0.95	1.74
DHQ	0.11	0.05	0.13
DLQ	0.04	0.07	0.05

* North American Vertical Datum of 1988

** MHHW = mean higher high water; MHW = mean high water; MTL = mean tide level; MSL = mean sea level; DTL = diurnal tide level; MLW = mean low water; MLLW = mean lower low water; Mn = MHW-MLW; Gt = MHHW-MLLW; DHQ = MHHW-MHW; DLQ = MLW-MLLW

*** calculated using NOAA methodology, USGS data and Lewes and Bowers gages as the primary stations for Bowers and Frederica respectively

**** output from the NOAA VDatum product

Table 5. Marsh zone and group definitions with relationships to river reaches.

Group ID Set 200	Group ID Set 100	marsh zone ID	River Reach	
			Distance Upstream (km)**	Numerical Model Grid ID (IIJJ)
201	101	1	0.5	70041
201	102	2	1	69037
201	103	3	2	68032
201	104	4	1.5	71035
201	106	6	1.5	71035
201	108	8	2	68032
201	108	10	3	62035
202	105	5	3.5	61038
202	107	7	4.5	58033
202	109	9	5.5	52032
202	111	11	6.5	49032
202	112	12	4.5	58033
202	112	14	5.5	52032
202	112	16	5	55032
203	113	13	7	47032
203	113	15	7	47032
203	117	17	7.5	46032
203	117	19	8.5	42032
203	118	18	6.5	49032
203	120	20	7	47032
203	120	22	6.5	49032
203	124	24	8	44032
204	121	21	9	40032
204	123	23	9.5	38032
204	123	25	9.5	38032
204	126	26	9	40032
204	127	27	11	31036
204	128	28	10	36033
204	132	32	10.5	35036
204	132	34	11	31036
204	132	36	11.5	30039

* Thuman et al. (2011)

** nominal distance upstream to middle of reach

Table 6. Reclassification of river reaches as defined in numerical model.

Numerical Model*		Reclass-ification
Grid ID (IIJJ)	Distance Upstream (km)**	Nominal Distance Upstream (km)**
70041	0.535	0.5
69037	1.105	1
71035	1.540	1.5
68032	2.000	2
64032	2.505	2.5
62035	3.030	3
61038	3.535	3.5
58037	4.030	4
58033	4.450	4.5
55032	4.915	5
52032	5.640	5.5
50032	6.140	6
49032	6.410	6.5
47032	7.075	7
46032	7.400	7.5
44032	7.935	8
42032	8.425	8.5
40032	9.125	9
38032	9.535	9.5
36033	9.985	10
35036	10.475	10.5
31036	10.995	11
30039	11.500	11.5
27040	12.050	12

* Thuman et al. (2011)

** distance upstream to middle of reach

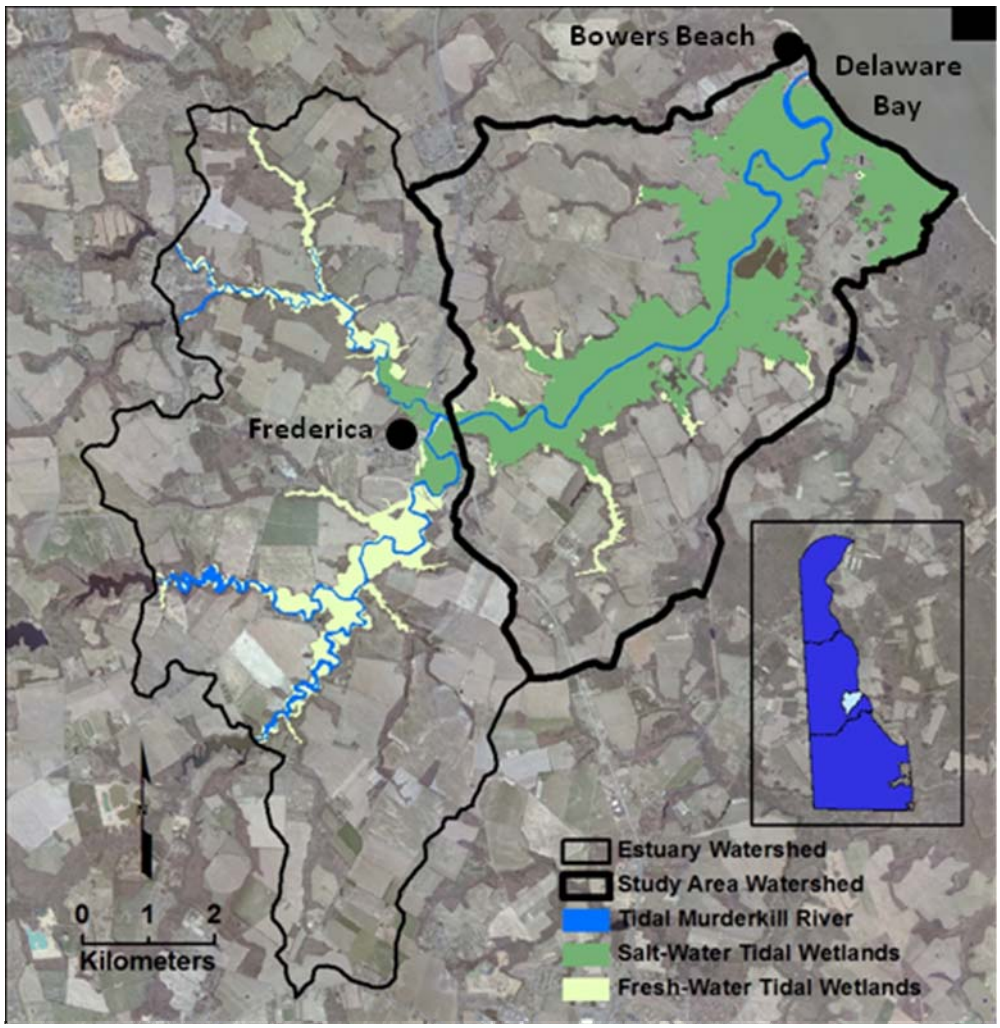

Figure 1. Murderkill River Estuary watershed, study area watershed, tidal Murderkill River, and tidal wetlands. The boundary between tidal wetlands and the uplands also represents the boundary of the estuary. The tidal portions of the Murderkill River, Spring Creek, Hudson Branch, and Browns Branch are aggregated into the "Tidal Murderkill River."

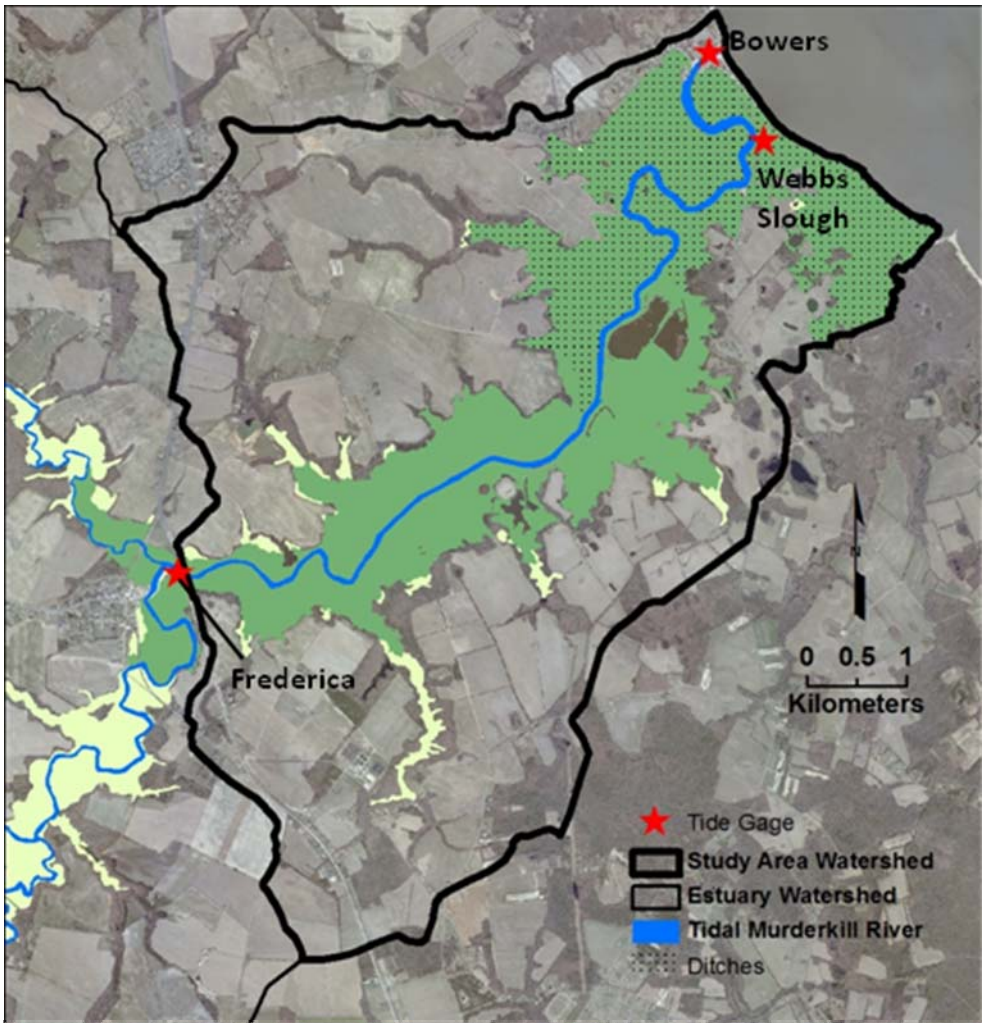

Figure 2. Study area watershed, tidal wetlands, tidal Murderkill River, locations of dense grids of ditches, and tide gages (Table 1).

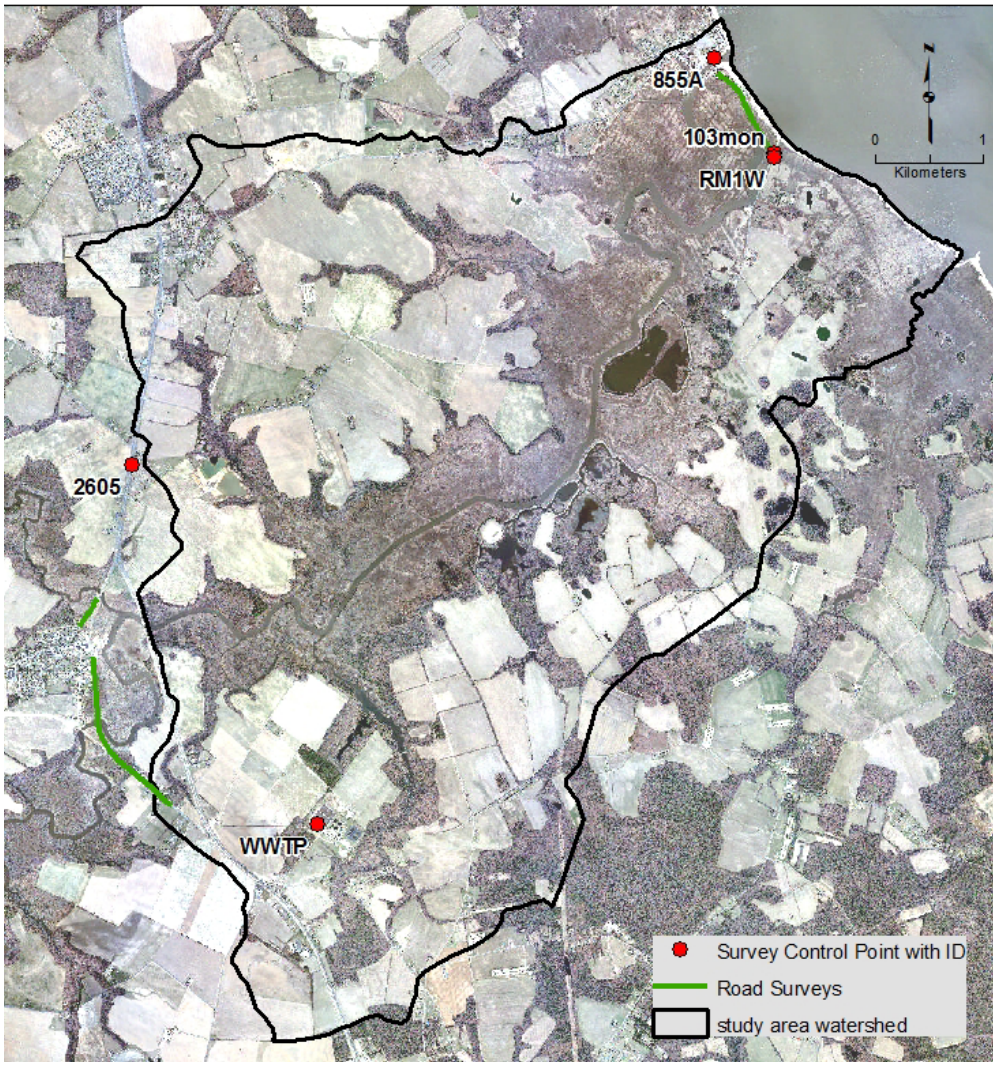

Figure 3. Survey control points and road surveys for comparison to LiDAR-derived elevations.

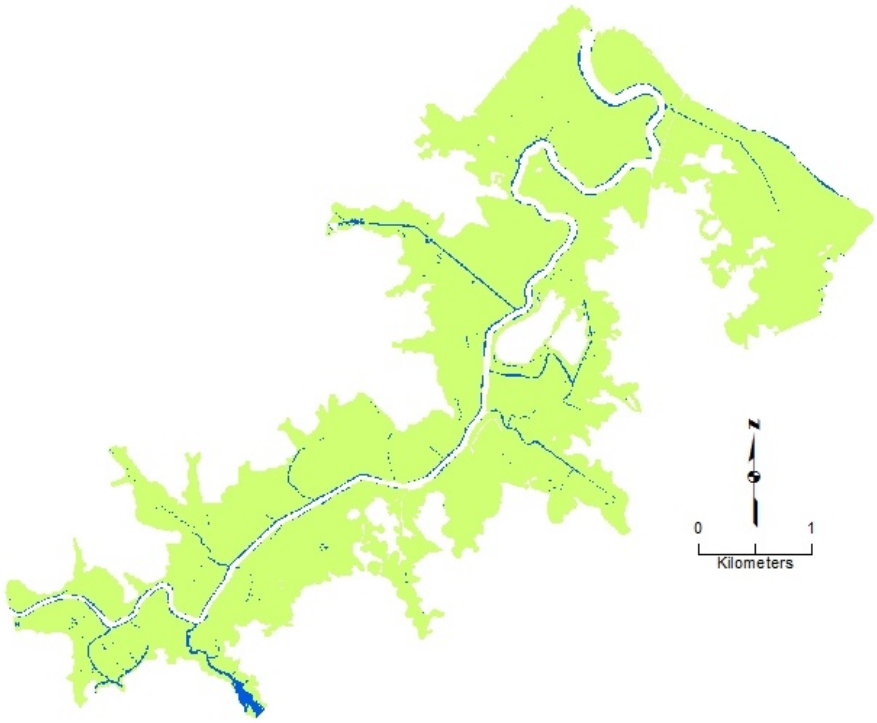

Figure 4. Wetland areas with elevations < 0.2 m (shown in blue) occur in linear patterns coincident with tidal channels and represent 4% of the total area. These areas are assumed to represent channels and are culled from the marsh zone raster layer.

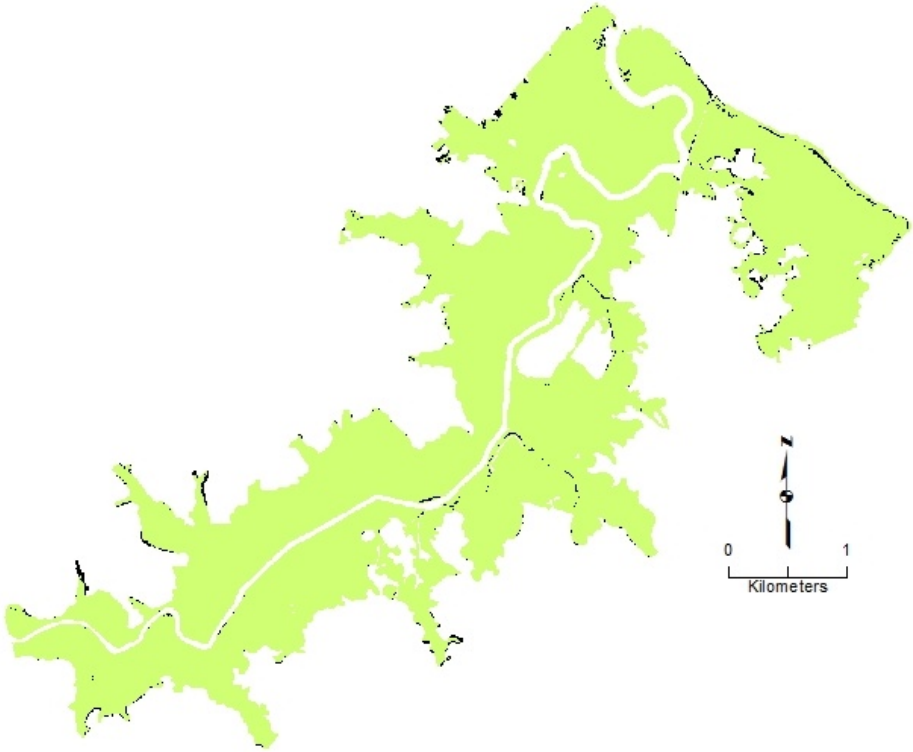

Figure 5. Wetland areas with elevations >1.2 m (black) represent small regions near the marsh/upland boundary (as defined in the DNREC SWMP data set) and small areas of high elevation within the marsh including impoundment dikes. These areas were culled from the marsh zone raster layer.

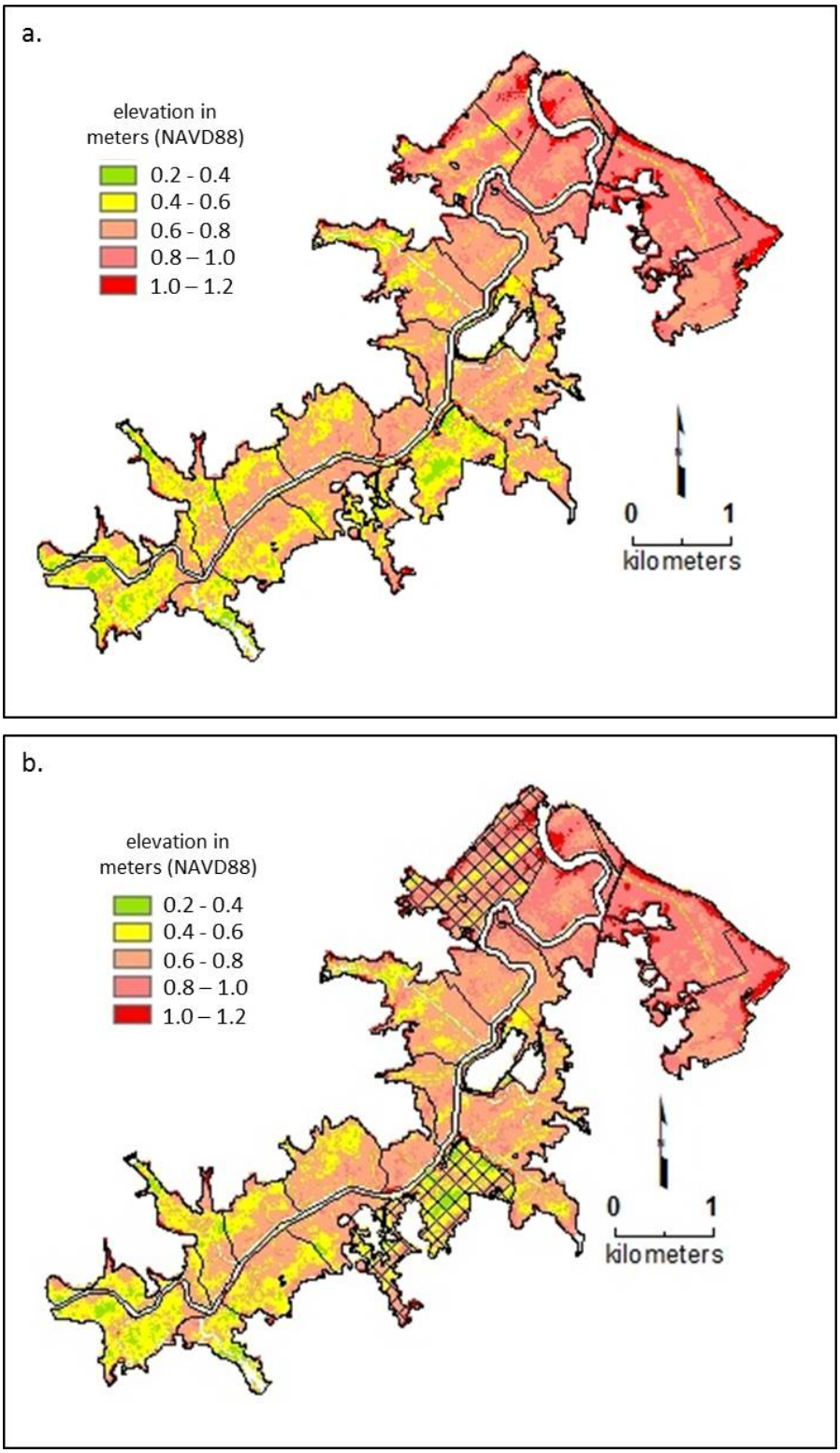

Figure 6. Tidal wetland elevation with marsh group boundaries for set 100. Hatches in b represent anomalous elevation distributions that were identified for groups 101, 105, and 120 (see text for explanation).

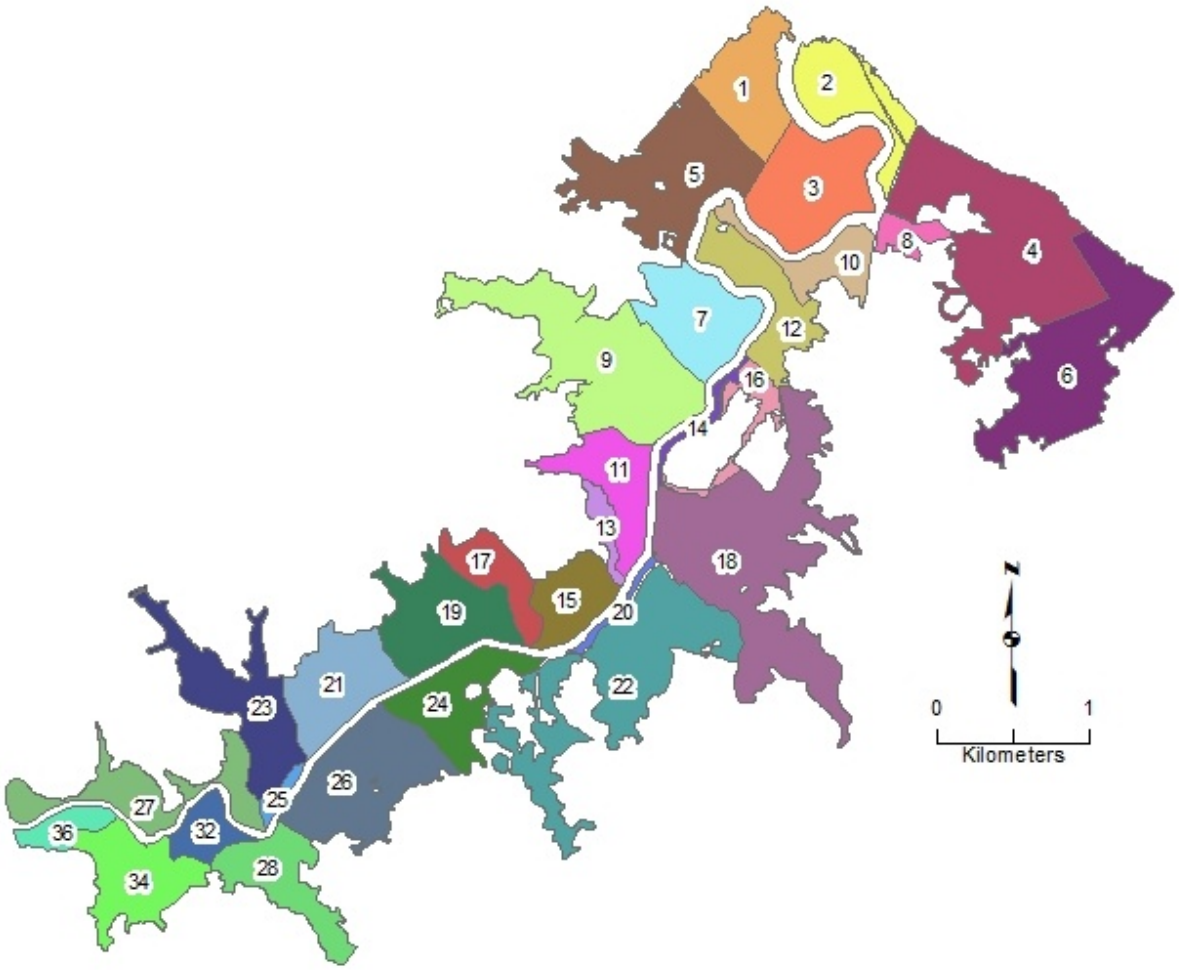

Figure 7. Marsh zones with marsh zone IDs.

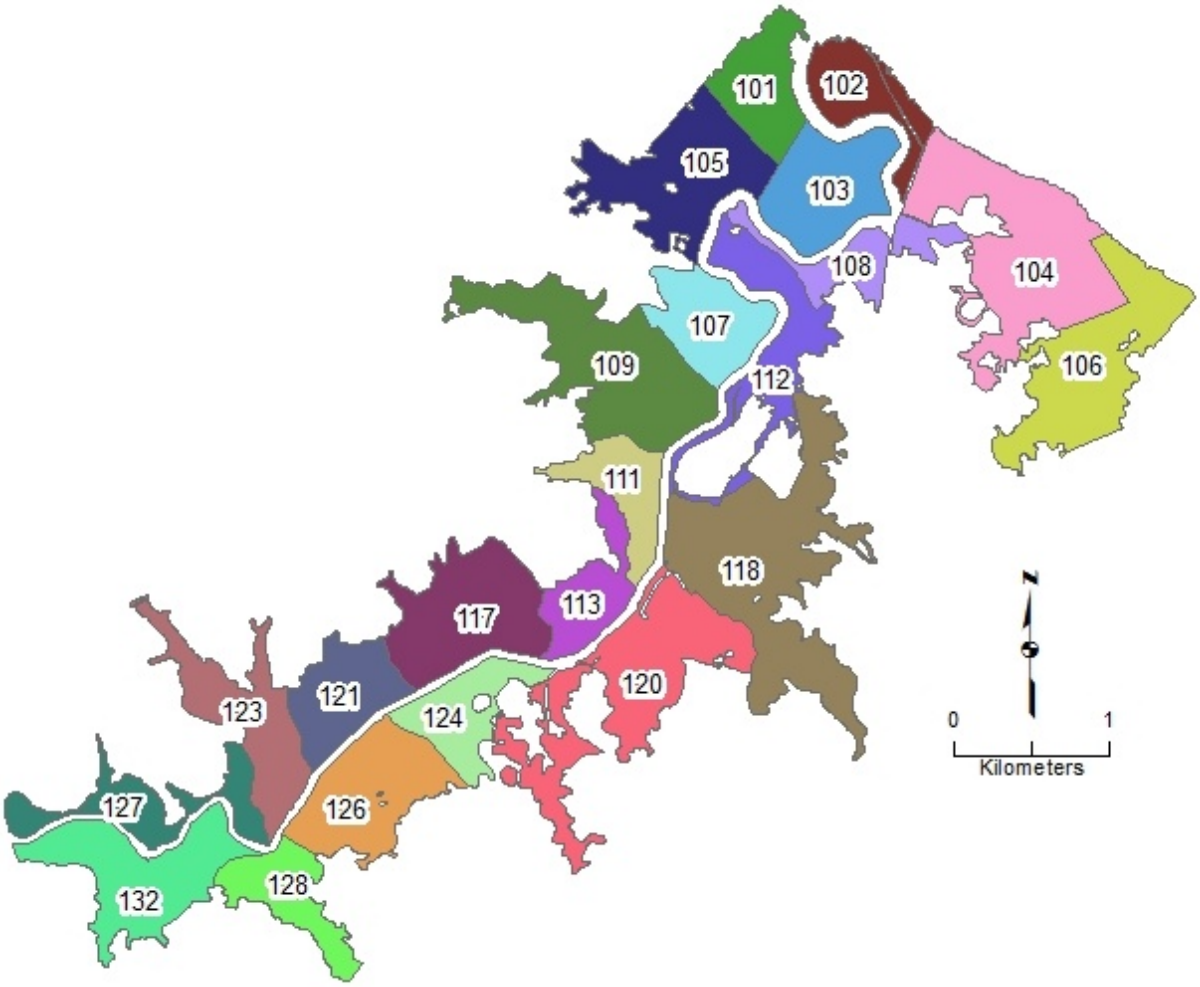

Figure 8. Grouped (aggregated) marsh zones in set 100 with group IDs.

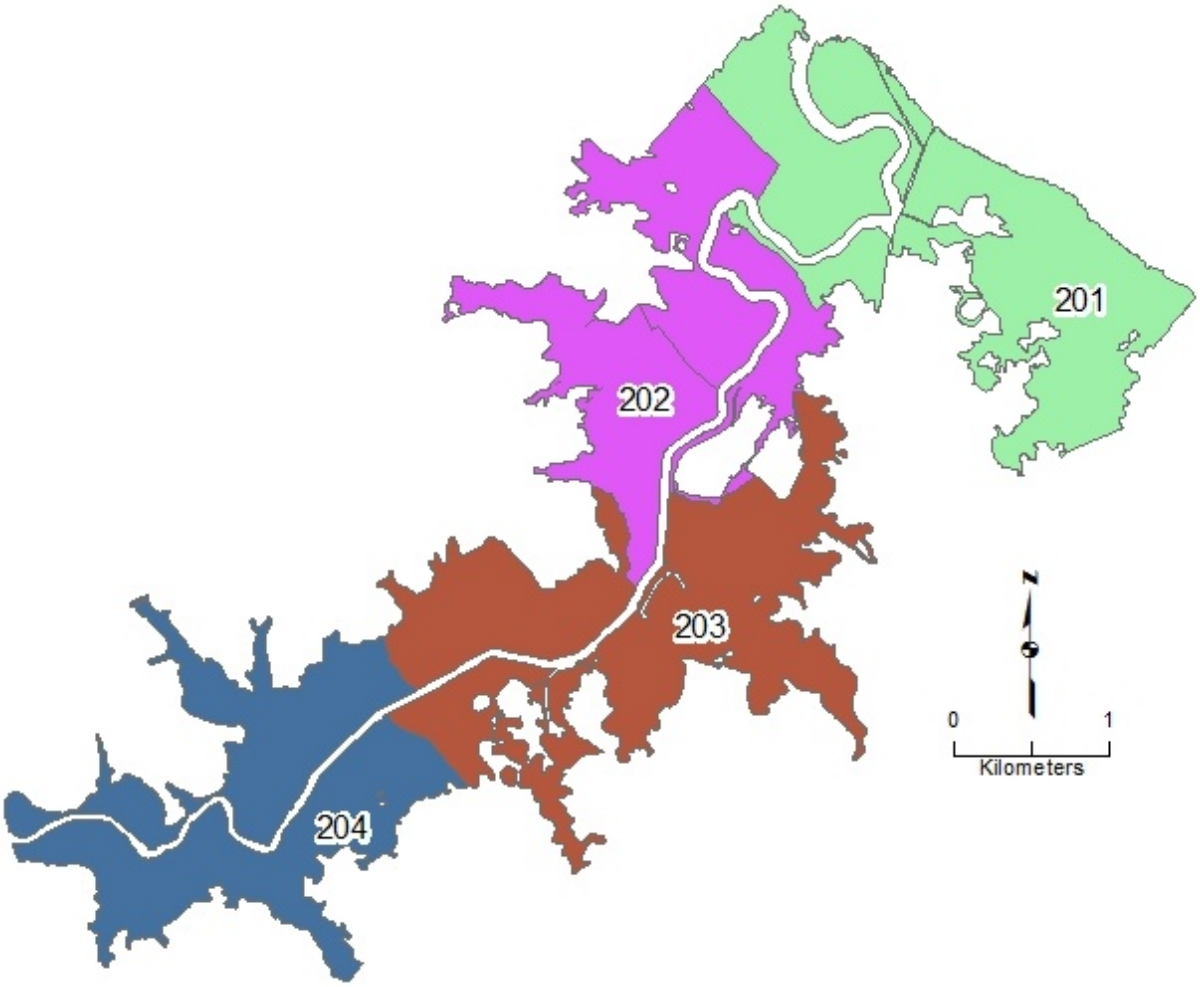

Figure 9. Grouped (aggregated) marsh zones in set 200 with group IDs.

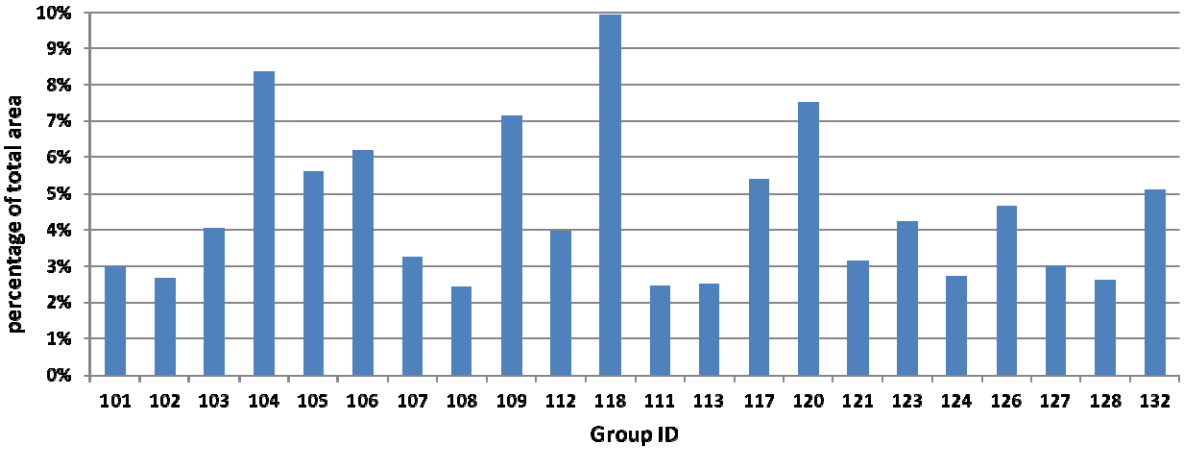

Figure 10. Relative areas of marsh groups in Set 100 as percentage of total tidal wetland area.

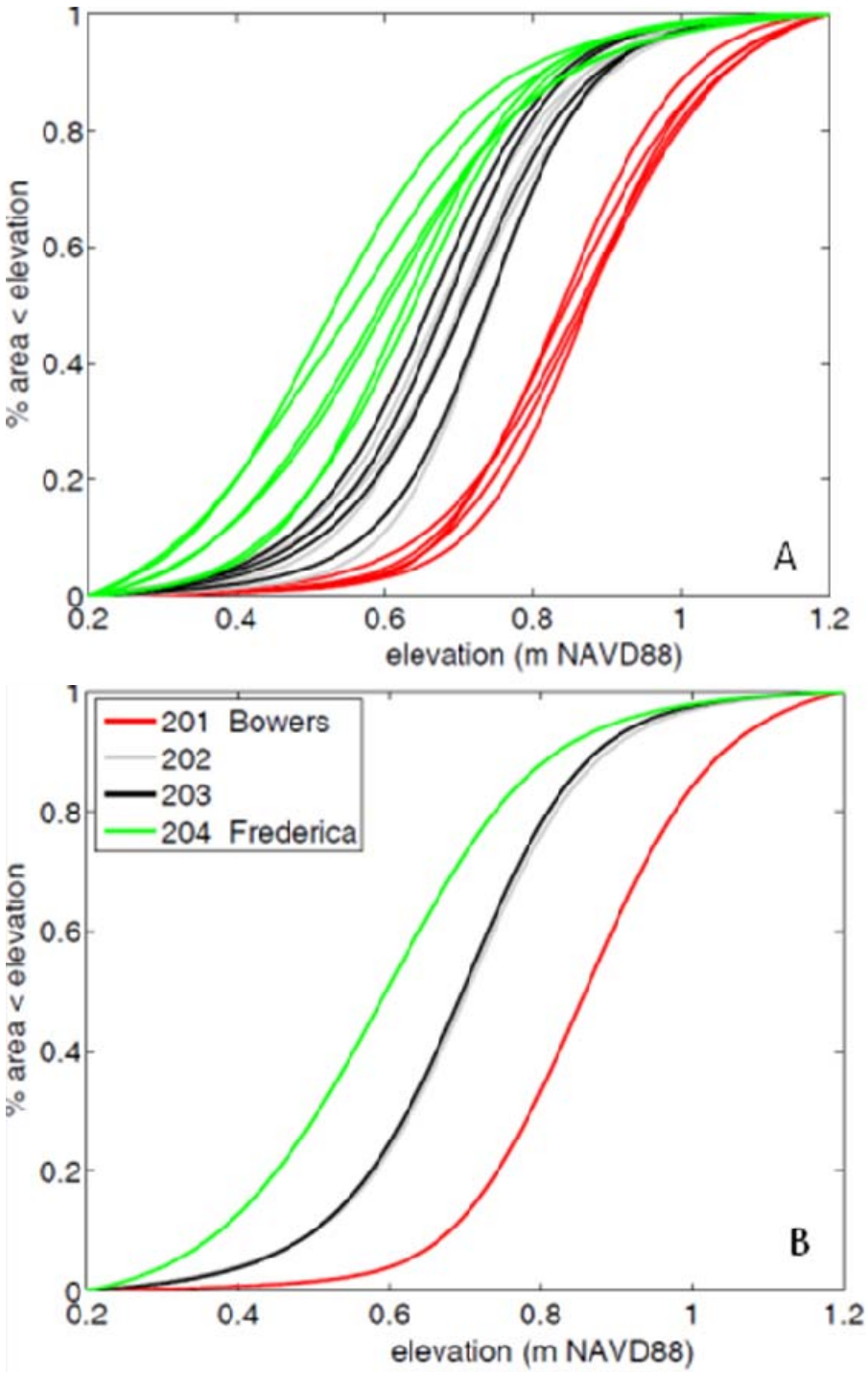

Figure 11. Cumulative probability distributions of wetland elevations. There is clearly an upstream decrease in marsh elevation from marsh group 201 (Bowers Beach) to marsh group 204 (). Line colors differentiate the same data in both (A) and (B). (A) Groups in Set 100. Colors indicate groups with similar elevation distributions and position along the river. (B) Groups in

Set 200. Data for groups shown in (A) are aggregated in (B).

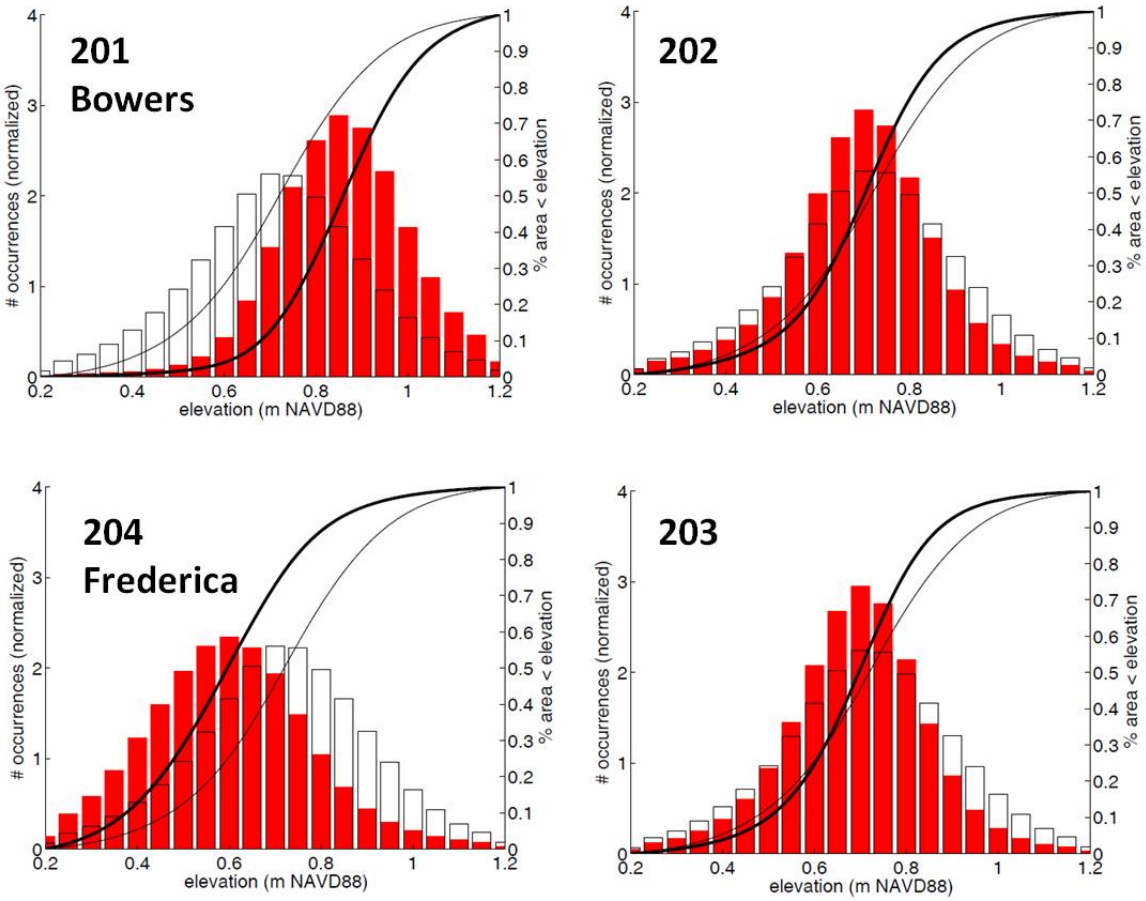

Figure 12. Histograms and cumulative probability distributions of elevations for four groups in set 200. Red bars and dark lines are for the group indicated. Hollow bars and gray lines are shown for the entire marsh for reference.

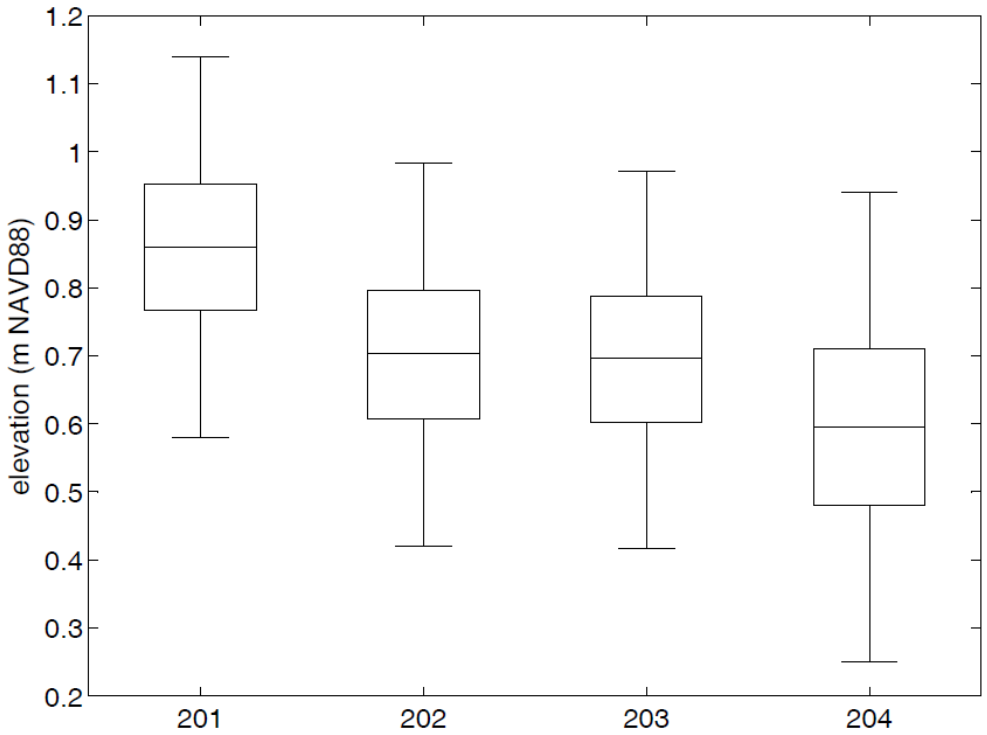

Figure 13. Box and whisker plot of elevation distributions for four groups in set 200. Middle bar is the median, bottom and top of box are 25th and 75th percentile, respectively. 99% of the data fall within the whisker range.

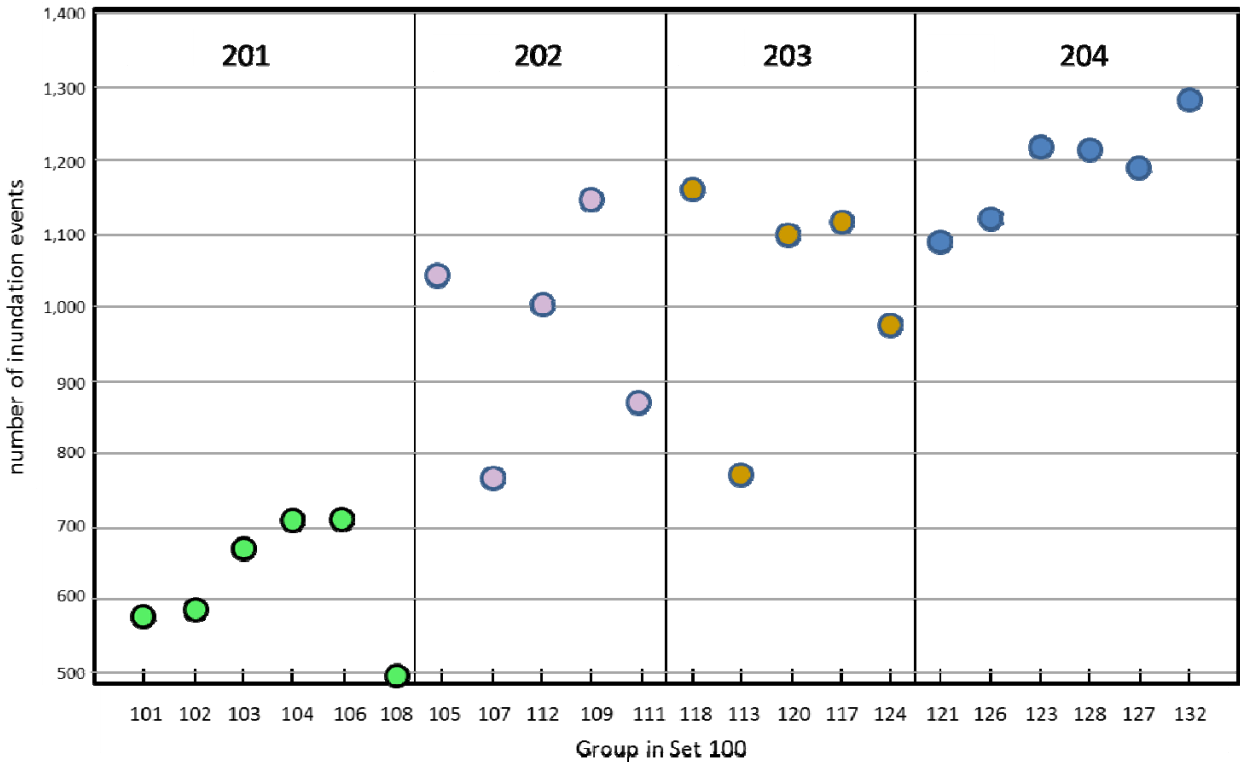

Figure 14. Number of inundation events for marsh groups in set 100 over a two-year period (2007-2008). Marsh groups shown in upstream order from left to right. Marker colors indicate marsh groups in set 200.

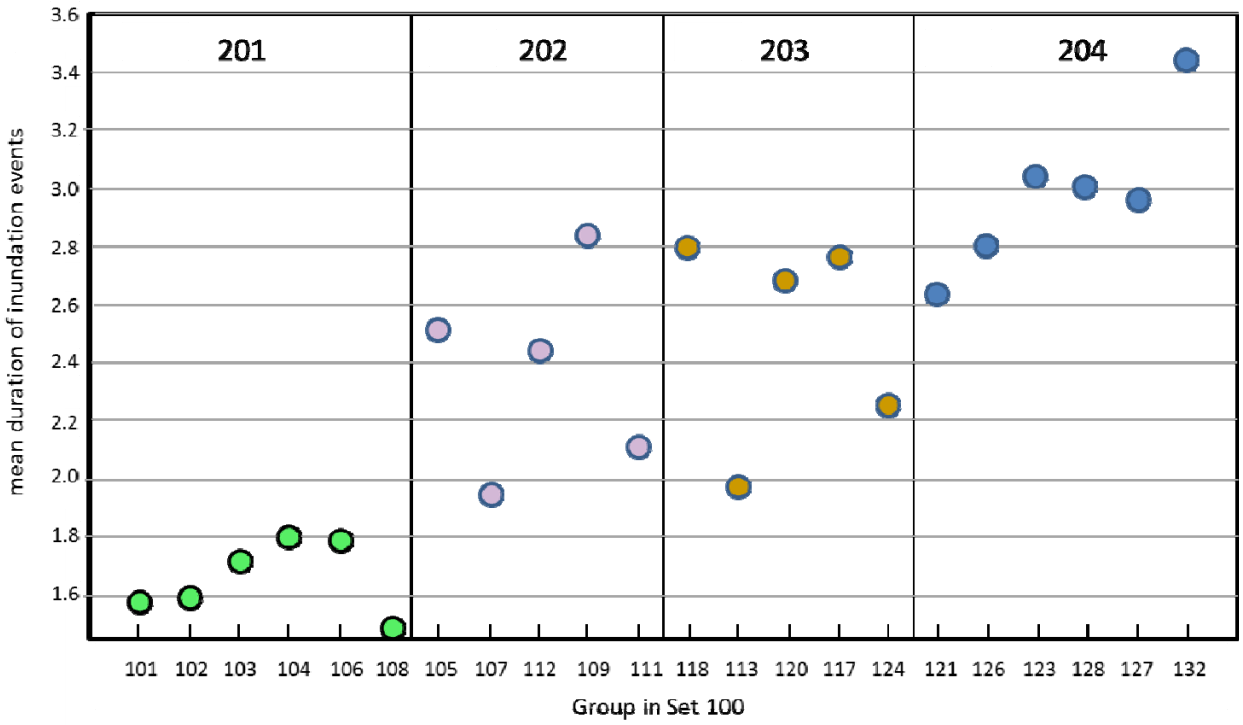

Figure 15. Mean duration of inundation events for marsh groups in set 100 over a two-year period (2007-2008). Marsh groups shown in upstream order from left to right. Marker colors indicate marsh groups in set 200.

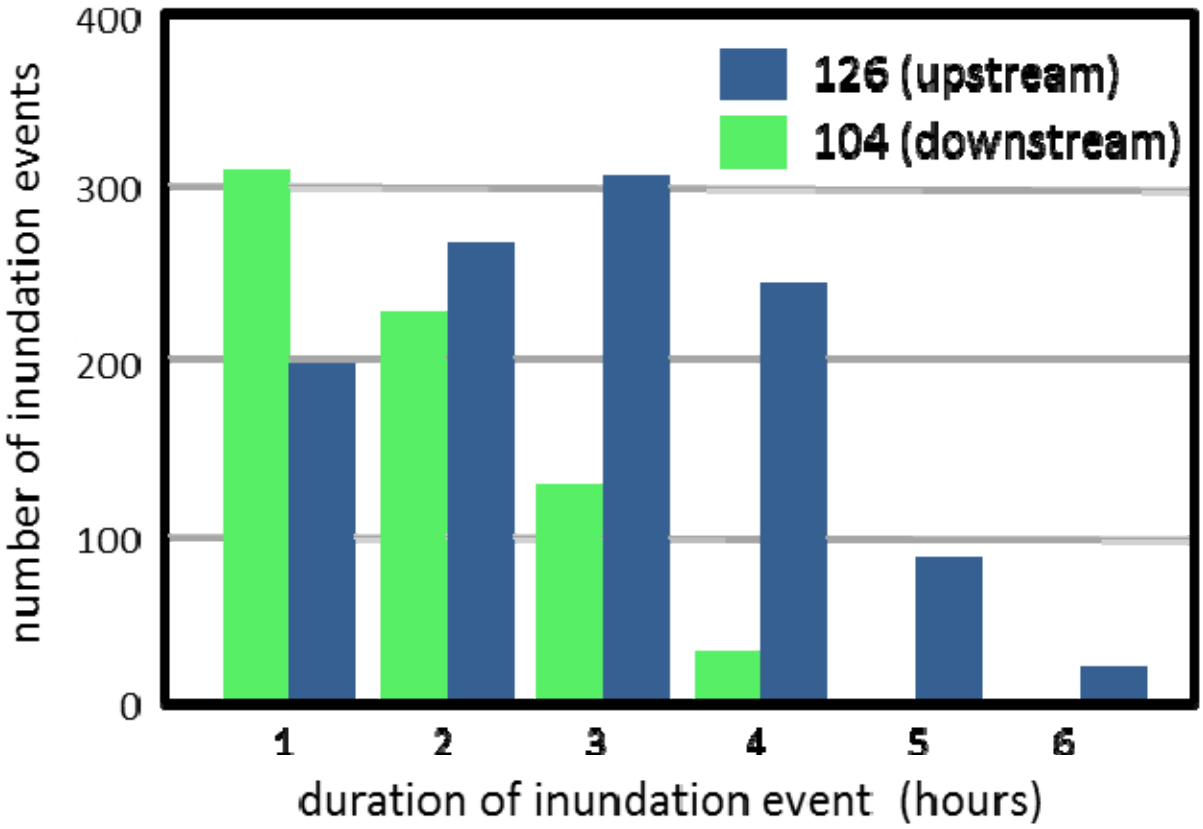

Figure 16. Histograms of duration of inundation events for marsh groups 104 (downstream) and 126 (upstream) over a two-year period (2007-2008).

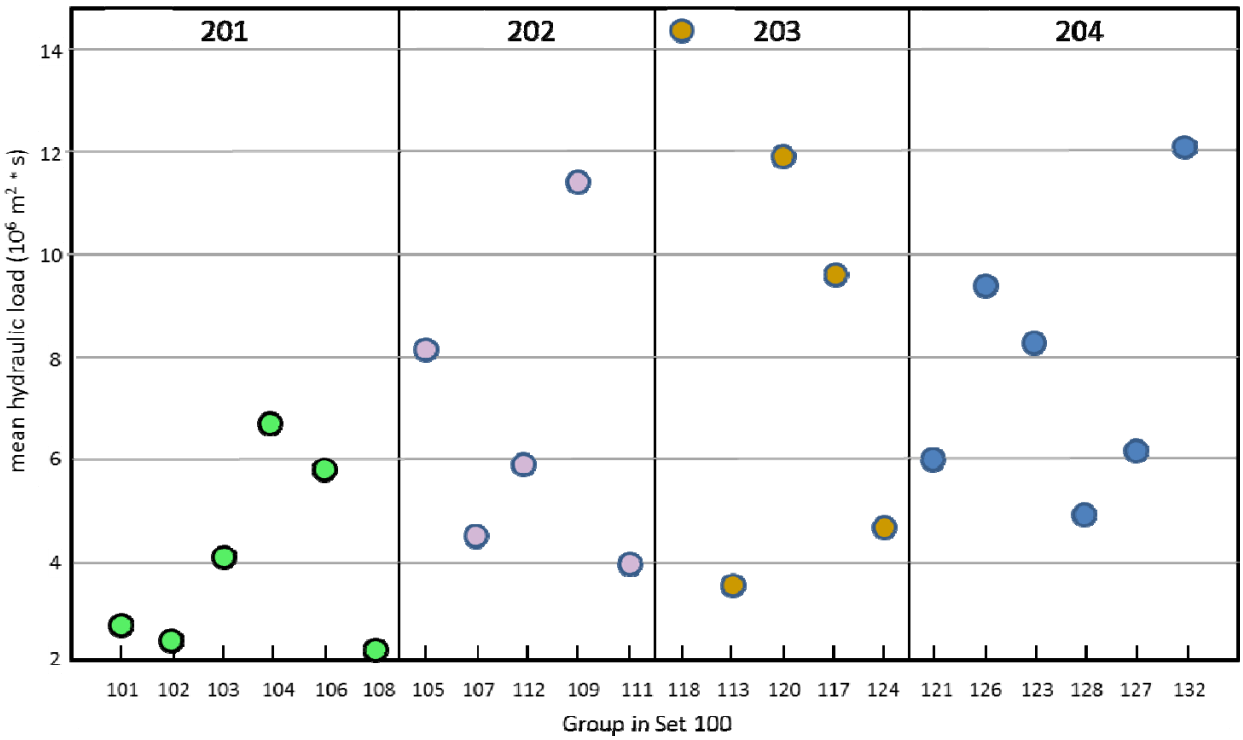

Figure 17. Mean hydraulic loads of inundation events for marsh groups in set 100 over a two-year period (2007-2008). Marsh groups shown in upstream order from left to right. Marker colors indicate marsh groups in set 200.

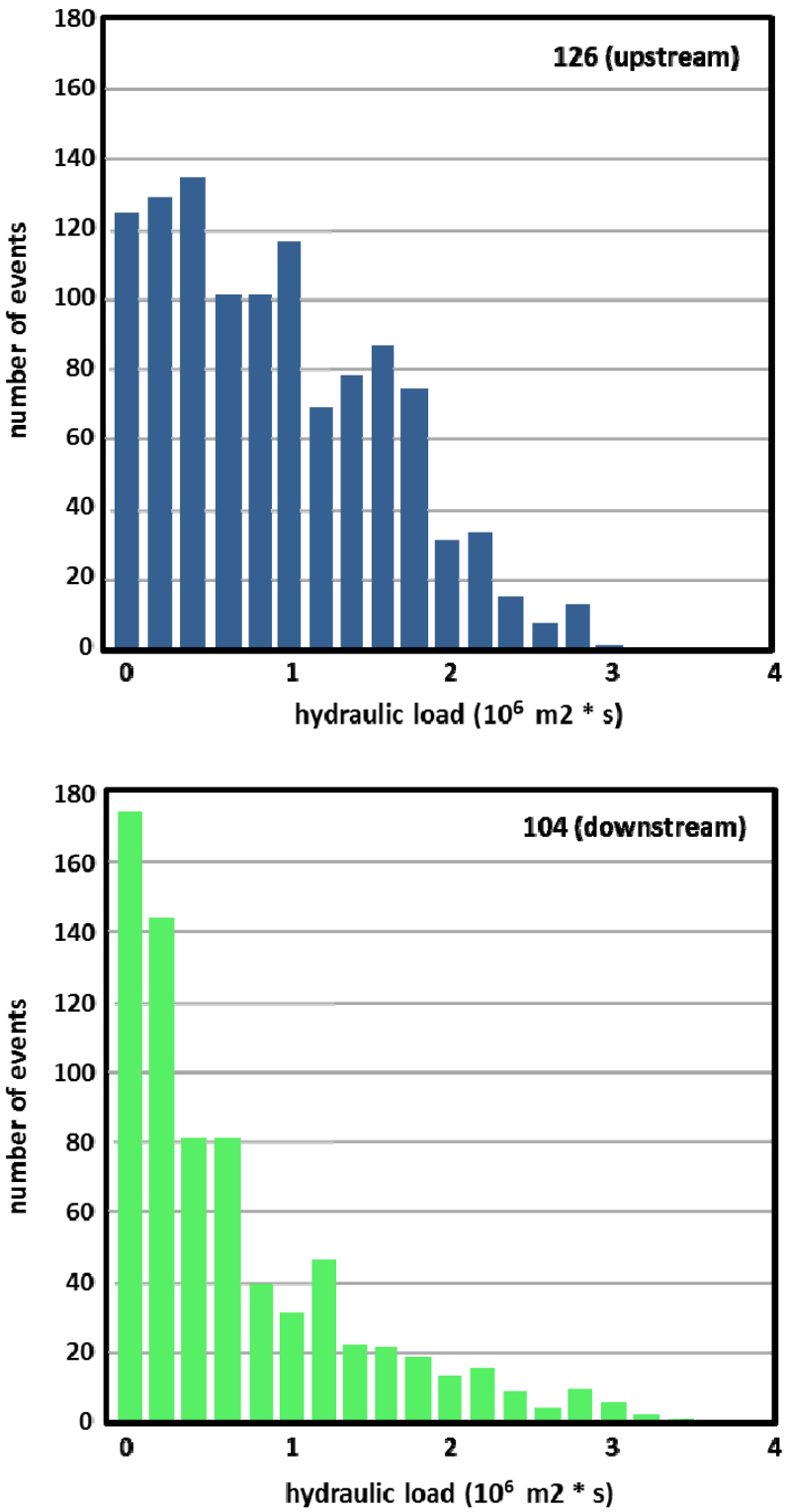

Figure 18. Histograms of hydraulic loads of inundation events for marsh groups 104 and 126.

APPENDICES

Appendix A
Parameterization tables

Table A1. Area (m^2) in each marsh zone with an elevation less than a set of NAVD88 elevations.

elevation (m)*	all marsh zones	marsh zone						
		1**	2	3	4	5**	6	7
0.25	68,745	5	508	584	1,256	926	780	840
0.3	169,978	23	1,156	1,424	2,712	3,177	1,796	1,952
0.35	321,704	91	2,008	2,476	4,596	8,129	2,828	3,288
0.4	547,116	308	3,332	3,820	6,716	18,003	4,268	5,144
0.45	874,321	930	5,124	5,508	9,352	35,836	6,112	7,712
0.5	1,334,057	2,520	7,948	8,324	13,112	65,011	8,532	12,316
0.55	1,966,242	6,142	12,600	13,020	19,032	108,253	13,152	21,752
0.6	2,804,545	13,492	19,688	21,728	29,200	166,314	24,156	40,848
0.65	3,858,154	26,781	30,984	38,564	49,424	236,936	49,232	76,612
0.7	5,078,535	48,192	48,160	68,384	87,324	314,754	98,340	131,712
0.75	6,356,411	78,927	71,900	115,216	154,464	392,434	173,300	198,256
0.8	7,559,425	118,241	102,480	177,360	259,040	462,680	264,004	262,212
0.85	8,597,522	163,050	138,480	247,652	396,120	520,226	358,592	310,176
0.9	9,434,074	208,557	177,000	315,644	545,324	562,933	449,184	340,128
0.95	10,066,945	249,737	212,972	370,968	679,240	591,646	529,136	356,928
1	10,511,995	282,942	242,712	410,968	780,556	609,133	591,592	365,768
1.05	10,807,863	306,799	264,428	437,264	847,496	618,781	636,868	370,136
1.1	10,995,081	322,072	279,324	452,268	889,096	623,603	667,188	372,840
1.15	11,116,405	330,784	289,784	460,440	915,528	625,786	688,276	374,508
1.2	11,195,725	335,213	297,016	464,456	933,576	626,682	702,120	375,508

* NAVD88 datum

** estimated from cumulative distribution function for corresponding group in Set 200

Table A1 (cont.). Area (m^2) in each marsh zone with an elevation less than a set of NAVD88 elevations.

elevation (m)*	marsh zone							
	8	9	10	11	12	13	14	15
0.25	20	6,472	304	1,132	740	304	140	600
0.3	48	15,320	640	2,620	1,772	664	388	1,480
0.35	124	27,204	1,072	4,664	3,044	1,212	684	2,440
0.4	176	43,684	1,632	7,696	4,752	1,968	1,060	3,832
0.45	312	67,660	2,380	12,276	7,316	3,100	1,632	5,960
0.5	484	102,564	3,632	20,764	12,352	4,732	2,492	9,456
0.55	724	155,412	5,596	35,644	22,008	7,496	3,856	15,828
0.6	1,128	233,564	9,628	60,524	40,204	11,656	6,104	27,388
0.65	1,644	336,828	17,652	95,784	70,684	17,956	9,448	47,176
0.7	2,572	450,352	31,540	137,600	112,148	27,196	13,600	77,604
0.75	4,100	555,348	52,764	180,232	158,960	37,456	18,068	115,504
0.8	7,016	637,948	79,536	215,812	202,556	47,596	22,336	151,540
0.85	12,576	694,728	108,640	242,032	240,356	56,112	25,540	178,544
0.9	20,928	730,472	136,216	257,928	267,560	62,068	28,124	195,172
0.95	31,704	753,140	158,888	267,352	284,804	66,160	30,076	204,096
1	43,300	767,696	175,020	272,412	294,196	68,516	31,664	208,688
1.05	53,956	778,048	185,720	275,236	299,012	69,788	33,024	211,200
1.1	62,724	785,508	191,716	276,884	301,060	70,488	34,236	212,584
1.15	69,320	790,840	195,264	278,008	302,332	70,820	35,280	213,584
1.2	73,892	794,808	197,012	278,828	303,164	71,068	36,356	214,156

* NAVD88 datum

Table A1 (cont.). Area (m^2) in each marsh zone with an elevation less than a set of NAVD88 elevations.

elevation (m)*	marsh zone							
	16	17	18**	19	20**	21	22	23
0.25	2,464	1,324	5,424	2,256	41	2,152	1,069	7,148
0.3	5,592	3,312	12,524	5,436	145	5,828	3,785	18,632
0.35	9,928	6,964	23,072	10,296	382	12,264	9,998	35,040
0.4	16,248	12,884	38,140	17,784	870	23,388	22,787	57,876
0.45	25,016	22,356	61,308	29,376	1,775	41,016	46,476	87,596
0.5	35,496	36,296	98,328	47,664	3,283	66,376	85,963	123,376
0.55	48,432	55,308	156,860	77,540	5,545	100,548	145,198	166,112
0.6	61,808	79,224	245,164	121,764	8,600	143,236	225,163	213,316
0.65	75,108	105,360	368,712	181,388	12,310	191,444	322,311	260,112
0.7	85,736	130,412	521,576	247,408	16,366	240,344	428,523	303,376
0.75	93,676	151,920	681,808	307,244	20,358	283,028	533,024	338,712
0.8	98,676	167,856	825,260	352,300	23,891	314,096	625,553	364,956
0.85	101,552	178,680	929,456	382,860	26,707	334,580	699,283	383,808
0.9	103,276	185,272	997,140	400,796	28,727	346,856	752,153	396,808
0.95	104,436	189,412	1,037,060	410,544	30,030	353,844	786,272	405,868
1	105,272	191,804	1,059,872	415,684	30,786	358,068	806,086	412,584
1.05	105,828	193,372	1,073,980	418,456	31,182	360,560	816,441	417,584
1.1	106,400	194,372	1,083,144	420,060	31,368	361,852	821,310	421,288
1.15	106,912	195,060	1,089,808	421,024	31,447	362,716	823,372	424,228
1.2	107,444	195,588	1,094,988	421,560	31,477	363,172	824,157	426,568

* NAVD88 datum

** estimated from cumulative distribution function for corresponding group in Set 200

Table A1 (cont.). Area (m^2) in each marsh zone with an elevation less than a set of NAVD88 elevations.

elevation (m)*	marsh zone							
	24	25	26	27	28	32	34	36
0.25	2,108	156	3,428	4,812	7,448	1,644	10,764	1,896
0.3	4,956	408	8,588	12,592	17,820	4,288	25,840	5,060
0.35	8,696	856	16,744	25,404	31,852	8,460	47,568	10,320
0.4	13,668	1,628	31,124	43,988	50,328	15,464	76,660	17,888
0.45	21,580	2,936	56,264	68,532	71,968	25,368	112,648	28,896
0.5	34,220	4,996	98,384	98,380	95,372	38,216	152,252	41,216
0.55	54,292	8,276	157,764	132,988	119,496	52,588	190,788	53,992
0.6	84,448	12,728	229,720	170,372	144,568	68,304	225,000	65,508
0.65	126,364	17,724	305,952	206,388	168,920	82,872	252,328	75,156
0.7	175,312	22,476	377,408	238,284	190,712	95,092	273,232	82,800
0.75	222,472	26,264	435,948	264,392	208,652	104,960	288,500	88,524
0.8	260,080	28,788	478,276	284,216	222,132	111,708	298,736	92,544
0.85	284,648	30,476	504,568	298,388	231,872	116,316	306,288	95,216
0.9	298,796	31,528	520,136	308,832	238,344	119,436	311,588	97,148
0.95	306,720	32,252	529,472	316,232	242,792	121,348	315,336	98,480
1	311,208	32,736	535,052	321,864	245,364	122,560	318,500	99,392
1.05	313,872	33,048	538,500	325,972	247,156	123,420	320,628	100,108
1.1	315,452	33,288	540,472	329,064	248,312	124,084	322,312	100,712
1.15	316,428	33,448	541,676	331,124	249,148	124,608	323,736	101,116
1.2	316,992	33,588	542,460	332,748	249,704	125,000	324,964	101,460

* NAVD88 datum

Table A2a. Area with an elevation less than a set of NAVD88 elevations for each group in set 100 contained in group 201.

set 100 ->	101	102	103	104	106	108
set 200 ->	201	201	201	201	201	201
elev (m)^	Area (m^2)					
0.25	5	508	584	1,256	780	324
0.3	23	1,156	1,424	2,712	1,796	688
0.35	91	2,008	2,476	4,596	2,828	1,196
0.4	308	3,332	3,820	6,716	4,268	1,808
0.45	930	5,124	5,508	9,352	6,112	2,692
0.5	2,520	7,948	8,324	13,112	8,532	4,116
0.55	6,142	12,600	13,020	19,032	13,152	6,320
0.6	13,492	19,688	21,728	29,200	24,156	10,756
0.65	26,781	30,984	38,564	49,424	49,232	19,296
0.7	48,192	48,160	68,384	87,324	98,340	34,112
0.75	78,927	71,900	115,216	154,464	173,300	56,864
0.8	118,241	102,480	177,360	259,040	264,004	86,552
0.85	163,050	138,480	247,652	396,120	358,592	121,216
0.9	208,557	177,000	315,644	545,324	449,184	157,144
0.95	249,737	212,972	370,968	679,240	529,136	190,592
1	282,942	242,712	410,968	780,556	591,592	218,320
1.05	306,799	264,428	437,264	847,496	636,868	239,676
1.1	322,072	279,324	452,268	889,096	667,188	254,440
1.15	330,784	289,784	460,440	915,528	688,276	264,584
1.2	335,213	297,016	464,456	933,576	702,120	270,904

^ elevation in meters using NAVD88 datum

Table A2b. Area with elevation less than a set of NAVD88 elevations for each group in set 100 contained in group 202.

set 100 ->	105	107	109	111	112
set 200 ->	202	202	202	202	202
elev (m)^	Area (m^2)				
0.25	926	840	6,472	1,132	3,344
0.3	3,177	1,952	15,320	2,620	7,752
0.35	8,129	3,288	27,204	4,664	13,656
0.4	18,003	5,144	43,684	7,696	22,060
0.45	35,836	7,712	67,660	12,276	33,964
0.5	65,011	12,316	102,564	20,764	50,340
0.55	108,253	21,752	155,412	35,644	74,296
0.6	166,314	40,848	233,564	60,524	108,116
0.65	236,936	76,612	336,828	95,784	155,240
0.7	314,754	131,712	450,352	137,600	211,484
0.75	392,434	198,256	555,348	180,232	270,704
0.8	462,680	262,212	637,948	215,812	323,568
0.85	520,226	310,176	694,728	242,032	367,448
0.9	562,933	340,128	730,472	257,928	398,960
0.95	591,646	356,928	753,140	267,352	419,316
1	609,133	365,768	767,696	272,412	431,132
1.05	618,781	370,136	778,048	275,236	437,864
1.1	623,603	372,840	785,508	276,884	441,696
1.15	625,786	374,508	790,840	278,008	444,524
1.2	626,682	375,508	794,808	278,828	446,964

^ elevation in meters using NAVD88 datum

Table A2c. Area with elevation less than a set of NAVD88 elevations for each group in set 100 contained in group 203.

set 100 ->	113	117	118	120	124
set 200 ->	203	203	203	203	203
elev (m)^	Area (m^2)				
0.25	904	3,580	5,424	1,110	2,108
0.3	2,144	8,748	12,524	3,930	4,956
0.35	3,652	17,260	23,072	10,380	8,696
0.4	5,800	30,668	38,140	23,657	13,668
0.45	9,060	51,732	61,308	48,251	21,580
0.5	14,188	83,960	98,328	89,246	34,220
0.55	23,324	132,848	156,860	150,743	54,292
0.6	39,044	200,988	245,164	233,763	84,448
0.65	65,132	286,748	368,712	334,621	126,364
0.7	104,800	377,820	521,576	444,889	175,312
0.75	152,960	459,164	681,808	553,382	222,472
0.8	199,136	520,156	825,260	649,444	260,080
0.85	234,656	561,540	929,456	725,990	284,648
0.9	257,240	586,068	997,140	780,880	298,796
0.95	270,256	599,956	1,037,060	816,302	306,720
1	277,204	607,488	1,059,872	836,872	311,208
1.05	280,988	611,828	1,073,980	847,623	313,872
1.1	283,072	614,432	1,083,144	852,678	315,452
1.15	284,404	616,084	1,089,808	854,819	316,428
1.2	285,224	617,148	1,094,988	855,634	316,992

^ elevation in meters using NAVD88 datum

Table A2d. Area with elevation less than a set of NAVD88 elevations for each group in set 100 contained in group 204.

set 100 ->	121	123	126	127	128	132
set 200 ->	204	204	204	204	204	204
elev (m)^	Area (m^2)					
0.25	2,152	7,304	3,428	4,812	7,448	14,304
0.3	5,828	19,040	8,588	12,592	17,820	35,188
0.35	12,264	35,896	16,744	25,404	31,852	66,348
0.4	23,388	59,504	31,124	43,988	50,328	110,012
0.45	41,016	90,532	56,264	68,532	71,968	166,912
0.5	66,376	128,372	98,384	98,380	95,372	231,684
0.55	100,548	174,388	157,764	132,988	119,496	297,368
0.6	143,236	226,044	229,720	170,372	144,568	358,812
0.65	191,444	277,836	305,952	206,388	168,920	410,356
0.7	240,344	325,852	377,408	238,284	190,712	451,124
0.75	283,028	364,976	435,948	264,392	208,652	481,984
0.8	314,096	393,744	478,276	284,216	222,132	502,988
0.85	334,580	414,284	504,568	298,388	231,872	517,820
0.9	346,856	428,336	520,136	308,832	238,344	528,172
0.95	353,844	438,120	529,472	316,232	242,792	535,164
1	358,068	445,320	535,052	321,864	245,364	540,452
1.05	360,560	450,632	538,500	325,972	247,156	544,156
1.1	361,852	454,576	540,472	329,064	248,312	547,108
1.15	362,716	457,676	541,676	331,124	249,148	549,460
1.2	363,172	460,156	542,460	332,748	249,704	551,424

^ elevation in meters using NAVD88 datum

Table A3. Area with an elevation less than a set of NAVD88 elevations for each group in set 200 and all total marsh in the study area.

elev (m)^	201	202	203	204	TOTAL			
	Area				Area			
	m^2				m^2	km^2	hectares	acres
0.25	3,457	12,714	13,126	39,448	68,745	0.07	6.87	17.0
0.3	7,799	30,821	32,302	99,056	169,978	0.17	17.00	42.0
0.35	13,195	56,941	63,060	188,508	321,704	0.32	32.17	79.5
0.4	20,252	96,587	111,933	318,344	547,116	0.55	54.71	135.2
0.45	29,718	157,448	191,931	495,224	874,321	0.87	87.43	216.0
0.5	44,552	250,995	319,942	718,568	1,334,057	1.33	133.41	329.7
0.55	70,266	395,357	518,067	982,552	1,966,242	1.97	196.62	485.9
0.6	119,020	609,366	803,407	1,272,752	2,804,545	2.80	280.45	693.0
0.65	214,281	901,400	1,181,577	1,560,896	3,858,154	3.86	385.82	953.4
0.7	384,512	1,245,902	1,624,397	1,823,724	5,078,535	5.08	507.85	1,254.9
0.75	650,671	1,596,974	2,069,786	2,038,980	6,356,411	6.36	635.64	1,570.7
0.8	1,007,677	1,902,220	2,454,076	2,195,452	7,559,425	7.56	755.94	1,868.0
0.85	1,425,110	2,134,610	2,736,290	2,301,512	8,597,522	8.60	859.75	2,124.5
0.9	1,852,853	2,290,421	2,920,124	2,370,676	9,434,074	9.43	943.41	2,331.2
0.95	2,232,645	2,388,382	3,030,294	2,415,624	10,066,945	10.07	1,006.69	2,487.6
1	2,527,090	2,446,141	3,092,644	2,446,120	10,511,995	10.51	1,051.20	2,597.6
1.05	2,732,531	2,480,065	3,128,291	2,466,976	10,807,863	10.81	1,080.79	2,670.7
1.1	2,864,388	2,500,531	3,148,778	2,481,384	10,995,081	11.00	1,099.51	2,716.9
1.15	2,949,396	2,513,666	3,161,543	2,491,800	11,116,405	11.12	1,111.64	2,746.9
1.2	3, 03, 85	2,522,790	3,169,986	2,499,664	11,195,725	11.20	1,119.57	2,766.5

^ elevation in meters using NAVD88 datum

Appendix B
Descriptive statistics of elevation

Table B1. Descriptive statistics for elevations of marsh groups in sets 100 and 200 and all marsh in study area. Elevations units are meters using the NAVD88 vertical datum. Table continues on next page.

Group	area m^2	mean	st dev	percentiles (percent of area that has a lower elevation than given elevation)									
				0	5	10	15	20	25	30	35	40	45
All tidal wetlands													
all*	11,200,924	0.72	0.19	0.20	0.36	0.43	0.49	0.53	0.57	0.60	0.63	0.66	0.68
Set 100													
101*	338,448	0.82	0.18	0.20	0.51	0.58	0.62	0.66	0.69	0.72	0.75	0.78	0.81
102	297,016	0.85	0.16	0.20	0.57	0.64	0.69	0.72	0.75	0.78	0.80	0.82	0.84
103	464,456	0.84	0.14	0.20	0.61	0.66	0.70	0.73	0.75	0.77	0.79	0.81	0.82
104	933,576	0.87	0.14	0.20	0.64	0.70	0.74	0.77	0.79	0.81	0.82	0.84	0.86
105*	627,684	0.76	0.17	0.20	0.46	0.53	0.58	0.61	0.64	0.67	0.70	0.72	0.74
106	702,120	0.85	0.15	0.20	0.63	0.67	0.70	0.73	0.75	0.77	0.79	0.81	0.83
107	375,508	0.74	0.13	0.20	0.54	0.59	0.62	0.65	0.67	0.68	0.70	0.71	0.73
108	270,904	0.87	0.15	0.20	0.62	0.68	0.72	0.74	0.77	0.79	0.81	0.83	0.85
109	794,808	0.68	0.17	0.20	0.39	0.47	0.52	0.55	0.58	0.60	0.62	0.64	0.66
111	278,828	0.70	0.15	0.20	0.46	0.53	0.57	0.59	0.61	0.63	0.65	0.67	0.69
112	446,964	0.70	0.17	0.20	0.40	0.48	0.54	0.57	0.60	0.63	0.65	0.67	0.69
113	285,224	0.74	0.14	0.20	0.50	0.57	0.61	0.64	0.66	0.68	0.69	0.71	0.73
117	617,148	0.66	0.15	0.20	0.40	0.47	0.51	0.54	0.57	0.59	0.61	0.63	0.65
118	1,094,988	0.70	0.16	0.20	0.44	0.51	0.55	0.59	0.61	0.63	0.65	0.67	0.69
120*	856,596	0.56	0.18	0.20	0.29	0.34	0.38	0.41	0.43	0.46	0.48	0.50	0.53
121	363,172	0.64	0.16	0.20	0.38	0.44	0.48	0.51	0.54	0.56	0.58	0.60	0.62
123	460,156	0.61	0.19	0.20	0.31	0.37	0.42	0.45	0.48	0.51	0.54	0.56	0.58
124	316,992	0.68	0.15	0.20	0.42	0.49	0.54	0.57	0.59	0.61	0.63	0.65	0.67
126	542,460	0.63	0.15	0.20	0.39	0.45	0.48	0.51	0.53	0.55	0.57	0.59	0.61
127	332,748	0.61	0.19	0.20	0.32	0.37	0.41	0.45	0.48	0.50	0.53	0.55	0.57
128	249,704	0.57	0.19	0.20	0.28	0.33	0.37	0.40	0.43	0.46	0.48	0.51	0.54
132	551,424	0.55	0.18	0.20	0.28	0.33	0.37	0.40	0.43	0.45	0.47	0.49	0.51
Set 200													
201*	3,006,520	0.86	0.15	0.20	0.61	0.67	0.71	0.74	0.76	0.78	0.80	0.82	0.84
202*	2,523,792	0.70	0.16	0.20	0.42	0.50	0.55	0.58	0.61	0.63	0.65	0.67	0.69
203*	3,170,948	0.69	0.15	0.20	0.42	0.50	0.54	0.57	0.60	0.62	0.64	0.66	0.68
204	2,499,664	0.60	0.18	0.20	0.31	0.37	0.41	0.45	0.48	0.50	0.53	0.55	0.57

* Elevation distributions for groups 101, 105, and 120 were replaced with pseudo-data representing the cumulative probability distributions of their associated group in set 200 (see text for explanation).

Table B1 (continued). Descriptive statistics for elevations of marsh groups in sets 100 and 200 and all marsh in study area. Elevations units are meters using the NAVD88 vertical datum.

Group	area m^2	mean	st dev	percentiles (percent of area that has a lower elevation than given elevation)										
				50	55	60	65	70	75	80	85	90	95	100
All tidal wetlands														
all*	11,200,924	0.72	0.19	0.71	0.73	0.76	0.78	0.81	0.84	0.87	0.90	0.95	1.00	1.20
Set 100														
101*	338,448	0.82	0.18	0.83	0.86	0.88	0.90	0.93	0.96	0.98	1.02	1.06	1.11	1.20
102	297,016	0.85	0.16	0.86	0.88	0.90	0.92	0.94	0.96	0.99	1.02	1.06	1.11	1.20
103	464,456	0.84	0.14	0.84	0.86	0.87	0.89	0.91	0.93	0.95	0.98	1.01	1.06	1.20
104	933,576	0.87	0.14	0.87	0.89	0.90	0.92	0.94	0.96	0.98	1.00	1.04	1.10	1.20
105*	627,684	0.76	0.17	0.76	0.78	0.80	0.83	0.85	0.87	0.90	0.93	0.98	1.04	1.20
106	702,120	0.85	0.15	0.84	0.86	0.88	0.90	0.92	0.95	0.97	1.00	1.04	1.10	1.20
107	375,508	0.74	0.13	0.74	0.76	0.77	0.79	0.80	0.82	0.84	0.86	0.90	0.95	1.20
108	270,904	0.87	0.15	0.87	0.89	0.91	0.93	0.95	0.97	0.99	1.02	1.06	1.11	1.20
109	794,808	0.68	0.17	0.68	0.69	0.71	0.73	0.75	0.77	0.80	0.83	0.88	0.96	1.20
111	278,828	0.70	0.15	0.70	0.72	0.73	0.75	0.77	0.79	0.81	0.84	0.88	0.93	1.20
112	446,964	0.70	0.17	0.71	0.73	0.75	0.77	0.79	0.81	0.84	0.87	0.91	0.97	1.20
113	285,224	0.74	0.14	0.74	0.75	0.77	0.78	0.80	0.82	0.84	0.87	0.90	0.95	1.20
117	617,148	0.66	0.15	0.66	0.68	0.70	0.71	0.73	0.75	0.78	0.81	0.84	0.90	1.20
118	1,094,988	0.70	0.16	0.71	0.73	0.74	0.76	0.78	0.80	0.82	0.85	0.89	0.96	1.20
120*	856,596	0.56	0.18	0.55	0.57	0.60	0.62	0.65	0.68	0.71	0.75	0.80	0.89	1.20
121	363,172	0.64	0.16	0.64	0.66	0.68	0.70	0.72	0.74	0.76	0.79	0.83	0.89	1.20
123	460,156	0.61	0.19	0.60	0.63	0.65	0.67	0.70	0.72	0.76	0.80	0.85	0.95	1.20
124	316,992	0.68	0.15	0.68	0.70	0.72	0.73	0.75	0.77	0.79	0.82	0.85	0.91	1.20
126	542,460	0.63	0.15	0.63	0.65	0.66	0.68	0.70	0.72	0.75	0.78	0.82	0.88	1.20
127	332,748	0.61	0.19	0.60	0.62	0.64	0.67	0.69	0.72	0.76	0.80	0.86	0.95	1.20
128	249,704	0.57	0.19	0.56	0.59	0.61	0.64	0.66	0.69	0.72	0.76	0.81	0.89	1.20
132	551,424	0.55	0.18	0.53	0.56	0.58	0.60	0.63	0.65	0.69	0.73	0.78	0.88	1.20
Set 200														
201*	3,006,520	0.86	0.15	0.85	0.87	0.89	0.91	0.92	0.94	0.97	0.99	1.03	1.09	1.20
202*	2,523,792	0.70	0.16	0.70	0.72	0.74	0.76	0.78	0.80	0.82	0.85	0.89	0.96	1.20
203*	3,170,948	0.69	0.15	0.70	0.71	0.73	0.75	0.77	0.79	0.81	0.84	0.88	0.94	1.20
204	2,499,664	0.60	0.18	0.60	0.62	0.64	0.66	0.69	0.71	0.74	0.78	0.83	0.91	1.20

* Elevation distributions for groups 101, 105, and 120 were replaced with pseudo-data representing the cumulative probability distributions of their associated group in set 200 (see text for explanation).