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David R. Wunsch, State Geologist

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CHARACTERIZATION OF TIDAL WETLAND INUNDATION IN THE MURDERKILL ESTUARY

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ABSTRACT

A parameterization of tidal marsh inundation was developed for the 1,200 hectares of tidal marsh along the 12-km reach of the tidal Murderkill River between Frederica and Bowers Beach in Kent County, Delaware. A parsimonious modeling approach was used that bridges the gap between the simple and often used "bathtub model" (instantaneous inundation based on tides in Delaware Bay), and the more complex modeling of shallow overland that results in the wetting and drying of tidal marshes. For this project, and many other modeling studies that include large areas of marsh, a complex modeling approach of marsh inundation is not warranted due to the lack of data on the dynamics of wetting and drying. A simple parameterization of the wetland inundation process coupled with more complex hydrodynamic and water-quality models can provide sufficient results for estimating the extent of hydrologic and biogeochemical interactions between a marsh and a river. The parameterization can also be used to evaluate anomalies in conservation of water mass and tidal phase offsets that can result from hydrodynamic models that do not explicitly model the dynamic flow and storage of water in tidal wetlands. In the parameterization, the marsh was divided into marsh tracts (n=31) based on hydrologic character and position along the river. A cumulative probability distribution of wetland elevation was calculated for each marsh tract from a digital elevation model. These cumulative probability distributions served as a simplification of the critical information contained in the raster data sets of marsh tracts and elevation. Each marsh tract was related to an adjacent river reach; the area in the tract that was below the stage of its related river reach was instantaneously inundated. Marsh tracts were aggregated into two sets of marsh groups (n=22 and n=4) for analysis and visualization of elevation, hydroperiod, and hydraulic loading. The parameterization was successfully implemented in a collaborative modeling study that created a set of mass loading functions to represent the import and export of chemical species to and from the wetlands. The parameterization was also used to evaluate conservation of water mass and phase offsets in tidal discharge due to the dynamic storage of water in intertidal areas.

Marsh elevations had a normal distribution with a mean elevation of 0.72 m and standard deviation of 0.19 m based on analysis of LiDAR data collected for this study. These values have a potential positive bias of 0.1 to 0.2 m resulting from the LiDAR beam not penetrating through the marsh vegetation. Nominal relief on the marsh at the scale of the study area was about 0.6 m (0.4 to 1 m absolute elevation using the NAVD88 datum). From Bowers Beach upstream to Frederica there was a decrease in marsh elevation with the mean elevation decreasing from 0.86 m to 0.60 m. This observation is consistent with measured accretion rates at four sites in the study area that document higher accretion rates upstream near Frederica (0.74 cm/yr) relative to downstream near Bowers (0.33 cm/yr). Upstream marshes are flooded more frequently and for longer duration than downstream marshes so there is more opportunity for accretion to occur.

INTRODUCTION

The periodic inundation and exposure of tidal wetlands is a primary controlling variable in many physical, chemical, and biological processes in estuaries with extensive wetlands (Cahoon and Reed, 1995; Friedrichs and Perry, 2001; Temmerman et al., 2005; French, 2006). Processes include the fate and transport of sediment and chemical compounds, in both dissolved and particulate forms, that are transported to and from the marsh platform by tidal water. The interactions of chemicals in the tidal water with sediments on the marsh platform depend on the biogeochemical reactions and their rates, which proceed as a function 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 of marsh platforms and the spatially dynamic and complex nature of the shallow-water flow, small variations in tidal stage can cause large changes in the areal extent and frequency 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 a marsh platform remain largely uncharacterized (Lawrence et al., 2004), and the capabilities of hydrodynamic models are outpacing the data required to validate the models (French, 2010). In this report, a parameterization of the process of marsh inundation is presented that was used in a coupled numerical model (HDR|Hydroqual, 2013) of the hydrodynamics and water quality of the Murderkill River. The parameterization uses a parsimonious approach because the hydrologic data are not available to constrain more complex estimates of inundation of this extensive marsh platform. The parameterization is a simplification of the process of dynamic overland flow of tidal water that causes wetting and drying of the marsh. The parameters used to represent this process are marsh elevation, tidal stage at several locations in the Murderkill River, and a simple segmentation of marsh areas into tracts based on hydrologic characteristics.

This study is driven by the need to better understand the causes of low dissolved oxygen concentrations 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 phosphorus) and the biochemical oxygen demands in the river are the likely causes of low dissolved oxygen concentrations (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 and oxygen depleted water (Ullman et al., 2013) from the extensive tidal wetlands adjacent to the river, and effluent from the Kent County Wastewater Treatment Plant (WWTP). HDR|Hydroqual (2013), a consulting firm, used a coupled numerical model of the hydrodynamics and water quality of the Murderkill River to investigate the causes of low dissolved oxygen concentrations. The model explicitly represents the hydrodynamic and biogeochemical processes in the river and the 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 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 (Ullman et al., 2013). To apply the results of these studies to the numerical model, the results must be normalized to a wetland area and coupled with a parameterization of marsh inundation. This report documents the parameterization of inundation used to model nutrient exchange between the river and wetlands. The parameterization was used by HDR|Hydroqual (2013) to create a set of loading functions representing import and export of chemical species to and from the wetlands. The parameterization was also used to evaluate the model hydrodynamics, particularly with issues of the 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 determine and map the elevation of marshes in the Murderkill Estuary in Kent County, Delaware, and then use this data to develop a model to quantify the inundation of tidal wetlands (salt marsh) in the estuary. The result can be used as a parameterization in a coupled numerical model of hydrodynamics and water quality to parameterize marsh inundation along a 12-km reach of the river between Frederica and Bowers Beach.

Acknowledgments

Funding for this project was provided by the Kent County Levy Court and the Delaware Geological Survey. Oversight was provided by Hans Medlarz from the Kent County, Delaware Department of Public Works and Hassan Mirsajadi from Watershed Assessment and Management Section, Delaware Department of Natural Resources and Environmental Control (DNREC), co-chairs of the Murderkill River Study Group. The work was greatly enhanced by the regular meetings and discussions of the Murderkill River Study Group and the network of colleagues it fostered. Particularly helpful discussions related to the presented work were with Andy Thuman of HDR|Hydroqual, Bill Ullman, Kuo Wong and Kent Price (deceased) from the University of Delaware, College of Earth, Ocean, and Environment, Anthony Aufdenkampe from Stroud Water Research Center, Tony Tallman and Mark Nardi from the United States Geological Survey, and Alison Rogerson from DNREC Watershed Assessment and Management Section. Reviews by Bill Ullman, John Callahan (Delaware Geological Survey), and Hassan Mirsajadi greatly improved the content of the report.

Study Area

The Murderkill Estuary is located in eastern Kent County, Delaware, and the Murderkill River discharges to Delaware Bay at the Town of Bowers Beach (Fig. 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, its tidal tributaries (Spring Creek, Hudson Branch, Browns Branch) and extensive tidal wetlands. About 16 km of the tidal reaches are classified as salt-water reaches, based on the vegetation in wetlands adjacent to the river (DNREC, 1994), and these extend about 14 km upstream from Delaware Bay. The estuarine watershed has an area of 94.0 km^2 with the estuary comprising 19 percent of the watershed area (1,788 hectares; 13 percent salt-water tidal wetlands, 4 percent fresh-water tidal wetlands, and 2 percent tidal surface water).

The study area is the lower part of the Murderkill 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 (Fig. 1). The upstream and downstream boundaries of the study area coincide with locations of tide gaging stations maintained by the U.S. Geological Survey (USGS; Fig. 1, Table 1). The study area watershed is 42.8 km^2 in area with the estuary comprising 30 percent. About 90 percent of the study area estuary is salt-water tidal wetlands (11.4 km^2); 93 percent of all salt-water tidal wetlands in the estuary are within the study area. These wetlands are salt marshes dominated by *Spartina alterniflora, Spartina patens,* and *Distichlis spicata* (Daiber, et al., 1976). Marshes in the downstream part of the estuary have extensive grids of ditches (Fig. 1). Elevations of the salt marsh platform range from about 0.2 to 1.2 meters-NAVD88 (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 (Wong, et al., 2009). The tidal 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

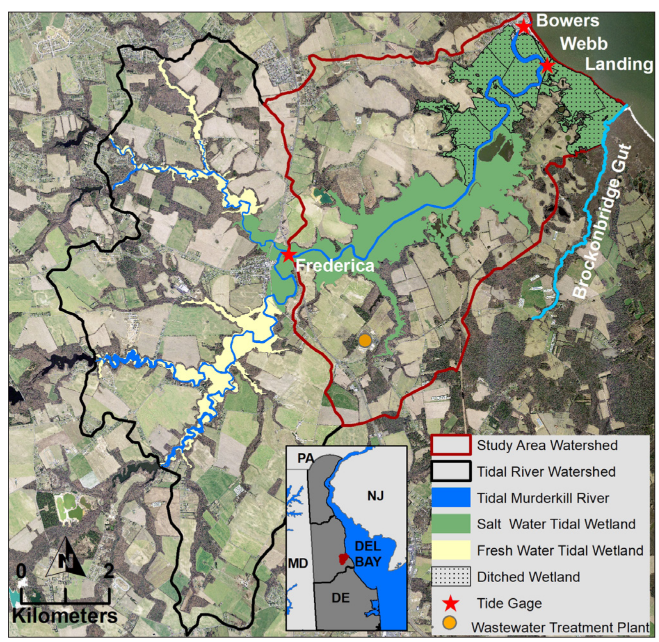


Figure 1. Study area, tidal Murderkill River watersheds, tidal Murderkill River, tidal wetlands, locations of ditches, tide gages (Table 1), and the Kent County Wastewater Treatment Facility. The inset shows the study area watershed (in red) in Kent County, Delaware.

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	-0.17
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	-0.55

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

largely absent by the time the tide reaches Frederica (Wong 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 (Wong et al., 2009).

The Murderkill River bisects the salt marshes in the study area as a large pass-through channel with flow to and from Delaware Bay and from the upstream Murderkill River. Numerous side channels branch off from the Murderkill River into the salt marsh, some of which may have been modified by human activity. The majority of the side channels are blind, with their headwaters within the salt marsh, but some are pass-through channels with their headwaters in the uplands. Based on limited visual observations and aerial thermal imaging in the southeastern part of the study area, the dominant pathway for salt marsh flooding appears to be from small side channels rather than from the larger side channels that connect to the Murderkill River. The larger channels and the Murderkill River likely serve as direct pathways to the marsh only during the highest tides due to berms that are commonly found adjacent to the large channels.

Inundation Modeling

Models of marsh inundation may range from simple estimates based on bathtub models (instantaneous inundation to the height of local tide) to complex hydrodynamic models of coupled overland, channel, and groundwater flows that include precipitation, evapotranspiration, and vegetation as parameters. Parsimonious modeling in this study bridges the gap between the simple bathtub model that uses the tidal height at Bowers Beach and the more complex 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 current study are limited to the fundamental components of marsh elevation, tidal stage at several locations in the Murderkill River, and a simple segmentation of marsh areas into tracts based on hydrologic characteristics. Each marsh tract was related to an adjacent river reach; the marsh area below the height of the water in its reach is instantaneously inundated. The calculation of inundation is driven by a specified time series of river stage in defined reaches and is independent of the source of the water elevation data; for this reason, the tidal height data can be from observations or a hydrodynamic model. In this report, output from a well-calibrated numerical model was used (HDR|Hydroqual, 2013). A more complex parameterization or process model is not warranted due to the lack of data to document actual inundated marsh areas along the 12-km river reach. Although inundation within each tract behaves as a bathtub model, it incorporates tidal propagation in the river at the scale of a marsh tract. A complex hydrodynamic model that includes overland flow in wetlands has an advantage in more closely representing reality but the drawback is long processing times for model runs. Having a simple parameterization of inundation within the more complex hydrodynamic model provides flexibility in testing 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 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. These original data are in vector format and are modified using ESRI ArcGIS software. Watershed boundaries were based on the DNREC HUC-12 boundaries for the Murderkill River (DataMIL, 2008a), as modified for the Murderkill River Study Group, to be consistent with statewide 2007 Light Detection and Ranging (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, 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 (Fig. 1). Brockonbridge Gut was chosen as a nominal boundary because the actual boundary in the marsh between the Murderkill River and Brockonbridge Gut is dynamic and difficult to specify.

The Murderkill River and tidal-wetland boundaries are based on the digital vector layer produced by the DNREC State Wetland Mapping Program (SWMP) (DNREC, 1994) and were reclassified and aggregated for this study to simplify into fresh and salt water components (Table 2). A small fraction (<2 percent of tidal wetlands in a tributary upstream of the WWTP) was 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 spatially consistent with an analysis of wetland elevations (see Results and Discussion).

Table 2. Reclassification of DNREC SWMP codes.

SWMP Tidal-Wetland Area	SWMP Code	New Code
tidal, salt water, regularly flooded	E2EM1/USNh	tswr
	E2EM1/Nh	tswr
	E2EM1/Nd	tswr
	E2EM1/N	tswr
tidal, salt water, irregularly flooded	E2EM1P	tswi
	E2EM1Pd	tswi
	E2EM1Ph	tswi
	E2SS3/1P	tswi
	E2SS4/3P	tswi
tidal, fresh water, seasonally flooded or temporarily flooded	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
	PF02/1R	tfwi
	PSS4S	tfwi
	PFO1S	tfwi
tidal, fresh water, riverine, permanently flooded	R1UBV	tfwriver
tidal, salt water, riverine, regularly flooded	R1EM2N	tswriver

Elevation Data

A local vertical control network was established using survey-grade global positioning system (GPS) techniques and was used for all other surveys. All horizontal positions are reported in meters in the UTM18N (Universal Transverse Mercator Zone 18 North) coordinate system using the NAD83 (North American Datum of 1983) datum and all vertical positions are reported in meters using the NAVD88 vertical datum. The network (Table 3) was least-squares adjusted using one fixed control point with GNSS Solutions software. The fixed control point was a monument (855A) with good vertical control (1 cm) that was recently resurveyed by the National Geodetic Survey (NGS).

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

A digital elevation model and set of points representing bare-earth elevations were supplied by the USGS (Nardi, 2009). The data are based on a survey the USGS conducted with an aerial LiDAR on January 23, 2008 (20:00 to 20:45 UTC) and February 5, 2008 (18:11 to 21:31 UTC) using the full-waveform of NASA's Experimental Advanced Airborne Research LiDAR (EARRL) 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 was based on a comparison of LiDAR-derived data points to 83 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 were 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 was done for LiDAR points less than 2 m from ground-control points. The DEM was 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*)

Table 3. Local survey control network.

ID (m)	Easting* (m)	Northing* (m)	Ellipsoid Height** (m)	Elevation***
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
RMW1	466148.2	4322423.4	-33.290	1.61

* UTM Zone 18N datum
** NAD83 datum
*** NAVD88 datum

heights was compared to LiDAR points to examine potential elevation bias due to the inability of the LiDAR beam to penetrate 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 the surveys used to establish the elevations of the gages. Elevations were reported by the USGS in feet using the older National Geodetic Vertical Datum of 1929 (NGVD29) vertical datum and converted to the NAVD88 vertical datum and units of meters using VERTCON software from the NGS. The reference monuments used by the USGS for vertical control were part of the established vertical control network and were adjusted so all were on same vertical NAVD88 datum.

Tidal datums (Table 4) were calculated for the Murderkill River gages at Bowers Beach and Frederica using the methodology suggested by the U.S. National Oceanic and Atmospheric Administration (NOAA) for gages with less than 18.6 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 to calculate tidal datums at Frederica. Using Bowers Beach tidal datums in the procedure for Frederica does not strictly follow NOAA suggested methodology, but using the datums from the distant Lewes gage (38 km from Bowers Beach) 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 water-surface elevations of the Murderkill River were supplied for each of the 77 model cells in the main stem of the river (12 km) for 2007 and 2008 from a hydrodynamic model of the estuary (HDR|Hydroqual, 2013). These time series drive the inundation modeling discussed in this report. The calibrated hydrodynamic model was constrained by measurements of water elevation, velocity, discharge, salinity, and temperature at the USGS gages at Bowers Beach and Frederica (HDR|Hydroqual, 2013). Water elevations were reported by HDR|Hydroqual in units of meters relative to sea level (MSL) but no explicit reference datum was supplied. Water elevations were adjusted to the established vertical control network by adding the mean tide level (MTL) in the NAVD88 datum at the Bowers Beach gage (Table 4) to all model-derived elevations.

Marsh Tracts and Groups

To evaluate spatial patterns in marsh platform elevations and calculate inundation as a function of local tidal stage, the SWMP layer of tidal wetlands was classified into 31 marsh tracts based on hydrologic character. The classification parameters were the geometric relationship with the Murderkill River and the existence of large tidal channels, ditches, and/or large impoundments. Each marsh tract has a boundary contiguous with the Murderkill River (with one exception in the southeastern part of the study area near Brockonbridge Gut). The classification was based on visual analysis of existing aerial photography obtained in 2007

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

(DataMIL, 2008b). Marsh elevations in the DEM were also considered in the classification but topographic highs were not strictly followed as boundaries; no data were available to accurately determine the boundaries of inundation and the boundaries most likely change with hydraulic conditions. Marsh tracts were converted from vector to raster format to enable raster processing using the marsh tracts with the DEM. Marsh-tract boundaries were modified during analysis to be consistent with wetland elevations. A marsh tract in raster format was the fundamental map unit used in the calculation of inundation area and frequency.

Marsh tracts were aggregated into larger marsh groups to facilitate analyses and visualization of results. A marsh group is an aggregate of one or more marsh tracts. Two sets of marsh groups were defined. Set 100 aggregates relatively small marsh tracts (< 0.11 km^2) with adjacent marsh into 22 marsh groups. Set 200 aggregates the marsh groups in Set 100 into 4 marsh groups based on similar elevation distributions and positions along the river (see Results and Discussion).

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

Inundation Calculation

The full parameterization of inundation requires associating inundation areas to sets of water-level elevations for each marsh tract along with a one-to-one relationship between each marsh tract with 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. In a marsh tract, the area below the elevation of water in the related river reach was instantaneously inundated or drained. The time series of water elevations in this report is from the output of a calibrated hydrodynamic numerical model (HDR|Hydroqual, 2013). An algorithm was developed to step through hourly time series of water elevations and calculate areas inundated for each marsh tract and group. This is essentially a step-wise, spatially distributed bathtub 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 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 was established as the common datum and the data sets were converted to this datum.

A local vertical control network was 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 by NGS, especially in the study area where documented land subsidence is high (>3mm/yr; Holdahl and Morrison, 1974). Monuments in areas similar to the current study area that are stated as having 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 to 10 years and relatively small survey areas in which all elevations can be referenced to one control monument, the relative elevation of that monument to surrounding monuments may not be important. In larger survey areas like in the current study, elevation surveys use multiple reference monuments; therefore, it is critical to confirm 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 five monuments (Fig. 2, Table 3) and includes the temporary monument (WWTP) used as control by the USGS for the LiDAR survey and the reference monuments used by the USGS to determine elevations of the tide gages (2605, 855A, RMW1). The NGS monument used by the USGS to establish the elevation of the Bowers Beach tide gage was used as a fixed vertical control point in the least-squares adjustment. Estimated uncertainty in NAVD88 elevations in the network was .04 m

USGS-reported water-level elevations from tide gages were adjusted (Table 1) to be consistent with the vertical control network. This adjustment was significant, especially

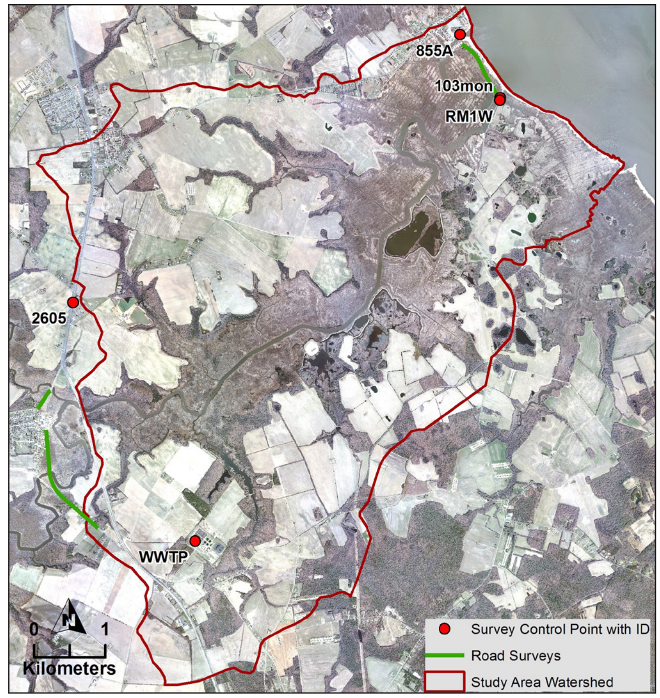


Figure 2. Survey control points and road surveys for comparison to LiDAR-derived elevations.

for tide elevations at the Bowers and Webbs Slough gages where over 50 percent of the correction was due to the current study using the published current NGS elevation of the reference monument and the USGS using an older value. Tide data were reported by the USGS with an implicit relative uncertainty of 0.002 m. An estimate of uncertainty for absolute water-level elevations used in the analysis was 0.04 m (based on the accuracy of the control network).

LiDAR-derived elevations were 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 (Fig. 2) 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 was adjusted to remove the global bias by adding 0.05 m to all cells. The format of the delivered bare-earth data were not conducive to analyzing and calculating elevation statistics for individual flight lines as suggested in the literature for low-relief terrain (Rosso et al., 2006; Sadro et al., 2007).

LiDAR-derived elevations were compared to a small GPS survey of the marsh platform under different types of vegetation to examine bias due to the potential inability of the LiDAR beam to penetrate 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 was 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 to account for this bias was made to the DEM or data presented in the tables in Appendices A and B because of the limited amount of ground control.

Model elevations of the Murderkill River stage from HDR|Hydroqual (2013) were 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

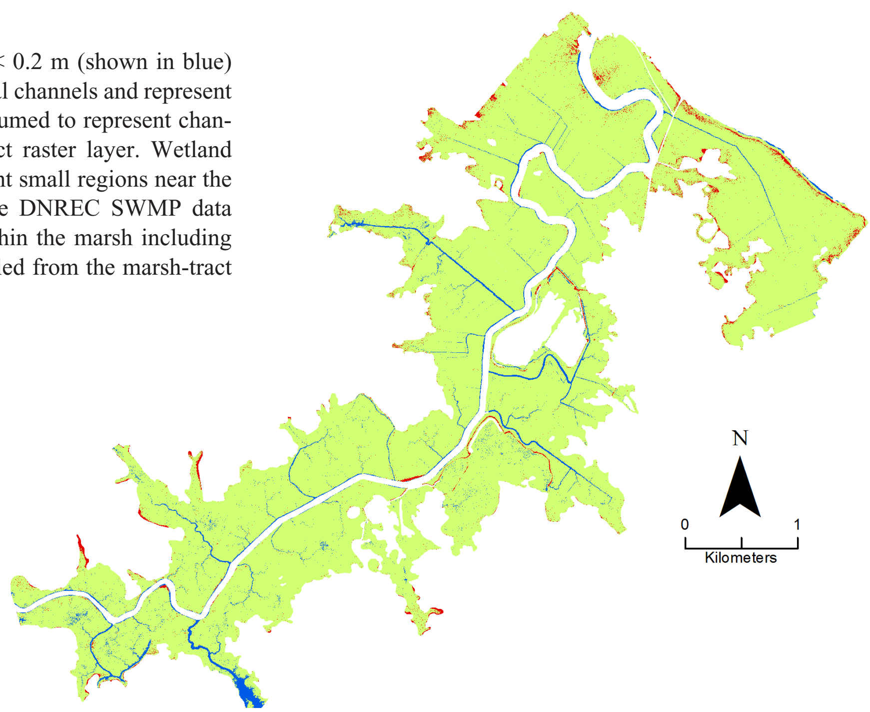
Tidal datums were calculated for the Bowers Beach and Frederica gages (Table 4). The MHW and MHHW tidal datums are the most important datums related to the inundation of the salt marsh platform. These tidal datums were used to compare the inundation results to the relationship between local tidal datums and vegetation types, often cited in the literature (Silberhorn, 1982; Carey, 1997; Field and Phillip, 2002). Most of the Murderkill Estuary is covered in *Spartina alterniflora*, which is indicative of low marsh. Results were 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 was a discrepancy of 8 to 9 cm for MHW and MHHW compared to those reported in the VDatum product. The discrepancy was 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 were 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 occur in linear patterns coincident with tidal channels and represent 4 percent of the total area (Fig. 3). In the inundation and statistical analyses, areas with elevations less than 0.2 m were considered tidal channels and were not included as marsh area. Because bathymetric data do not exist for these tidal channels, volumes cannot be calculated, but could be significant because of the large number of ditches. Spatial patterns at the high end of the distribution indicate that elevations >1.2 m represent small regions near the marsh/upland boundary as defined in the SWMP data set and small areas of high elevation within the marsh (Fig. 3). All inundation and statistical analyses exclude areas with elevations > 1.2 m. The resultant areas with elevations between 0.2 m and 1.2 m are considered marsh areas for the current study (Fig. 4) and constituted 94 percent of the tidal wetlands in the SWMP layer.

Elevations in the entire study area had a normal distribution (t-test at 1 percent significance level) with a mean elevation of 0.72 m and standard deviation of 0.19 m. 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 possibility of the LiDAR beam not penetrating through the vegetation canopy. Nominal relief on the marsh at the scale of the study area was about 0.6 m based on the difference between the 5th and 95th percentiles of the elevation distribution for the marsh platform. This was much higher than the 0.17 +/- 0.014 m relief reported for a set of Delaware Bay marshes (Carey, 1997) but those were limited to the landward portion of salt marshes located less less than 4 km from Delaware Bay. The marsh was split into smaller areas based on the hydrologic characteristics, defined here as marsh tracts and marsh groups (Figs. 5-7, Table 5) to facilitate calculation, analysis,

Figure 3. 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 were assumed to represent channels and were culled from the marsh-tract raster layer. Wetland areas with elevations >1.2 m (red) 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-tract raster layer.



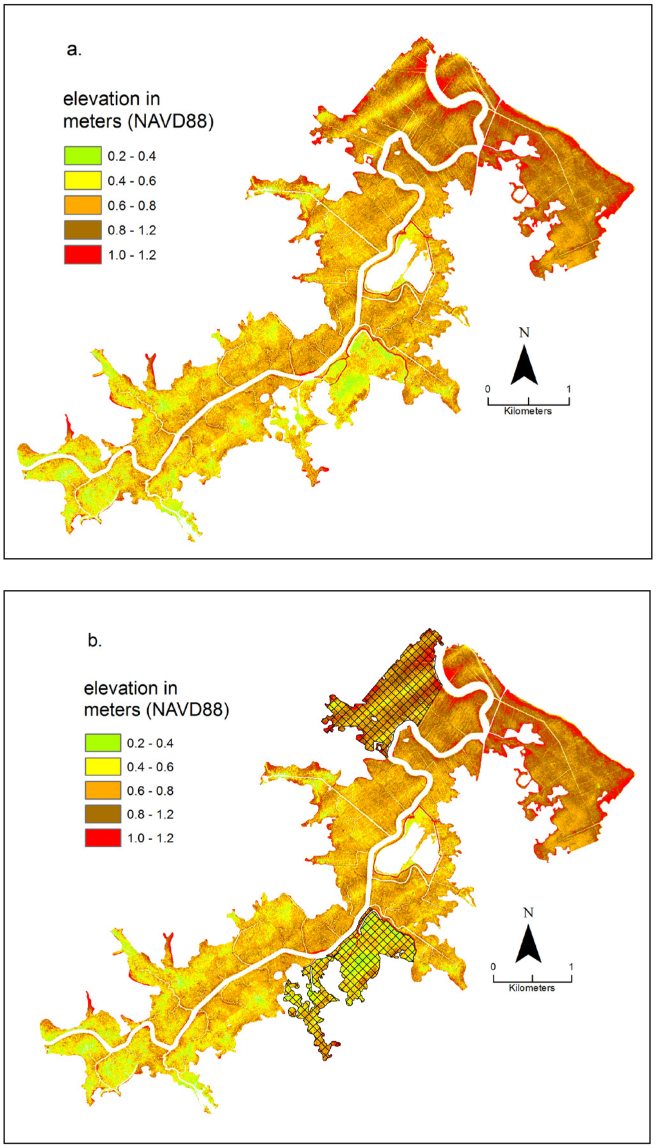


Figure 4. (a) Tidal wetland elevation; (b) hatches represent anomalous elevation distributions that were identified for Groups 101, 105, and 120. Anomalous lineations are due to aircraft flight lines.

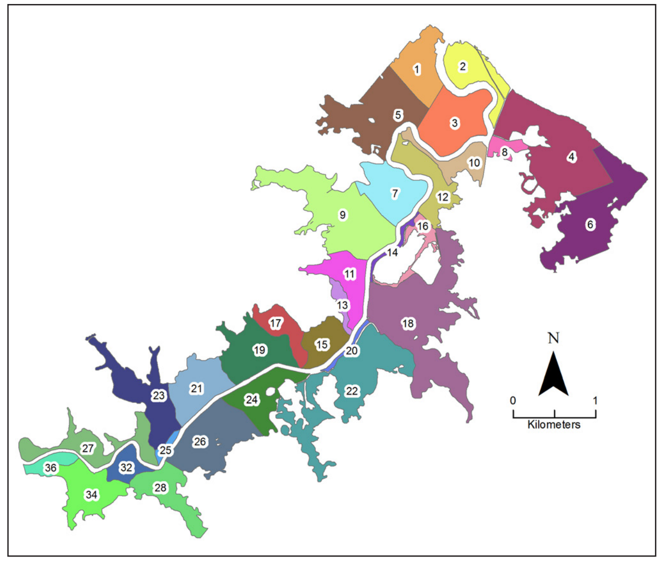


Figure 5. Marsh tracts with IDs.

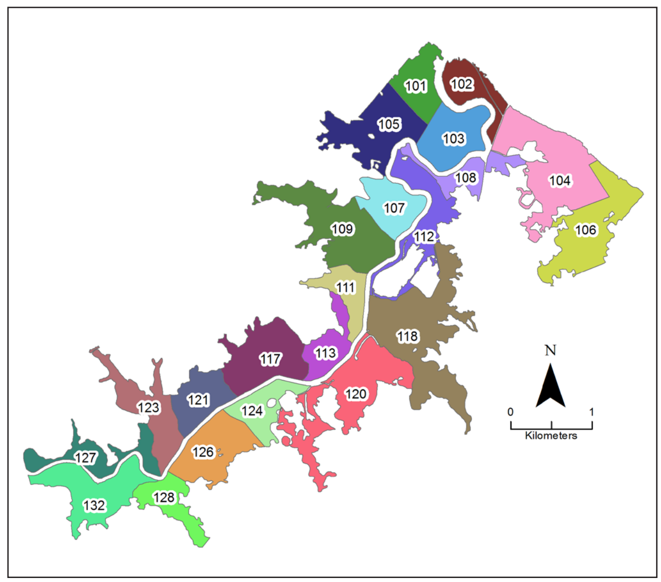


Figure 6. Grouped (aggregated) marsh tracts in Set 100 with group IDs.

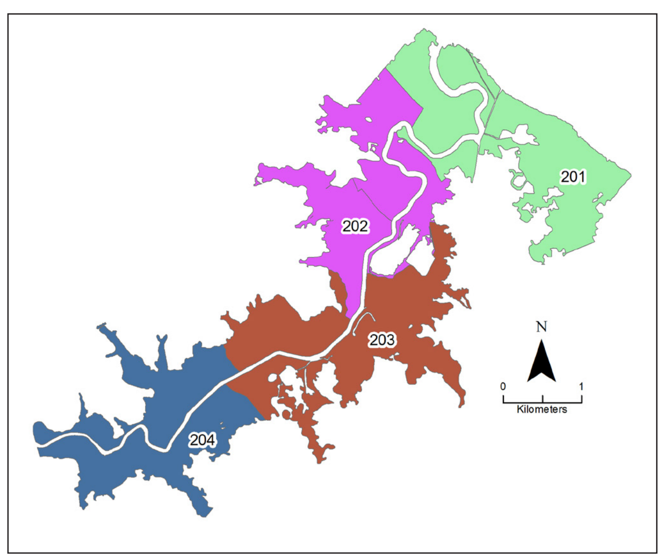


Figure 7. Grouped (aggregated) marsh tracts in Set 200 with group IDs.

and visualization. Marsh tracts (Fig. 5) ranging in size from 0.03 to 1.09 km^2 are the fundamental map units used in the calculation of inundation. Using the small marsh tracts 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 tracts aggregated together to facilitate analysis and visualization. Two sets of marsh groups were defined. Set 100 (Fig. 6) aggregates adjacent small marsh tracts into marsh groups in order to minimize the difference in marsh area between groups. Areas for marsh groups in Set 100 range from 0.27 to 0.93 km^2. Set 200 (Fig. 7) further aggregates the groups in Set 100 into four groups based on elevation distributions and positions along the river. Areas for marsh groups in Set 200 range from 2.5 to 3.2 km^2.

Histograms and cumulative probability distributions of elevation were examined for all groups in Sets 100 and 200. Set 100 consists of 22 marsh groups (Fig. 6) with the area

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

Group ID Set 200	Group ID Set 100	Marsh Tract ID	River Reach: Distance Upstream (km)*	River Reach: 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

* nominal distance upstream to middle of reach

** HDR|Hydroqual (2013)

of each marsh group representing two to ten percent of the total marsh area (Fig. 8). Anomalous elevation distributions were identified for Groups 101, 105, and 120. Processing artifacts (striping) were evident in marsh Groups 101 and 105; large areas of standing water mischaracterized as marsh were evident in marsh Group 120 (Fig. 4). To facilitate a consistent analysis of inundated area, elevation distributions of the marsh tracts (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 (Fig. 9). These pseudo-data were used in all subsequent analyses. Set 200 aggregates marsh groups from set 100 into four groups (Fig. 7) based on similar elevation distributions (Figs. 9 and 10) and their position along the river (Figs. 6 and 7). Groups 202 and 203 have similar elevation distributions (Figs. 9 and 10) but were 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 tract (Table A1 Appendix A) using raster overlay methods. Table A1 (Appendix A) is a parameterization of the critical information contained in the raster data sets of marsh tracts and elevation. Therefore, values listed in Table A1 (Appendix A) and not the raster data sets themselves were used directly in the inundation calculations. Results were then aggregated by groups in Sets 100 and 200 (Tables A2 and A3 Appendix A). This methodology incorporates the spatial and temporal variation in water levels in the Murderkill River with the results placed into a structure more conducive to analysis and visualization.

From Bowers upstream to Frederica there was a decrease in average marsh elevation, as quantified in Figures 9-11, with the mean elevation decreasing from 0.86 m to 0.60 m (Appendix B). This elevation difference was 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 was clearly important for understanding salt-marsh inundation in the estuary and underscores the value 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 (French and Spencer 1993; Friedrichs and Perry, 2001; Mudd et al, 2010) at the smaller length scale of less than two km with salt-marsh elevations typically decreasing with distance away from the channels and marsh edges that act as the source of water with suspended sediment. 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) with a flow-through channel rather than a blind-headed channel in the marsh. This is likely due to the difficulty of reducing uncertainty in elevation measurements and failure to use a common vertical datum to clearly document such a trend. Lower elevations on marsh platforms are typified by higher sediment accretion rates (Letzsch and Frey 1980; Cahoon and Reed, 1995; Stoddart et al., 1989; French and Spencer 1993; Friedrichs and Perry, 2001, Temmerman et al., 2005; French, 2006). Although sediment accretion on a marsh platform results from a multitude of complex processes (Friedrichs and Perry, 2001; French, 2006), measured accretion rates at four sites in the study area (Velinsky et al., 2010; Stuart, 2010) document an increase in accretion

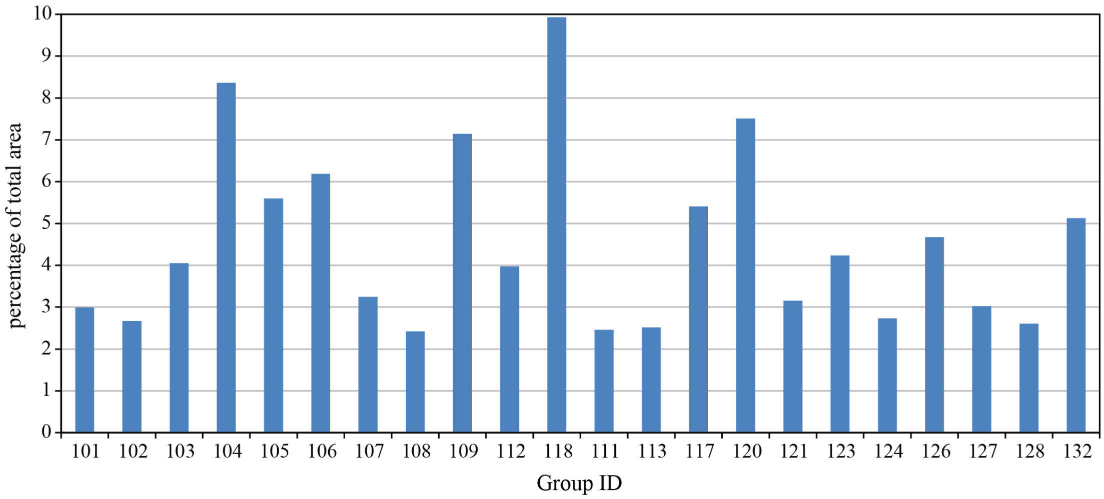


Figure 8. Relative areas of marsh groups in Set 100 as percentage of total tidal wetland area.

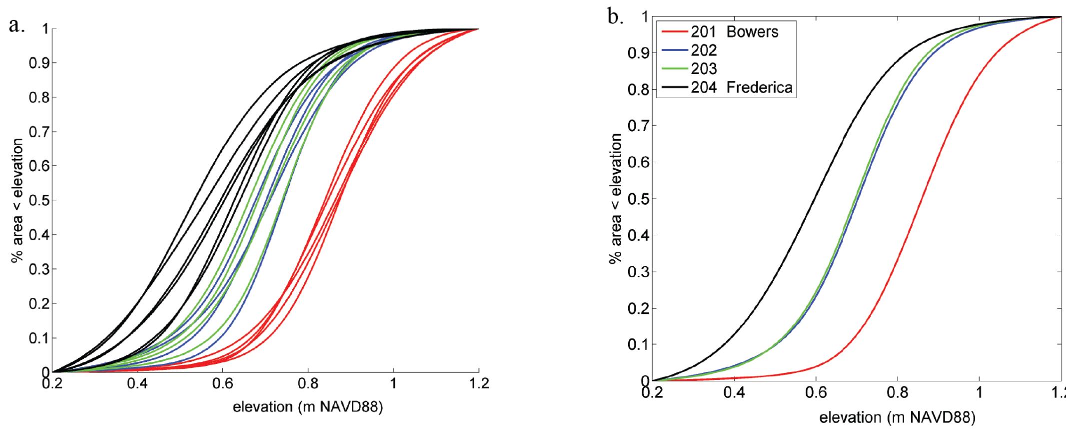


Figure 9. Cumulative probability distributions of wetland elevations. There is clearly an upstream decrease in marsh elevation from marsh Group 201 (Bowers Beach) to marsh Group 204 (Frederica). Line colors differentiate the same data in both (a) and (b). (a) Groups in Set 100. Colors indicate how aggregated into Set 200 groups. (b) Groups in Set 200. Data for groups shown in (a) are aggregated in (b).

upstream from near Bowers Beach (0.33 cm/yr) to Frederica (0.74 cm/yr) (Table 7) that is consistent with the trend of marshes with lower elevations having higher accretion rates.

Inundation Parameterization

The components used to analyze inundation are (1) a table with the area in each marsh tract having an elevation less than a set of NAVD88 elevations (Table A1 Appendix A), (2) a one-to-many relationship between marsh tracts and river reaches where one river reach may relate to many marsh tracts but a marsh tract can only relate to one river reach (Tables 5 and 6), and (3) a text file with time series of hourly tidal water levels for reaches of the Murderkill River during 2007 and 2008, output from a calibrated numerical model (HDR|Hydroqual, 2013). In the results shown below, the area of each marsh tract that was below the stage of its related reach on an hourly time step was assumed to be instantaneously inundated for the next hour. As noted above, the relationships between marsh tracts and groups (Table 5) were used to aggregate the results (Appendix A Tables A2 and A3 and Appendix B).

The tables in Appendix A and B were used directly as lookup tables in the parameterization of marsh inundation. Using Table A1 (Appendix A) as a lookup table requires the assumption of instantaneous flooding as discussed above. Using Tables A2 or A3 (Appendix A) as lookup tables provides a coarser spatial parameterization and would require assigning each marsh group to a river reach using relationships in Tables 5 and 6 as guides. Appendix B represents the information given in Tables A2 and A3 (Appendix A) as cumulative probability statistics. Alternatively, the tables in Appendices A and B could be used 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 directly within the current parameterization, if desired. This requires the assumption that the correction is a zonal (the same correction is applied to all pixels in a

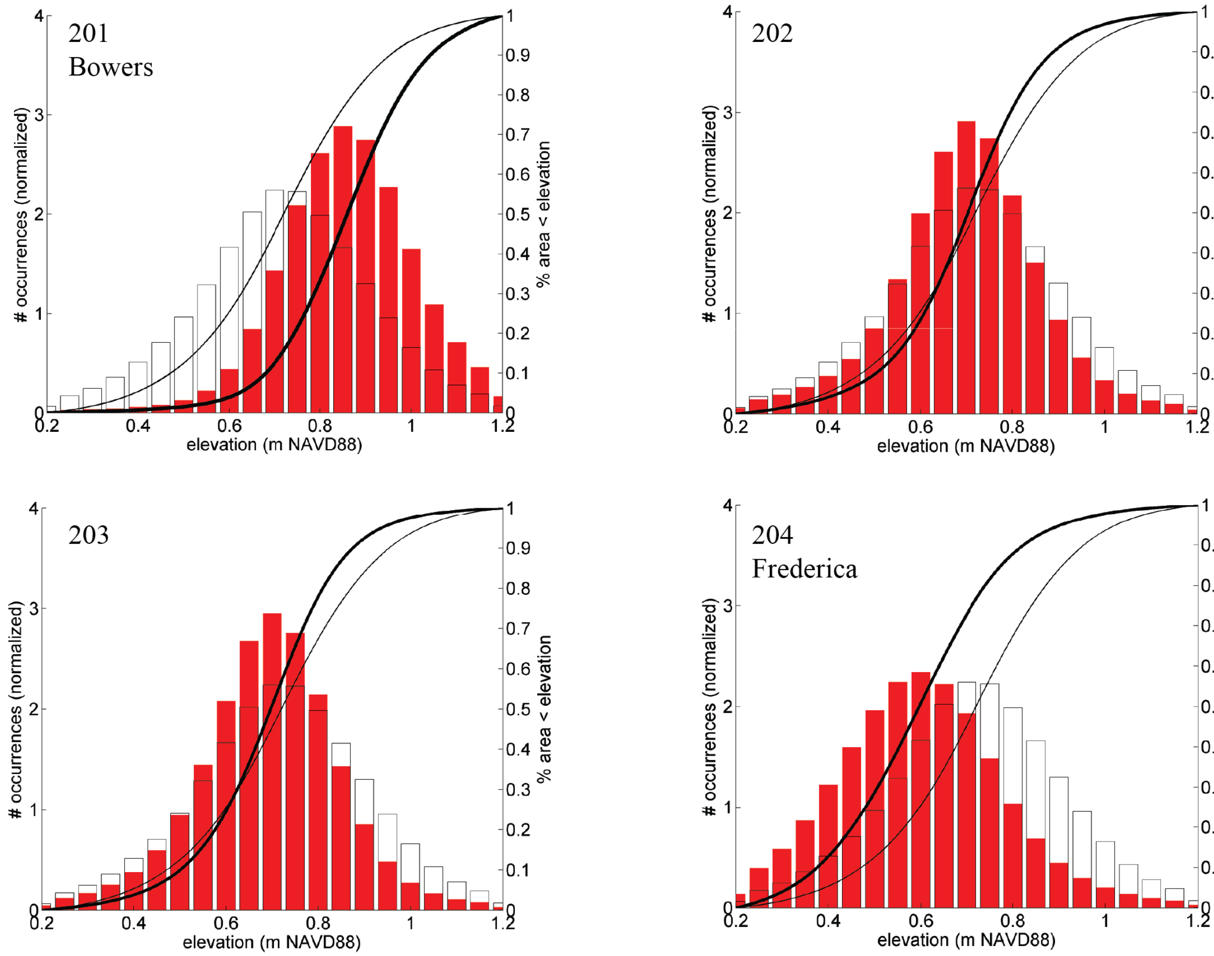


Figure 10. Histograms and cumulative probability distributions of elevations for four groups in Set 200. Red bars and dark lines are for the group indicated. Hollow bars and gray lines are shown for the entire marsh for reference.

marsh tract DEM) or global (the same correction is 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*) within a marsh tract. If a positive zonal bias in elevation is assumed, then subtract the assumed value from the elevation column in Table A1 (Appendix A) for each distinct marsh tract. A zonal bias cannot be used on the aggregated information in Tables A2 and A3 (Appendix A). To aggregate results, the user must utilize information from Table 5 after calculating results for each marsh tract. A zonal bias cannot be used on the aggregated information in Appendix B. If a global positive bias in elevation is assumed, simply subtract the assumed value from the elevation column in Tables A1, A2, and A3 (Appendix A). 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 Appendix B and a global positive bias, subtract the assumed bias from the elevation given in the table.

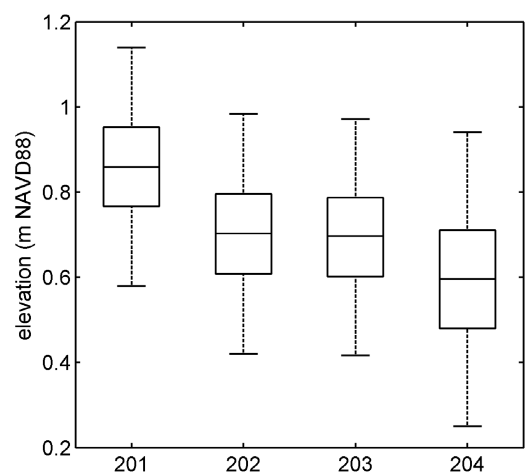


Figure 11. Box and whisker plot of elevation distributions for four groups in Set 200. Middle bar is the median, bottom and top of box are 25th and 75th percentile, respectively. Ninety-nine percent of the data fall within the whisker range.

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

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

Numerical Model*		Reclassification
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

* HDR|Hydroqual (2013)
** distance upstream to middle of reach

(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 were done to evaluate the differences in hydroperiod between marsh groups. A 2-year time period (2007 and 2008) was 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 (12.6 acres) and represents 10 percent of the mean area of marsh groups in Set 100. Of the 1,402 high tides that occurred over the 2-year period, there were about 1,100 to 1,300 events (78 to 93 percent in the upstream marshes, but only 600 to 700 events (43 to 50 percent) in the downstream marshes (Fig. 12). The mean duration of inundation events in the upstream marshes (Fig. 12) was 2.6 to 3.4 hours compared to 1.6 to 1.8 hours in the downstream marshes. Therefore, upstream marshes are flooded more frequently and for longer duration (Fig. 13) based on this model. This pattern is in agreement with Velinsky et al. (2010) and Stuart (2010) and other literature (Cahoon and Reed, 1995; Friedrichs and Perry, 2001; Temmerman et al., 2005; French, 2006) with more frequent and longer inundation resulting in higher accretion rates in the upstream direction (Table 7). The downstream marsh in Figure 13 is Webbs Marsh, where the short duration and low frequency of inundation calculated was 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 is one hour (the minimum time step) downstream compared to three hours in upstream marshes (Fig. 13).

A point of discussion is the assumption of instantaneous inundation and draining of marsh tracts. As a first approximation, it seems reasonable to assume that any actual time lag in flooding is offset by a time lag in draining. A more robust parameterization that includes a time lag ("time of concentration" method) could be used to assess this assumption but it would still be unconstrained by local observation or 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. However, the downstream marshes have extensive grids of mosquito ditches and documentation of the changes in the hydrology of these systems due to ditching is largely anecdotal, both at this site and within the literature.

Hydraulic loading

Flooding of the marsh brings tidal water in contact with sediments, vegetation, and organic detritus on the marsh platform, enabling biogeochemical reactions that ultimately

Table 7. Comparison of elevation, hydroperiod, and accretion rate.

Core*	Distance Upriver	Marsh Tract	Set 100 Group	Set 200 Group	Set 100 Mean Elevation (m)	Set 200 Mean Elevation (m)	Mean Inundation Duration (hrs)	Accretion Rate* (cm/yr)
MK1	11	34	132	204	0.55	0.6	3.45	0.74
MK2	10	27	127	204	0.61	0.6	2.9	0.74
MK3	6.8	13	113	203	0.74	0.69	2	0.6
MK4	1.6	2	102	201	0.85	0.86	1.6	0.33

* Velinsky et al., 2010

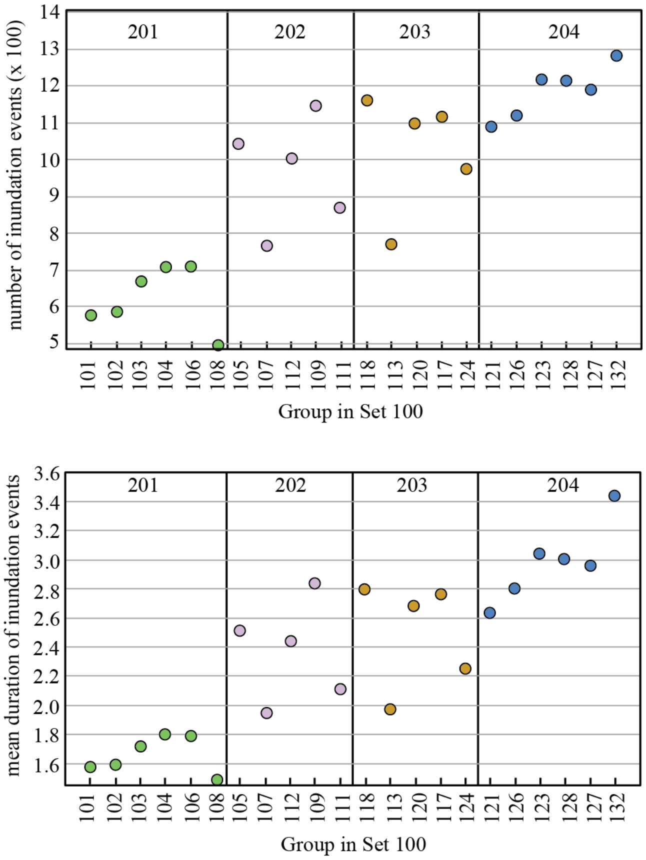


Figure 12. (a) Number and (b) mean duration of inundation events for marsh groups in Set 100 over a two-year period (2007-2008). Marsh groups shown in upstream order from left to right. Marker colors indicate marsh groups in Set 200.

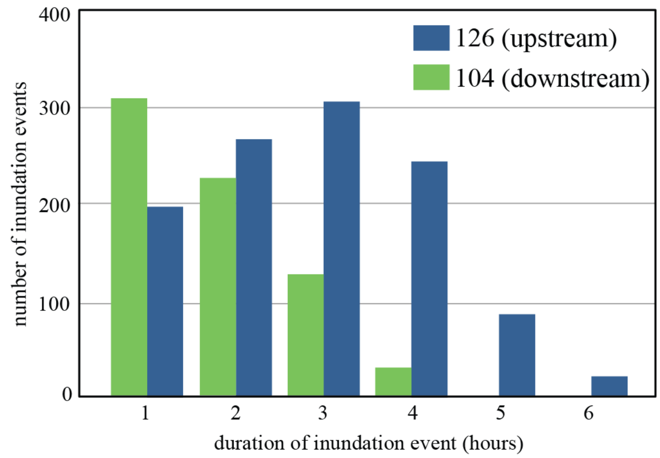


Figure 13. Histograms of duration of inundation events for marsh Groups 104 (downstream) and 126 (upstream) over a two-year period (2007-2008).

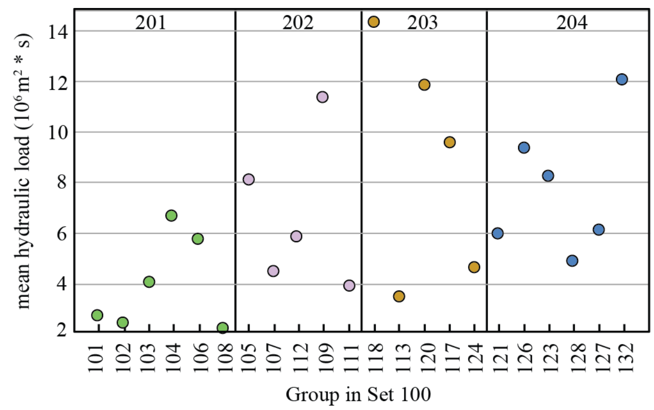


Figure 14. Mean hydraulic loads for marsh groups in Set 100 over a two-year period (2007-2008). Marsh groups shown in upstream order from left to right. Marker colors indicate marsh groups in Set 200.

alter the chemistry of the tidal water as it drains off the marsh back into the tidal river. The draining water may be the same water that flooded the marsh or may be shallow groundwater that discharges into the channel due to the increased hydraulic head caused by the flooding and subsequent infiltration. Both components (flood water and groundwater) are present in marsh effluent but the relative amounts change during the tide (Ullman et al., 2013). Regardless of the mechanism, as a first approximation, we can assume that the wetted area of the marsh is proportional to changes in water chemistry, recognizing that other factors are important. The other key parameter that affects water chemistry is the duration of a wetting event because a longer event allows more time for reactions to occur. Hydraulic load combines these two factors 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 calculated for the two-year time period (2007-2008) are shown in Figures 14 and 15, respectively. The hydraulic load for each event can be multiplied by a mass loading rate (units of kg / [$m^2 \cdot s$]) and summed over time to determine mass loads (units of kg).

CONCLUSIONS

A parameterization of inundation was developed for the 1,200 hectares of tidal marsh along the 12-km reach of the tidal Murderkill River between Frederica and Bowers Beach. The parameterization was built in support of a numerical model investigating causes of low dissolved oxygen concentration in the river. In the parameterization, the marsh was divided into marsh tracts (n=31) based on hydrologic character and position along the river. A cumulative probability distribution of wetland elevation was calculated from a digital elevation model for each marsh tract. Each marsh tract is related to an adjacent river reach; the area in the tract that is below the stage of its related reach is instantaneously inundated. HDR|Hydroqual (2013) successfully implemented the parameterization to create a set of loading functions that represent import and export of chemical species to and from the wetlands. The parameterization was also used by HDR|Hydroqual (2013) to evaluate conservation of water mass and phase offsets in tidal discharge due to the dynamic storage of water in intertidal areas.

Marsh tracts (n=31) were aggregated into two sets of marsh groups (n=22 and n=4) for analysis and visualization of elevation, hydroperiod, and hydraulic loading. Set 100 aggregates adjacent small marsh tracts into marsh groups in order to minimize the difference in marsh area between groups. Set 200 further aggregates the groups in Set 100 into

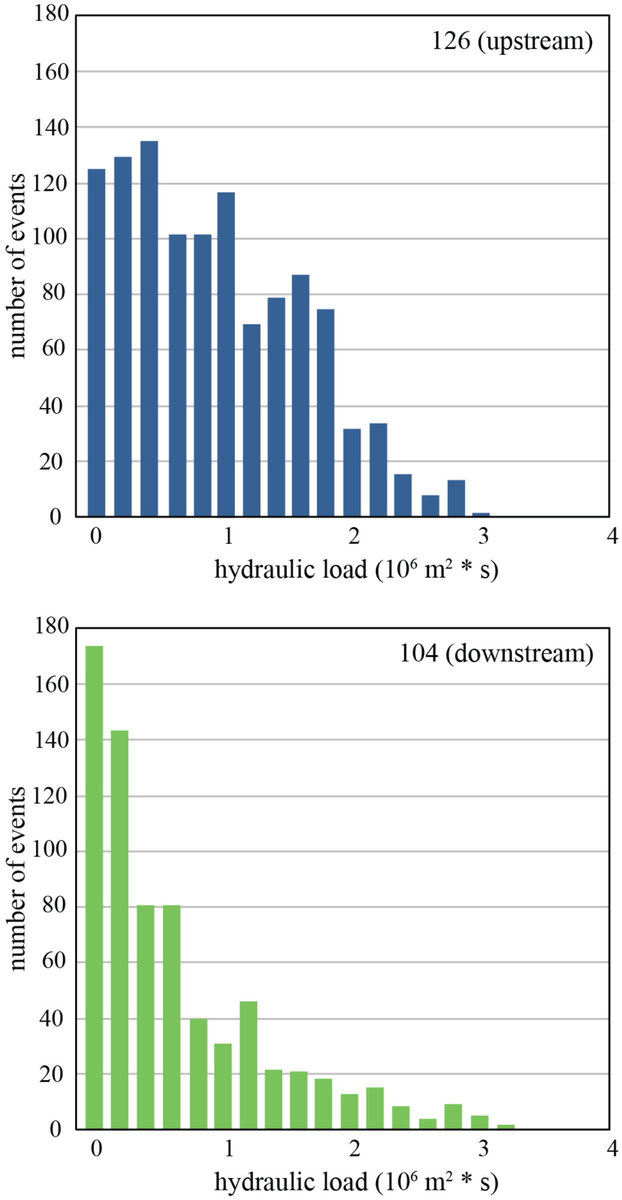


Figure 15. Histograms of hydraulic loads of inundation events for marsh Groups 126 and 104.

four groups based on elevation distributions and positions along the river.

Marsh elevations had a normal distribution with a mean elevation of 0.72 m and standard deviation of 0.19 m. These values have a potential positive bias of 0.1 to 0.2 m due to the possibility of the LiDAR beam not penetrating through the vegetation canopy. Nominal relief on the marsh at the scale of the study area was about 0.6 m (0.4 to 1 m). From Bowers upstream to Frederica there was a decrease in marsh elevation with the mean elevation decreasing from 0.86 m to 0.60 m. This observation is consistent with measured accretion rates at four sites in the study area (Velinsky et al., 2010; Stuart, 2010) that document an increase in accretion from Bowers Beach (0.74 cm/yr) upstream to Frederica (0.33 cm/yr). Of the 1,402 high tides that occurred over the 2-year period, there were about 1,100 to 1,300 (78 to 93 percent) inundation events in the upstream marshes, but only 600 to 700 (43 to 50 percent) events in the downstream marshes. The mean duration of inundation events in the upstream marshes was 2.6 to 3.4 hours compared to 1.6 to 1.8 hours in the downstream marshes; therefore, upstream marshes are flooded more frequently and for longer duration based on this model. This pattern is in agreement with site specific accretion data (Velinsky et al., 2010; Stuart, 2010) and other literature with more frequent and longer inundation resulting in higher accretion rates in the upstream direction.

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Appendix A
Parameterization Tables

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

elevation (m)*	all marsh tracts	marsh tract						
		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 tract with an elevation less than a set of NAVD88 elevations.

elevation (m)*	marsh tract							
	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 tract with an elevation less than a set of NAVD88 elevations.

elevation (m)*	marsh tract							
	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 tract with an elevation less than a set of NAVD88 elevations.

elevation (m)*	marsh tract							
	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 Set 200	101 201	102 201	103 201	104 201	106 201	108 201
elevation (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

*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 Set 200	105 202	107 202	109 202	111 202	112 202
elevation (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

*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 **Set 200**	**113** **203**	**117** **203**	**118** **203**	**120** **203**	**124** **203**
elevation (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

* 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 Set 200	121 121	123 123	126 126	127 127	128 128	132 132
elevation (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

* NAVD88 datum

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

elev	201	202	203	204	TOTAL			
(m)*		Area (m^2)			Area			
					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	3,003,285	2,522,790	3,169,986	2,499,664	11,195,725	11.20	1,119.57	2,766.5

* 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.

Group	area (m^2)	mean elevation (m)	st dev	percentiles (% of area that has a lower elevation than given elevation)									
				0	5	10	15	20	25	30	35	40	45
All tidal wetlands													
all*	11,195,725	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*	335,213	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*	626,682	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*	855,634	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	3,003,285	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	2522790	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	3169986	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 were replaced with pseudo-data representing the cumulative probability distributions of their associated group in Set 200 (see text for explanation).

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

Group	area (m^2)	mean elevation (m)	st dev	percentiles (% of area that has a lower elevation than given elevation)										
				50	55	60	65	70	75	80	85	90	95	100
<u>All tidal wetlands</u>														
all	11,195,725	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
<u>Set 100</u>														
101*	335,213	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*	626,682	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*	855,634	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
<u>Set 200</u>														
201	3,003,285	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	2,522,790	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	3,169,986	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 were replaced with pseudo-data representing the cumulative probability distributions of their associated group in Set 200 (see text for explanation).