SEDIMENTARY RESPONSE OF THE DELAWARE ESTUARY TO TROPICAL CYCLONES IRENE AND LEE IN 2011

by

Daniel I. Duval

A thesis submitted to the Faculty of the University of Delaware in partial fulfillment of the requirements for the degree of Master of Science in Marine Studies

Spring 2013

SEDIMENTARY RESPONSE OF THE DELAWARE ESTUARY TO TROPICAL CYCLONES IRENE AND LEE IN 2011

by

Daniel I. Duval

Approved: ____
Christopher K. Sommerfield, Ph.D.
Professor in charge of thesis on behalf of the Advisory Committee

Approved: ____
Mark A. Moline, Ph.D.
Director of the School of Marine Science and Policy

Approved: ____
Nancy M. Targett, Ph.D.
Dean of the College of Earth, Ocean, and Environment

Approved: ____
James G. Richards, Ph.D.
Vice Provost for Graduate and Professional Education

ACKNOWLEDGMENTS

First, I must express utmost gratitude to my advisor, Dr. Christopher Sommerfield. This work was only possible because of his patience and support. Though my path here has meandered, with his help I have reached the destination I most desired.

My thanks to Dr. Robert Chant, who helped to shape and redefine my understanding of estuarine circulation, mooring instrumentation, and finer cooking. The last, sadly, will likely always be beyond my grasp.

Dr. James Pizzuto was kind enough to agree to be on my committee despite having never met me before. He offered a different perspective and helped refine the river input.

Thanks to Eli Hunter, who was irreplaceable on our cruises, breaking what was fixed and fixing what broke. My labmates, Jared Halonen, Dack Stuart, and Brandon Boyd , were all extremely helpful in both science and beyond.

John Biddle was helpful in both work and play, providing advice and perspective when needed. Similarly, Monica Stegman helped contain the insanity which led to this thesis.

Thanks to my family for their unending support and understanding.

The research described in this thesis was funded by a National Science Foundation award (OCE-0928496) to Dr. Christopher K. Sommerfield. Additional support was graciously provided by the School of Marine Science and Policy, University of Delaware.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

Tropical cyclones have a major influence on the hydrodynamics of Mid-Atlantic rivers and estuaries, and by extension on processes and rates of sediment transport. In 2011 the passage of Hurricane Irene and Tropical Storm Lee through the Delaware River Basin was recorded by sensors deployed throughout the region, and the resulting observations provided unique insights into the coupled hydrodynamic and sedimentary response of the Delaware Estuary. The combined suspended sediment input of the two main tributaries, the Delaware and Schuylkill rivers, was over 1,300,000 metric tons during the two-week storm period. Time series records of sediment transport along the axis of the estuary suggested that most of the sediment transported during the storms was bed material resuspended within the estuary, not new material delivered from above the head of tide. Significantly, the resuspended sediment flux was equal to or greater than the river influx. Despite the large volume of freshwater delivered to the estuary, salt was not completely flushed from the mouth of Delaware Bay, and the resident suspended sediment inventory was retained. The storm-produced sediment pulse was attenuated and assimilated during passage from the upper to lower estuary, and near the head of Delaware Bay was strongly buffered by mixing associated with the large intertidal volume of the bay. Salinity and velocity measurements indicated that, although the salt intrusion was pushed ~55 km down-estuary during Tropical Storm Lee, the two-layer estuarine circulation remained sufficiently vigorous to trap suspended sediment supplied from the upper estuary. A shipboard survey conducted shortly after the storms suggested that much of the

suspended sediment was transported laterally from the axial channel to the adjacent subtidal flats, thereby increasing the potential for permanent deposition.

Chapter 1

INTRODUCTION

Coastal storms have a significant impact on the circulation and sediment dynamics of mid-latitude estuaries. Rainfall and runoff delivers large quantities of freshwater and suspended sediment from watersheds to rivers, while storm surge, winds, and waves increase resuspension and erosion of river-estuary channels and coasts. In the Mid-Atlantic region of the United States, subtropical northeaster storms are widely regarded as the most geomorphically effective type of coastal storm on account of their frequency and particular conditions of wind and rainfall (Zhang et al., 2000; Keim et al., 2004). By comparison tropical cyclones (tropical storms and hurricanes) are infrequent, and observations of their effects on estuaries are few.

In August and September 2011, Hurricane Irene and Tropical Storm Lee passed through the Mid-Atlantic and provided a rare opportunity to examine effects of tropical cyclones on estuaries throughout the region (Cheng et al., 2013). This thesis examines the sedimentary response of the Delaware Estuary to these storms, using measurements from instrument platforms and shipboard observations.

1.1 Previous Work

The majority of literature on storm effects in Mid-Atlantic estuaries centers on hydrodynamic responses (Valle-Levinson et al., 2002; Li et al., 2006; Gong et al., 2007; Li et al., 2007; Cho et al., 2012). Comparatively less is known about direct and indirect effects of storms on sedimentary processes, though it is widely recognized that tropical cyclones can have a disproportionate impact on sediment delivery to estuaries from river drainage basins due to intense rainfall and runoff (Meade, 1969; Meade, 1982; Nichols, 1993; Gong and Shen, 2009). Nichols (1977) described the response of the Rappahanock Estuary in Virginia to Tropical Storm Agnes (in 1972), one of only a few detailed accounts of storm effects on estuarine hydrodynamics and sediment transport. He identified four distinct stages of the estuarine response: 1) initial response; 2) shock; 3) rebound; and 4) recovery. The initial response was a depression in the salinity field, specifically, seaward translocation of the salt intrusion (1 ppt isohaline), and a change from partially mixed stratification to salt wedge conditions. The shock stage occurred within 2-3 days of peak freshwater discharge at the head of tide, and was characterized by elevated seaward flow at the surface and strengthened landward flow at depth, which together intensified stratification. The rebound stage followed within 4-6 days and involved weakening seaward surface flow, persistent landward flow at depth, and up-estuary migration of the salt intrusion. The recovery stage took place within 12-30 days of peak discharge during which the two-layer estuarine circulation weakened and the system returned to partially mixed stratification conditions.

The sedimentary response of the Rappahanock Estuary began with a 10-fold increase in suspended sediment concentrations (SSC) in the upper estuary, two days after peak river discharge at the head of tide. In the lower estuary, SSC similarly increased to levels 5-10 times greater than average, but before the main-stream flow arrived on Day 3. Nichols (1977) interpreted this as storm-enhanced tidal resuspension from the bed, the most immediate source of sediment in the estuary. Although the Rappahannock typically does not have an estuarine turbidity maxima (ETM), one formed landward of the salt front 5 days after peak river discharge. After 7 days the ETM migrated landward along with the salt front, dissipating and disappearing within 30 days of formation. Seaward sediment transport at the surface peaked during the shock stage (Days 2-3), while maximal landward sediment transport lagged by a couple days. Despite this lag landward transport in the lower layer was sufficient to balance seaward transport in the upper layer. From the mass balance Nichols (1977) concluded that 90% of the storm-sediment influx was retained within the estuary.

1.2 Study Area

The Delaware Estuary (Figure 1) is the second largest estuary on the U.S. East Coast, and is home to one of the largest freshwater ports in the world, the Philadelphia-Wilmington complex. The estuary is 215 km in length from the head of tide to the Atlantic coast, and consists of a tidal freshwater river (from Trenton, New Jersey to Philadelphia, Pennsylvania), an oligohaline upper estuary (Philadelphia to

Artificial Island, New Jersey), a mesohaline lower estuary (Artificial Island to Bombay Hook, Delaware), and a polyhaline estuarine bay. Bottom sediments in the tidal river and upper estuary consist of sand and gravel with patches of rapidly depositing river mud (Biggs and Beasley, 1988). Estuarine silt and silty-clay characterize the bottom in the lower estuary, where suspended sediments from landward and seaward sources become trapped by convergent estuarine circulation within the ETM. Bottom sediments in Delaware Bay are primarily coastal sands that have between transported landward from the eroding Atlantic shore. Based on US Geological Survey (USGS) streamflow records, the Delaware River, Schuylkill River, and Brandywine-Christina River supply ~80% of the total freshwater discharge to Delaware Estuary, with mean annual discharges of 330, 77, and 19 m^3/s, respectively (Sommerfield and Wong, 2011). According to Mansue and Commings (1974), these three rivers contribute over 80% of the total annual suspended load to the estuary, estimated at 1-2 million metric tons per year (mt/yr).

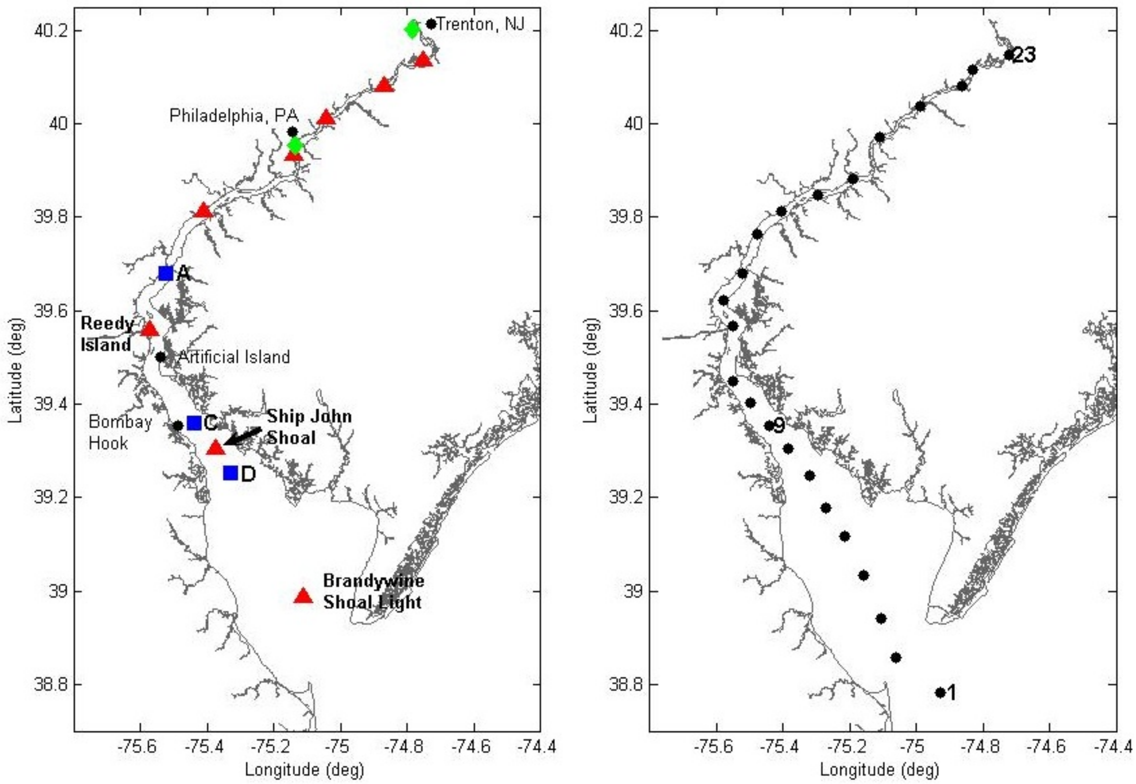

Figure 1. Locations of observational sites and shipboard sampling stations. Left: red triangles are NOAA PORTS stations, blue squares are Rutgers moorings with letter designation, and green diamonds are USGS stations. Right: Water sampling stations 1-23.

The hydrodynamics of Delaware Estuary are well studied (Pape and Garvine, 1982; Wong and Garvine, 1984; Wong and Moses-Hall, 1998; Janzen and Wong, 2002, Wong and Sommerfield, 2009). The estuary exhibits classical two-layer gravitational circulation, with seaward flow at the surface and landward flow at depth. This two-layer flow is believed to extend to the continental shelf, with bottom water drawn as far as 40 km from the bay mouth (Pape and Garvine 1982). Remote (continental shelf) and local (estuary and bay) winds have a major influence on the hydrodynamics of the estuary. Wong and Garvine (1984) found that sea level at the mouth of Delaware is forced primarily by remote winds parallel to the shoreline. Surface currents in the main channel are frictionally tied to local wind forcing (Wong and Moses-Hall, 1998). Bottom currents, however, are tied to local sea level setup, in opposition of the wind direction. Strong, down-estuary winds reinforce the two-layer gravitational circulation by strengthening density stratification, whereas up-estuary winds lead to destratification and weakening of this circulation. On the shallow subtidal flats of the estuary, currents and salinity are depth-independent and strongly influenced by the local wind field. Janzen and Wong (2002) investigated the relative importance of remote and local winds on subtidal currents in Delaware Bay, finding evidence for a bi-directional current that is locally wind-driven, regardless of the magnitude and orientation of remote winds.

Recent research in the estuary has focused on mechanisms of suspended sediment transport in relation to freshwater discharge, tides, and gravitational circulation. Cook et al. (2007) investigated sediment transport in the upper estuary during a period of typical springtime river discharge in 2005. They found that the magnitude and spatiotemporal variability of sediment transport was related to proximity of pools of easily resuspendable bottom sediment. In the vicinity of fine-sediment depocenters, suspended sediment concentration was correlated with current velocity. Sediment fluxes increased 3-4 fold during freshwater discharge events due to enhanced ebb currents and bed resuspension. Mass balance suggested that the amount of sediment exported from the study segment was threefold larger than the amount imported, and twofold larger than the mass delivered by rivers at the head of tides. From this imbalance Cook et al. (2007) concluded that the estuary bed is a quantitatively important source of sediment that can redistributed during times of elevated bottom stress.

Sommerfield and Wong (2011) examined the effects of a 2005 northeaster storm on sediment flux in the Delaware Estuary. Despite high river discharge (>6700m^3/s), unit-width sediment flux estimates indicated deposition occurring within the estuary. Resuspension also played a role, as the quantity of sediment delivered to the estuary was greater than the new riverine sediment. Gravitational circulation was found to be the primary method of sediment entrapment in the estuary, controlling the along-estuary limits of the turbidity maximum and the suspended sediment inventory. Gravitational circulation along with tidal pumping were suggested to control the locus and sediment concentration of the ETM. Tidal pumping over the subtidal flats was also suggested as the mechanism for permanent deposition.

1.3 Hurricane Irene and Tropical Storm Lee

In late August 2011 Hurricane Irene tracked along the southern Atlantic margin, made landfall in North Carolina, and passed within ~30 km of Delaware Bay late on August 27-28 (Figure 2). Winds in the bay were up-estuary several days leading up to Hurricane Irene, and then switched abruptly to strongly down-estuary, reaching speeds in excess of 21 m/s early on the 28th (Figure 3). At this time atmospheric pressure over Delaware Bay dipped to 970 mb. Widespread coastal flooding occurred along the tidal Delaware River and upper estuary due to the combination of wind-produced surge, low atmospheric pressure, and rainfall runoff. The lower Delaware River Basin received 12-20 cm of precipitation between August 24 and 29 (Delaware River Basin Commission, 2011). Discharge of the Delaware River at the head of tide at Trenton (USGS 01463500) started to increase on the 28th, reached 4100 m^3/s on the 29th, and did not drop below 1000 m^3/s until September 2 (Figure 4). The Schuylkill River at the head of tide at Philadelphia (USGS 01474500) responded similarly but with a lower peak flow of 2400 m^3/s on the 29^{th} (Figure 4). Delaware River turbidity increased rapidly on the 28th, reached ~500 FNU late in the day, and then decreased before the peak in river discharge (Figure 5). Fifty kilometers downstream in the tidal Delaware, turbidity at the Ben Franklin Bridge station (USGS 01467200) began to rise on August 27 and peaked at ~200 FNU on the 29^{th} (Figure 5).

Tropical Storm Lee made landfall in Louisiana on September 4 and continued to track northward, inland toward the Mid-Atlantic region (Figure 2). Although NOAA stopped tracking this storm after it reached western North Carolina on September 7, the low-pressure system continued to track northwestward and reached the Delaware River Basin on the 8^{th}. Winds over Delaware Bay were weaker (12.4 m/s maximum on September 8) and more variable compared to Hurricane Irene, and atmospheric pressure did not drop below 1000 mb. As the storm approached northeasterly winds on September 6 quickly reversed to southeasterly on the 7^{th} and 8^{th} (Figure 3). Lee caused significant flooding throughout the region, and was most intense in the western edge of the Delaware River Basin. Between September 5 and 9, Lee dropped an average 12-18 cm of precipitation in the lower part of the Basin (Delaware River Basin Commission, 2011). Although the intensity of rainfall during Lee was somewhat less than that during Irene, the cumulative rainfall averaged regionally was larger because Lee tracked along the western edge of the Basin. Consequently, river peak flows were higher during Lee and the duration of elevated river discharge was longer.

Delaware River discharge started to rise on September 5, peaked at ~5500 m^3/s on the 8th, and did not fall below 1000 m^3/s until the 16th (Figure 4). Schuylkill River discharge followed a similar pattern, peaking at ~1900 m^3/s on September 8. Delaware River turbidity increased more gradually during Lee than with Irene, and the maximal value (~200 FNU on the 8th) fell short of the turbidity peak produced by Irene, even though peak river discharge was larger during Lee (Figure 5). Unfortunately, the turbidity sensor at the Trenton station went offline during the end of Lee, so a complete record is unavailable. As was observed during Irene, river turbidity at the Ben Franklin Bridge peaked (~200 FNU) 1-2 days after the turbidity peak at the Trenton station (Figure 5). Storm Lee had a major influence on river-estuary turbidity throughout the region, and satellite imagery showed widespread plumes of sediment-laden in the Delaware Estuary and Chesapeake Bay (see Appendix Figure A1.) Effects of Tropical Storm Lee on sediment transport in upper Chesapeake Bay are described by Cheng et al. (2013).

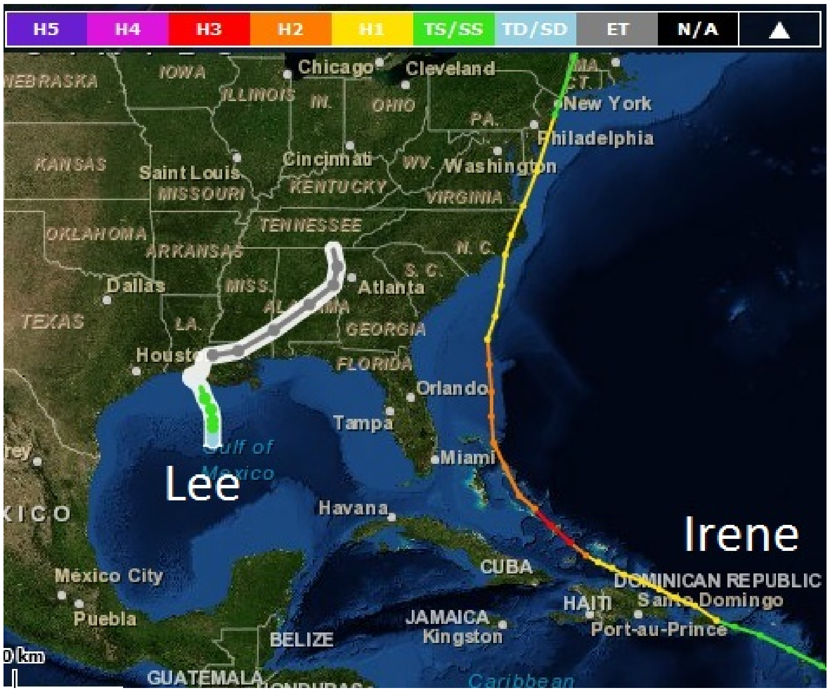

Figure 2. NOAA storm tracks for Hurricane Irene and Tropical Storm Lee in 2011. See text for explanation. Figure accessed from NOAA's Historical Hurricane Tracks website (http://www.csc.noaa.gov/hurricanes/#).

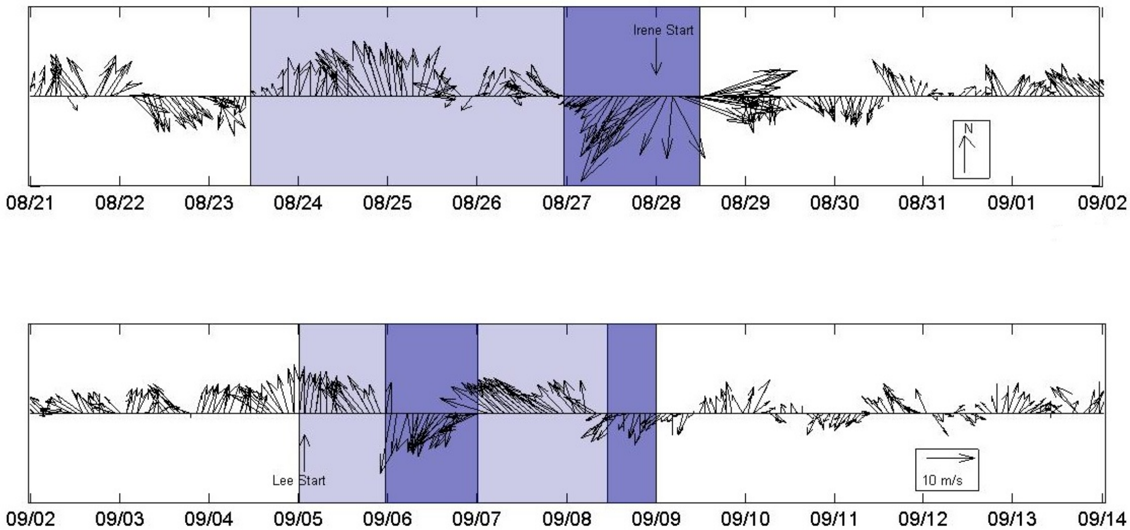

Figure 3. Wind speed and direction measured at Ship John Shoal (NOAA 8537121) for August and September 2011. Periods of up-estuary and down-estuary winds are framed in light purple and dark purple, respectively. The green dot indicates the start of Irene, the red dot the start of Lee.

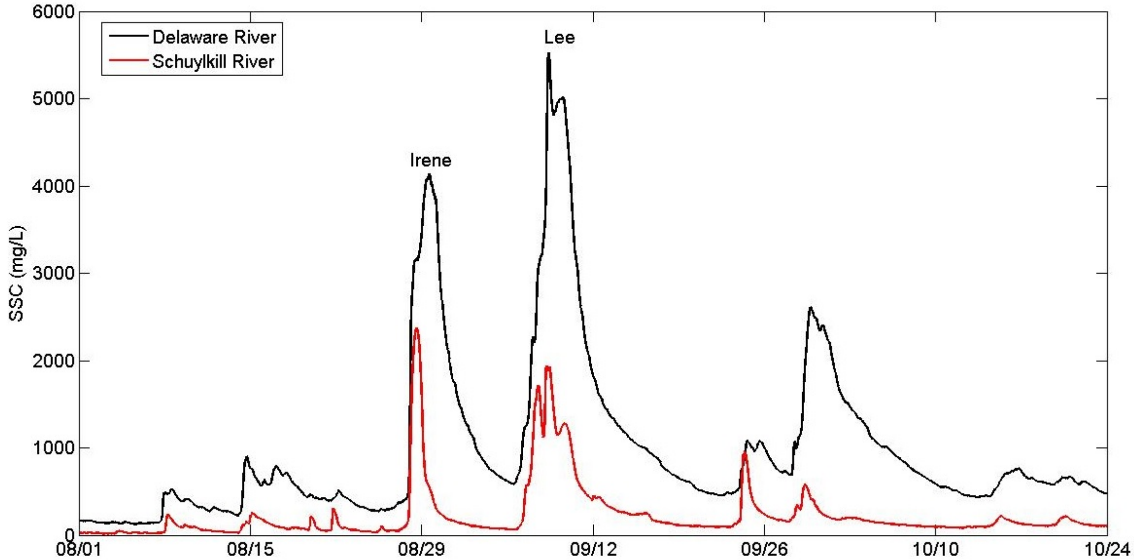

Figure 4. Records of river water discharge (m^3/s) for the Delaware River at Trenton (black) and the Schuylkill River at Philadelphia (red). See text for station locations and description of data.

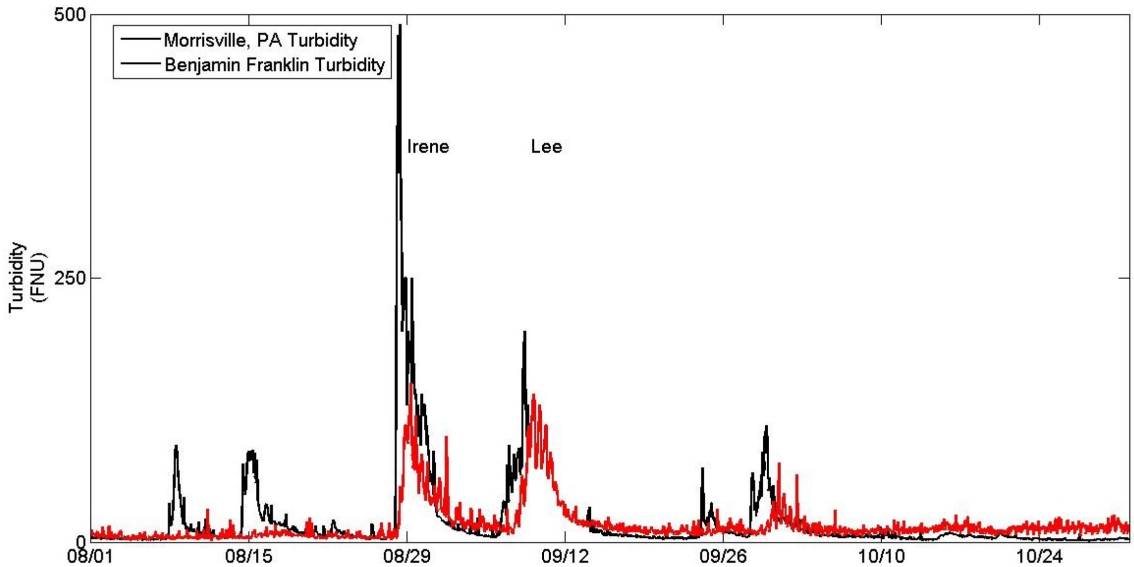

Figure 5. Records of turbidity in FTU for the Delaware River at Trenton (black, the USGS sensor is across-river in Morrisville, PA) and the Delaware at Ben Franklin Bridge (red).

1.4 Research Objectives and Hypotheses

The overall goal of this work is to advance our general understanding of tropical cyclone effects on estuarine hydrodynamics and sediment transport. Specific objectives are as follows:

1. Quantify storm-produced sediment loads discharged by Delaware and Schuylkill rivers in 2011, and estimate sediment travel times from the head of tide to the turbidity maximum zone of the estuary
2. Determine the relative influences of freshwater discharge and wind forcing on estuarine currents and sediment transport during the storms

3. Compare and contrast the storm response of the Delaware Estuary to that of other estuaries

To meet these objectives, and drawing from the observations of Nichols (1977) in the Rappahannock Estuary, the following hypotheses were used to investigate the response of the Delaware Estuary:

H1. The salt intrusion and null zone of gravitational circulation will be pushed down-estuary due to storm-produced freshwater discharges, but the particular hydraulic geometry of the estuary will buffer these discharges and prevent complete flushing of salt.

H2. The suspended sediment inventory of the estuary will increase due to new riverine sediment as well as through bed resuspension and erosion within the estuary.

H3. Most of the storm-produced sediment will remain trapped within the estuary. The region of vigorous gravitational circulation will move seaward under such inflows, but it will not exit the estuary, and consequent the resident sediment inventory will remain trapped within the estuary.

Chapter 2

DATA COLLECTION AND ANALYSIS

The data used in this study were collected through a combination of instrument deployments and shipboard sampling in the Delaware River and estuary in 2010 and 2011. Additionally, hydrologic and oceanographic data available through the USGS National Water Information Service (NWIS) and NOAA's Physical Oceanographic Real-Time System (PORTS) were used. A full summary of the data used in this study are listed in the Appendix (T1).

2.1 River Flow and Suspended Sediment

River water discharge and gravimetrically determined SSC are required to estimate daily or event-specific sediment loads directly or indirectly through use of flow-duration rating curves. River discharge is continuously measured by the USGS for the three largest tributaries of Delaware Estuary at the head of tides: 1) the mainstem Delaware River at Trenton; 2) the Schuylkill River at Philadelphia; 3) and the Brandywine River at Wilmington. However, as is the case with many rivers in the United States discrete SSC data are much harder to come by than river discharge. Although the USGS reported daily mean SSC values for the Delaware, Schuylkill, and Brandywine rivers from the late 1940s to early the early 1980s (discussed in Mansue and Commings, 1974), from the 1980s to present only periodic measurements were made and archived. More often than not the NWIS-archived SSC data are too sparse to develop rating curves to predict sediment concentration and sediment load on the basis of river discharge. Fortunately, enough SSC data are available for the Delaware and Schuylkill Rivers to estimate sediment delivery to the estuary.

2.2 Shipboard Measurements

As part of an NSF-funded collaboration between the University of Delaware and Rutgers University, eight identical hydrographic surveys of the Delaware Estuary were conducted aboard the RV *Sharp* between March 2010 and December 2011. The 200-km survey transect extended from the mouth of Delaware Bay (Station 1) to just short of the head of tides near Trenton (Station 23; see Figure 1). During each survey the water column was profiled for salinity and SSC at 23 stations. An RBR X620 CTD (conductivity, temperature, depth) affixed with a D&A OBS-3 sensor was used to measure continuous depth profiles of salinity and optical backscatter, respectively. A submersible pump was attached to the CTD package at the position of the OBS-3 sensor to collect discrete water samples for gravimetric SSC measurements in the lab, which were used to calibrate the optical backscatter data (see the Appendix B1-3 for regression plots). Casts consisted of lowering the instrument package to within 1 m of the bottom at which point a sample was pumped, and then raising it to within 1 m of the surface for another sample. The salinity and SSC profiles obtained for each survey were spatially interpolated and contoured in Matlab to construct axial sections of the estuary.

2.3 Estuary Mooring Observations

The University of Delaware-Rutgers study involved a series of oceanographic mooring deployments in Delaware Estuary during 2010-2011, and fortunately the moored instrumentation was mostly operational during the passage of Hurricane Irene and Tropical Storm Lee. Three moorings (Stations A, C, and D) were deployed along the estuary adjacent to the shipping channel (Figure 1). Moorings A and D bracketed the typical position of the null zone of estuarine circulation as determined previously (Sommerfield and Wong, 2011), and Mooring C was situated near the center of the ETM region. Instrumentation used for Mooring A included surface and bottom conductivity-temperature (CT) sensors and a 1000 kHz Nortek Acoustic Wave and Current profiler (AWAC) current profiler. The surface CT sensor was a Sea-Bird SeaCAT model SBE 37 SM, whereas the bottom was a SeaCAT model SBE 16+. The data series for Mooring A extended from 5 June to 2 September 2011, after which the entire mooring system was dragged ~3 km seaward by strong ebb-tidal currents generated by Hurricane Irene. Instrumentation for Mooring C included a SeaCAT model SBE 37 SM and a 1200 kHz RD Instruments (RDI) Acoustic Doppler Current Profiler (ADCP). The ADCP record for Mooring C extended from 13 August to 26 September 2011, but no CT data were obtained for this period. Mooring D used the same CT setup as Mooring A but a 600 kHz RDI ADCP was used to profile currents.

Unfortunately the ADCP data for Mooring D was later deemed unusable, although surface and bottom CT data were available for most of the storm period. The moored instrumentation and observational periods are summarized in Table 1.

Table 1. Moored instrumentation and period of useable data in 2011.

Mooring name	Instruments deployed	Period (2011)
A	Surface - CT - SBE 37 SM	06/05 - 09/02
	Mooring - CT - SBE 16+	06/05 - 09/02
	Mooring - Nortek AWAC 1000 kHz	06/05 - 09/02
C	Mooring - CT - SBE 37 SM	06/30 - 08/01
	Mooring - RDI ADCP 1200 kHz	08/13 - 09/26
D	Surface - CT - SBE 37 SM	06/05 - 09/17
	Mooring - CT - SBE 16+	06/05 - 09/17
	Mooring - RDI ADCP 600 kHz	06/05- 06/05

2.4 Data Analysis

Suspended sediment loads for the Delaware and Schuylkill rivers were computed as follows:

$$L = \sum_{i=1}^{n} \hat{C}_i Q_i \partial t \qquad (1)$$

where L is the 30-minute mean sediment load (in kg/s), Q is the 30-minute mean water discharge (m^3/s), and $\hat{C}$ is the suspended sediment concentration (kg/m^3) predicted using a sediment rating curve. Rating curves for the Delaware and Schuylkill rivers were constructed using USGS-NWIS daily mean sediment concentration and water discharge measurements. Data for the Delaware River and Schuylkill Rivers extends from 1983 to 2010 and 1975 to 2004, respectively. Daily mean *C* was scatter-plotted versus *Q*, and a power-function curve was fit to the data by least-squares regression (Appendix, D2). The regression equations predict $\hat{C}$ as a function of measured *Q*. Values of $\hat{C}$ was used with Equation 1 to compute a continuous time series of sediment load to the estuary for the 2011 storm period. Suspended sediment delivered by the Brandywine River was ignored in this study as the suspended sediment load is about an order of magnitude smaller than the Delaware and Schuylkill river loads.

The rating curves were created by least-squared linear regression of log-transformed data, which when back-transformed has been shown to underestimate (bias) the true suspended sediment concentration in rivers (Ferguson, 1986). Ferguson proposed a simple correction factor to correct for the transformation bias. The correction factor is:

$$CF = \exp(2.65s^2) \tag{2}$$

where s^2 is the variance between the observed and predicted values. The variance was computed as follows:

$$s^2 = \sum_{i=1}^{n} (\log C_i - \log \hat{C}_i)^2 / (n-2) \tag{3}$$

where *C* is the measured sediment concentration, $\hat{C}$ is the predicted sediment concentration, and *n* is the number of data points. The standard error ($\sqrt{s^2}$) was also calculated to estimate the error of the modeled suspended sediment load; for the Delaware and Schuylkill rivers the errors are respectively $\pm 43\%$ and $\pm 41\%$ of the reported sediment load.

ADCP current data were rotated in order to align dominant direction of currents with the axis of the estuarine channel, such that "u" and "v" became the direction of the streamwise (along-channel) and cross-stream (across-channel) velocity, respectively. The directional convention adopted for this study is negative and positive for down- and up-estuary velocity, respectively. Suspended sediment concentration was computed from OBS-3 calibrated ADCP echo intensity as described by Holdaway et al. (1999) and Gartner (2004). Acoustically determined and optically derived sediment mass concentration are related as follows:

$$\hat{C}_i = 10^{A(ABS+B)+C} \quad (4)$$

where A, B, and C are regression coefficients, ABS is acoustic backscatter, $\hat{C}_i$ and is the modeled suspended sediment concentration (mg/L). For Mooring A, acoustic backscatter was regressed against gravimetrically determined SSC for water samples collected during the cruises (Appendix D1, n=6). For Mooring C the calibration was based on only the minimum and maximum SSC values measured at the site during cross-channel shipboard surveys conducted by Rutgers University (Appendix D2, n=2). The shape of the regression was assumed to be similar to Mooring A. Velocity and SSC were interpolated to relative depth above the bottom, with the surface equal to one and bottom equal to zero.

Time series of suspended sediment fluxes per unit width (mass/area/time) were calculated from velocity and SSC data acquired at Moorings A and C using methods described in Sommerfield and Wong (2011). The instantaneous, tidally varying sediment flux at a given depth was calculated as:

$$F = U(z)C(z) \quad (5)$$

where U is the along channel velocity, C is suspended sediment concentration, and z is depth (binned as per ADCP profile bins). Integrating Equation (3) over the depth and averaging over the tidal cycle gives the total residual (non-tidal) sediment flux per unit width of flow (F_T).

The instantaneous velocity and SSC can be decomposed into the sum of tidally averaged (non-tidal advection) and tidally varying (tidal pumping) components. The advective sediment flux was calculated as follows:

$$F_A = \bar{U}(z)\bar{C}(z) \quad (6)$$

where overbars denote a tidal average. In this study tidal averaging was accomplished using a 36-hour Butterworth low-pass filter. The advective sediment flux is the mass transport on the mean current produced by river discharge and density-driven estuarine circulation. The tidal pumping flux was computed as follows:

$$F_p = U^{'}(z)C^{'}(z) \quad (7)$$

where the prime denotes tidal fluctuations about the tidally averaged value. The tidal pumping flux is the mass transport produced by correlated tidal fluctuations in U and SSC. F_P was calculated as the low-pass filtered product of the 36-hour high-pass filtered velocity and SSC data. Depth-dependent sediment fluxes were computed in a similar manner, but rather than depth-integrating the instantaneous sediment flux, the advective and tidal pumping fluxes were determined per depth *z*.

Chapter 3

RESULTS AND INTERPRETATION

3.1 Freshwater Inflow and Suspended Sediment Loads

During the course of the two storms, an estimated 1.3x10^6 metric tons (mt) of suspended entered the Delaware Estuary from the Delaware and Schuylkill Rivers at the heads of tide (Figure 6). This mass of sediment is equal to the long-term mean annual sediment load for the entire Delaware estuary (Mansue and Commings, 1974). In terms of river discharge and sediment loading, individually the

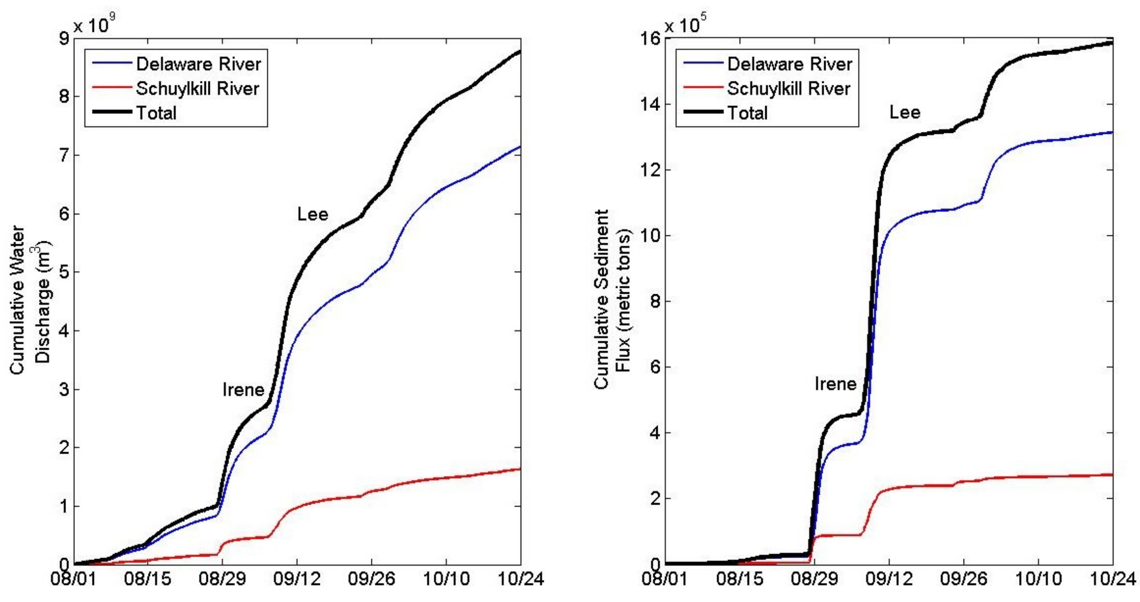

Figure 6. Cumulative water discharge (m^3/s, left) and sediment load (metric tons, right) for the Delaware and Schuylkill rivers.

rivers responded differently to Hurricane Irene and Tropical Storm Lee. Peak discharge of the Delaware River was higher (Figure 4), and the resulting cumulative sediment load was larger, during Lee than Irene. This may reflect the different trajectories of the storms, Irene to the east of Delaware River Basin and Lee directly along the Basin axis. Conversely, peak discharge of the Schuylkill River was higher during Irene but the cumulative sediment load was much larger following Lee, presumably because the period of elevated river discharge was longer. Hence, both rivers supplied more sediment to the estuary during Lee but for different reasons.

3.2 Salinity Time Series

Up-estuary winds several days prior to Irene corresponded to increasing salinity in lower Delaware Estuary (Figure 7). As the winds shifted to down-estuary, salinity initially increased before decreasing rapidly throughout the estuary and Bay. During Irene the water at Reedy Island (USGS 01482800) was completely fresh and remained so until mid-September 2011, and at Ship John Shoal salinity decreased from 13 to 1 PSU. Lee caused a more significant reduction in salinity than Irene, presumably because Lee produced a larger pulse of freshwater at the estuary head. During Lee the 1 PSU isohaline was pushed down-estuary to Ship John Shoal. Salinity at Brandywine Shoal Light (NOAA 8555889) near the mouth of Delaware Bay dropped from 23 PSU on September 8 to 14 PSU on the 10^{th}. Although the estuary was significantly freshened following Lee, because the salt front was not pushed from the estuary sediment retention was favored.

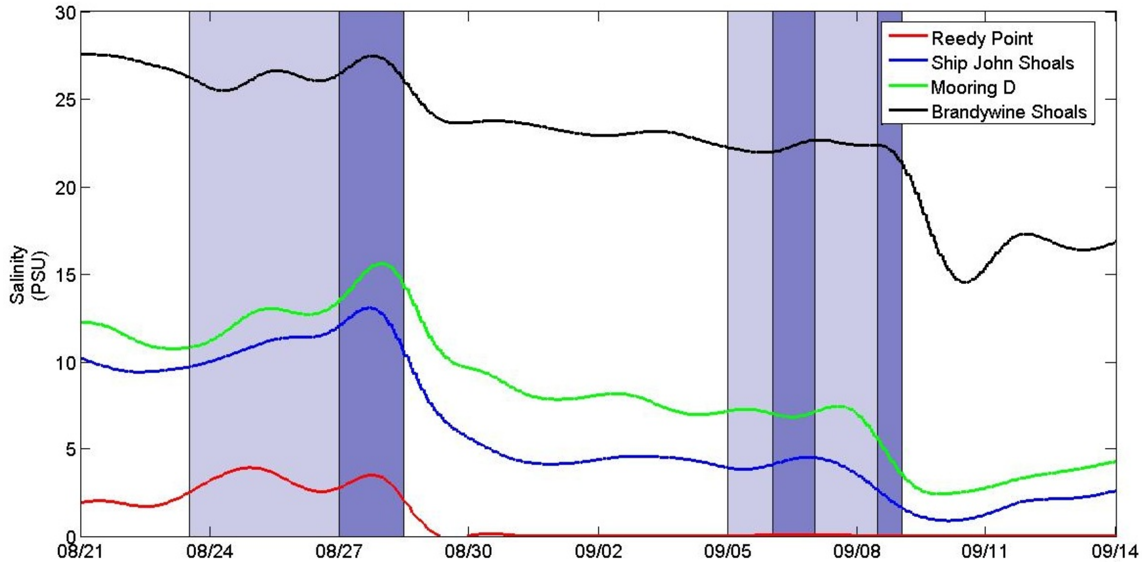

Figure 7. Low-pass filtered surface salinity (PSU) at Reedy Point, Ship John Shoal, Mooring D, and Brandywine Shoal. Periods of up-estuary and down-estuary winds are framed in light purple and dark purple, respectively.

3.3 Salinity and Suspended Sediment Sections

Axial surveying of the estuary during fair-weather conditions on 3 June 2011 revealed typical salinity and SSC distributions (Figure 8). At the time of this survey the salt intrusion (1 PSU) fell near the upper-to-lower estuary transition (between stations 12 and 13), and the center of the ETM was present in 1-5 PSU waters by Artificial Island (near Station 11). Note that the null zone of gravitational circulation typically falls in the vicinity of Artificial Island (Sommerfield and Wong, 2011). Vertical salinity stratification was most pronounced (5-8 PSU) between Stations 4 and 9. At its center, ETM surface and bottom SSC measured 141 and 376 mg/L, respectively, decreasing up- and down-estuary. At the time of this survey the axial sediment inventory (calculated by integrating SSC over depth and length) was ~$8.6x10^5$ mt.

The second survey on September 16 indicated that storms Irene and Lee had dramatically changed conditions in the estuary (Figure 9). The salt intrusion was pushed ~20 km seaward of its June 3 position, and while the lower estuary and bay were freshened, the vertical stratification (5-8 PSU) was similar to that observed on the June survey. The SSC distribution had changed drastically, however. The locus of the turbidity maximum was not evident, and SSC values reached only 71 and 218 mg/L, respectively, at the surface and bottom near its usual location. The axial sediment inventory (~$7.7x10^5$ mt) was less than that measured during the June survey. Either most of the resident sediment inventory of the ETM had been dispersed laterally from the estuary, or a large amount of material was deposited.

A survey on December 15 revealed the estuary had outwardly recovered from the storms (Figure 10). The salt intrusion was present just up-estuary of its September 16 position, consistent with reduced freshwater inflow, and a well-developed ETM was present in 1-5 PSU waters. High-SSC water extended throughout the water column, from 120 mg/L at the surface to 526 mg/L at the bottom. The axial sediment inventory was largest during the December survey at $1.4x10^6$ mt.

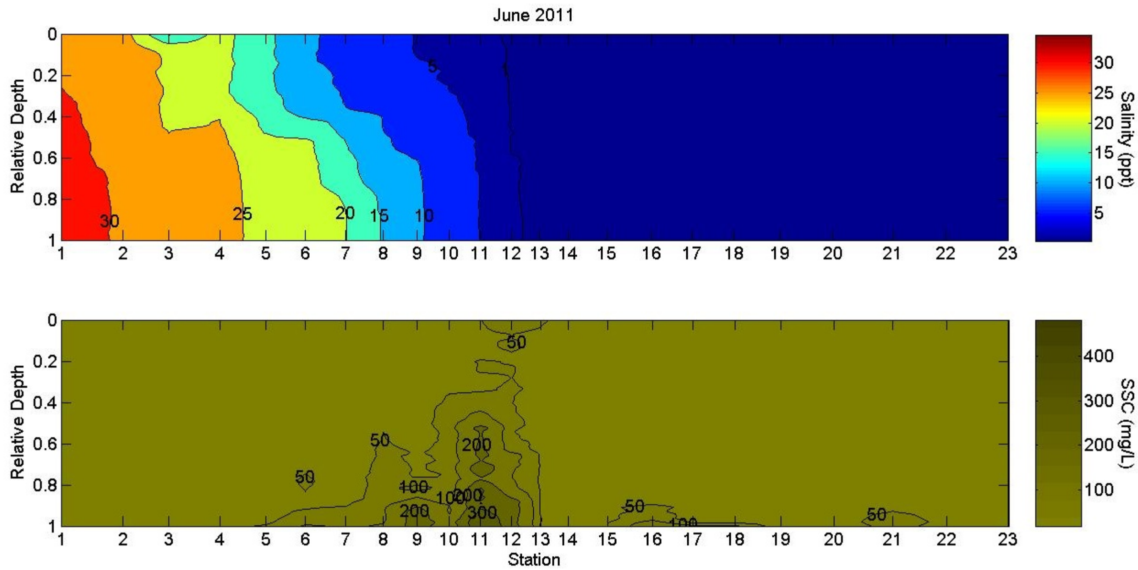

Figure 8. Axial sections of estuary salinity (PSU) and SSC (mg/L) measured on 3-4 June 2011.

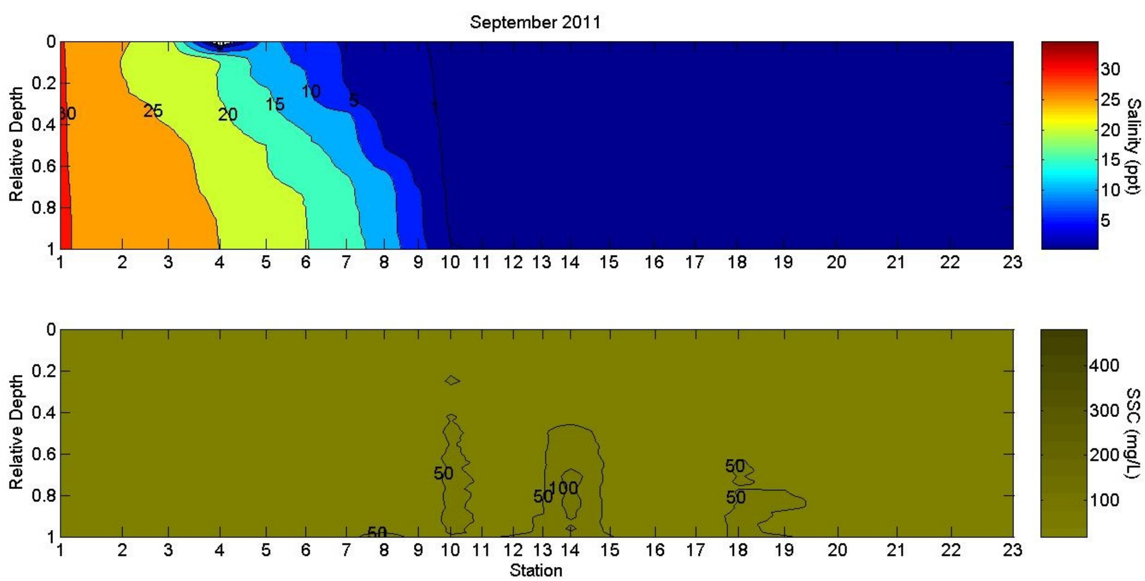

Figure 9. Axial sections of estuary salinity (PSU) and SSC (mg/L) measured on 16-17 September 2011.

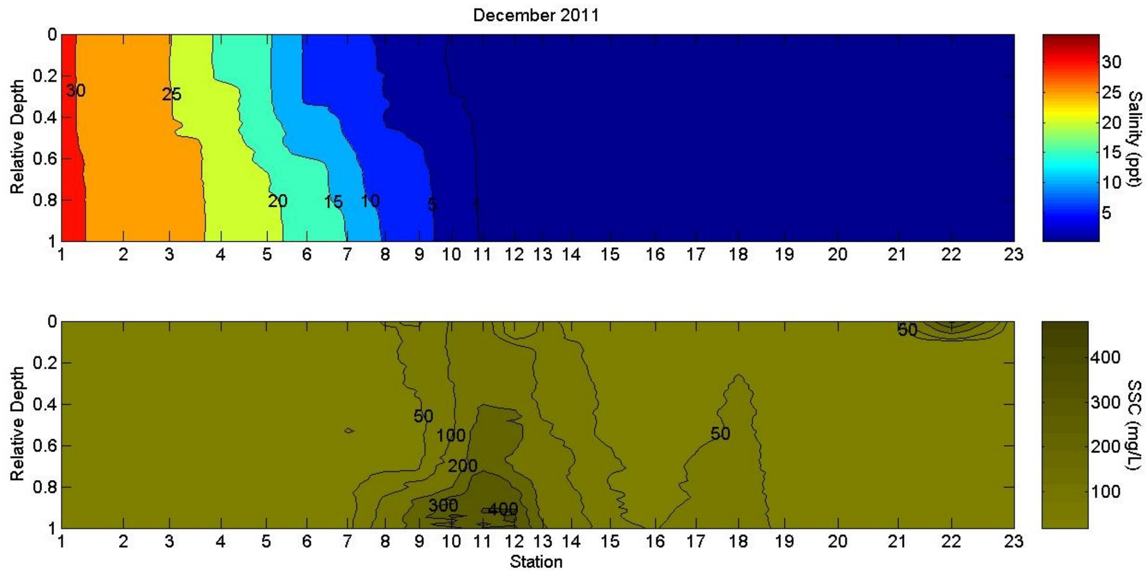

Figure 10. Axial sections of estuary salinity (PSU) and SSC (mg/L) measured on 13-14 December 2011.

3.4 Velocity and Sediment Transport

Although Mooring A instrumentation was operational during Hurricane Irene, the mooring itself was dragged down-estuary of its deployment location shortly after the storm passed, thus no data are available for Tropical Storm Lee at this site. Based on the depth-averaged velocity at Mooring A, the second flood tide on September 28 was completely damped during the time of down-estuary winds; for a period of 12-15 hours currents throughout the water column were ebb-directed (Figure 11). Tidal damping has been observed previously in estuaries; for example, during Hurricane Floyd (in 1999) Valle-Levinson et al. (2002) observed that freshwater outflow was sufficient to dampen flood tidal currents at all depths in the Chesapeake Bay. Interestingly, no tidal damping was observed at Mooring C during storm Lee despite the higher river discharge it produced. Hence, the tidal damping event during Irene was mostly likely a consequence of strong down-estuary winds and to a lesser extent river discharge.

The depth-averaged, tidally averaged current in the upper estuary at Mooring A increased from -0.1 m/s (down-estuary mean current) before the storm reached the Delaware River Basin to -0.5 m/s on August 29 (Figure 11). There was only a nominal increase in the depth-averaged SSC on August 29; tidally varying SSC reached a maximum of ~60 mg/L on the 29th. The down-estuary mean current was largely responsible for the magnitude and direction of the advective sediment flux, which was consistently down-estuary and increased fourfold during Irene (Figure 11). The tidal pumping flux was weakly down-estuary to zero prior to Irene, increasing by a factor of 2-3 during the storm. The increase in pumping flux magnitude can be explained by tidal transport of sediment delivered from up-estuary locations, whereas the ebb-orientation of the pumping flux reflects the stronger ebb-tidal currents (relative to flood) at this location.

The flood tide on August 28 was similarly damped at Mooring C in the lower estuary, but the effect on tidal currents was less pronounced than at Mooring A (Figure 12). Depth-averaged SSC increased and decreased in association with both storms, but reached slightly higher values during Irene. The advective sediment flux at Mooring C was predominately up-estuary prior to Irene, reversed to down-estuary during the storm and then returned to up-estuary by September 2. During Lee the advective sediment flux was more strongly down-estuary and remained so for 7 days.

As was observed at Mooring A, the tidal pumping flux peaked after the advective sediment flux peak in association with the storms. However, in contrast to Mooring A, the tidal pumping flux was of the same magnitude (during Irene) or larger (during Lee) than the advective flux (Figure 12). This difference implies presence of an easily resuspendable sediment pool in the vicinity of Mooring C, consistent with its location within the turbidity maximum zone. In summary, depth-averaged advective and tidal pumping sediment fluxes were dominantly down-estuary during both storms, but storm Lee generated larger fluxes than Irene largely because of its higher freshwater discharge.

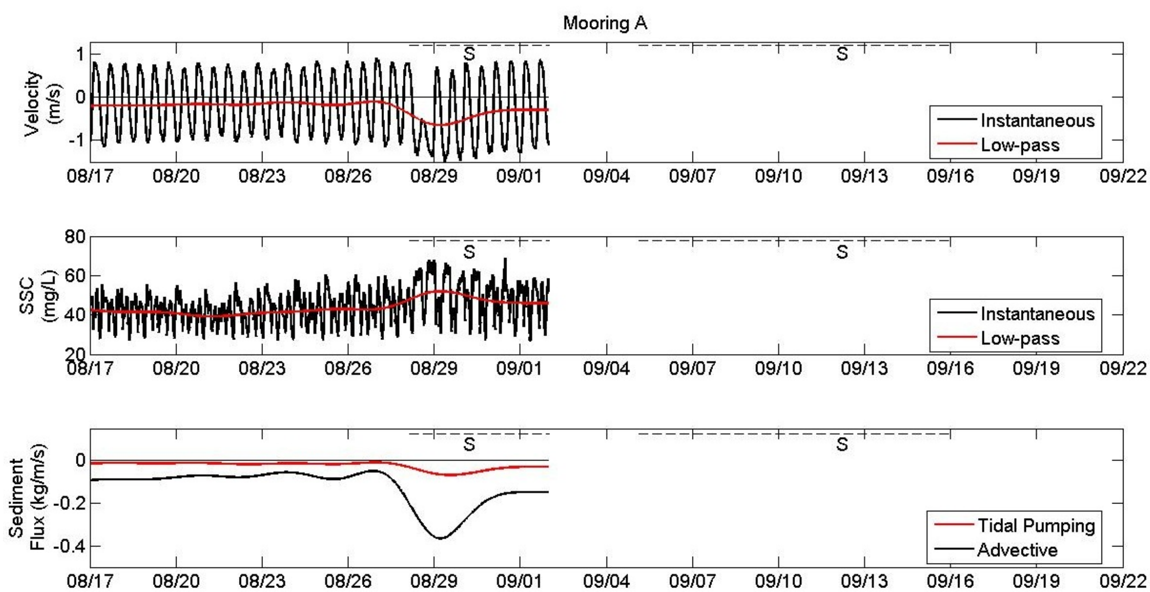

Figure 11. Depth-averaged velocity (m/s), SSC (mg/L), and sediment flux (kg/m/s) at Mooring A. Negative and positive values are down- and up-estuary, respectively. The dashed lines represent the storm periods, and 'S' denotes a spring tide.

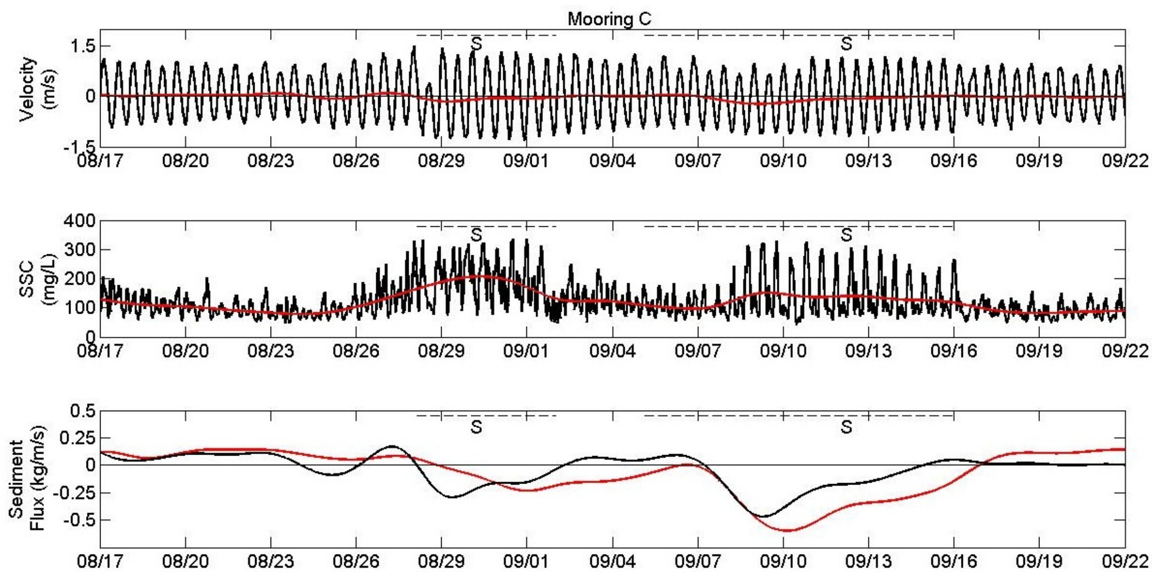

Figure 12. Depth-averaged velocity (m/s), SSC (mg/L), and sediment flux (kg/m/s) at Mooring C. Negative and positive values are down- and up-estuary, respectively. The dashed lines represent the storm periods, and 'S' denotes a spring tide. See legend from Figure 11.

Chapter 4

DISCUSSION

4.1 Hydrodynamic Response

The response of the Delaware Estuary to Hurricane Irene and Tropical Storm Lee in 2011 was broadly similar to that of the Rappahannock Estuary following Tropical Storm Agnes in 1972 (Nichols, 1977). Hence, the Delaware Estuary observations are supportive of Hypotheses 1 and 2 put forth above. One difference was the initial increase in surface-water salinity in the lower estuary during the approach of Irene, which was not observed in the Rappahannock by Nichols (1977), perhaps due to a lack of continuously recording sensors in that study. Li et al. (2007) observed (and modeled) a similar wind influence on salinity in Chesapeake Bay in association with Hurricane Isabel (2003), finding that up-estuary winds deepened the surface mixed layer, de-stratified the water column, and increased the salinity of surface water. North et al. (2004) modeled the effects of wind in the estuarine salinity field, finding that up-estuary winds destratify the water while simultaneously moving the salt intrusion down-estuary under a seaward barotropic gradient. Conversely they found that down-estuary winds stratified the water column and caused the salt limit to migrate up-estuary, and also intensified caused down-estuary surface currents and enhanced up-estuary flow at depth. Similarly, the increase in surface salinity during the approach of Irene can be explained in part by up-estuary winds and destratification (see Figure 13).

Surface salinity in the estuary continued to increase even as the winds shifted to down-estuary during passage of Irene, which according to the interpretation above should have stratified the estuary. The difference may be related to wind strength. For example, Cho et al. (2012) examined the different responses of Chesapeake Bay to hurricanes

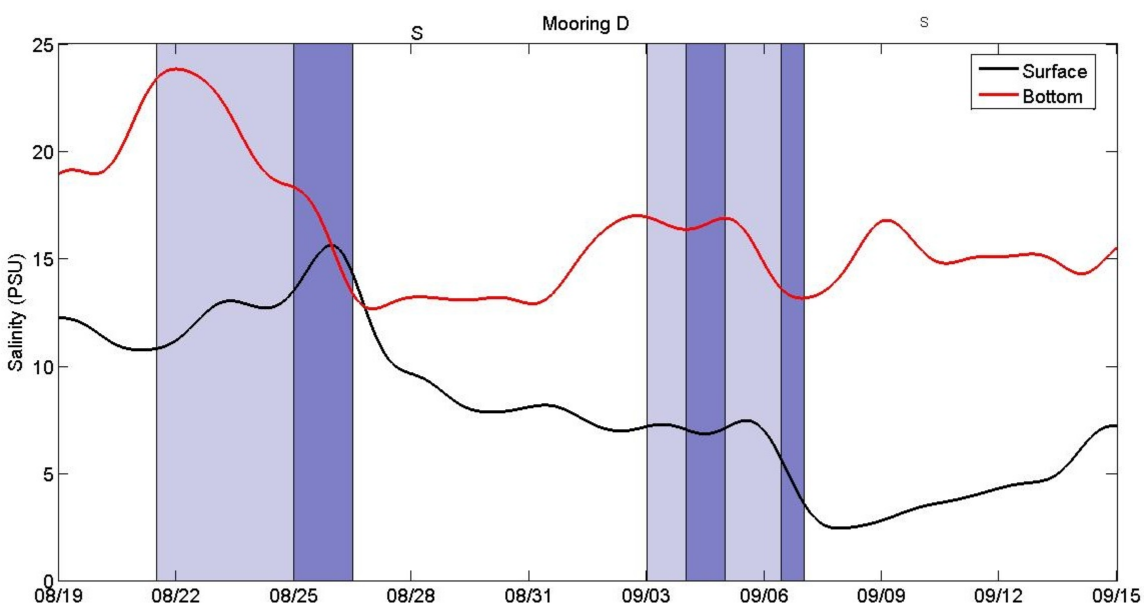

Figure 13. Records of low-pass filtered surface and bottom salinity (PSU) at Mooring D. 'S' denotes a spring tide. Periods of up-estuary and down-estuary winds are framed in light purple and dark purple, respectively. Note the progressive decrease in stratification during the period of up-estuary winds (Irene), and complete mixing during the reversal to down-estuary winds.

Floyd (1999) and Isabel (2003), finding that stratification increased under *moderate* down-estuary winds but decreased under *strong* down-estuary winds. As shown in Figure 13, when the wind shifted from up-estuary to strongly down-estuary during Irene, the increased wind speed (>20 m/s) continued to destratify the water column until it became completely mixed. Stratification resumed after 1-2 days, but remained weak for 5 days. During this period mixing was most likely enhanced by higher-than-average astronomical tides (August 27-September 3). Rebound of the estuary from Irene began around September 1 with restratification of the water column, but was incomplete on account of storm Lee. The rebound from the combined effects of Irene and Lee did not begin until September 10th, when salinity began to increase (Figure 7). Full recovery must have taken much longer given the position of the salt intrusion during the axial survey on December 16 (Figure 10), which was still somewhat seaward of its position in June. Recovery from the storms was overshadowed by a spate of river discharge events between October and December, which depressed salinity in the estuary to unusually low levels for several months. According to the USGS statistics, in terms of river discharge 2011 was the wettest year on record (since 1913) in the Delaware River Basin. Mean annual discharge of the Delaware River at Trenton was 617 m^3/s, exceeding the previous annual high of 555 m^3/s in 1928.

4.2 Sedimentary Response

Suspended sediment concentration in the estuary started to increase at the same time that turbidity increased at the heads of tide, thus the origin of this increase must have been produced by bed resuspension, the most immediate sediment source, rather than sediment from the drainage basin. Some combination of down-estuary winds and freshwater discharge were responsible for increasing the bottom stress to beyond the critical shear stress for cohesive sediments. Only later would new river sediment have arrived at the observational sites in the estuary. To constrain the timing of river-to-estuary sediment movement, a simple transport model was used to track the transit of a water parcel from Trenton to Mooring D in the lower estuary. The tidal river and upper estuary was divided into five contiguous segments by the NOAA Ports water level stations. Segment-averaged velocities were calculated and combined to estimate the travel distance of a water parcel. In this model the rate of change of water volume divided by channel cross-sectional area gives the down-stream water velocity:

$$U = \frac{1}{A}\frac{d}{dt}\left[\int h \cdot w dx\right] + \frac{Q}{A} \tag{8}$$

where U is the streamwise velocity, Q is river discharge at the heads of tide, A is the cross-sectional area of the channel, h is water level, w is the channel width, and dx is the segment length. Cross-sectional areas were determined from gridded bathymetry available for the estuary, and water levels were obtained from the six landward NOAA PORTS stations (Figure 1, left). For the first four segments Q is Delaware River discharge measured at Trenton, and Schuylkill River discharge was added to segment five. Modeling was limited to the tidal (freshwater) river where the mean non-tidal flow is uniformly down-estuary (Wong and Sommerfield, 2009). Down-estuary transit of a water parcel approximates the travel time of sediment transported only as *washload*. Transit of suspended load should lag behind washload because it becomes separated from the streamwise flow during times of settling and deposition at slack water.

As shown in Figure 14, a water parcel starting at the head of tide on August 28 would have reached the Benjamin Franklin Bridge on the 29th and Mooring A on September 2. In the upper estuary, where the cross-sectional area is relatively small, Irene would have rapidly moved the parcel down-estuary. Clearly, there was not enough time for Irene-produced washload to transit the full length of tidal river and estuary and produce the SSC peak observed at either Mooring A or C on August 29 (Figure 11). Hence, at least initially, all of the storm-produced sediment flux at the moorings during Irene was a consequence of bed resuspension within the estuary, consistent with prior observations (Cook et al., 2007; Sommerfield and Wong, 2011).

The case for significant within-estuary sourcing of sediment can be made by comparing sediment fluxes among the measurement sites. For example, the peak flux of river sediment produced in association with Hurricane Irene was 2158 kg/s (Figure 15),

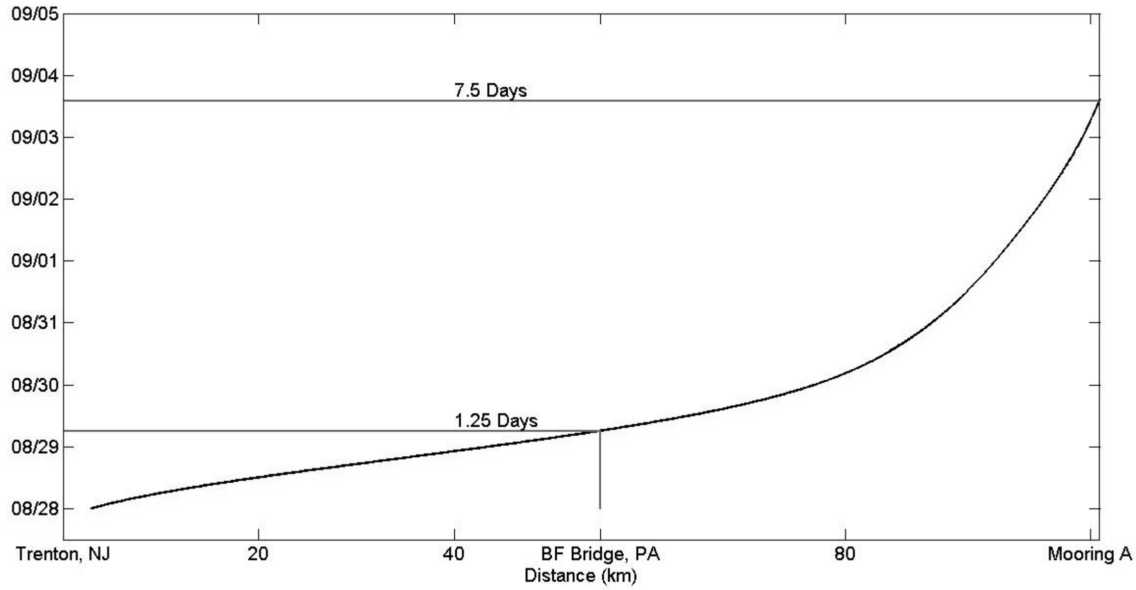

Figure 14. Plot showing the along-estuary distance (0=Trenton) traveled by a water parcel based on Eq. 8. Benjamin Franklin (BF) Bridge and Mooring A shown for distance.

whereas the peak advective flux at Mooring A was about 0.37 kg/m/s (Figure 16). Averaged over the 2.4 km width of the estuary at Mooring A, the sectionally averaged flux would have been 888 kg/s, over 40% of the river influx. Knowing that Irene-produced river sediment could not have reached Mooring A by August 30, most of this flux must have been derived from bed resuspension within the tidal river and uppermost estuary segments. In the lower estuary at Mooring C the peak advective sediment flux during Irene was 0.29 kg/m/s, not much lower than the peak flux measured at Mooring A, and 0.47 kg/m/s during Lee (Figure 15). The Mooring C fluxes are significant given that the estuary is 7.7 km wide at this location. For example, averaging the river sediment load of 2158 kg/s over the estuary cross section at Mooring C gives a unit-width flux 0.28 kg/m/s. Again, the relative magnitude of measured sediment fluxes during the storms argues for significant resuspension of bed sediment between the upper and lower estuary.

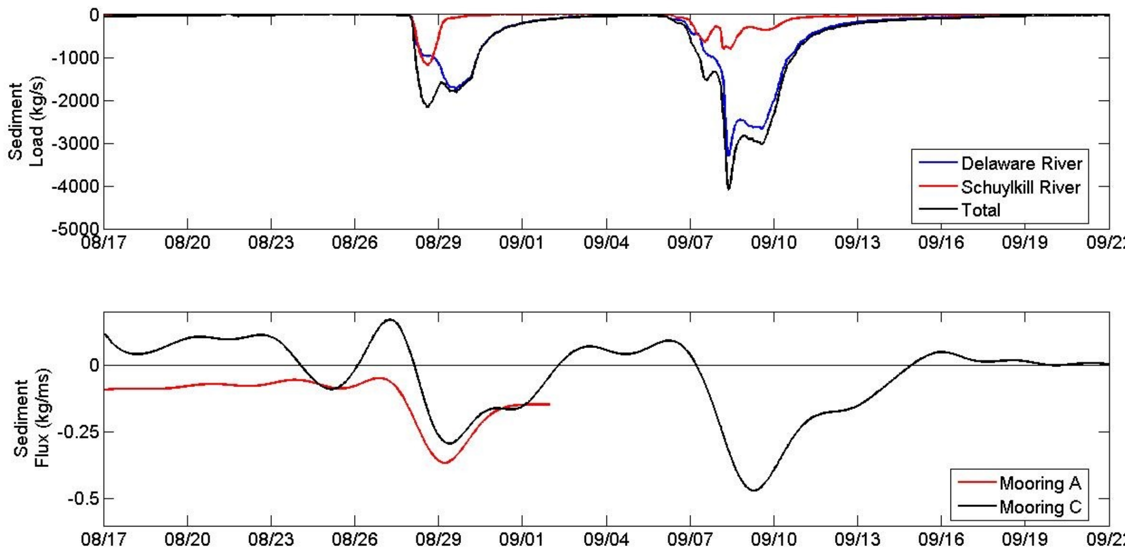

Figure 15. Records of sediment load at the heads of tide (top) and depth-averaged flux per unit width at the mooring sites (bottom). Negative and positive fluxes are down- and up-estuary, respectively.

4.3 Sediment Dispersal and Entrapment

Sommerfield and Wong (2011) examined the sediment response of Delaware Estuary to a northeaster storm in 2005 which caused Delaware River discharge to exceed 6700 m^3/s. They found that more suspended sediment was delivered to the estuary from the tidal river segment than from above the heads of tide, and that there was a convergence of sediment flux near the null point present between the 1 and 5

PSU isohalines. Despite the large influx of freshwater and seaward displacement of salt, two-layer gravitational circulation was not shut down, and the null point remained within the lower estuary. Consequently, the landward, near-bottom component of the gravitational current contributed to the entrapment of sediment and retention within the estuary.

The along-estuary position of the estuarine null point (and more broadly the tidally varying null zone) generally coincides with the ETM. Lacking information on the location of the null zone during the 2011 storms, the axial positions of the 1 and 5 PSU isolines can be used as a surrogate, given that the null zone generally falls within this salinity range (e.g., Sommerfield and Wong, 2011). Using records of surface salinity available from the Reedy Island, Ship John Shoal, and Brandywine Shoal Light stations, the positions of the 1 and 5 PSU isohalines were spatially interpolated and plotted (Figure 14).

Further insight on sediment dispersal and trapping is provided by records of depth-dependent residual velocity, SSC and sediment flux measured at Mooring C. As shown in Figure 16, two-layer gravitational circulation (seaward surface flow and landward flow at depth) was well-developed in the lower estuary at Mooring C prior to Hurricane Irene. When Irene reached the Delaware River Basin the null point was pushed seaward of the mooring site and the residual current was down-estuary throughout the water column. During this time maximum down-estuary velocity coincided with maximum bed resuspension and SSC, and the down-estuary advective sediment flux was maximal near the surface (Figure 16). By September 2 the null point had migrated up-estuary, the gravitational circulation was again well-developed, and the advective sediment flux was seaward at the surface and landward at the bottom.

During storm Lee, the null point and gravitational circulation were pushed well seaward of Mooring C for about a week, and the residual current down-estuary throughout the water column. The maximum down-estuary transport was near the bottom, in contrast to the near-surface flux during Irene. According to the transit plot (Figure 14), sediment entering the estuary at the onset of Irene would have passed mooring C on September 13th when the residual currents were ebb-oriented at all depths. It would not have reached Mooring D until late September, after gravitational circulation was restored at Mooring C. The null point was at no point pushed from the lower estuary into Delaware Bay, thus sediment entering the estuary from the head of tide should have been trapped within the estuary landward of the Mooring D location. This is evident by the up-estuary, near-bottom sediment flux at Mooring C starting on September 15, which most likely represents material that bypassed this location during the storm period.

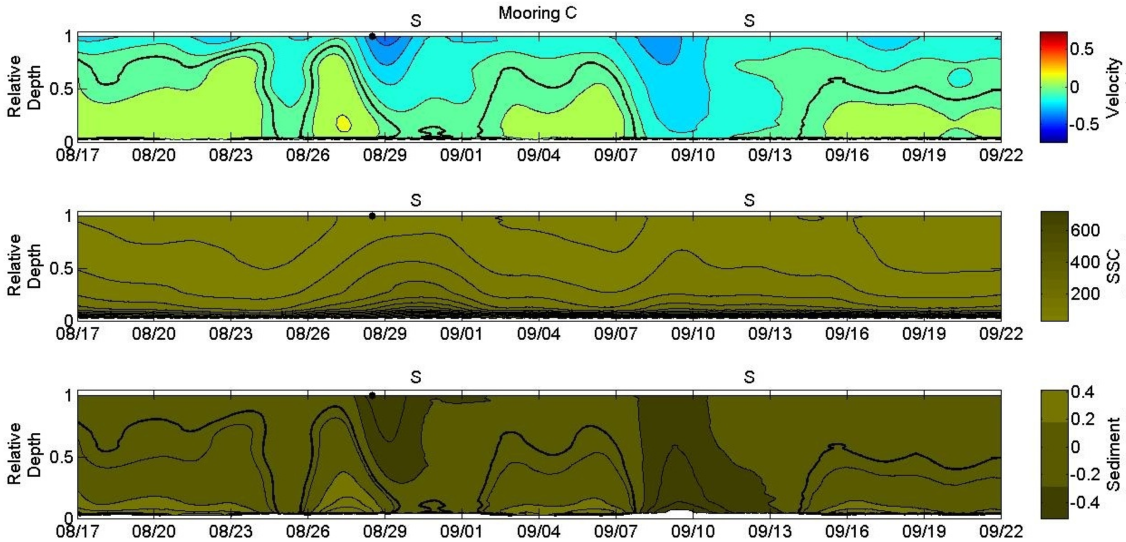

Figure 16. Tidally averaged, depth-varying velocity (m/s), SSC (mg/L), and advective sediment flux (kg/m/s) at Mooring C during the two storms. Negative and positive fluxes are down- and up-estuary, respectively. The surface of zero residual velocity is depicted by the heavy line in the topmost panel.

Chapter 5

CONCLUSIONS

The hydrodynamic response of Delaware Estuary to tropical cyclones Irene and Lee in 2011 was comparable to that observed for other Mid-Atlantic estuaries during other storms. Salinity in the bay and lower estuary increased prior to Irene, as was observed by Reay and Moore (2005), Gong et al. (2007), Gong and Shen (2009), and Cho et al. (2012). This increase was due to up-estuary winds deepening the mixed layer depth before strong down-estuary winds completely destratified the estuary. Despite the effects of winds and high river discharge, the salt limit was not pushed past the seaward extent of the ETM zone at mooring D, indicating that gravitational circulation (and sediment trapping), remained active in the estuary during the storms. Restratification occurred as a result of the horizontal salinity gradient, as described for the Chesapeake Bay by Li et al. (2006, 2007). A flood tide was completely damped at mooring A and partially damped at mooring C in response to local wind forcing during Hurricane Irene. **Despite this damping a corresponding increase in down-estuary flow was not evident.** The down-estuary flux of sediment at both mooring locations peaked after the damped tide, but the relative influences of wind and freshwater discharge on these peaks was not determined in this study.

As was observed by Cook et al. (2007) and Sommerfield and Wong (2011), sediment stored within the estuary was resuspended during the storms. According to the simple transport model, there was insufficient time for washload sediment from the river to be responsible for the peaks in sediment at moorings A and C. Furthermore, accounting for the width of the estuary, it is likely that the amount of sediment that passed mooring C during Irene and Lee was greater than the amount of new sediment that entered the estuary from rivers. **As such, resuspension of previously deposited material was a major source of suspended sediment during the storms in 2011.**

Irene and Lee both experienced conditions that should increase the system's ability to export sediment from the estuary. During Irene, wind forcing fully damped a flood tide at mooring A, and partially damped the flood tide at mooring C. During storm Lee, river discharge was great enough to push gravitational circulation seaward of mooring C. Both storms were followed soon afterwards by spring tides, which from previous work is known to increase the system's ability to export sediment by breaking down stratification and mixing sediment into the upper water column where seaward flow can transport it to the bay (Sommerfield and Wong, 2007). **Based on analysis of currents and salinity data from the moorings, it is likely that new river sediment was trapped within the tidal river and estuary, not exported to Delaware Bay.**

The September 2011 shipboard survey revealed that, although a large amount of storm-produced sediment was delivered by the Delaware and Schuylkill rivers, and that an equal (if not greater) amount of bed sediment was resuspended, very little sediment was present in suspension along the axis of the estuary one week after storm Lee (Figure 9). Some of the sediment delivered to (or resuspended within) the estuary must have been deposited in off-channel areas during the course of the storms (e.g., Humberston and Sommerfield, 2012). Sommerfield and Wong (2011) found that the subtidal flats are one location for permanent deposition of sediment in the estuary. Hence, the extent of across-estuary sediment transport during storms can have an enormous impact on fate of storm-produced sediment.

In summary, the Delaware Estuary's response to Irene and Lee evokes a system with large stores of mud capable of being resuspended by wind, wave, and river discharge. These stores are equal to or greater than what might be delivered by river tributaries over the same time period. The ability of the estuary to buffer high discharge flows allows for the trapping of almost all river borne sediment, and most resuspended sediment as well. Even during conditions where export is most likely, export of sediment to the Bay remains low. Strong winds can cause resuspension in the estuary and even damp flood tides, but appear to play a secondary role to the effects of gravitational circulation and tidal pumping.

REFERENCES

Biggs, R., and Beasley, E. 1988. Bottom and suspended sediments in the Delaware River and Estuary. In: Majumdar, S., Miller, E., Sage, L. Ecology and Restoration of the Delaware River Basin. The Pennsylvania Academy of Science. Pp. 116-131.

Cheng, P., Li., M., and Yi, L., 2013. Generation of an estuarine sediment plume by a tropical storm. Journal of Geophysical Research. Vol. 118. pp. 1-13.

Cho, K., Wang, H., Shen, J., Valle-Levinson, A., and Teng, Y. 2012. A modeling study on the response of Chesapeake Bay to hurricane events of Floyd and Isabel. Ocean Modeling. Vol. 49-50. pp. 22-46.

Cook, T. L., Sommerfield, C. K., Wong, K.-C. 2007. Observations of tidal and springtime sediment transport in the Upper Delaware Estuary. Estuarine, Coastal and Shelf Science. Vol. 72. pp. 235-246.

Delaware River Basin Commission. 2011. FLOOD SUMMARY – August 28 – September 9, 2011 Hurricane Irene and Tropical Storm Lee.

Ferguson, R.I. 1986. River loads underestimated by rating curves. Water Resources Research. Vol. 22. No. 1. pp. 74-76.

Gartner, J. W. 2004. Estimated suspended solids concentrations from backscatter intensity measured by an acoustic Doppler current profiler in San Francisco Bay, California. Marine Geology. Vol. 211. pp. 169–187.

Gong, W. and Reay, W.G. 2007. The hydrodynamic response of the York River Estuary to Tropical Cyclone Isabel, 2003. Estuarine, Coastal and Shelf Science. Vol. 73. pp. 695-710.

Gong, W. and Shen, J. 2009. Response of sediment dynamics in the York River Estuary, USA to tropical cyclone Isabel of 2003. Estuarine, Coastal and Shelf Science. Vol. 84. pp. 61-74.

Holdaway, G. P., Thorne, P. D., Flatt D., Jones, S. E., and Prandle, D. 1999, Comparison between ADCP and transmissometer measurements of suspended sediment concentration, Continental Shelf Research. Vol. 19. pp. 421–441.

Humberston, J. L. and Sommerfield, C. K. 2012. Radionuclide indicators of seasonal sediment deposition in the Delaware Estuary. Poster presentation : Ocean Sciences Meeting 2012. February 20-24. Salt Lake City, UT.

Janzen, C. D. and Wong, K.-C. 2002. Wind-forced dynamics at the estuary-shelf interface of a large coastal plain estuary. Journal of Geophysical Research. Vol. 107. No. C10. pp. 3138.

Keim, B. D., Muller, R. A., and Stone, G. W. 2004. Spatial and temporal variability of coastal storms in the North Atlantic Basin. Marine Geology. Vol., 210. pp. 7-15.

Li, M., Zhong, L., Boicourt, W., Zhang, S., and Zhang, D. 2006. Hurricane-induced storm surges, currents and destratification in a semi-enclosed bay. Geophysical Research Letters. Vol. 33. L024992.

Li, M., Zhong, L., Boicourt, W., Zhang, S., and Zhang, D. 2007. Hurricane-induced destratification and restratification in a partially-mixed estuary. Journal of Marine Research. Vol. 65. pp. 169-192.

Mansue, L. J. and Commings, A. B. 1974. Sediment transport by streams draining into the Delaware Estuary. U.S. Geological Survey Water-Supply Paper 1532-H.

Meade, R. H. 1969. Landward transport of bottom sediments in estuaries of the Atlantic Coastal Plain. Journal of Sedimentary Petrology. Vol. 39. pp. 222-234.

Meade, R. H. 1982. Sources, Sinks, and Storage of River Sediment in the Atlantic Drainage of the United States. The Journal of Geology. Vol. 90. pp. 235-252.

Nichols, M. M. 1977. Response and Recovery of an Estuary Following a River Flood. Journal of Sedimentary Petrology. Vol. 47. No. 3. pp. 1171-1186.

Nichols, M. M. 1993. Response of coastal plain estuaries to episodic events in the Chesapeake Bay region. In: MEHTA, A. (Editor): Nearshore and Estuarine Cohesive Sediment Transport. New York: Springer-Verlag, 1-20.

North, E., Chao, S., Sanford, L., and Hood, R. 2004. The influence of wind and river pulses on an estuarine turbidity maximum: numerical studies and field observations in Chesapeake Bay. Coastal and Estuarine Research Federation. Vol. 27. No. 1. pp. 132-146.

Pape, E. H. and Garvine, R. W. 1982. The subtidal circulation in Delaware Bay and adjacent shelf waters. Journal of Geophysical Research. Vol. 87. No. C10. pp. 7955-7970.

Reay, W. G. and Moore, K. A. 2005. Impacts of Tropical Cyclone Isabel on Shallow Water Quality of the York River Estuary. Hurricane Isabel in Perspective. Chesapeake Research Consortium, CRC Publication 05-160, Edgewater, MD.

Sommerfield, C. K. and Wong, K.-C. 2011. Mechanisms of sediment flux and turbidity maintenance in the Delaware Estuary. Journal of Geophysical Research. Vol. 116. No. C01005.

Valle-Levinson, A., Wong, K., and Bosley, K. 2002. Response of the lower Chesapeake Bay to forcing from Hurricane Floyd. Continental Shelf Research. Vol. 22. pp. 1715-1729.

Wong, K.C. and Garvine, R.W. 1984. Observations of wind-induced, subtidal variability in the Delaware Estuary. Journal of Geophysical Research. Vol. 89. No. C6. pp. 10589-10597.

Wong, K., and Moses-Hall, J. 1998. The tidal and subtidal variations in the transverse salinity and current distributions across a coastal plain estuary. Journal of Marine Research. Vol. 56. pp. 489-517.

Wong, K., and Sommerfield, C.K., 2009. Variability of currents and sea level in the upper Delaware Estuary. Journal of Marine Research. Vol. 67. pp. 479–501.

Zhang, K., Douglas, B., and Leatherman, S. 2000. Twentieth-Century Storm Activity along the U.S. East Coast. Journal of Climate. Vol. 13. pp. 1748-1761.

Appendix A

DATA TABLE

Table A.1. Data sources.

Source	Data Available	Coverage	Data Resolution
University of Delaware/ Rutgers University	River SSC	03/2010 - 12/2011	Near Daily
	Axial Surveys	03/2010 - 12/2011	Seasonal
	Moorings (ADCP,CTD)	Varied	10-20 minute
USGS - 01463500 Delaware River at Trenton, NJ	SSC	09/1949 - 03/1982	Daily
	"	11/1950 - Current	Random
	River Discharge (Trenton, NJ)	10/1912 - Current	Daily and Hourly
	Turbidity (Morrisville, PA)	06/2004 - Current	Daily and Hourly
USGS - 01473800 Schuylkill River at Manayunk, PA	SSC	11/1947 - 01/1982	Daily
	"	07/1982 - 09/1986	Daily
USGS - 01474500 Schuylkill River at Philadelphia, PA	River Discharge	10/1931 - Current	Daily and Hourly
	SSC	02/1975 - 09/2004	Random
NOAA Ports - 8557380 Lewes, DE	Water Level	01/1996 - Current	6-minute
	Wind	03/2001 - Current	6-minute
	Atmospheric Pressure	08/2002 - Current	6-minute
NOAA Ports - 8555889 Brandywine Shoal Light, DE	Water Level	11/1997 - Current	6-minute
	Wind	06/2002 - Current	6-minute
	Atmospheric Pressure	06/2002 - Current	6-minute
	Conductivity	06/2002 - Current	6-minute
NOAA Ports - 8537121 Ship John Shoals, NJ	Water Level	08/2002 - Current	6-minute
	Wind	07/2002 - Current	6-minute
	Atmospheric Pressure	07/2002 - Current	6-minute
	Conductivity	07/2002 - Current	6-minute

NOAA Ports - 8551910 Reedy Point, DE	Water Level	05/1996 - Current	6-minute
	Atmospheric Pressure	01/0999 - Current	6-minute
NOAA Ports - 8545240 Philadelphia, PA	Water Level	01/1996 - Current	6-minute
	Atmospheric Pressure	01/2000 - Current	6-minute

Appendix B

SATELLITE IMAGE

Figure B.1. Satellite image of the Chesapeake and Delaware bays shortly after Tropical Storm Lee on 12 September 2011. Note the large amount of suspended sediment in surface waters. Image accessed from www.eyesonthebay.net.

Appendix C

AXIAL SURVEY OBS CALIBRATIONS

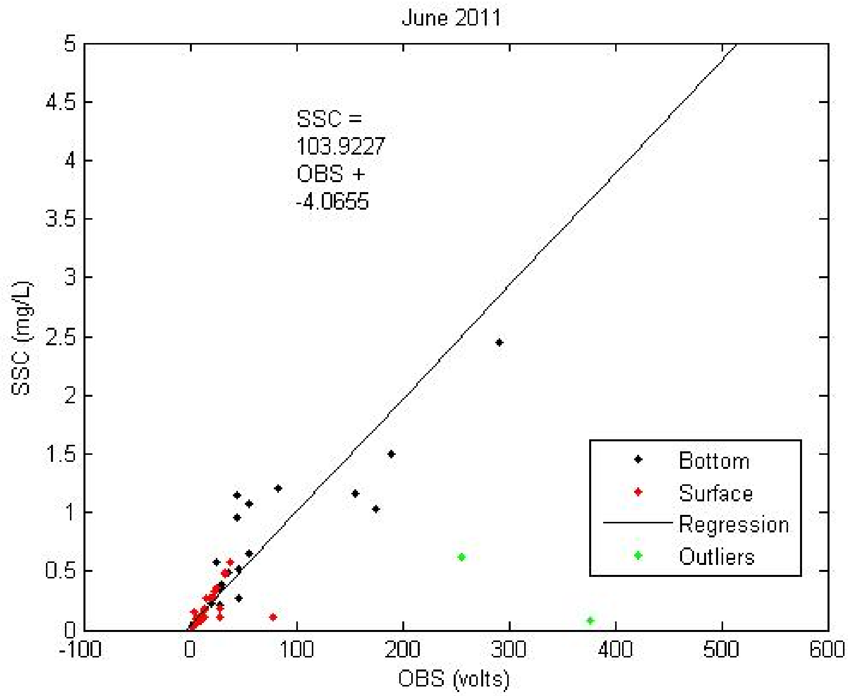

Figure C.1. June 2011 OBS/SSC calibration, n = 44.

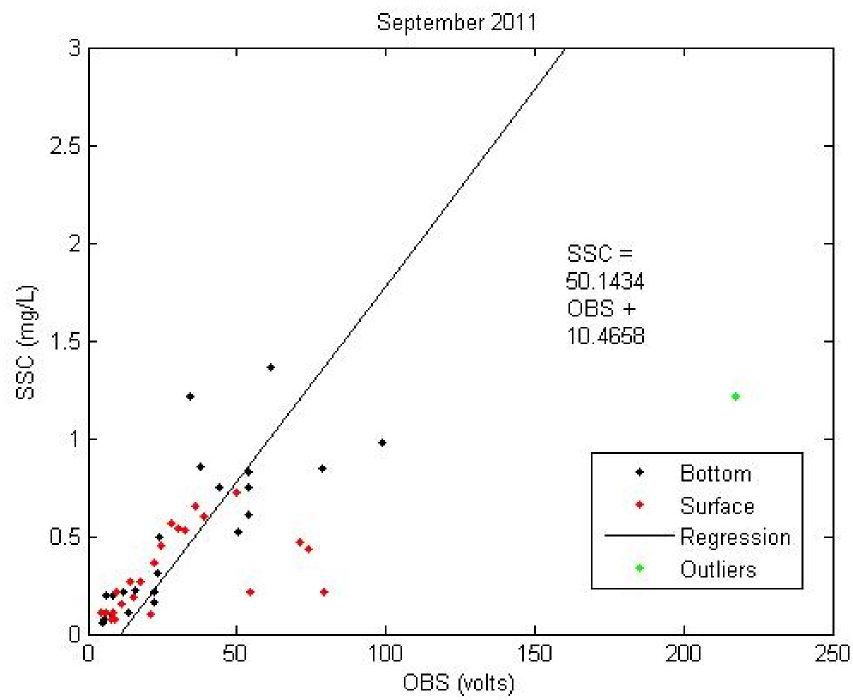

Figure C.2. September 2011 OBS/SSC calibration, n = 45.

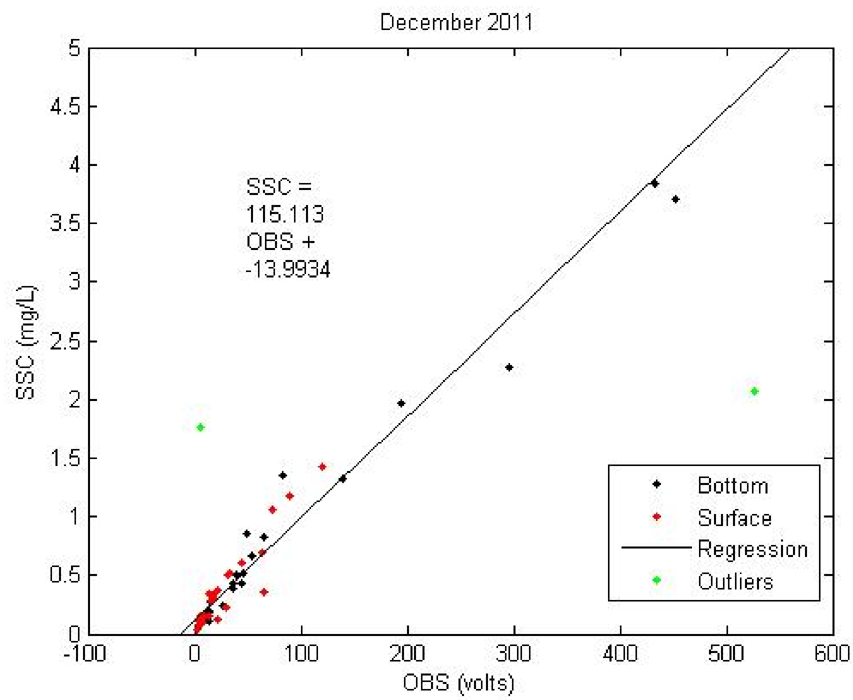

Figure C.3. December 2011 OBS/SSC calibration, n = 44.

Appendix D

FLOW DURATION RATING CURVES

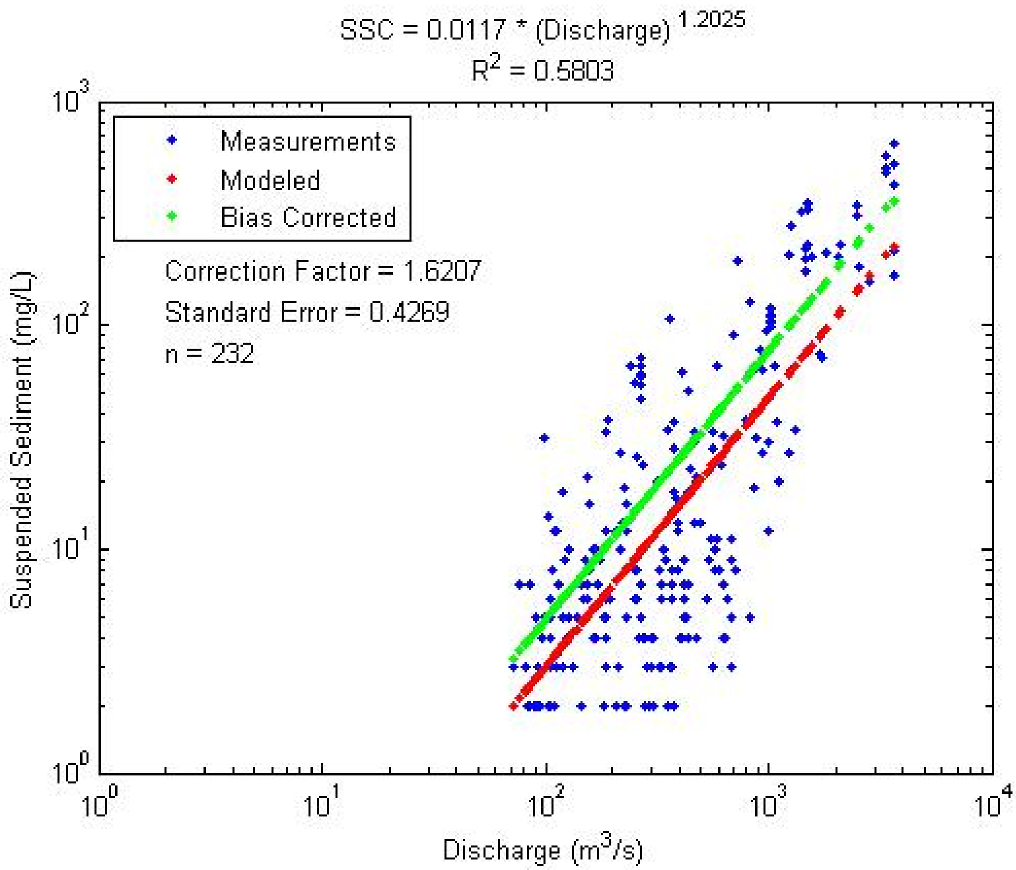

Figure D.1. Delaware River sediment rating curve used to calculated suspended sediment loads as discussed in the text.

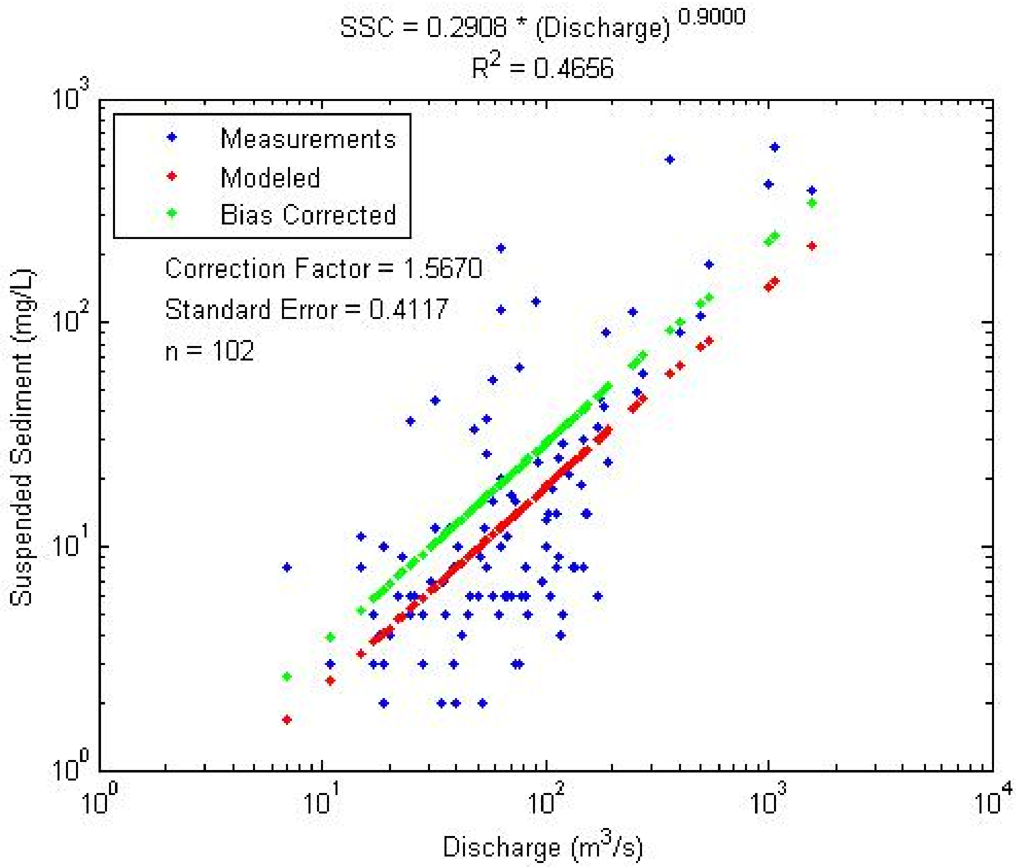

Figure D.2. Schuylkill River sediment rating curve used to calculated suspended sediment loads as discussed in the text.

Appendix E

ADCP BACKSCATTER CALIBRATIONS

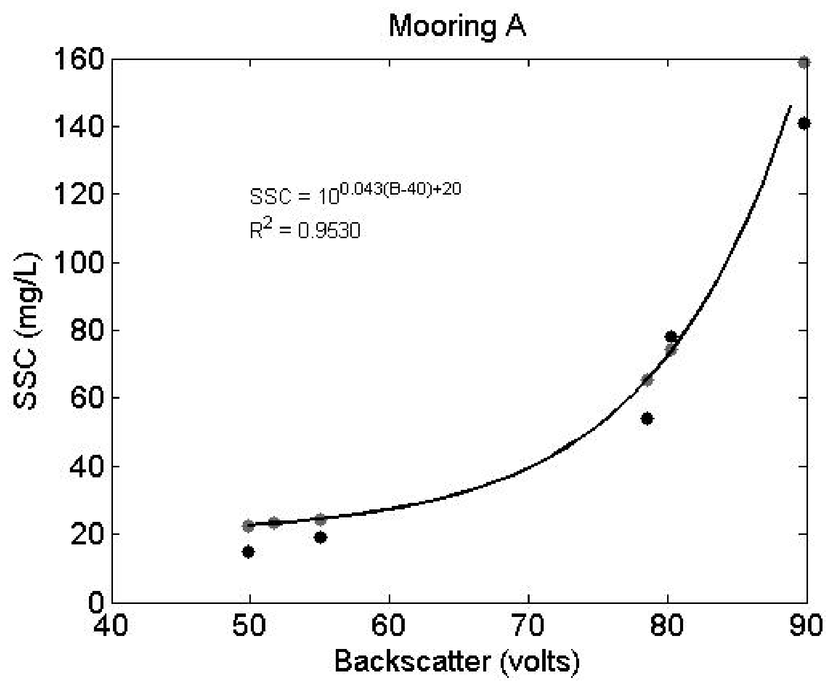

Figure E.1. Mooring A ADCP backscatter calibration.

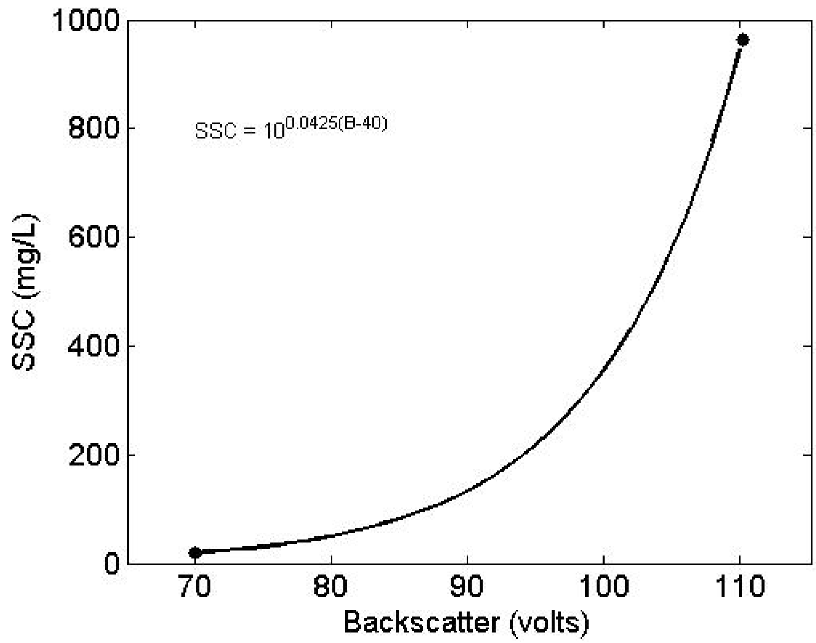

Figure E.2. Mooring C ADCP backscatter calibration.