ERDC/CHL TR-17-13

Coastal and Hydraulics Laboratory

US Army Corps of Engineers®
Engineer Research and Development Center

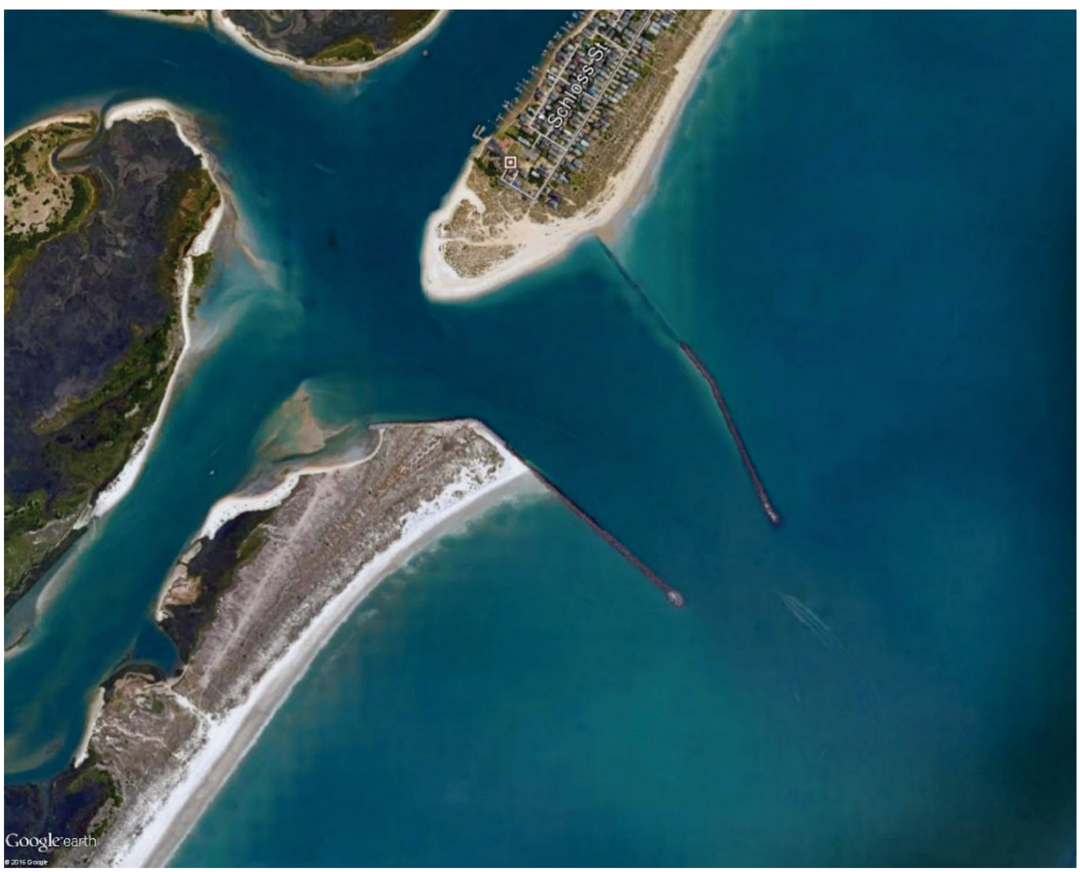
ERDC
INNOVATIVE SOLUTIONS for a safer, better world

Regional Sediment Management (RSM) Program

Sediment Budget Analysis; Masonboro Inlet, North Carolina

Kevin B. Conner and Linda S. Lillycrop

August 2017



Sediment Budget Analysis; Masonboro Inlet, North Carolina

Kevin B. Conner

U.S. Army Engineer District, Wilmington
P. O. Box 1890
Wilmington, NC 28403

Linda S. Lillycrop

U.S. Army Engineer Research and Development Center
Coastal and Hydraulics Laboratory
3909 Halls Ferry Road
Vicksburg, MS 39180-6199

Final report

Prepared for U.S. Army Corps of Engineers
Washington, DC 20314-1000

Under Project 454632, "Sediment Budget Analysis, Masonboro Inlet, NC"

Abstract

A sediment budget analysis was performed for the vicinity of Masonboro Inlet and adjacent beaches, by the U.S. Army Engineer District, Wilmington, for understanding response of the inlet complex and associated beaches to dredging of Masonboro Inlet and to dredged material placement operations along the beaches of Masonboro Island (south side of inlet) and Wrightsville Beach (north side of inlet). The analysis provides valuable information to assess the most effective beneficial use of dredged material from the Masonboro Inlet complex.

The analysis of longshore sediment transport calculations showed a net transport towards Masonboro Inlet from both sides of the inlet. The calculated transport rate from Masonboro Island onto the offshore ebb shoal of the inlet complex was 78,530 cubic yards per year (cy/yr) while the transport rate from Wrightsville Beach into the inlet and offshore ebb shoal of the inlet complex was 147,232 cy/yr.

The sediment transport calculated at the western end of Masonboro Island near Carolina Beach Inlet was 361,493 cy/yr to the west, within 2% of the previously estimated rate of 354,000 cy/yr (USACE 2000) for the area. The sediment transport rate calculated on the eastern end of Wrightsville Beach was 43,427 cy/yr toward the east.

Contents

Figures and Tables

Figures

Tables

Preface

This study was conducted for Headquarters, U.S. Army Corps of Engineers (HQUSACE), Washington, DC, under the USACE Regional Sediment Management (RSM) Program; Project 454632, "Sediment Budget Analysis; Masonboro Inlet, North Carolina" Project. The USACE RSM Program Manager was Ms. Linda S. Lillycrop, CEERD-HN-C. Mr. Jeffrey A. McKee was the HQUSACE Navigation Business Line Manager overseeing the RSM Program.

The work was performed by the U.S. Army Engineer District, Wilmington (SAW), and by the Coastal Engineering Branch (CEERD-HN-C) of the Navigation Division (CEERD-HN), U.S. Army Engineer Research and Development Center, Coastal and Hydraulics Laboratory (ERDC-CHL). At the time of publication, Ms. Tanya M. Beck was Chief, CEERD-HN-C; Dr. Jackie S. Pettway was Chief, CEERD-HN; and Mr. W. Jeff Lillycrop (CEERD-CHL) was the ERDC Technical Director for Civil Works and Navigation Research, Development, and Technology Transfer (RD&T) portfolio.

At the time of publication, the Deputy Director of ERDC-CHL was Mr. Jeffrey R. Eckstein, and the Director was Mr. José E. Sánchez.

The commander of ERDC was COL Bryan S. Green, and the Director was Dr. David W. Pittman.

Unit Conversion Factors

Multiply	By	To Obtain
cubic yards	0.76455	cubic meters
cubic yards per year	0.76455	cubic meters
feet	0.3048	meters
miles (statute)	1.609344	kilometers

1 Introduction

Regional Sediment Management (RSM) Program

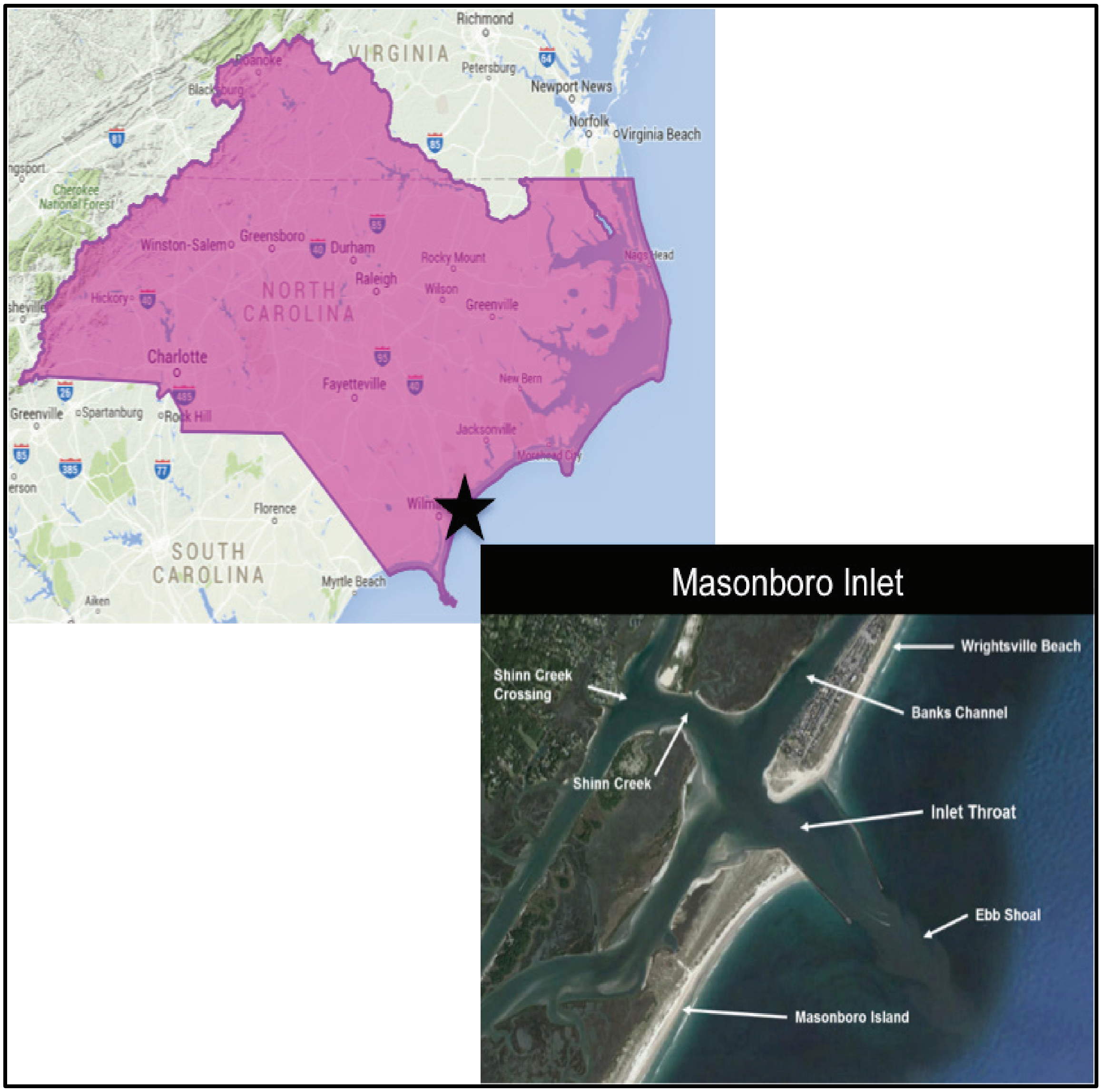
RSM is a systems-based approach to manage sediments and is implemented collaboratively with other federal, state, and local agencies. The objective of the U.S. Army Corps of Engineers (USACE) Regional Sediment Management (RSM) Program is to improve the management of sediments across multiple projects, manage sediments as a regional-scale resource, and implement adaptive management strategies which support sustainable navigation and dredging, flood and storm damage reduction, and environmental practices that increase operational efficiencies, the value of sediments, and social and environmental/ecosystem benefits, while reducing lifecycle costs. RSM is also a means to involve stakeholders to leverage resources, share technology and data, identify needs and opportunities, and develop solutions to improve the utilization and management of sediments.

Implementation of RSM develops a better understanding of the regional sediment transport processes through integration of regional data and application of tools that improve knowledge of the regional processes, provides a means to understand and share demands for sediment, and results in identifying and implementing adaptive management strategies to optimize use of sediments and streamline projects. The adaptive management strategies are developed and implemented through application of the best available science and engineering practices and use of policies that permit regional approaches. Benefits of this approach are improved partnerships with stakeholders, improved sediment utilization and project management on a regional scale, improved environmental stewardship, and reduced overall lifecycle costs (Lillycrop et al. 2011).

Background

Masonboro Inlet is a federally authorized Navigation Project located on the southeastern coast of North Carolina (Figure 1). It provides an entrance channel connecting the Atlantic Intracoastal Waterway (AIWW) to the Atlantic Ocean. The inlet is protected by dual jetties and is the only fully stabilized inlet in North Carolina. The north jetty, completed in 1966, was the first weir jetty constructed in the United States. The south jetty was constructed 14 years later and was completed in 1980. The inlet is bordered on the north (upcoast) by Wrightsville Beach, which has an active Hurricane Storm Damage Reduction Project. Downcoast of the inlet lies Masonboro Island, which is an undeveloped, state-managed National Estuarine Reserve.

Figure 1. Location map, Masonboro Inlet. (USACE Wilmington District in pink.)



Sand from the north passing over the weir and depositing in the inlet deposition basin serves as the source for renourishment of Wrightsville Beach. Sediment from the inlet deposition basin is backpassed northward to Wrightsville Beach and is also bypassed southward to Masonboro Island to mitigate downdrift impacts of the stabilized inlet. Studies undertaken in the late 1970s and early 1980s assessed the impact of the navigation project on the adjacent beaches, established cost-sharing formulae, and recommended sand bypassing/backpassing ratios that are still used today to manage the demands for sediment resources at the project site.

Objective

The objective of this study was to develop a sediment budget for the vicinity of Masonboro Inlet and adjacent beaches, to better understand the sediment sources, sinks, and transport patterns within the region.

A sediment budget provides an understanding of the sediment sources and sinks to quantify transport of littoral sediments, both natural and man induced, into and out of the region of interest for a given time period. The present study conducted the analysis of a sediment budget for understanding the response of the beaches and associated inlet complex to the dredging of Masonboro Inlet and to dredged material placement operations along the beaches of Masonboro Island (south side of the inlet) and Wrightsville Beach (north side of the inlet). The analysis provides valuable information to assess the most effective beneficial use of dredged material from the Masonboro Inlet complex.

Approach

The sediment budget analysis was conducted utilizing the application of the USACE Sediment Budget Analysis System (SBAS) (Rosati and Kraus 2001; Dopsovic et al. 2002). SBAS is a software tool for calculating and displaying local and regional sediment budgets that can include single or multiple inlets, estuaries, bays, and adjacent beaches.

A sediment budget is an accounting of sediment gains and losses, or sources and sinks, within a specified cell or in a series of connecting cells over a time period of interest. The difference between sediment sources and sinks in each cell or over the entire study area must equal the change in sediment volume within the cell or region, accounting for dredging and placement activities over the period.

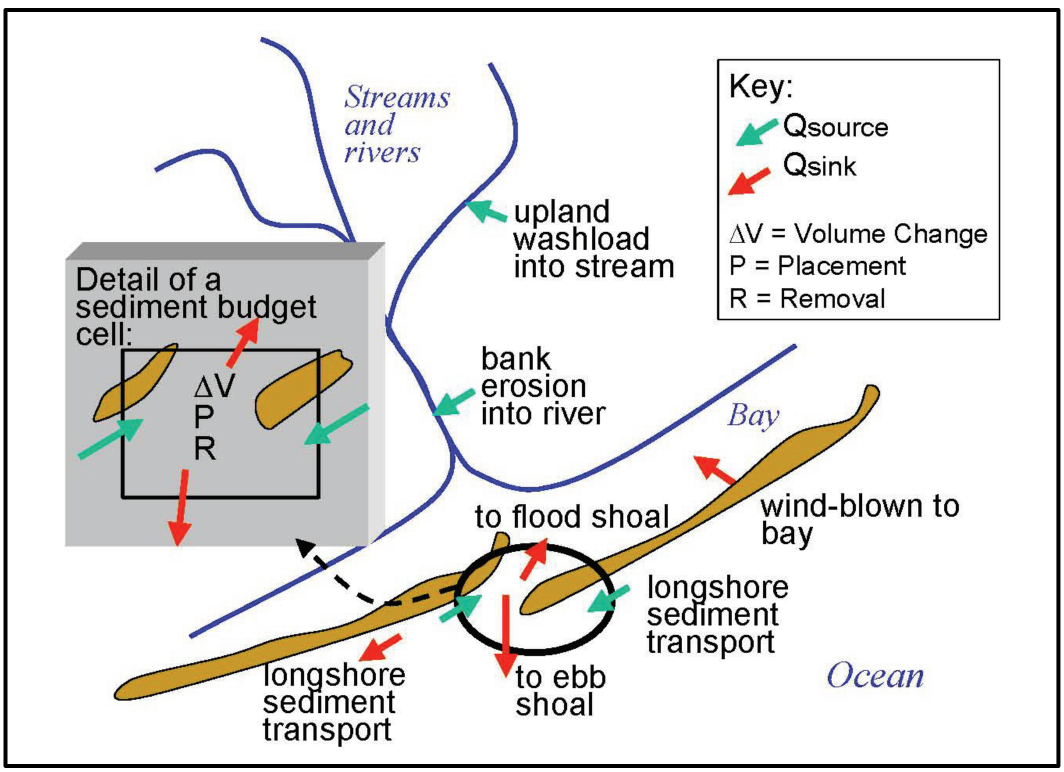
The algebraic expression for the sediment budget is given by the following equation:

$$\sum Q_{\text{source}} - \sum Q_{\text{sink}} - \Delta V + \text{P} - \text{R} = \text{Residual} \quad (1)$$

where Q_{source} and Q_{sink} are the sources and sinks to the control volume, respectively, and ΔV is the net change in volume within the cell. *P* and *R* are the amounts of material placed into and removed from the cell, respectively. *Residual* represents the degree to which the cell is balanced. For a balanced cell, the residual is zero.

For a region consisting of many contiguous cells, the budgets for each cell must balance to achieve a balanced budget for the entire study area. The terms used in Equation (1) are in consistent units, either as volume or as volumetric rate of change. For the present study, all units are expressed as rate of change in cubic yards per year. Figure 2 schematically illustrates typical parameters included in the sediment budget. Sources include longshore sediment transport and dredged material placement along the islands, where the source of the placed material is located within the inlet complex. Typical sediment budget sinks include longshore sediment transport, channel dredging, and losses to shoals. Note that a source to one cell can represent a sink from other cells.

Figure 2. Typical sediment budget parameters (after Dopsovic et al. 2002).



2 Masonboro Inlet Sediment Budget Cells

The extent of the Masonboro Inlet sediment budget includes approximately 7.3 miles of coastline along Masonboro Island (located south of Masonboro Inlet), approximately 4.0 miles of coastline along Wrightsville Beach (located north of the inlet), the inlet through its connection to the AIWW, and a portion of Banks Channel that serves as a borrow source for the Coastal Storm Damage Reduction (CSDR) project on Wrightsville Beach. The time period of interest spans 40 years, from 1974 to 2014; however, this varies for each analysis cell based on data availability. This 40-year analysis period includes four dredging and placement activities in 1998, 2002, 2006, and 2010. The most recent placement in April 2014 is not included in the analysis.

The study area was divided into 16 littoral cells for the sediment budget analysis as shown in Figure 3. The cell divisions along the beaches were based on similar bathymetric features observed in the available survey data and separated by areas along the beach that have received historic placement of material over the analysis period. This resulted in six cells along Masonboro Island (Cells 1 through 6) and five cells along Wrightsville Beach (Cells 7 through 11). The inlet area is comprised of five cells. Cell 12 represents the ebb shoal seaward of the jetties. The inlet throat between the jetties, represented as Cell 13, is a designated source of borrow material for the CSDR project on Wrightsville Beach. Banks Channel, represented by Cell 14, is another source of material for the CSDR project. The remaining two cells are Shinn Creek (Cell 15) and the Shinn Creek Crossing at the Intracoastal Waterway (Cell 16).

The current sediment budget primarily addresses littoral sediments or sediments derived principally from the beaches, consisting of generally sandy material. Other sediments consisting of fine-grain sand, silt, and mud are also known to be present in the system and are generally found to deposit farther offshore beyond the designated cell boundaries. There are also some fine sediment deposits within Shinn Creek (Cell 15) and Shinn Creek Crossing (Cell 16); however, these deposits are relatively minor.

Figure 3. Littoral cells for the Masonboro Inlet, SBAS analysis.

3 Sediment Budget Cell Values

The sediment budget computed by SBAS for each cell was derived from beach profile surveys and bathymetric surveys of the channel and surrounding shoal areas taken over the period of 1974–2014. The available surveys were supplemented by dredging and beach disposal records to account for material deposited into or dredged from the cell. The results were a value assigned to each cell for the net volume change, ΔV, the amount of sediment placed, *P,* and the quantity of material removed, *R*. Each quantity is expressed as an equivalent unit volume (cubic yard per year) over the 40-year period of analysis.

Beach cells

The values computed for all the beach cells are summarized in Table 1. The net volume change, ΔV*,* is based on comparison of the 1997 and 2013 beach profile surveys for Wrightsville Beach and 1999 through 2009 beach profile surveys for Masonboro Island. Each cell length extended offshore to the observed depth of closure. The placement, *P,* includes all material disposed during the dredging operations over the respective time periods.

For Wrightsville Beach, a total of 2,911,263 cubic yards (cy) of sediment were placed over the period of analysis, which included four placements along approximately the same section of beach and represented in Cell 9. This total equates to an overall placement rate of 181,000 cubic yards per year (cy/yr). In terms of measured net volume change, two of the five cells (Cells 7 and 11) were found to have net losses, and the remaining three had net gains. The cells showing a negative ΔV were located along the southern end of Wrightsville Beach, within the fillet area of the north jetty and within the fill placement area that represents approximately the middle half of Wrightsville Beach (Cell 9).

Overall, the volumetric cell gains were less than the computed cell losses along Wrightsville Beach, resulting in a ΔV of -140,760 cy measured over the period of analysis. This equates to a rate of -8,705 cy/yr. A comparison of the placement rate to the measured volume change rate implies that there should be an overall sediment requirement of 189,700 cy/yr along Wrightsville Beach to achieve a balanced budget.

Table 1. Beach cell values used in sediment budget calculations for Wrightsville Beach and Masonboro Island.

Wrightsville Beach Cell Values									
		Delta Volume (ΔV)		Placement (P)					
	Profile	Measured	Rate	Mar-98	Mar-02	Mar-06	Jan-10	Total	Rate
SBAS Cell		CY	CY/YR	CY	CY	CY	CY	CY	CY/YR
7	Profile 3-30	-41,516	-2567						
8	Profile 39-49	37,756	2335						
9	Profile 60-159	-283,460	-17530	1,116,573	783,690	560,000	451,000	2,911,263	181,000
10	Profile 168-200	45,024	2784						
11	Profile 200-220	101,435	6273						
Total		**-140,760**	**-8,705**	**1,116,573**	**783,690**	**560,000**	**451,000**	**2,911,263**	**181,000**

Masonboro Island Cell Values									
		Delta Volume (ΔV)		Placement (P)					
	Profile	Measured	Rate	Mar-98	Mar-02	Mar-06		Total	Rate
SBAS Cell		CY	CY/YR	CY	CY	CY		CY	CY/YR
1	Profile 10-31	-160,660	-17,463						
2	Profile 40-80	184,670	20,073						
3	Profile 90-140	-19,877	-2,161	555,654	518,826			1,074,480	116,791
4	Profile 150-210	-383,504	-41,685			120,000.00		120,000	13,043
5	Profile 219-270	-1,531,877	-166,508						
6	Profile 290-403	-942,480	-102,443						
Total		**-2,853,728**	**-310,188**	**555,654**	**518,826**	**120,000**		**1,194,480**	**129,835**

For the beach cells along Masonboro Island, a total of 1,194,480 cy of material was placed over three placement cycles between 1998 and 2006. This resulted in an equivalent placement rate of 129,835 cy/yr. For Masonboro Island, net volume change for each analysis cell was found to have net losses, with the most significant losses occurring along the southern third of the island in Cells 5 and 6. The measured volume change over the entire island was a loss of -2,853,728 cy, or a unit ΔV equaling -310,188 cy/yr. In comparing the overall placement rate with the measured rate of volume change, the Masonboro Island cells would collectively have to receive a net influx of 440,200 cy/yr to achieve a sediment balance for the island.

Channel cells

For the beach sediment budget, the overall volume change was computed for cells comprising the inner portion of Masonboro Inlet through the AIWW crossing. Data availability varied throughout the system by reach. For this analysis, historical research was limited to years 2005–2014, where adequate coverages of the inlet areas were available. Future updates to this sediment budget will further refine and improve the calculated shoaling rates used in the development of this sediment budget. The inlet throat area is represented by Cell 13, which represents the authorized dredging area between the jetties. The computed ΔV along with R, the volume removed by dredging, are listed in Table 2 for the channel cells.

The measured volume change for the inlet throat area (Cell 13) over the period of March 2006 through April 2014 was a gain of 151,650 cy. This period of analysis included two dredging events in April 2006 and March 2010. During these dredging occurrences sediment was removed and placed onto the adjacent beaches, with approximately 18% of the material going to Masonboro Island and 82% going to Wrightsville Beach in 2006. During the 2010 event, approximately 55% was placed on Masonboro Island and approximately 45% was placed on Wrightsville Beach.

Table 2. Channel cell values used in sediment budget calculations for Wrightsville Beach and Masonboro Island.

Inlet Channel Cells										
		Delta Volume (ΔV)		Removal (R)						Shoaling Rate
	Profile	Measured	Rate	Apr-06	Mar-09	Mar-10	Aug-13	Total Maint	Rate	Rate
SBAS Cell		CY	CY/YR	CY		CY	CY	CY	CY/YR	CY/YR
13	Inlet Throat	151,650	18,750	469,600.00		746,700.00		1,216,300.00	152,040	97,100.00
14	Banks Channel	-356,360	-50,140	232,900.00		257,300.00		490,200.00	61,280	13,400.00
15	Shinn Creek	25,230	8,720							11,260.00
16	Shinn Creek Crossing	-62,760	-10,720		37,070.00		29,060.00	66,130.00	7,460	7,200.00
Total		**-242,240**	**-33,390**	**702,500**	**37,070**	**1,004,000**	**29,060**	**1,772,630**	**220,780**	**128,960**

The total amount of material removed by maintenance dredging was 1,216,300 cy based on the dredge operation logs from the contracts. In terms of volume change rate, the equivalent ΔV amounts to a gain of 18,750 cy/yr for the inlet throat area. By comparison, the average annual removal rate is 152,040 cy/yr based on the maintenance dredging volumes. Therefore, to achieve an overall sediment balance within the channel area, a net influx of sediment is needed in the amount of 170,790 cy/yr. This quantity is the sum of the volume change plus the quantity removed. In accordance with Equation (1),

$$\sum Q_{source} = \Delta V + R, \ or$$

$$\sum Q_{source} = 18{,}750\ cy/yr + 152{,}040\ cy/yr = 170{,}790\ cy/yr$$

The Banks Channel area, located behind Wrightsville Beach and represented by Cell 14, functions as a designated borrow source for the CSDR project on Wrightsville Beach. The measured volume change for the Banks Channel area (Cell 14) over the period covering March 2006 through April 2013 was a loss of 356,360 cy. This period of analysis included the same two dredging and placement operations previously discussed for April 2006 and March 2010. The total amount of material removed by maintenance dredging was 490,200 cy based on the dredge operation logs from the contract. In terms of volume change rate, the equivalent ΔV amounts to a loss of 50,140 cy/yr for this area. By comparison, the average annual removal rate is 61,280 cy/yr based on the maintenance dredging volumes. To achieve an overall sediment balance within the channel area, a net influx of sediment is needed in the amount of 11,140 cy/yr. This quantity is the sum of the volume change plus the quantity removed. In accordance with Equation (1),

$$\sum Q_{source} = \Delta V + R, \ or$$

$$\sum Q_{source} = -50{,}140\ cy/yr + 61{,}280\ cy/yr = 11{,}140\ cy/yr$$

The Shinn Creek area represented by Cell 15 is the connection between Banks Channel and the Intracoastal Waterway. The measured volume change for Cell 15 over the period of May 2011 through April 2014 was a gain of 25,230 cy. Limited survey data are available for this area. Communication with the Wilmington District (SAW) Operations Division indicated the area is not regularly dredged, and as a result, there is no calculation for annual removal of material from Shinn Creek. In terms of volume change rate, the equivalent *ΔV* amounts to a gain of 8,720 cy/yr for this area. To achieve an overall sediment balance within the channel area, a net influx of sediment is needed in the amount of 8,720 cy/yr. This quantity is the sum of the volume change plus the quantity removed. In accordance with Equation (1),

$$\sum Q_{source} = \Delta V + R, \ or$$

$$\sum Q_{source} = 8{,}720 \ cy/yr + 0 = 8{,}720 \ cy/yr$$

The final area of analysis within the channel is the Shinn Creek Crossing of the AIWW, which is represented by Cell 16. The measured volume change for this area (SBAS Cell 16) over the period of May 2008 through March 2014 was a loss of 62,760 cy. This period of analysis included two dredging events where dredged material was removed from the system and placed in upland disposal areas. These occurred in March 2009 and August 2013. The total amount of material removed by maintenance dredging was 66,130 cy based on survey measurements of the area. In terms of volume change rate, the equivalent *ΔV* amounts to a loss of 10,720 cy/yr for this area. By comparison, the average annual removal rate is 7,460 cy/yr, based on the available survey data. Therefore, to achieve an overall sediment balance within the channel area, a net outflow of sediment is needed in the amount of 3,260 cy/yr. This quantity is the sum of the volume change plus the quantity removed. In accordance with Equation (1),

$$\sum Q_{source} = \Delta V + R, \ or$$

$$\sum Q_{source} = -10{,}720 \ cy/yr + 7{,}460 \ cy/yr = -3{,}260 \ cy/yr$$

Table 2 presents the computed shoaling rates for each channel reach. These rates were computed based on the channel surveys following each dredging cycle using a least square regression method. Where sufficient data were available to represent multiple dredging cycles, shoaling rates were computed for each dredging cycle and averaged to develop a representative shoaling rate for the area. The sum of the shoaling rates over the inlet reaches discussed above amounts to 128,960 cy/yr. This value falls short of the 187,390 cy/yr needed to achieve the collective balance of the inner channel cells. The discrepancy may be related to multiple factors, including survey data availability (both temporal and in coverage extent) and accuracy of dredging records.

Offshore shoal

Table 3 presents the volumetric change data associated with the shoal area located offshore of the Masonboro Inlet jetties. This area is represented by Cell 12. The offshore volumetric change has a high degree of uncertainty in the analysis, resulting from a limited survey database as well as a limited coverage of overlapping data. The period covered in the analysis of the offshore data was 1974 through 2010 with only four surveys included in this time period, specifically surveys conducted in 1974, 1998, 2008, and 2010.

Table 3. Offshore shoal area cell values used in sediment budget calculations for Wrightsville Beach and Masonboro Island.

Offshore Shoal			
		Delta Volume (ΔV)	
	Profile	Measured	Rate
SBAS Cell		CY	CY/YR
12	Offshore Shoal	1,186,081	34,400
Total		**1,186,081**	**34,400**

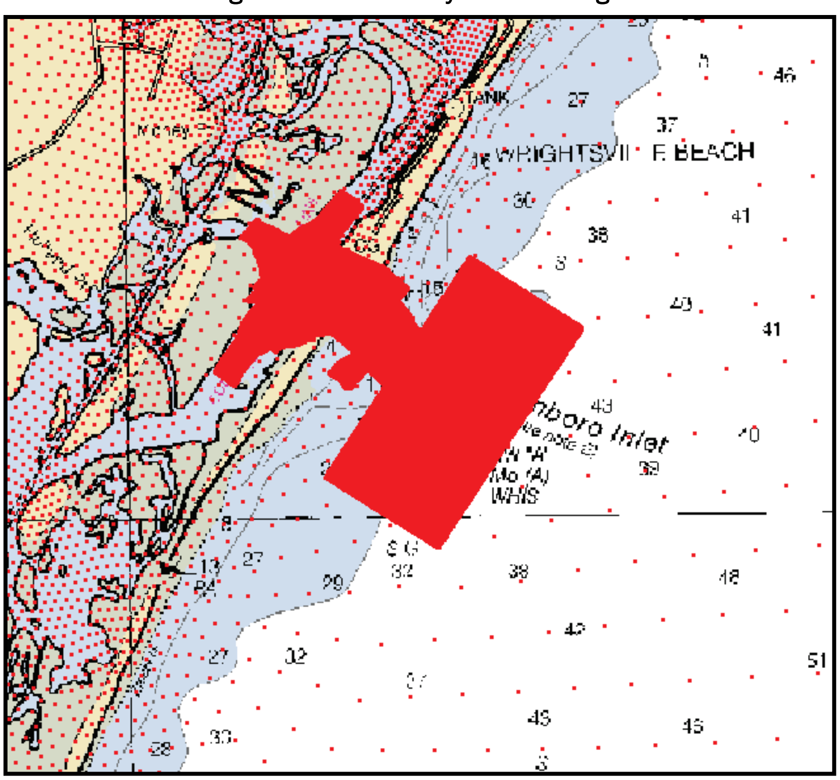
As indicated in the Table 3, the change measured over the period of analysis is a net gain for the offshore shoal of 1,186,080 cy. The equivalent annual ΔV rate of change is 34,400 cy/yr.

4 Sediment Fluxes

Longshore sediment transport rates were calculated at selected locations of interest along Masonboro Island and Wrightsville Beach. These transport rates were computed using the latest version of the U.S. Army Engineer Research and Development Center (ERDC), Coastal Modeling System (CMS) numerical simulation wave model (CMS-Wave) (Lin et al. 2008, 2011). CMS-Wave simulates a steady-state spectral transformation of directional random waves co-existing with ambient currents in the coastal zone. The model operates on a coastal half-plane, implying waves can propagate only from the seaward boundary toward shore. It includes features such as wave generation, wave reflection, and bottom frictional dissipation.

CMS-Wave requires accurate bathymetry data to construct a computational grid over which waves propagate and transform. The bathymetry used for the CMS-Wave grid was obtained during a 2010 survey. The data set is referenced to the North Carolina State Plane Coordinate System and to the vertical mean tidal level datum, which represents the vertical datum of the model. Figure 4 shows the boundaries of the survey data sets.

Figure 4. 2010 survey data coverage.



The CMS-Wave model domain includes Masonboro Inlet and the offshore ERDC Wave Information Studies (WIS) Station 63298 (http://wis.usace.army.mil) that provides hindcast modeled incident waves to force the CMS-Wave model (Figure 5). The grid boundaries were located away from the study area to eliminate boundary effects and ensure accurate development and propagation of the modeled parameters. The grid extends approximately 14.6 kilometers (km) along the shoreline and 12.0 km offshore (Figure 5). The offshore grid boundary is aligned with WIS Station 63298. The model grid consists of 119,948 grid cells, with increased resolution in the nearshore area to adequately resolve wave energy propagation in the study area. The grid orientation was 143.83° (counterclockwise from east). The bathymetry of the CMS-Wave grid was obtained by interpolating survey data to the grid cells, shown in Figure 6.

Figure 5. Extent of CMS-Wave grid.

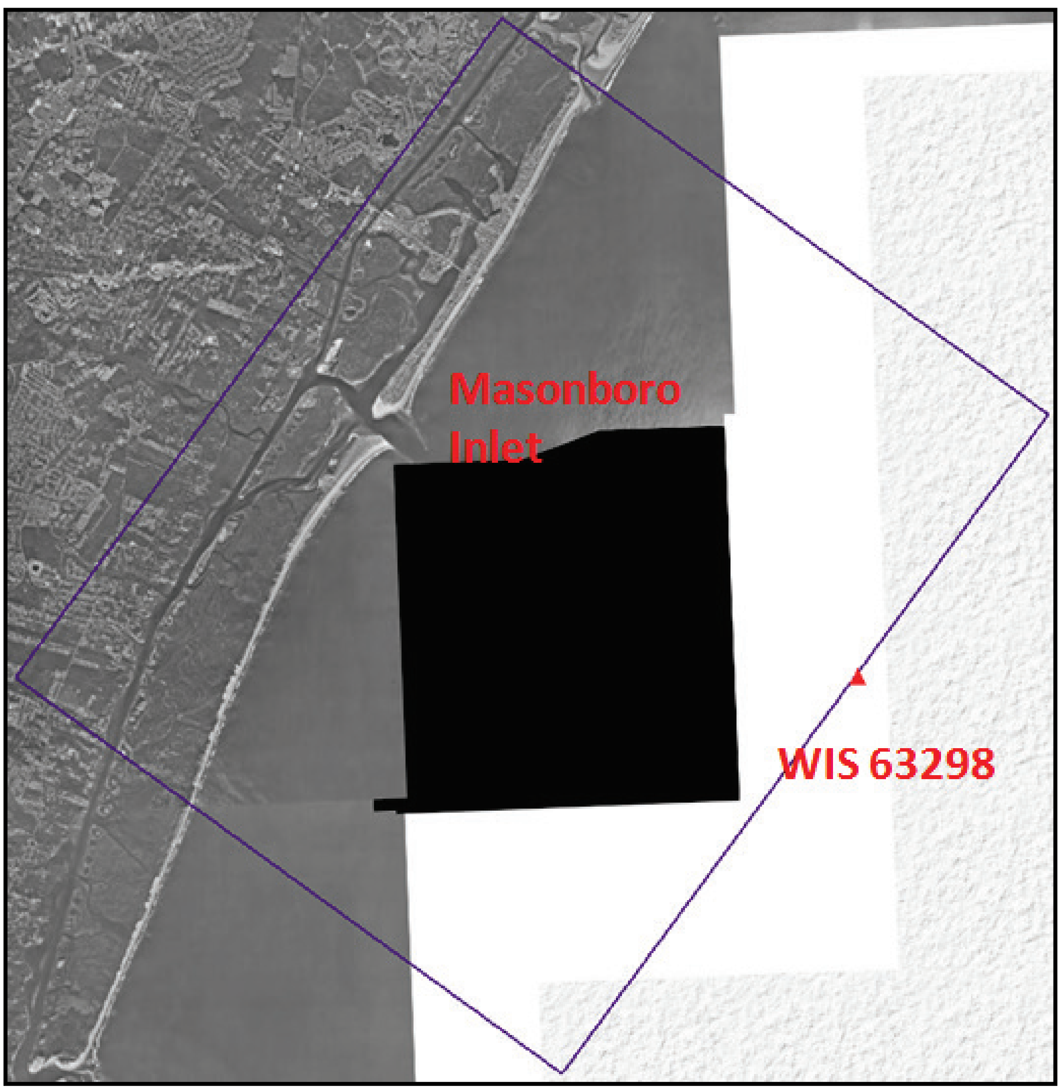
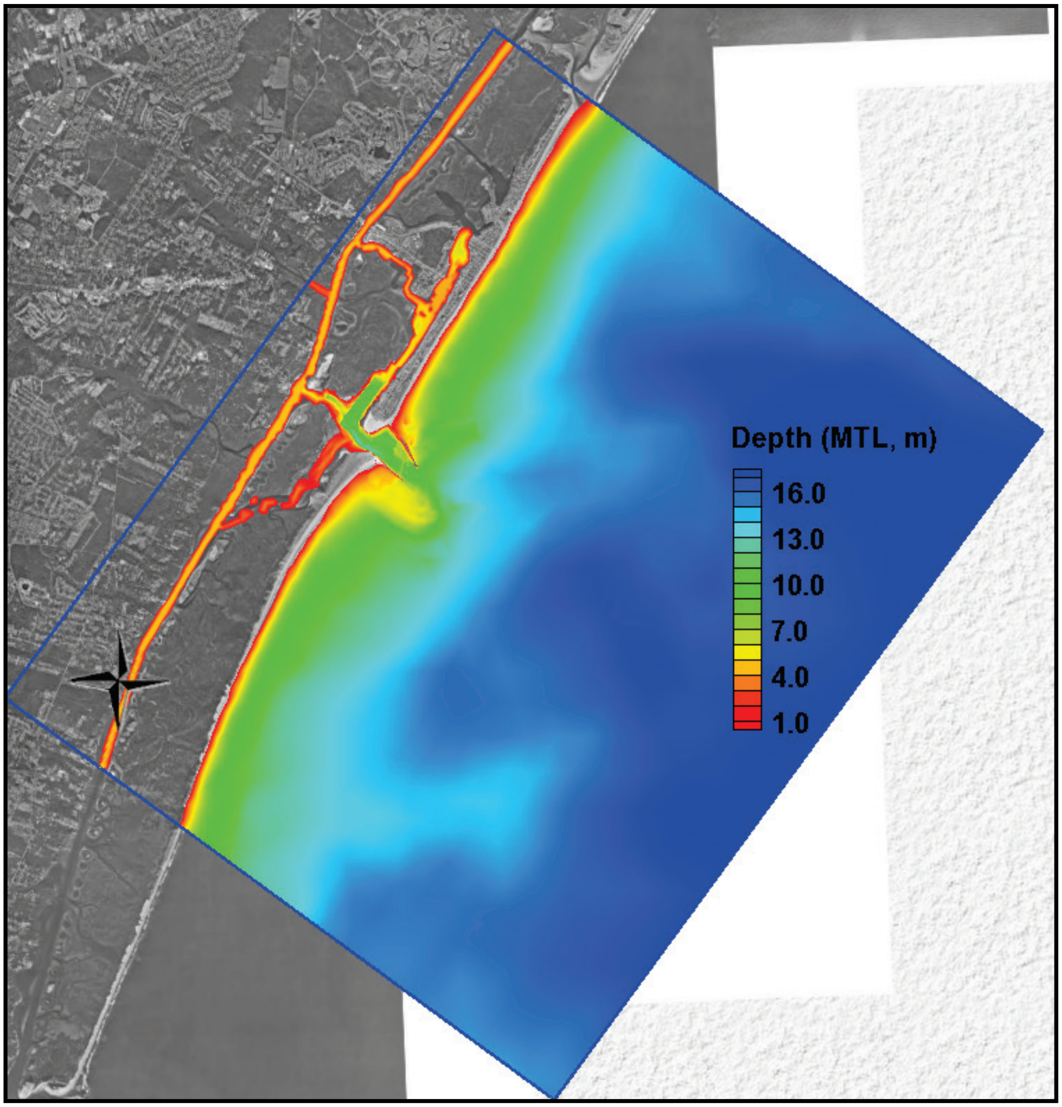


Figure 6. CMS-Wave grid bathymetry.



The CMS-Wave model was forced with directional wave spectra at the offshore grid boundary. Wave data used to determine the offshore wave conditions were obtained from the WIS Station 63298 located at Latitude 34.083° N and Longitude 77.667° W in water depth of 16 meters (m). The offshore wave climate provides representative wave boundary conditions. The model was not forced with wind or current fields, which are optional.

Figure 7 shows the wave rose diagram of wave height versus wave direction percent occurrence at WIS Station 63298 during 1980–2012. The figure shows that waves come mainly from the southeast quadrant. Table 4 presents the percent occurrence of heights and periods of all directions at WIS Station 63298 where wave heights generally range between 0 to 6.0 m, and wave periods range between 5 to 16 seconds (sec).

Figure 7. Wave rose diagram at WIS Station 63298.

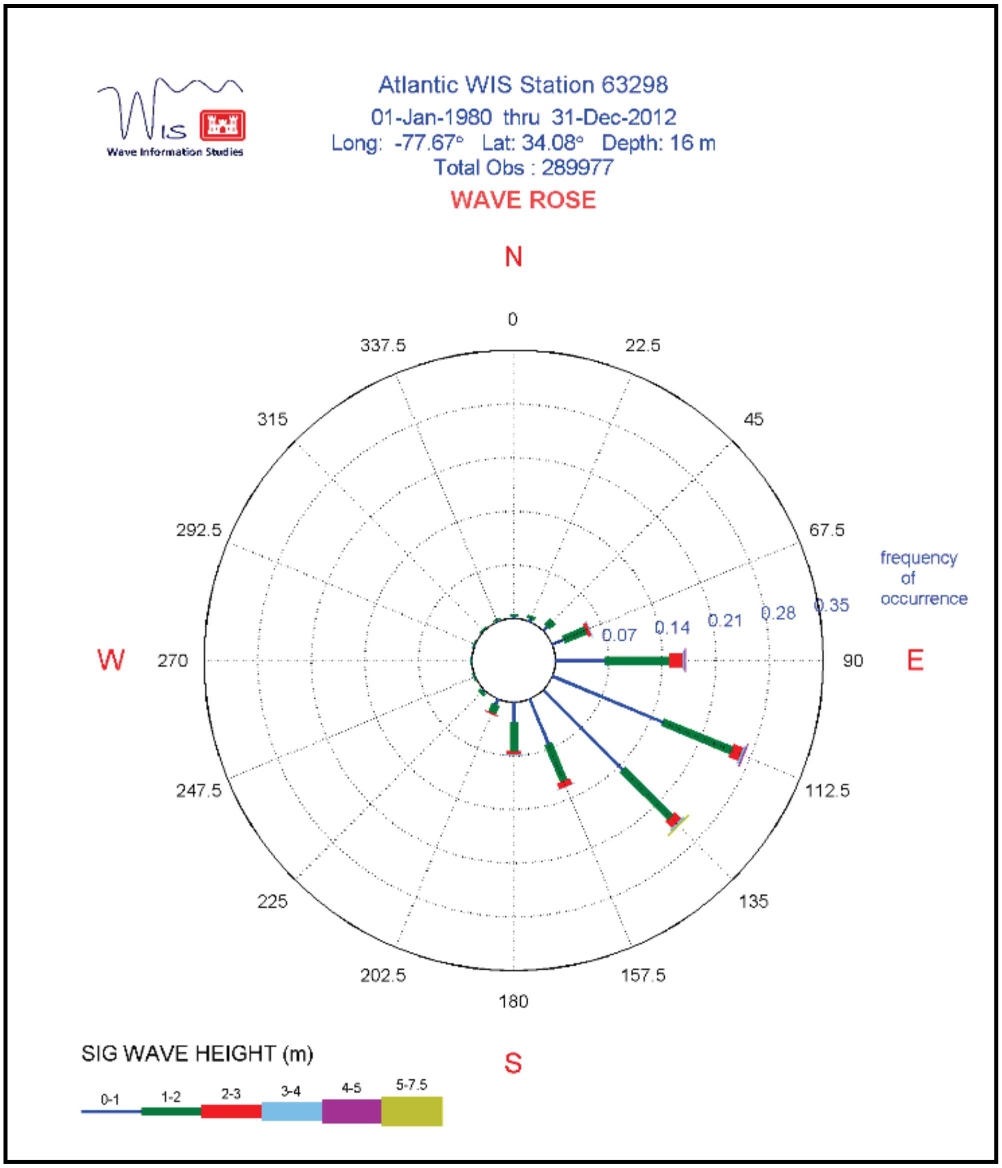


Table 4. Percent occurrence of wave heights and periods for all directions at WIS Station 63298.

ATLANTIC WAVE HINDCAST : ST63298_v02
ALL MONTHS FOR YEARS PROCESSED : 1980 - 2012
STATION LOCATION : (-77.67 W / 34.08 N)
DEPTH : 16.0 m

PERCENT OCCURRENCE (X1000) OF HEIGHT AND PERIOD
FOR ALL DIRECTIONS

NO. CASES : 289976
NO. CALMS : 19

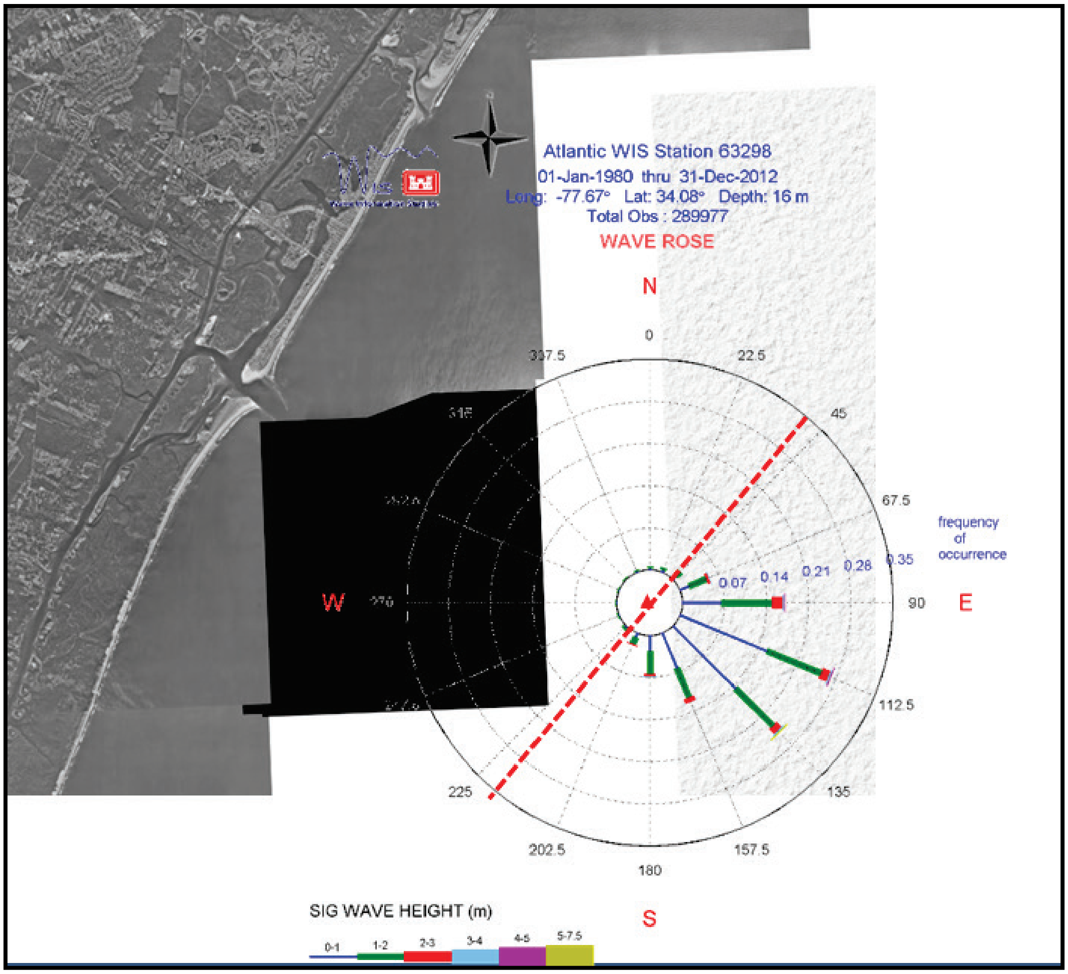
HEIGHT IN METERS	PARABOLIC FIT OF PEAK SPECTRAL WAVE PERIOD (IN SECONDS) <5.0	5.0-5.9	6.0-6.9	7.0-7.9	8.0-8.9	9.0-9.9	10.0-11.9	12.0-13.9	14.0-15.9	16.0-LONGER	TOTAL
0.00- 0.10	.	.	.	.	.	.	.	.	.	.	6
0.10- 0.49	280	173	545	1074	1066	1350	1170	335	116	28	6137
0.50- 0.99	3708	2866	3255	4917	8256	9640	8542	1515	521	188	43408
1.00- 1.49	2194	3655	3401	2981	3538	5355	7680	1913	467	123	31307
1.50- 1.99	104	778	1866	1603	1649	1491	2891	1131	314	47	11874
2.00- 2.49	.	16	300	673	800	723	969	591	170	41	4283
2.50- 2.99	.	2	4	114	317	352	483	278	137	58	1745
3.00- 3.49	.	.	.	2	45	127	275	115	63	35	662
3.50- 3.99	.	.	.	.	6	18	111	62	50	21	268
4.00- 4.49	.	.	.	.	1	2	41	33	31	6	114
4.50- 4.99	.	.	.	.	.	2	6	19	24	7	58
5.00- 5.99	.	.	.	.	.	1	6	17	40	29	93
6.00+	.	.	.	.	.	.	.	.	2	.	2
TOTAL	6286	7490	9371	11364	15678	19061	22174	6009	1935	583	

MEAN Hmo(M) = 1.1 LARGEST Hmo(M) = 6.2 MEAN TPP(SEC) = 8.9 FINITE

The WIS station mean-maximum summary table states the maximum monthly wave height and period during the 32 years of hindcast were examined. The maximum wave height and period were 6.15 m and 20.62 sec, respectively. From these statistics, a set of discrete conditions was selected for simulations. The wave height range was defined at 0.5 m interval from 0.0 m to 1.5 m, and at 2 m interval from 1.5 m to 4.0 m, and at 2.5 m interval from 4.0 m to 7.5 m. The wave period range was 5 to 13 sec at a 2 sec interval, and 13 to 20 sec at a 4 sec interval. The wave directions were incremented every 15°. Significant wave height, wave period, and vector mean wave direction (degrees clockwise from True north) were adopted in the analysis.

The regional shore line adopted in the study is oriented at 36.17° clockwise from north, as shown in Figure 8. Statistics were performed for onshore wave direction bands only (60° – 210°). Waves directed offshore were not considered in the analysis.

Figure 8. Orientation of regional shoreline and onshore wave bands at WIS Station 63298. (Black area is missing photography from the aerial image.)



The 32 years of hindcast record were used to develop a binned approach based on joint probability of wave direction, period, and height. A MathWorks MATLAB routine was used to calculate the joint probability of wave direction, period, and height. Table 5 shows the selected direction-period-height bins used to synthesize the wave climate. The total number of occurrences from the selected bins was 263,709, which represent approximately 91% of the total waves (289,976) at WIS Station 63298.

The frequency of occurrence of all possible height-period-direction combinations was estimated. The number of populated (non-zero) wave bin combinations listed in Table 5 is 367. For each wave bin, representative wave conditions with percent of occurrence more than 0.5 (or 0.5%) were selected to represent the normal or the most commonly occurring conditions in the wave climate for this study. Accordingly, 51 wave conditions with total percent of occurrence of approximately 62% were selected to represent the prevailing wave climate in the study area (Table 6). Also, four wave conditions with extreme wave heights and reasonable percent of occurrence were selected to represent storm conditions, as shown in Table 6.

Table 5. Selected wave bins.

Bin	Wave Direction (degree from North)	Wave Period (sec)	Significant Wave Height (ft)
1	60.0 – 75.0	5.0 - 7.0	0.00 - 0.50
2	75.0 – 90.0	7.0 - 9.0	0.50 - 1.00
3	90.0 – 105.0	9.0 - 11.0	1.00 - 1.50
4	105.0 – 120.0	11.0 - 13.0	1.50 - 2.00
5	120.0 – 135.0	13.0 - 15.0	2.00 - 3.00
6	135.0 - 150.0	15.0 - 20.0	3.00 - 4.00
7	150.0 - 165.0		4.00 - 5.00
8	165.0 - 180.0		5.00 - 7.50
9	180.0 – 195.0		
10	195.0 – 210.0		

Table 6. Representative wave conditions at WIS Station 63298.

Wave Condition	Wave Direction (degree from north)	Wave Period (sec)	Wave Height (m)	Percent of Occurrence
1	127.5	10	0.75	4.85
2	112.5	10	0.75	3.80
3	127.5	8	0.75	2.85
4	112.5	8	0.75	2.51
5	142.5	10	0.75	2.43
6	127.5	10	1.25	2.04
7	97.5	10	0.75	1.87
8	112.5	10	1.25	1.87
9	142.5	8	0.75	1.65
10	112.5	12	0.75	1.53
11	97.5	12	1.25	1.47
12	112.5	12	1.25	1.42
13	127.5	12	1.25	1.42
14	97.5	12	0.75	1.39
15	172.5	6	1.25	1.37
16	127.5	12	0.75	1.37

Wave Condition	Wave Direction (degree from north)	Wave Period (sec)	Wave Height (m)	Percent of Occurrence
17	97.5	10	1.25	1.35
18	157.5	6	0.75	1.26
19	142.5	6	0.75	1.18
20	157.5	10	0.75	1.17
21	157.5	6	1.25	1.16
22	142.5	10	1.25	1.11
23	97.5	8	0.75	0.99
24	127.5	8	1.25	0.98
25	172.5	6	0.75	0.97
26	127.5	6	0.75	0.88
27	82.5	6	1.25	0.88
28	187.5	6	1.25	0.81
29	112.5	6	0.75	0.78
30	112.5	8	1.25	0.77
31	142.5	8	1.25	0.73
32	142.5	6	1.25	0.69
33	82.5	10	1.25	0.68
34	157.5	8	0.75	0.68
35	142.5	12	0.75	0.66
36	82.5	12	1.25	0.65
37	127.5	12	1.75	0.65
38	127.5	10	0.25	0.64
39	112.5	12	1.75	0.62
40	127.5	8	0.25	0.62
41	112.5	10	0.25	0.62
42	97.5	12	1.75	0.61
43	157.5	10	1.25	0.60
44	82.5	10	0.75	0.60
45	97.5	10	1.75	0.59
46	97.5	8	1.25	0.59
47	112.5	8	0.25	0.57
48	97.5	6	1.25	0.55
49	142.5	12	1.25	0.55
50	82.5	12	0.75	0.53
51	67.5	6	1.25	0.51

Wave Condition	Wave Direction (degree from north)	Wave Period (sec)	Wave Height (m)	Percent of Occurrence
52	112.5	12	2.5	0.30
53	142.5	8	2.5	0.21
54	97.5	12	3.5	0.10
55	127.5	17.5	6	0.03

When wave angles deviate by approximately 60° or more from shore-normal direction, wave energy reduction from offshore to shore is usually significant (Thompson et al. 1999). Wave conditions within bins 1 and 10 deviate by 66.17° and 83.83°, respectively, from shore-normal direction. Therefore, only one wave condition (with low percent of occurrence) was selected from bin 1 as representative of the prevailing wave climate of the area.

The ERDC Surface-water Modeling System (SMS) (Zundel 2005) includes the capability to generate incident spectra using a TMA one-dimensional, shallow-water spectral shape (named for the three storm data sets used to develop the spectrum: TEXEL [lightship *Texel*], MARSEN [Marine Remote Sensing Experiment at the North Sea], and ARSLOE [Atlantic Ocean Remote Sensing Land-Ocean Experiment]) (Bouws et al. 1985). For each of the selected 55 wave conditions, TMA wave spectra were implemented by SMS software.

CMS-Wave model simulations were conducted for the synthesized 55 wave conditions to estimate the potential longshore transport in the study area. Figure 9 shows wave transformation for the most prevailing wave or Condition 1. Figure 10 shows wave transformation for a storm wave or Condition 52. Wave parameters were extracted at the two nearshore locations or points shown in Figure 11 to estimate the associated potential longshore transports. CMS-Wave estimates the breaking index. A value of 1.0 for the breaking index indicates wave breaking. The two points shown in Figure 11 were located seaward of the breaker line.

Figure 9. Wave transformation for most prevailing wave or condition 1.

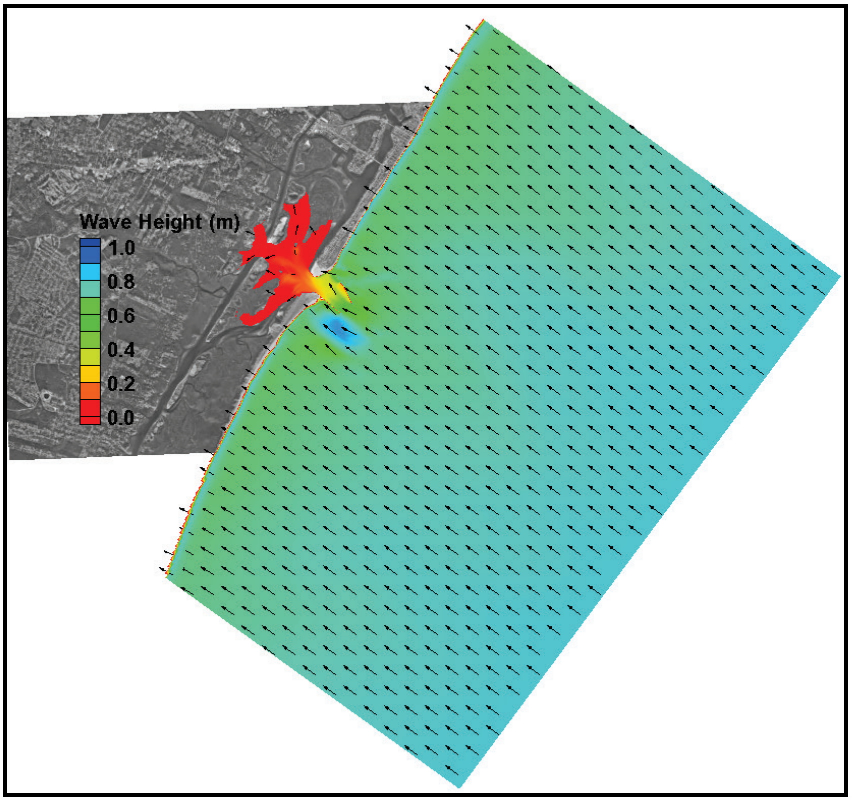


Figure 10. Wave transformation for a storm wave or condition 52.

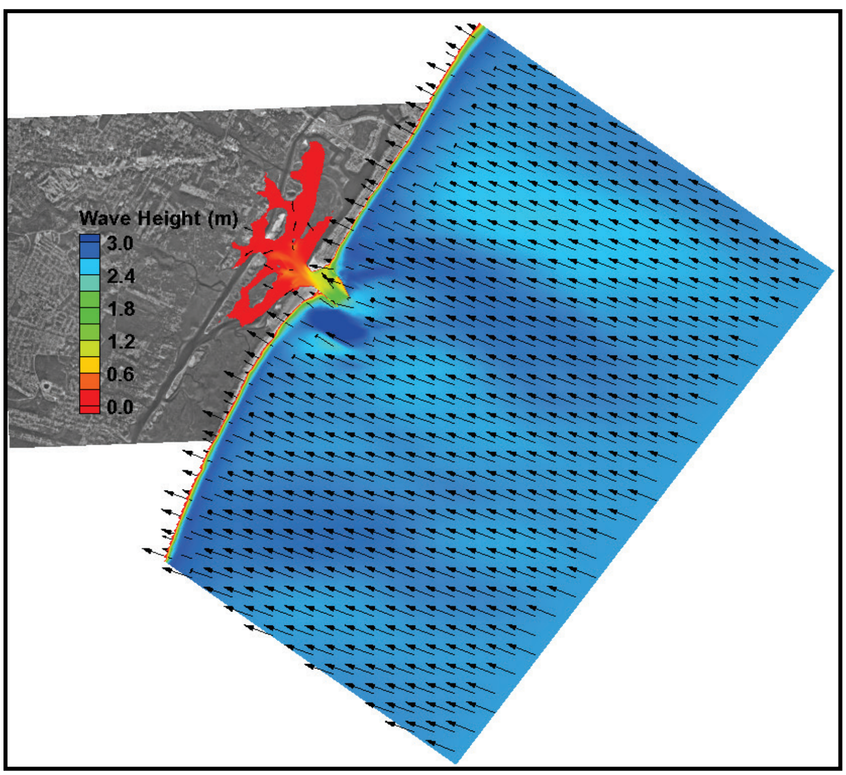


Figure 11. Location of potential longshore transport calculation Points 1 and 2.

The approach used to estimate the littoral transport in the area was similar to the method used by Thompson et al. (1999). Thompson et al. (1999) used the ERDC Steady Wave (STWAVE) (Smith 2001; Smith et al. 2001) to transform each incident wave condition to near-breaking and then transform the near-breaking wave to a point at which breaking begins by using the assumption of straight parallel bottom contours. The potential longshore transport rate from that breaking wave height and angle is computed. The WIS wave data were used to force the model, and the potential transport rate due to each incident wave condition was converted to an annual potential transport volume of sediment. Finally, potential transport contributions from all incident wave conditions were summed to give an estimate of annual longshore transport (Thompson et al. 1999).

The following equation was used to calculate the potential longshore sediment transport rate (USACE 2002):

$$Q = KH_{bs}^{2.5}\sin(2\alpha b) \qquad (2)$$

where:

Q = potential longshore transport rate
K = constant coefficient
H_{bs} = significant wave height at breaking
α_b = breaking wave angle relative to bottom contours.

Following standard convention, longshore transport directed to the right of an observer on the beach facing the ocean is positive, and transport toward the left is negative.

The coefficient K in Equation (2) was equal to 0.023 (Thompson et al. 1999) as used previously to calculate the potential longshore transport along Bald Head Island and Oak Island/Caswell Beach, NC (USACE 2011).

The wave-driven sediment transport potentials were computed from breaking conditions for each representative wave condition, proportionately to the probability of occurrence of each condition. The local shoreline angles near Points 1 and 2 were 36^o and 28^o, respectively. Results of all cases were grouped to calculate annual longshore sediment transport potentials. The computed longshore transport at Point 1 (east of the inlet) was estimated to be 147,000 cy/yr with its direction being toward the inlet. The net transport at Point 2 (west of the inlet) was estimated to be 81,140 cy/yr and was also directed toward the inlet.

5 Results and Discussion

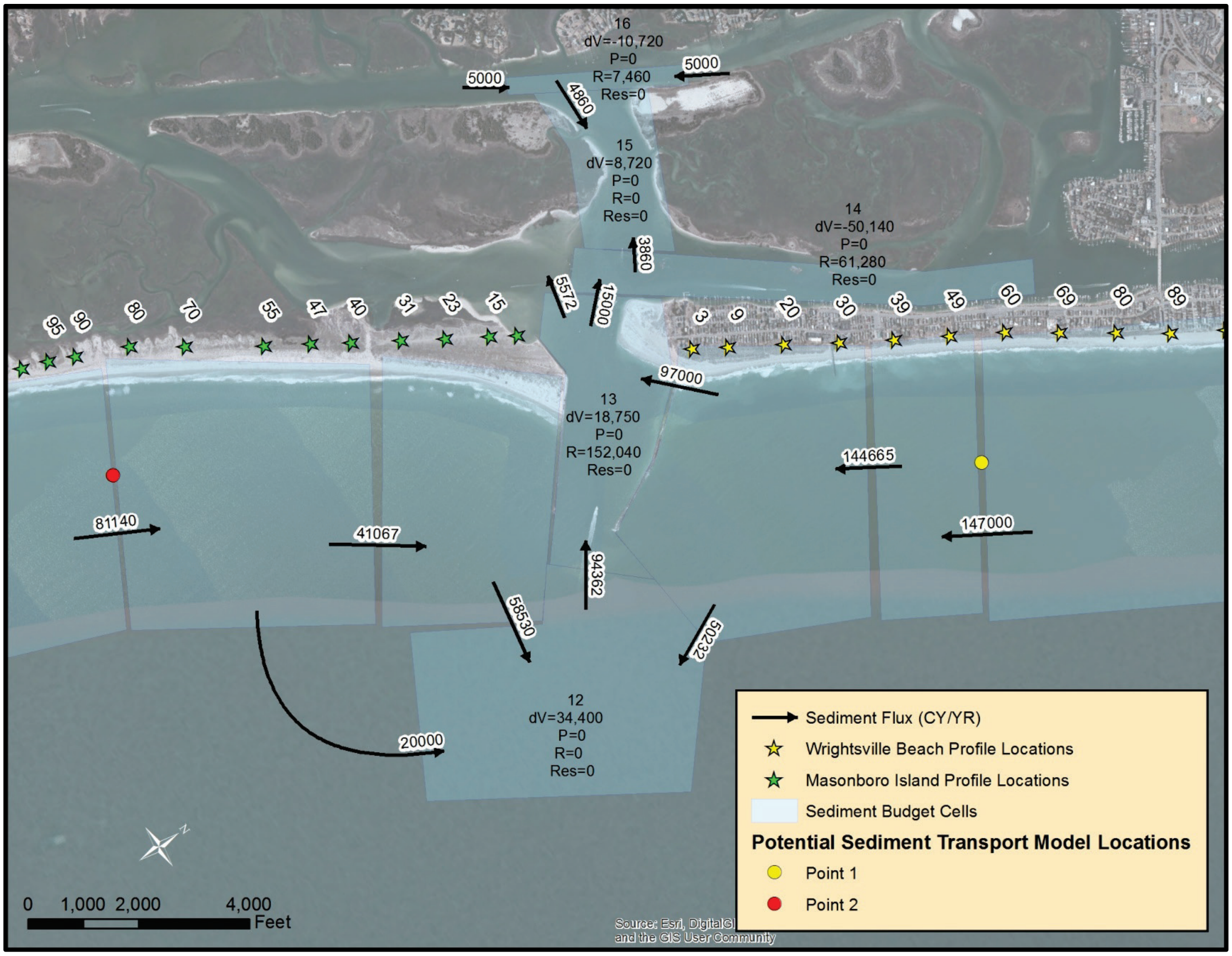
Results

Results of the sediment budget analysis for Masonboro Inlet are presented for (1) the inlet and offshore ebb shoal cells, (2) Masonboro Island cells, and (3) Wrightsville Beach cells. The resulting computational analyses determined the sediment flux values that were assumed necessary to achieve a balance within each cell (residual = zero), as well as the overall balance of the whole system. Detailed information for each cell includes ΔV, P, R, and the residual. The three specific areas of the sediment budget system are discussed.

Inlet and offshore ebb shoal cells

Figure 12 displays the cell division within the inlet area complex. Because the south jetty is impermeable, easterly longshore transport from Masonboro Island was assumed to be directed completely into the ebb shoal (Cell 12). Westerly transport from Wrightsville Beach (147,232 cy/yr) was split with approximately 65% directed over the north jetty weir into the inlet throat cell (97,000 cy/yr) and approximately 35% directed into the offshore ebb shoal Cell 12 (50,232 cy/yr). This computed split was necessary to balance the cells, based on the shoal and erosion rates previously calculated by beach and inlet reach. To balance the inlet system, it was assumed that a portion of the material transported into the offshore Cell 12 was retained (34,400 cy/yr), and the reminder of the sediment was transported landward into the inlet throat Cell 13 (94,362 cy/yr). A sink was considered from the offshore Cell 12 seaward; however, balancing the inlet cells required all known transport to be directed toward the inlet. Even with this assumption, the transport rate toward the inlet (Cells 13–16) is 191,362 cy/yr, which is less than the annual removal rate calculated for the inlet cells (220,780 cy/yr).

Figure 12. Masonboro Inlet sediment budget analysis cells.



The inlet throat sediment flux was balanced, and the remaining material was directed toward two areas. This included 15,000 cy/yr directed into the Banks Channel (Cell 14) while the remaining material (5,572 cy/yr) was assumed to feed the shoal on the west side of the inlet on the landward side of Masonboro Island. No data are available for this area. However, local knowledge of the region indicates there is increased shoaling in the area, consisting mostly of beach quality material. These computed quantities are necessary to balance the remainder of the cells, with the flux calculation points on the ends of Masonboro Island and Wrightsville Beach at the inlet serving as the control features.

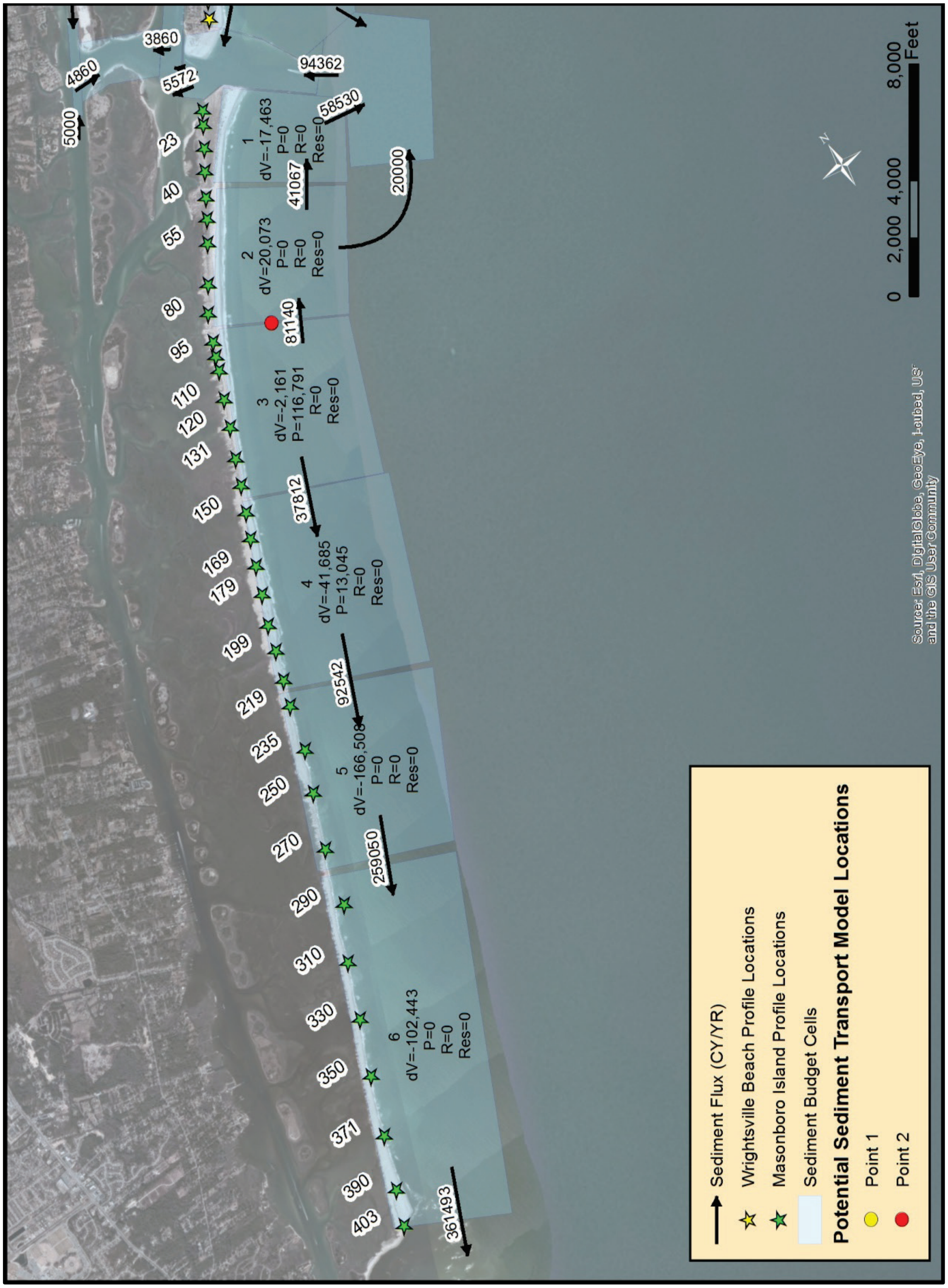
After the sediment quantities were balanced within the Banks Channel cell, the remaining yardage was directed into Cell 15, known as Shinn Creek. Analysis of this area was limited to only four surveys (May 2011, March 2012, March 2013, and April 2014) that indicated the area is shoaling at 8,720 cy/yr. SAW Operations Division indicated the area is not included as a navigable waterway and has not been dredged by the USACE. To balance the shoaling within this area, it was necessary to assume transport into the Shinn Creek region from the Shinn Creek Crossing section located in the Intracoastal Waterway, in addition to the material being transported into the area from Banks Channel.

The final region within the inlet area is Shinn Creek Crossing (Cell 16) where Shinn Creek intersects the Intracoastal Waterway. This region is maintained by the USACE on an as-needed basis. Ten historic surveys of the area were available ranging from May 2008 through March 2014. Analysis of these surveys indicates that the average shoaling rate for the area is 10,720 cy/yr, and the average dredging volume is 7,460 cy/yr. Material from this area is not considered beach quality and is disposed to one of the local upland disposal areas. To balance this final cell, an influx of approximately 10,000 cy/yr of sediment is required and assumed to be originating from the waterway/upland erosion due to the fine-grained nature of the dredge material.

Masonboro Island cells

Sediment transport along Masonboro Island was calculated by the CMS modeling described previously. Figure 13 shows the computation cells for Masonboro Island, as well as the location of the potential sediment transport location (Point 2) used in the CMS model. The balance of the cells comprising Masonboro Island (Cells 1 thru 6) was started at the specified longshore transport boundary between Cells 2 and 3. Proceeding eastward from this boundary, each successive cell was balanced by forcing the next longshore flux value to result in a zero cell residual. The result is increasing net westward transport moving along Masonboro Island until reaching the last cell near Carolina Beach Inlet. Calculated transport at the terminal (western) end of the island is 361,493 cy/yr to the west, away from Masonboro Inlet. This compares well with the Masonboro Island sediment budget computed between 1987 and 1992 (USACE 2000), whichshows the sediment transport at this location to be approximately 354,000 cy/yr, a difference of 2%.

Figure 13. Masonboro Island sediment budget analysis cells.



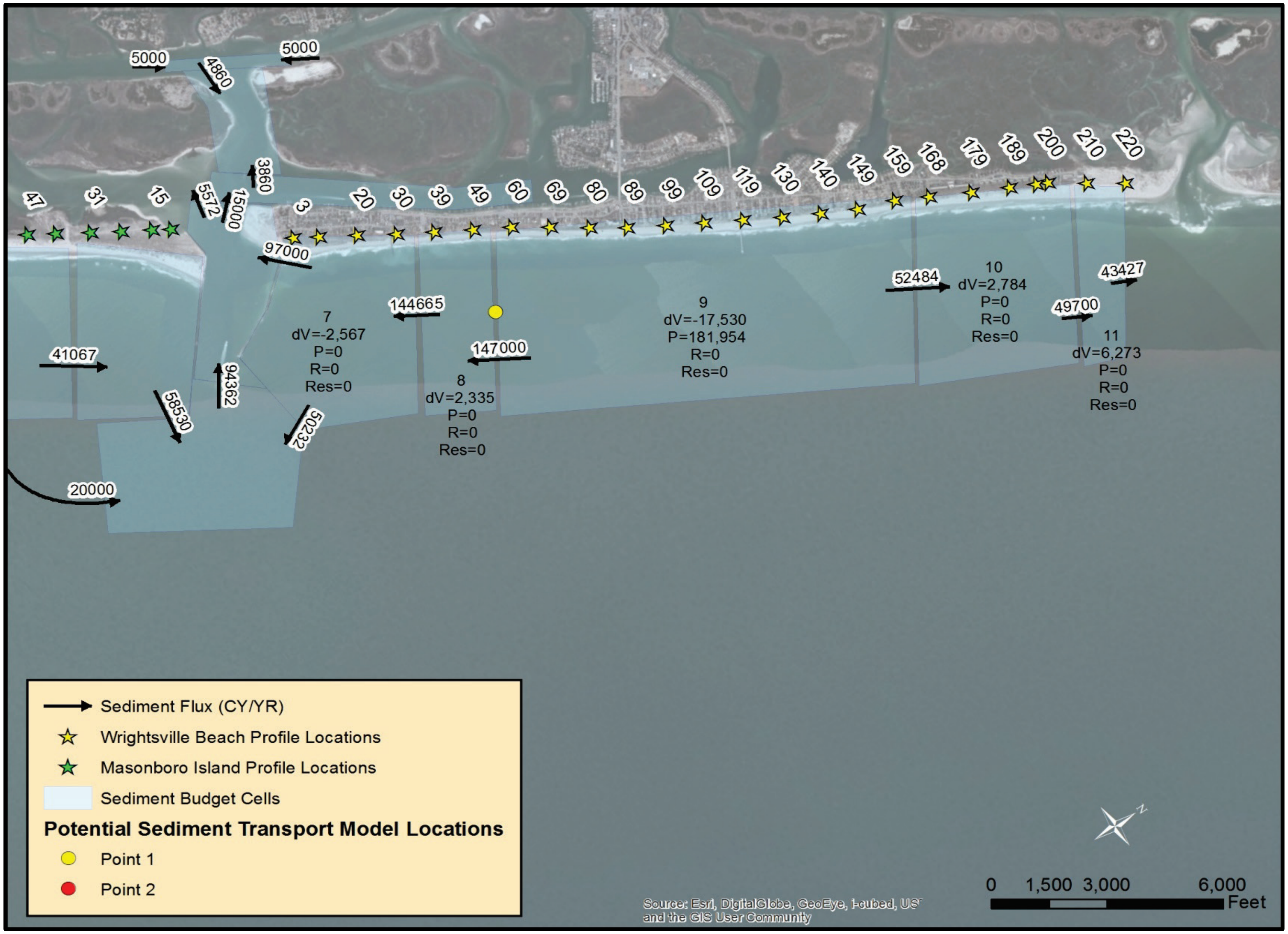
A similar process was performed for the cells proceeding eastward from the specified longshore transport boundary. After balancing the eastern cells along Masonboro Island (Cells 1 and 2) the remaining sediment material was directed into the Offshore Shoal (Cell 12) as described earlier. Material from Cell 1 was computed to be 58,530 cy/yr to the shoal, and material from Cell2 was computed to be 20,000 cy/yr to the shoal. The total quantity forced into the offshore shoal cell on the eastern end of Masonboro Island was 78,530 cy/yr.

Wrightsville Beach cells

For the beach cells comprising Wrightsville Beach (Cells 7 through 11 in Figure 14), the balancing was started at the assumed longshore transport boundary between Cells 8 and 9. Each successive cell was balanced by forcing the next longshore flux value to result in a zero cell residual. This results in a net eastward transport towards the inlet throughout Cells 7 and 8. The total transport rate from the most western cell (Cell 7) into the inlet and offshore shoal is calculated to be 147,232 cy/yr. To balance the computations, this volume per year requires approximately 65% (97,000 cy/yr) being transported over the weir portion of the jetty and approximately 35% (50,232 cy/yr) being deposited into the offshore shoal cell (previously discussed under section “Inlet and Offshore Ebb Shoal Cells”).

For the cells east of the transport boundary (Cells 9 through 11), a similar approach was made by balancing the cell nearest the transport boundary and shifting residual sand east. This balancing was calculated for each cell and resulted in net western transport values throughout the region. The total transport rate from the eastern-most cell of Wrightsville Beach (Cell 11) was calculated to be 43,427 cy/yr toward the east, away from Masonboro Inlet.

Figure 14. Wrightsville Beach sediment budget analysis cells.



6 Conclusions

The following conclusions have been deduced from this sediment budget analysis of Masonboro Inlet and the vicinity.

- The computed longshore sediment transport values indicate a net transport towards Masonboro Inlet from both sides of the inlet.
- The eastern transport rate from Masonboro Island (Cells 1 and 2) into the offshore ebb shoal of the inlet complex was calculated to be 78,530 cy/yr. The western transport rate from Wrightsville Beach (Cell 7) into the inlet (97,000 cy/yr) and onto the offshore ebb shoal (50,232 cy/yr) totaled 147,232 cy/yr. This total calculated sediment material entering the inlet and shoal complex (225,762 cy/yr) is approximately 65% (147,232 cy/yr) from Wrightsville Beach and 35% (78,530 cy/yr) from Masonboro Island. This constitutes approximately a 65% to 35% split of the combined material entering the inlet and ebb shoal.
- The western transport rate from Wrightsville Beach (Cell 7) was computed to be 147,232 cy/yr , with approximately 65% (97,000 cy/yr) going over the weir into the inlet and approximately 35% (50,232 cy/yr) moving onto the ebb shoal. Again, this also constitutes approximately a 65% to 35% split of the material from the western end of Wrightsville Beach going into the inlet and onto the shoal, respectively.
- Sediment transport at the western end of Masonboro Island near Carolina Beach Inlet (Cell 6) was calculated to be 361,493 cy/yr to the west away from Masonboro Inlet and was within 2% of the previously calculated transport rate of 354,000 cy/yr (USACE 2000) for the area. The sediment transport rate on the eastern end of Wrightsville Beach (Cell 11) was calculated to be 43,427 cy/yr toward the east, also away from Masonboro Inlet.

The results of this study will assist in developing an updated sand management strategy which optimizes the use of sediment within the Masonboro Inlet complex.

References

Bouws, E., H. Gunther, W. Rosenthal, and C. L. Vincent. 1985. "Similarity of the Wind Wave Spectrum in Finite Depth Water: 1; Spectral form." *Journal of Geophysical Research* 90(C1):975–986. http://dx.doi.org/10.1029/JC090iC01p00975

Dopsovic, R., L. Hardegree, and J. D. Rosati. 2002. *SBAS-A: SBAS for ArcView© Application*. ERDC/CHL CHETN-XIV-7. Vicksburg, MS: U.S. Army Engineer Research and Development Center. http://acwc.sdp.sirsi.net/client/search/asset/1011264

Lillycrop, L. S., J. D. Rosati, J. M. Wozencraft, and R. Dopsovic. 2011. "Advancement of Technologies for Practicing Regional Sediment Management." In *Proceedings, Coastal Sediments Conference, 2011*. Miami, FL.

Lin, L., Z. Demirbilek, H. Mase, J. Zheng, and F. A. Yamada. 2008. *CMS-Wave: A Nearshore Spectral Wave Processes Model for Coastal Inlets and Navigation Projects*. ERDC/CHL TR-08-13. Vicksburg, MS: U.S. Army Engineer Research and Development Center. http://acwc.sdp.sirsi.net/client/search/asset/1000803

Lin, L., Z. Demirbilek, and H. Mase. 2011. "Recent Capabilities of CMS-Wave; A Coastal Wave Model for Inlets and Navigation Projects." In *Proceedings, Symposium to Honor Dr. Nicholas Kraus. Journal of Coastal Research*. Special Issue 59, 7–14. http://dx.doi.org/10.2112/SI59-002.1

Rosati, J. D., and N. C. Kraus. 2001. *Sediment Budget Analysis System (SBAS: Upgrade for Region Applications*. ERDC/CHL CHETN-XIV-3. Vicksburg, MS: U.S. Army Engineer Research and Development Center. http://acwc.sdp.sirsi.net/client/search/asset/1011242

Smith, J. M. 2001. *Modeling Nearshore Wave Transformation with STWAVE*. ERDC/CHL CHETN-I-64. Vicksburg, MS: U.S. Army Engineer Research and Development Center. http://acwc.sdp.sirsi.net/client/search/asset/1000342

Smith, J. M., A. R. Sherlock, and D. T. Resio. 2001. *STWAVE: Steady-State Spectral Wave Model User's Manual for STWAVE, Version 3.0*. ERDC/CHL SR-01-1. Vicksburg, MS: U.S. Army Engineer Research and Development Center. http://acwc.sdp.sirsi.net/client/search/asset/1000103

Thompson, E. F., L. Lin, and D. L. Jones. 1999. *Wave Climate and Littoral Sediment Transport Potential; Cape Fear River Entrance, and Smith Island to Ocean Isle Beach, North Carolina*. TR-CHL-99-18. Vicksburg, MS: U.S. Army Corps of Engineers, Engineer Research and Development Center. http://acwc.sdp.sirsi.net/client/search/asset/1000606

U.S. Army Corps of Engineers (USACE), Wilmington District. 2000. *Special Report: Impact of Navigation and Storm Damage Reduction Projects on Masonboro Island, North Carolina*. Wilmington, NC: U.S. Army Corps of Engineers, Wilmington District.

USACE. 2002. *Coastal Engineering Manual*. EM 1110-2-1100: Part III, Coastal Sediment Processes; Chapter 2, Longshore sediment transport. Washington, DC: Headquarters, U.S. Army Corps of Engineers.

USACE. 2011. *Sediment Budget Analysis; Cape Fear Entrance, North Carolina*. Wilmington, NC: U.S. Army Corps of Engineers, Wilmington District.

Zundel, A. K. 2005. *Surface-Water Modeling System Reference Manual; Version 9.0*. Provo, UT: Brigham Young University, Environmental Modeling Research Laboratory.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE
August 2017

2. REPORT TYPE
Final Report

3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE
Sediment Budget Analysis; Masonboro Inlet, North Carolina

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Kevin B. Conner and Linda S. Lillycrop

5d. PROJECT NUMBER
454632

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) (see reverse)

8. PERFORMING ORGANIZATION REPORT NUMBER
ERDC/CHL TR-17-13

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Army Corps of Engineers
Washington, DC 20314-1000

10. SPONSOR/MONITOR'S ACRONYM(S)
HQUSACE

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT
A sediment budget analysis was performed for the vicinity of Masonboro Inlet and adjacent beaches, by the U.S. Army Engineer District, Wilmington, for understanding response of the inlet complex and associated beaches to dredging of Masonboro Inlet and to dredged material placement operations along the beaches of Masonboro Island (south side of inlet) and Wrightsville Beach (north side of inlet). The analysis provides valuable information to assess the most effective beneficial use of dredged material from the Masonboro Inlet complex.

The analysis of longshore sediment transport calculations showed a net transport towards Masonboro Inlet from both sides of the inlet. The calculated transport rate from Masonboro Island onto the offshore ebb shoal of the inlet complex was 78,530 cubic yards per year (cy/yr) while the transport rate from Wrightsville Beach into the inlet and offshore ebb shoal of the inlet complex was 147,232 cy/yr.

The sediment transport calculated at the western end of Masonboro Island near Carolina Beach Inlet was 361,493 cy/yr to the west, within 2% of the previously estimated rate of 354,000 cy/yr (USACE 2000) for the area. The sediment transport rate calculated on the eastern end of Wrightsville Beach was 43,427 cy/yr toward the east.

15. SUBJECT TERMS
Coastal sediments, Littoral drift, Masonboro Inlet (N.C.), Sedimentation and deposition, Sediment transport

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
					Kevin B. Conner
Unclassified	Unclassified	Unclassified	SAR	41	**19b. TELEPHONE NUMBER** *(Include area code)* 910-251-4867

7. Performing Organization Name(s) and Address(es) (concluded)

U.S. Army Engineer District, Wilmington
P. O. Box 1890
Wilmington, NC 28403

U.S. Army Engineer Research and Development Center
Coastal and Hydraulics Laboratory
3909 Halls Ferry Road
Vicksburg, MS 39180-6199