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Coastal and Hydraulics Laboratory

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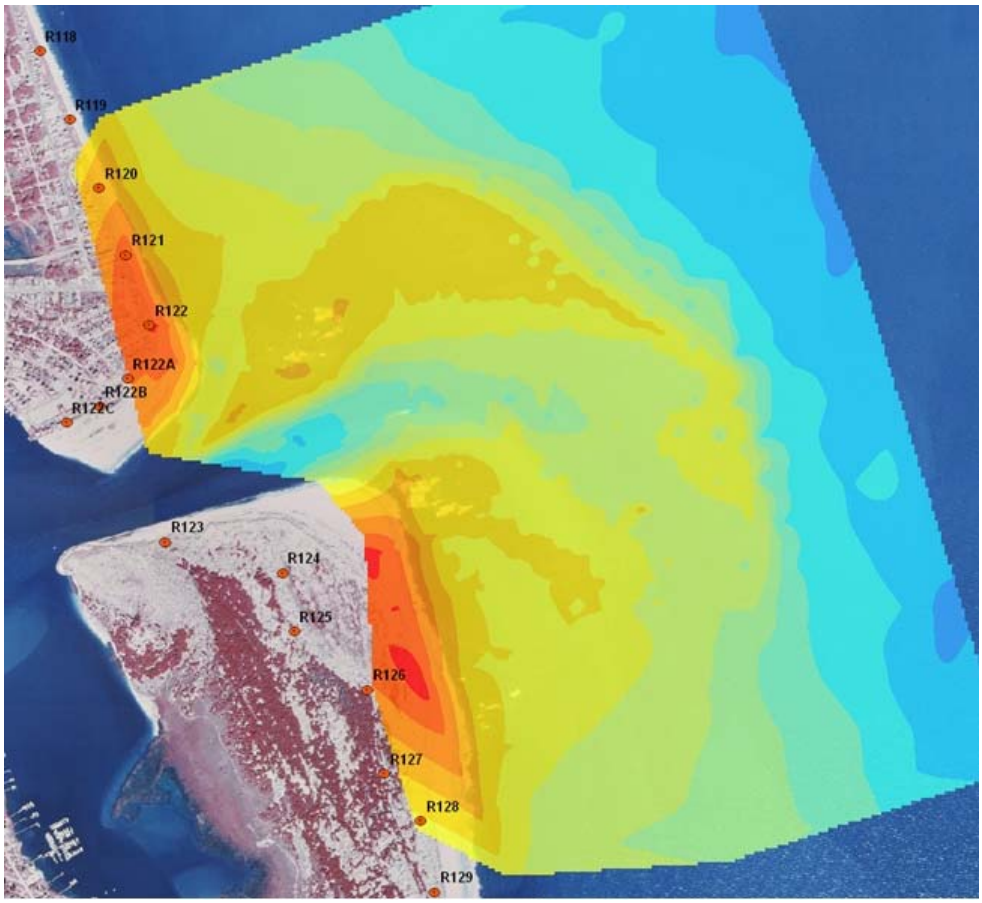
Coastal Inlets Research Program

St. Johns County, St. Augustine Inlet, FL

Report 1: Historical Analysis and Sediment Budget

Kelly Legault, Julie D. Rosati, Jason Engle, and Tanya M. Beck

August 2012



Bathymetry of St. Augustine Inlet, 1998

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St. Johns County, St. Augustine Inlet, FL

Report 1: Historical Analysis and Sediment Budget

Kelly Legault, Julie D. Rosati, Jason Engle, and Tanya M. Beck

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U.S. Army Engineer Research and Development Center
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Report 1 of a series

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Abstract

This report is the first in a series documenting analyses for St. Augustine Inlet and adjacent beaches within St. Johns County, Florida. The study quantified beach and inlet volumetric change to evaluate the historical and future impacts of the ebb shoal mining and adjacent beach nourishment. The majority of the analyses applied volume change from 1999 to 2010 determined from adjacent beach profiles and bathymetric surveys of the inlet. The total rate at which the inlet removed sand from the littoral system, the "total inlet sink," was balanced by volume change north and south of the inlet. A system of equations was developed to use these measurements and ranges in viable net and gross transport rates to develop a "Family of Solutions" representing viable sediment budgets for the region. The centroid of a narrowed set of solutions was formulated into a representative 1999 to 2010 sediment budget. Findings indicated that the alongshore extent of inlet impact south of the inlet for the 1999 to 2010 period were similar to a previous budget from 1974 to 1995, but extended further north during the later period. The rate at which the inlet removed sand from the littoral system was less in the latter 1999 to 2010 period relative to the former 1974 to 1995 period, indicating the ebb shoal continues to decrease the rate of accretion. Through examination of the time rate of change for the ebb shoal from 1940 to 2010, the accretion rate has decreased by 320,000 cu yd/yr over the 70 years examined. The study also evaluated whether the behavior of the beach and/or inlet changed fundamentally following either 2003 or 2005 mining of the ebb shoal. All of the analyses indicated that the inlet trapped less sediment in the post-dredge time period than it had before dredging. While the processes governing why the inlet might have trapped less is still an active topic of speculation, it is evident that the inlet borrow area did not cause an overall increase in sediment trapping at the inlet.

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Preface

This report documents a quantitative analysis of the regional coastal processes and gives a sediment budget for St. Johns County, FL, performed by the U.S. Army Engineer District, Jacksonville District (hereafter, the Jacksonville District) and the Coastal and Hydraulics Laboratory (CHL), U.S. Army Engineer Research and Development Center (ERDC). This study is the first in a series of reports for the St. Johns County region. The objective of this report is to provide a sediment budget based on long-term profile evolution and to attempt to answer questions posed by local authorities that address the impact of federal projects to the regional coastal processes, including a navigation channel at St. Augustine Inlet.

The study effort was conducted during fiscal year 2010 by staff of the U.S. Army Corps of Engineers (USACE), Jacksonville District, Water Resources Engineering Branch (WREB) and by staff at the Coastal Inlets Research Program (CIRP), a navigation research and development program of Headquarters, U.S. Army Corps of Engineers.

This study was performed by Dr. Kelly Legault and Jason Engle, Coastal Engineering, U.S. Army Engineer District, Jacksonville, Dr. Julie Dean Rosati, Coastal Processes Branch, Flood and Coastal Division, and Tanya M. Beck, Coastal Engineering Branch (CEB), Navigation Division (ND), Coastal and Hydraulics Laboratory. Information and coordination in support of this study, as well as study review, were provided by Jacksonville District personnel. Peer reviews of this study were provided by Kevin Bodge, Olsen Associates Inc., and Lori Hadley, WREB, Jacksonville District. Dr. Julie Dean Rosati was CIRP Program Manager. This study was supported by the CIRP and the Regional Sediment Management (RSM) Program, funded by the U.S. Army Corps of Engineers, Headquarters (HQUSACE). Linda Lillycrop (CEB), CHL, is Program Manager of the RSM Program. The CIRP and RSM Programs are administered for Headquarters at the U.S. Army Engineer Research and Development Center (ERDC), Coastal and Hydraulics Laboratory (CHL) under the Navigation Systems Program of the U.S. Army Corps of Engineers. James E. Walker is HQUSACE Navigation Business Line Manager overseeing CIRP and RSM. W. Jeff Lillycrop, CHL, is the Navigation Technical Director. This work was conducted under the

general administrative supervision Dr. Jeffrey P. Waters, Chief, CEB, and Dr. Rose M. Kress, Chief, ND.

At the time of publication of this report, COL Kevin Wilson, EN, was Commander and Executive Director. Dr. Jeffery P. Holland was ERDC Director.

Unit Conversion Factors

Multiply	By	To Obtain
cubic yards	0.7645549	cubic meters
feet	0.3048	meters
miles (U.S. statute)	1,609.347	meters
yards	0.9144	meters

1 Introduction

1.1 Objective

A comprehensive analysis of spatial and temporal data for St. Johns County, FL, was performed by the U.S. Army Engineer District, Jacksonville (hereafter, the Jacksonville District), and the Geomorphic Evolution Work Unit of the Coastal Inlets Research Program (CIRP) at the Coastal and Hydraulics Laboratory (CHL). These data were formulated into a present-day sediment budget to clearly define regional sediment dynamics for the purpose of subsequent regional sediment modeling and management studies. This is the first report in a series of three reports for St. Johns County. Report II presents modeling and analysis of the primary tidal inlet, St. Augustine Inlet, a significant sediment resource in the region, prior to and following sand mining of the ebb tidal shoal (Beck and Legault 2012a). Report III documents application of a regional shoreline and inlet shoal evolution model, GenCade, which calculated regional longshore sediment transport and evolution of sand placed on the beaches (Beck and Legault 2012b).

The overall objective of this study documented in Report 1 was to quantify beach and inlet volumetric change to such a degree as to answer contingent questions concerning the historical and future impact of the management practices in the area. Of particular interest were analyses to estimate the alongshore region of influence of the inlet and the inlet's net sink effect. A secondary product of this analysis is an updated regional sediment budget for use in long-term planning of the sediment resources and shore protection needs for the county.

The historical management practices at St. Augustine Inlet, a federal navigation channel, and the adjacent beaches have involved dredging the navigation channel and placing that material onto the adjacent beaches in moderate quantities (~200-500K cu yd) since the 1970s (Dredging Information System (DIS) Database, maintained by the Jacksonville District). In the 2000s, severe erosion at St. Augustine Beach, a historical erosion hotspot south of St. Augustine Inlet, prompted local authorities to conduct larger scale nourishment projects to protect the shoreline. The St. Augustine Beach Shore Protection Project (SPP) placed 4.2 mil cu yd (million cubic yards) and 2.8 mil cu yd from 2001 to 2005, which was mined from the outer lobe of the ebb shoal of St. Augustine Inlet Beach. Figure 1 shows the location of the county and the subreaches.

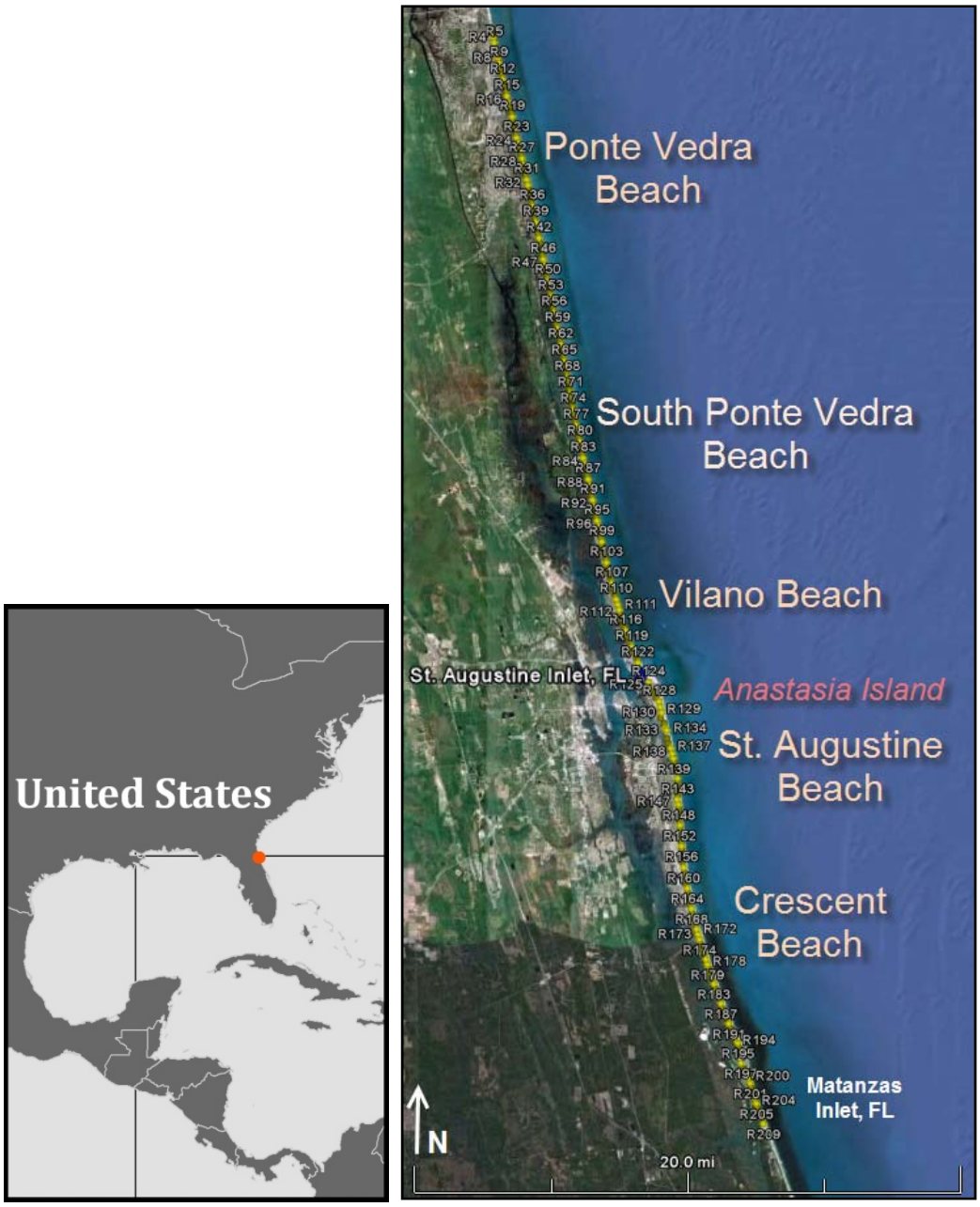


Figure 1. Study area location map for St. Johns County, Florida (left), and area beaches and location of FL Department of Environmental Protection (FLDEP) beach profile monuments, R-Monuments R-4 through R-209 (right).

1.2 Area

The regional study area for the project at St. Johns County spans the northern Florida coast from Ponte Vedra Beach south to Matanzas Inlet. There are three coastal projects within the county that are active and have been since the inlet was relocated 1940 and authorized in 1941 (Taylor 1994): the St. Augustine Inlet Navigation Project, the Intracoastal Waterway

(IWW) Navigation Project, and the St. Augustine Beach Shore Protection Project (SPP). Figure 2 illustrates these projects and the Vilano Reach SPP presently under assessment as of 2012 as part of a USACE feasibility study.

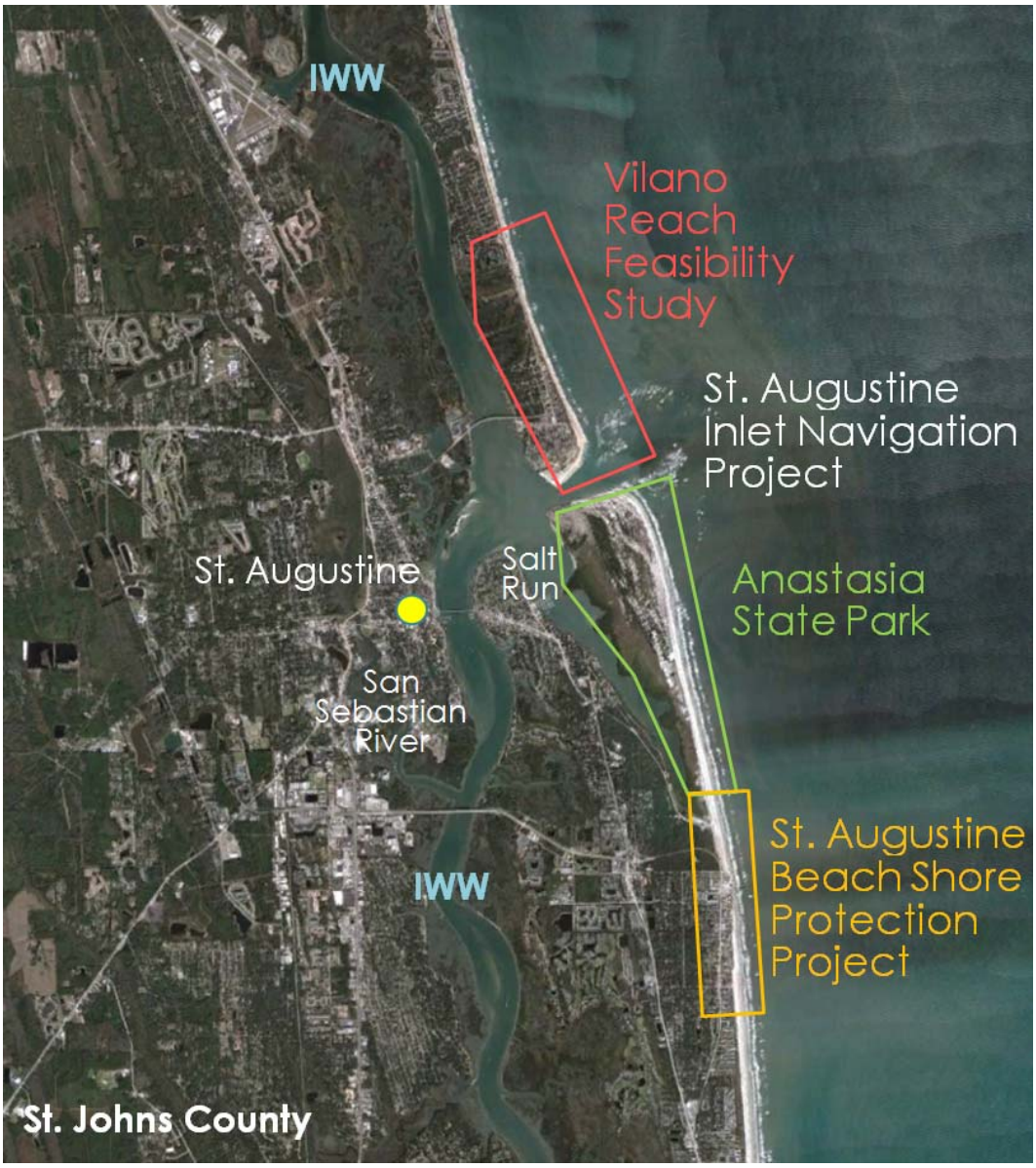


Figure 2. The U.S. Army Corps of Engineers' federal projects in St. Johns County, FL.

1.3 Procedure

Beach profile surveys were analyzed for volume change for the time period from 1999 – 2010. The 1999 data are available by R-monument for the St. Johns County coastline from the Florida Department of Environmental Protection (FDEP) website: http://www.dep.state.fl.us/beaches/data/his-shore.htm; the 2010 data were collected for the USACE District, Jacksonville by Taylor

Engineering. Beach profiles were imported into the Regional Morphology Analysis Program (RMAP) which was used for analysis of volume change at each profile location. These volumetric changes at each profile (volume per unit distance along the beach) were multiplied by a representative distance between adjacent profiles to generate volumetric change along the beach.

For development of the sediment budget, the Bodge Method (Bodge 1999; Coastal Engineering Manual Part V-6) was applied. This method uses the volumetric change rate of the inlet sink and the updrift and downdrift beaches as calculated from the profile data, and evaluates these against a range in viable net and gross transport rates for the region. The method also assigns a likely range in values for bypassing, inlet-induced erosion, and impoundment at jetties (if any) for both updrift and downdrift beaches. The resulting calculations that balance the known volumetric changes represent a "Family of Solutions" that each represent a viable budget. These results can be narrowed to better represent the more likely conditions during the period of the budget.

1.4 Purpose

The purpose of this study was four-fold:

- Update the regional sediment budget for the 1999 to 2010 time period;
- Compare the 1999 to 2010 budget to an earlier budget from 1974 to 1995 (Srinivas and Taylor 1998) to understand how coastal processes, inlet volume, and beach change varied between the two periods;
- Understand how mining sand from the St. Augustine Inlet ebb tidal shoal for beach restoration has affected the adjacent beaches; and
- Demonstrate sediment budget methodology.

1.5 Report organization

This report is organized in six chapters. Chapter 1 provides an introduction to the region and study objectives. Chapter 2 discusses the regional coastal processes as well as geomorphologic and engineering history of the project. Data applied for the analyses herein are presented in Chapter 3, and Chapter 4 presents the analyses of these data. The regional sediment budget is developed in Chapter 5. Chapter 6 presents a summary of the study and discusses major findings.

2 Regional Setting and History

2.1 Location and geomorphology

Northeastern Florida lies along a passive continental margin of western North America along the Atlantic Ocean. The coast is characteristic of a barrier-inlet system that consists primarily of littorally-derived, reworked, riverine siliciclastic sediments with varying amounts of bioclastic locally-derived material. PBS&J (2009) describe the major geologic formations along this coastal region: the littorally-derived beach ridge and dune sands, the undifferentiated Holocene sediments and the Pleistocene Anastasia Formation. The largely cemented carbonate material in the Anastasia Formation contributes to different locations along the St. Johns County coast in relation to continental shelf outcrops. PBS&J (2009) conducted an extensive analysis of sediments within the nearshore along northern St. Johns County and determined that sediments are mostly littorally-derived with varying amounts of carbonate and little to no riverine input. The carbonate shell hash and quartz make up the majority of sand concentration, and are greatly varied in distribution alongshore. Figure 3 shows the variation in mean grain size for eight cross-shore samples at eight profiles north of St. Augustine Inlet. In general, coarsest sands are observed at mean sea level (sample at 0) and finer sands are noted shoreward and seaward of sea level (+15 ft and -15 ft elevations), although there are exceptions (see R-77 at +15 ft) and variability in grain sizes (maximum ~ 1.7 mm and minimum ~0.15 mm). In general, carbonate shell hash along the study area is in its greatest presence along South Ponte Vedra and Vilano beaches, is least present across the inlet ebb-tidal delta, and is in varying concentrations along the southern beaches of St. Augustine Beach and further south.

St. Augustine Inlet is a stabilized navigation channel and is centrally located within the north-south trending county shoreline, oriented at ~165 degrees from true north. The mixed-energy inlet has characteristic stable inlet bypassing resulting in the headland at Anastasia Island that is characteristic of mixed-energy drumstick barrier islands (Fitzgerald 1988). The inlet was relocated in 1940 from the prior southward-migrating location shown in Figure 4. Since inlet relocation, the former ebb tidal shoal has migrated onshore and formed Anastasia Island (Taylor 1994).

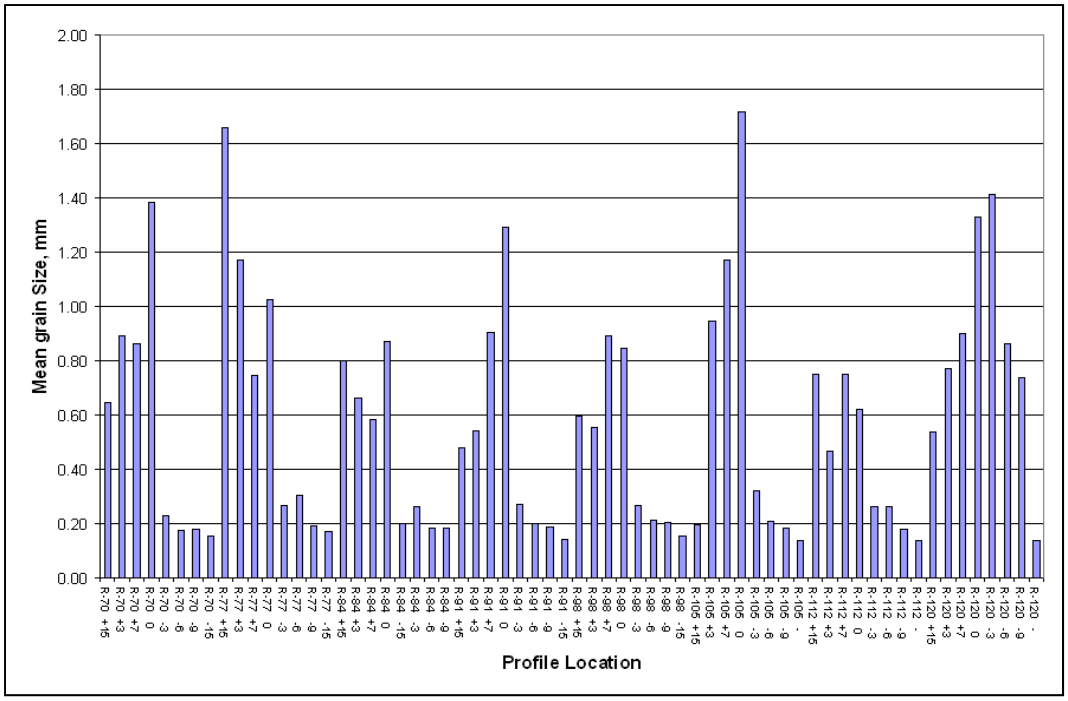


Figure 3. Mean grain size of eight cross-shore beach and nearshore sample locations (MSL, ft) from eight profiles along the South Ponte Vedra and Vilano beaches (PBS&J 2009).

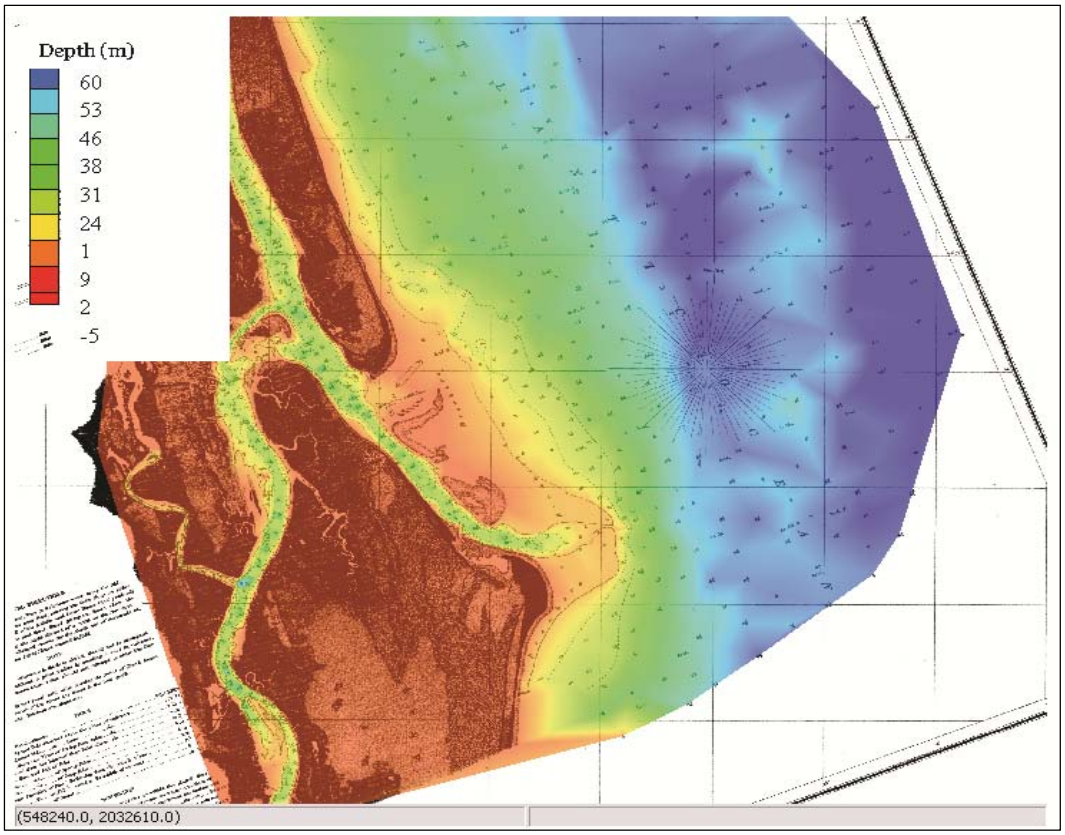


Figure 4. A digitized NOS navigation map illustrating the historical position and morphology of St. Augustine Inlet in 1862. The downdrift attachment point to the south is the approximate position of the future pier and seawall at St. Augustine Beach.

2.2 Coastal processes

The wave climate is seasonal with moderate wave exposure as defined by Walton and Adams (1976), and the tidal range is on the lower end of the mesotidal range (6 – 13 ft) with a spring high tidal range of 6 ft and a mean of 5 ft (NOAA 2010). Table 1 describes the general tide and wave characteristics of the area. Wave energy is typically greatest during the winter season, with waves from the north averaging 4- 6 ft or greater in height (USACE 2010). Overall, the net sediment transport along northeastern Florida is from the north to the south, caused by winter storms, with a seasonal reversal in net sediment transport direction during the summer months.

Table 1. General characteristics of the tide and waves in the Vicinity of St. Augustine Inlet, Florida.

General Characteristic	Value	Description
Mean Tidal Range	4.5 ft	Astronomical Tide (Taylor 1996)
Spring Mean Tidal Range	5.3 ft	Astronomical Tide (Taylor 1996)
Mean Significant Wave Height	3.6 ft	WIS Hindcast Database (USACE 2010)
Mean Peak Wave Period	7 s	WIS Hindcast Database (USACE 2010)
Range of Mean Significant Wave Height	1.8 – 5.9 ft	WIS Hindcast Database (USACE 2010)
Range of Mean Peak Wave Period	4.8 - 10 s	WIS Hindcast Database (USACE 2010)

2.3 Navigation and engineering

St. Augustine Inlet is a shallow-draft navigation channel with dredging limited to the outer ebb tidal shoal as a source of beach nourishment, and inner flood tidal shoals to clear navigation hazards and provide beach sand. All dredged sediment is typically medium to fine beach-quality sand and is placed on the adjacent beaches. From 2000 to 2003 and in 2005, the ebb tidal shoal and portions of the inner flood tidal shoals were dredged 7.2 mil cu yd and a total of 7 mil cu yd of sand was placed on the downdrift beaches.

In the next section, data used to develop the sediment budget are described.

3 Data

3.1 Beach profiles

An extensive series of beach profile surveys have been conducted along the St. Johns County coastline as shown in Table 2. These data are available on the FDEP website: http://www.dep.state.fl.us/beaches/data/his-shore.htm (FDEP 2000). Profile data for 2010 were collected by the Jacksonville District with the same baseline positions, or R-monument locations. Figure 5 shows the location of each profile by R-monument in relationship to the borrow area. Note that some monuments have been renamed "T" after previous monument locations were lost through erosion or cannot be located because of accretion and burial. Data from 1972 through 2010 were analyzed for general understanding of regional morphology, and the sediment budget was formulated using the 1999 and 2010 data.

Figure 6 shows representative profiles far north and south of St. Augustine Inlet, at R-109 and R-140, respectively. North of the inlet (Figure 6a), typical dune crest elevations are +20 ft or greater, berm crest elevations are +4 to +6 ft, and bar depths are between -8 and -10 ft, all elevations relative to North American Vertical Datum 1988 (NAVD88). Profiles far south of the inlet (Figure 6b) have been accretive through time because of welding of the former ebb tidal shoal onto the beach after the inlet was relocated. Typical dune crests south of the inlet are +18 to +20 ft with recent development of foredunes at +7 to +10 ft NAVD88; berm crests are similar to those north of the inlet. Bar depths south of the inlet range from -7 to -14 ft NAVD88.

Directly north of the inlet, beaches are influenced by inlet processes as shown in Figure 7 for the 2010 profiles at R-120, R-121, and R-122. The profile at R-120 is the furthest of the three from the inlet, and the profile shows a nearshore bar at -6 ft NAVD88, which is similar to profiles further north. However, closer to the inlet (R-121 and R-122), sediment transport processes are modified by inlet shoals and tidal flow, resulting in shallow ebb shoal bars and flood marginal channels.

South of the inlet, the northern end of Anastasia Island is closely connected to, and greatly influenced by the ebb tidal shoal and tidal-induced processes. Beach profiles at the northern tip of Anastasia Island are shown in Figure 8 for R-123 through R-125, and Figure 9 for R-126 through R-128. The influence of the inlet is evident from the deep flood marginal channels (-30 ft) adjacent to relatively shallow ebb tidal shoal morphology (-10 to -20 ft).

Table 2. St. Johns County profile data.

Title Year	Survey Date			Source	Mon. Range		Notes (elev. ref. NAVD88)
	Upland	Beach	Offshore		North	South	
1972		Aug-Sep 1972	Aug 1972	FDEP	1	209	Every 3rd line goes offshore (-35 to -40 ft). In between lines only extend to wading depth (-2 to -8 ft).
1984	Aug-Sep 1979	Mar-Jun 1984	May 1984	FDEP	1	209	Every 3rd line goes offshore (-35 to -40 ft). In between lines only extend to wading depth (-2 to -8 ft).
1986	Aug-Sep 1979	Jul-Sep 1986	May 1984	FDEP	1	209	Every 3rd line goes offshore (-35 to -40 ft). In between lines only extend to wading depth (-2 to -8 ft). Not all profiles include upland data
1992		Oct 1992		FDEP	110	122	Beach survey only. Profiles extend from R-mon to wading depth.
1993		Jul-Aug 1993		FDEP	3	207	Profile only at every 3rd mon. Beach survey only. Profiles extend from R-mon to wading depth.
1995		Sep 1995		FDEP	103	115	Beach survey only.
1996		Apr 1996		FDEP	200	209	Beach survey only. Additional profiles taken between R-mons.
1997		Feb 1997		FDEP	190	209	Beach survey only. Profiles extend from R-mon to wading depth.
1999		Feb-Apr 1999	Feb-Apr 1999	FDEP	1	207	Beach & Offshore survey for each profile line. Extends from R-mon to offshore depth (-35 to -40 ft)
2003		Jun-Aug 2003	Jun-Jul 2003	FDEP	1	209	Beach & Offshore survey for each profile line. Extends from R-mon to offshore depth (-35 to -40 ft)
2003		May 2003	May 2003	FDEP	117	157	Beach & Offshore survey. Extends from R-mon to offshore depth (-20 to -35 ft)
2005		Jun-Aug 2005	Jun 2005	FDEP	109	157	Beach & Offshore survey. Extends from dune to offshore depth (-20 to -35 ft)
2005		Dec 2005	Dec 2005	FDEP	109	157	Beach & Offshore survey. Extends from dune to offshore depth (-20 to -35 ft)
2006		Apr 2006	Apr 2006	FDEP	109	157	Beach & Offshore survey. Extends from dune to offshore depth (-20 to -35 ft)
2007		Jul-Aug 2007	Aug 2007	FDEP	109	157	Beach & Offshore survey. Extends from R-mon to offshore depth (-20 to -35 ft)
2007	Mar 2007	Mar 2007		FDEP	82	109	Upland and Beach survey only.
2007	Aug-Oct 2007	Sep-Oct 2007	Aug 2007	FDEP	1	209	Complete Survey. Extends from dune to offshore depth (-30 to -40 ft)
2010	Jul-Aug 2010	Jul-Aug 2010	Jul-Aug 2010	USACE	72	151	Extends from dune to offshore depth (-30 to -40 ft)

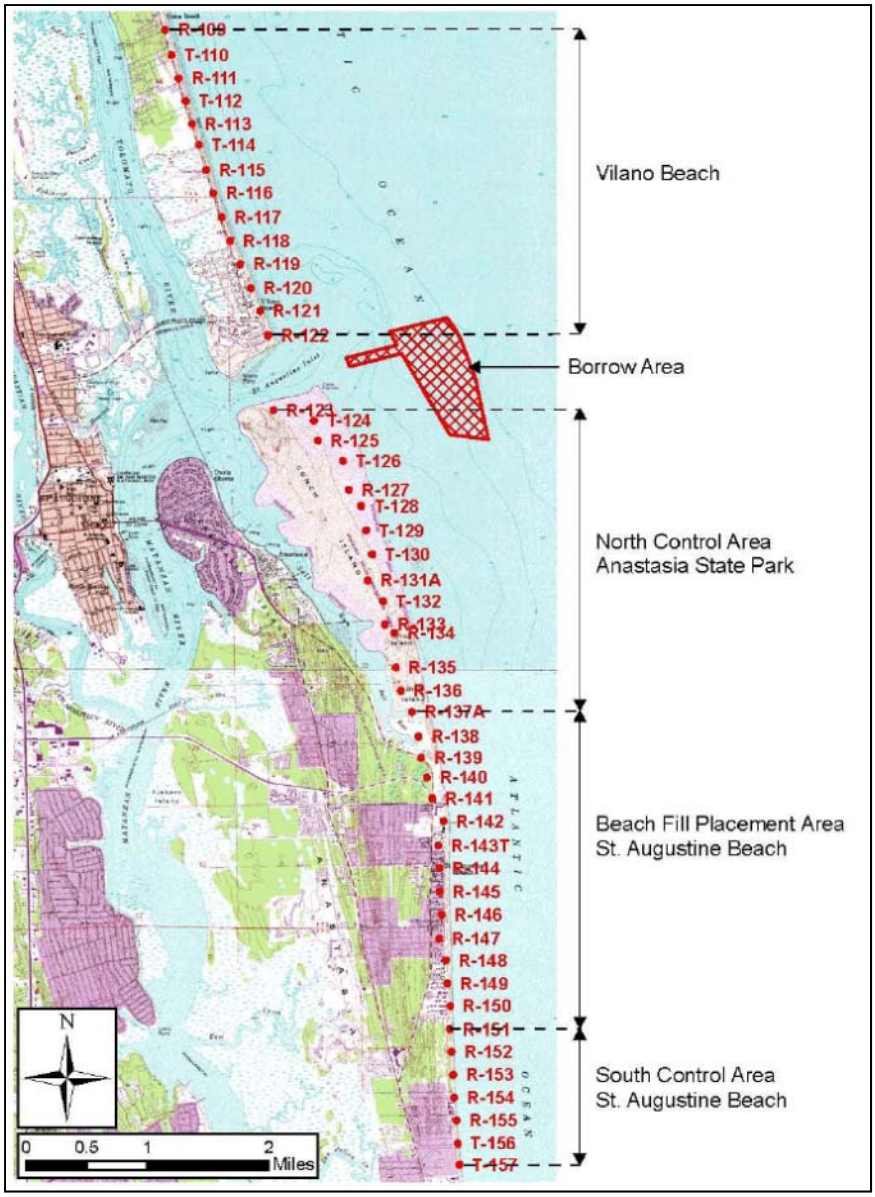
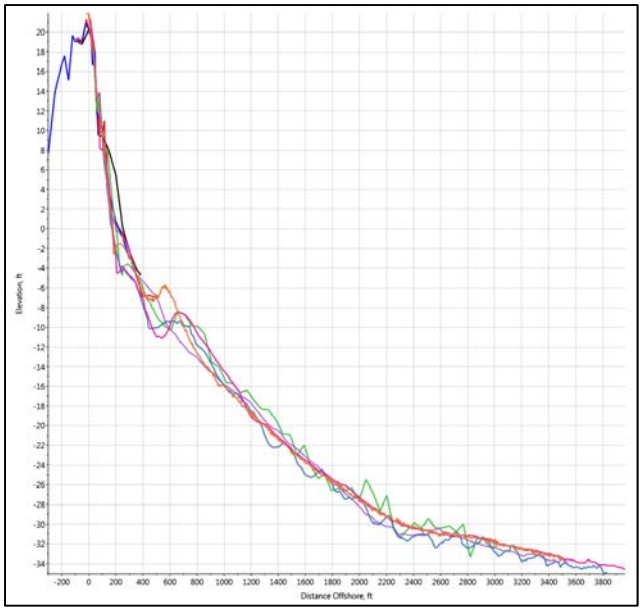
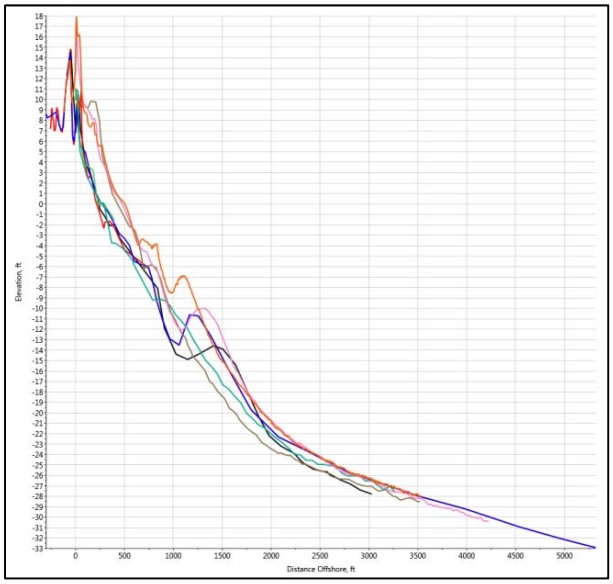


Figure 5. Location map showing R-monuments and borrow site for 2001-2003 and 2005 nourishment projects (from Arnouil and Trundnak 2011).

Beach profile data for profiles south of the inlet from T-124 to R-126 show that the subaerial and subaqueous profiles have eroded to the greatest landward extent in 2010 for the period over which measurements were taken since 1984 (Figures 10 through 12). Profile R-127 has eroded back to the 1986 subaerial position (Figure 13), and Profile R-128 is slightly seaward of the 1986 condition (Figure 14). Profile R-129 (Figure 15) shows relative stability with the beach seaward of all other profile positions except for immediately after the beach nourishment in 2003.



(a) R-109 north of St. Augustine Inlet



(b) R-109 north of St. Augustine Inlet

Figure 6. Representative cross-shore beach profiles north and south of St. Augustine Inlet.

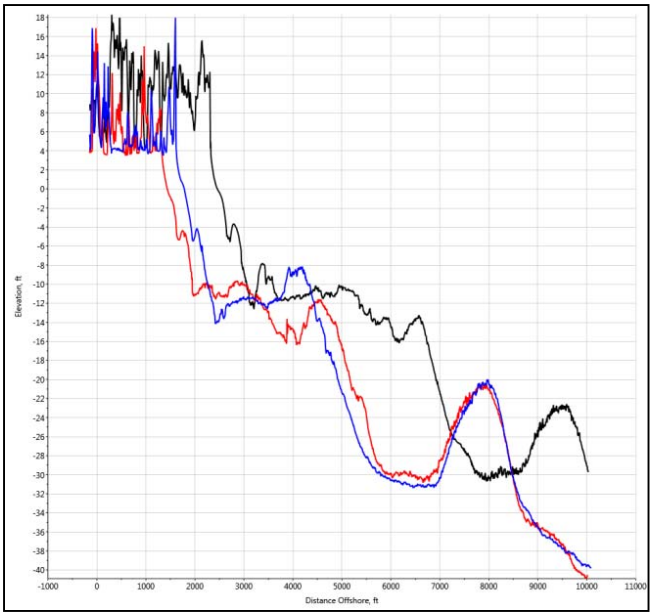


Figure 8 . Cross-shore beach profiles directly south of St. Augustine Inlet: R-123, R-124, and R-125 in 2010.

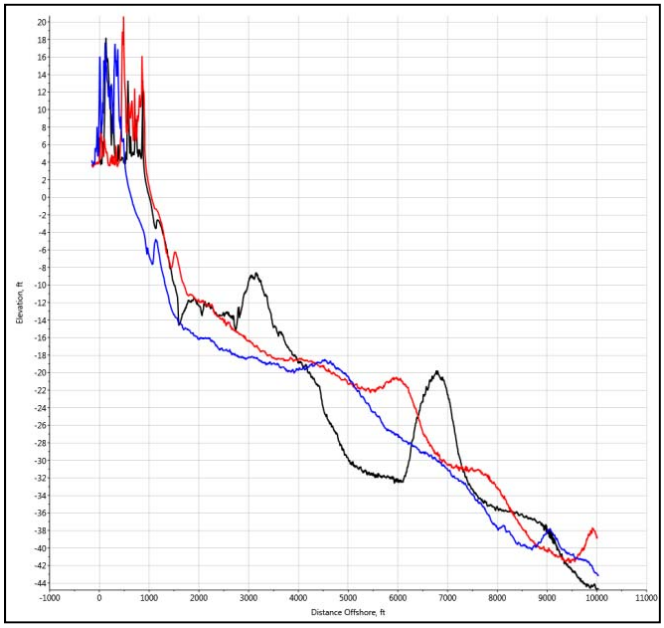


Figure 9. Cross-shore beach profiles further south of St. Augustine Inlet: R-126, R-127, and R-128 in 2010.

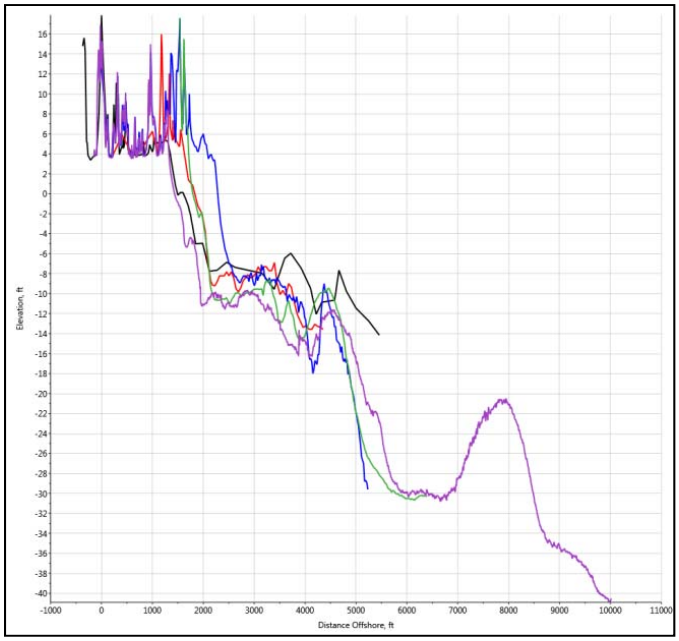


Figure 10. Cross-shore beach profile T-124 from 1984 to 2010.

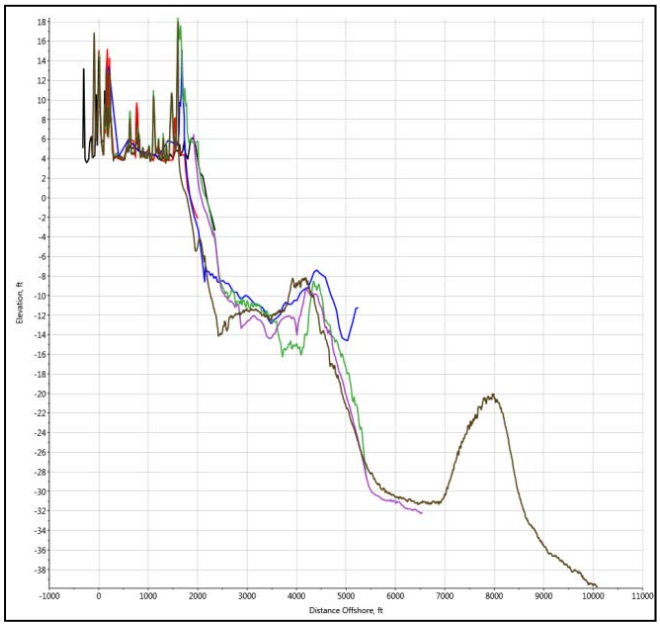


Figure 11. Cross-shore beach profile R-125 from 1984 to 2010.

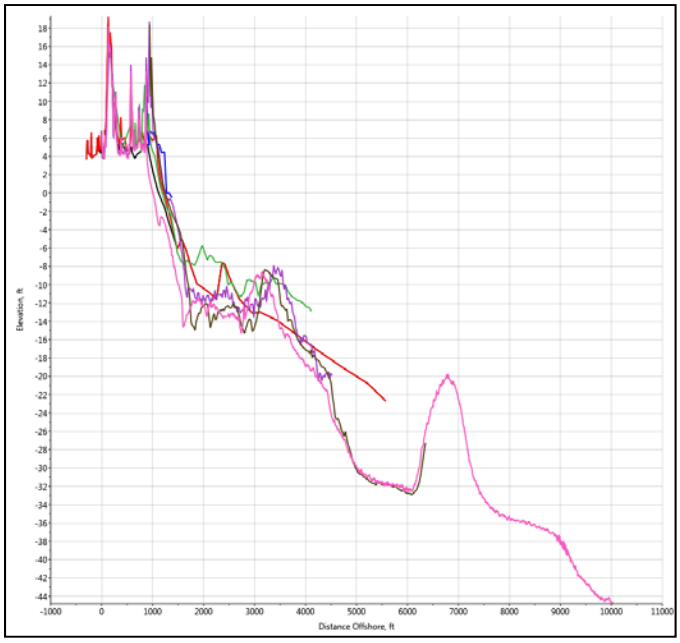


Figure 12. Cross-shore beach profile T-126 from 1984 to 2010.

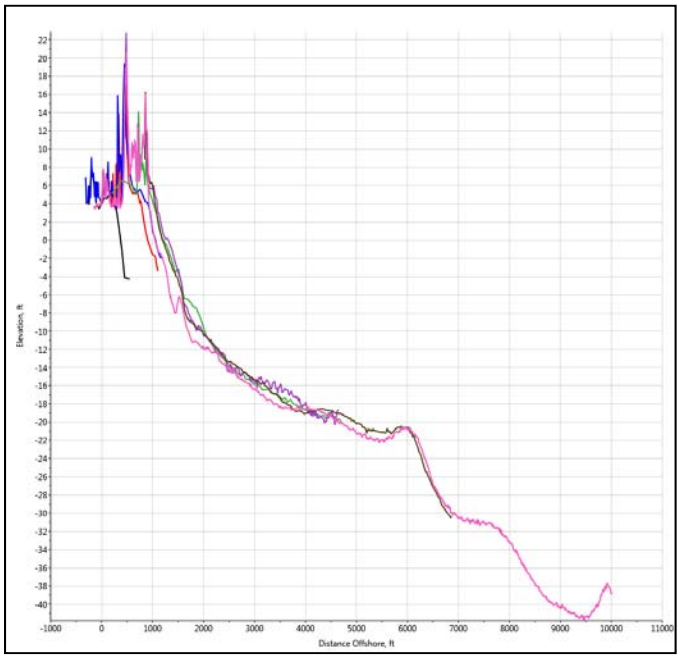


Figure 13. Cross-shore beach profile R-127 from 1984 to 2010.

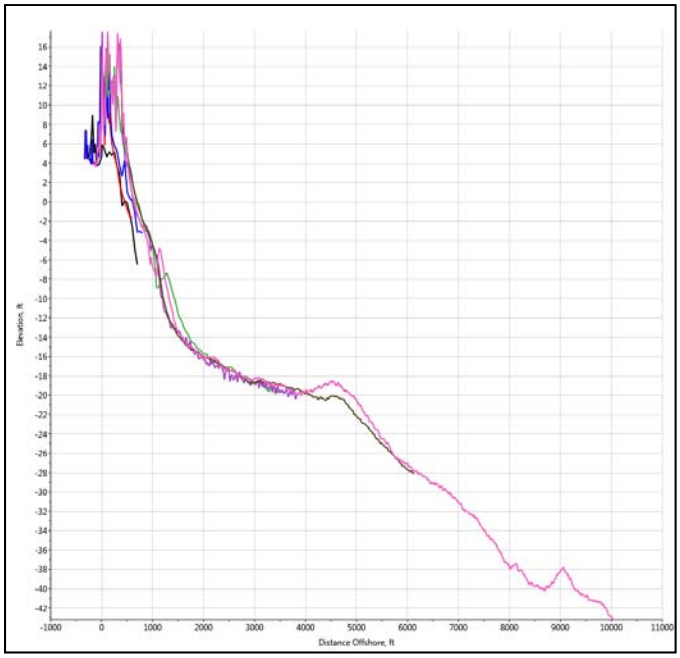


Figure 14. Cross-shore beach profile R-128 from 1984 to 2010.

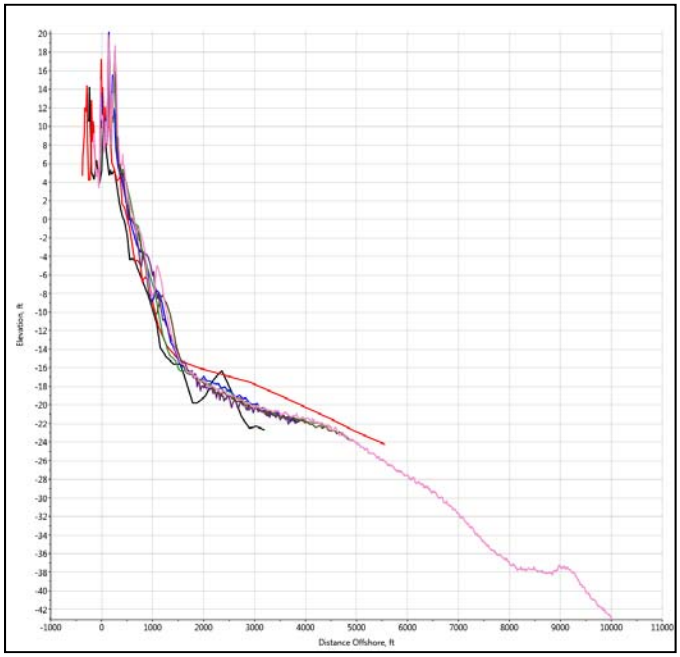


Figure 15. Cross-shore beach profile T-129 from 1984 to 2010.

3.2 Bathymetric data

Bathymetric data for the St. Augustine Inlet ebb tidal shoal from 1998 to 2010 were merged with the profile data to develop the sediment budget.

All data were adjusted to Florida State Plane northeast horizontal coordinate system with elevations relative to NAVD88.

Table 3 lists the survey history for the ebb shoal at St. Augustine Inlet.

Table 3. Ebb shoal survey history.

Description	Dates
1998	Sep 30 – Dec 31, 1998
2003 Post-Fill	Mar 17 – Jun 17, 2003
2004 Post-Storm	Nov 2004
2005 Post-Fill	Mar 3, 2006
2006	May 17-18, 2006
2007	Dec 13, 2007
2008	Dec 2008; 2-6 Jan 2009
2010	Oct 2010

Although a survey of the ebb shoal was obtained in 2009, the data are inadequate for quantitative analysis of the borrow area owing to the sparse resolution in the region. Further, a significant vertical offset existed in the preliminary data set, which has subsequently been corrected. These data were not utilized herein. For the remaining surveys, hydrographic survey points were interpolated to create a raster surface of the study area using natural neighbor interpolation.

After both shore protection projects, the borrow site from the ebb tidal shoal is clearly visible in the 2007 and 2008 bathymetries (Figures 16 and 17). The mining also included a portion of the inlet channel which helped straighten the channel. By 2008 (Figure 17), the northern lobe of the ebb tidal delta was encroaching on the channel and the thalweg once again began to curve to the southeast.

The 2010 bathymetry (Figure 18) shows some infilling on the outer edge of the borrow site as well as realignment of the south channel margin shoal to an orientation parallel to the new channel.

The connectivity between Anastasia Island and the ebb shoal through the cross-shore migration of ebb swash bars makes this region particularly sensitive to changes in the ebb shoal bathymetry and volume. This phenomenon will be discussed in Section 4.4.

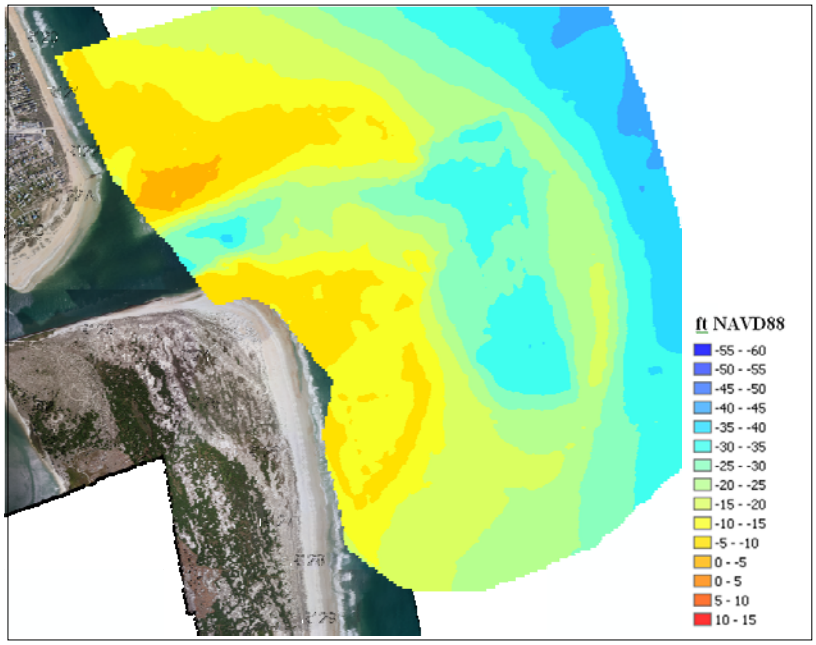


Figure 16. Ebb shoal bathymetry, Vilano and Anastasia Islands, 2007.

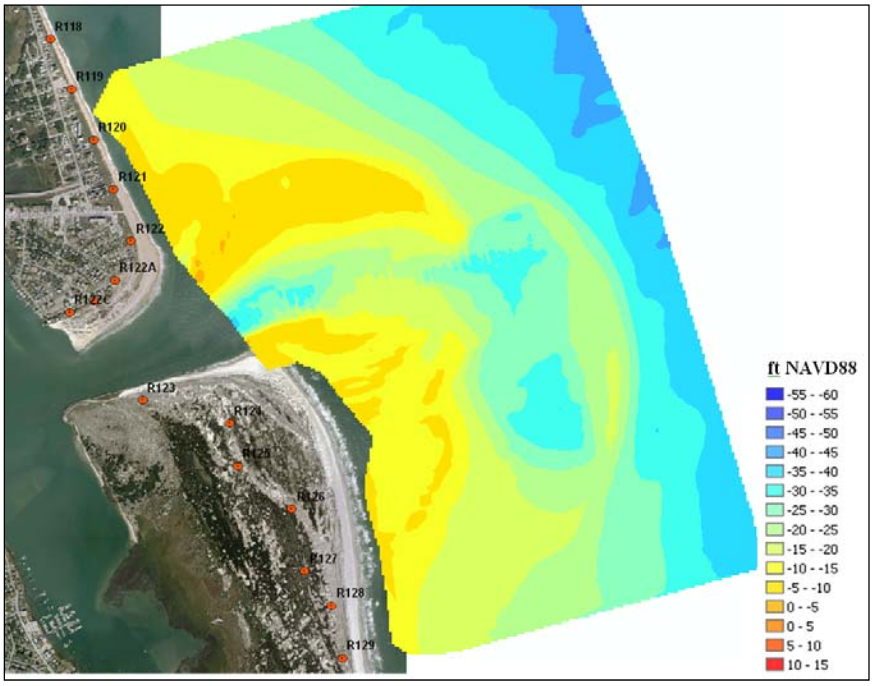


Figure 17. Ebb shoal bathymetry, Vilano and Anastasia Islands, 2008.

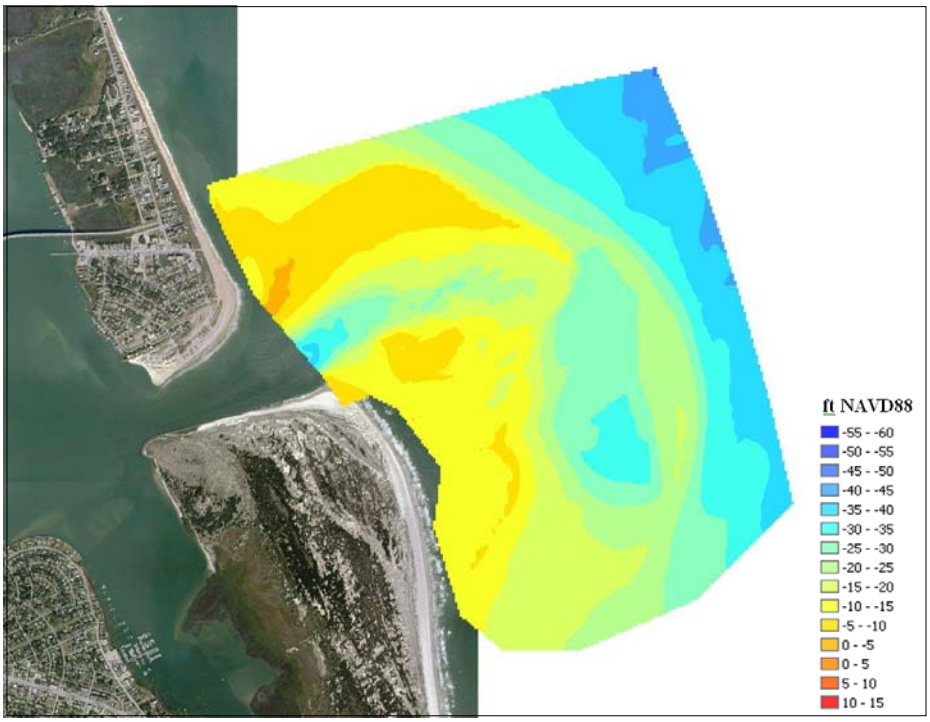


Figure 18. Ebb shoal bathymetry, Vilano and Anastasia Islands, October 2010.

3.3 Ebb shoal mining and beach nourishment

As shown in Table 4, the ebb tidal shoal (and portions of the flood tidal shoal) was mined in 2003 and 2005. This sand was placed on beaches south of the inlet. Table 4 lists recent beach nourishment and ebb shoal mining activities. Figure 19 shows the authorized borrow site with the 2007 ebb shoal bathymetry.

Table 4. Ebb shoal mining and beach nourishment history.

Project	Vol. Dredged (cu yd)	Vol. Placed (cu yd)	Placement Area	Construction Dates
2003 Project Phase 1	4.5 mcy	4.2 mcy	R-145 to R-151	Sept 2001-Oct 2001
2003 Project Phase 2			T-132 to R-151	Apr 2002 – Jan 2003
2005 Project	2.8 mcy	2.8 mcy	R-137A to R-151	Jun 2005 – Nov 2005

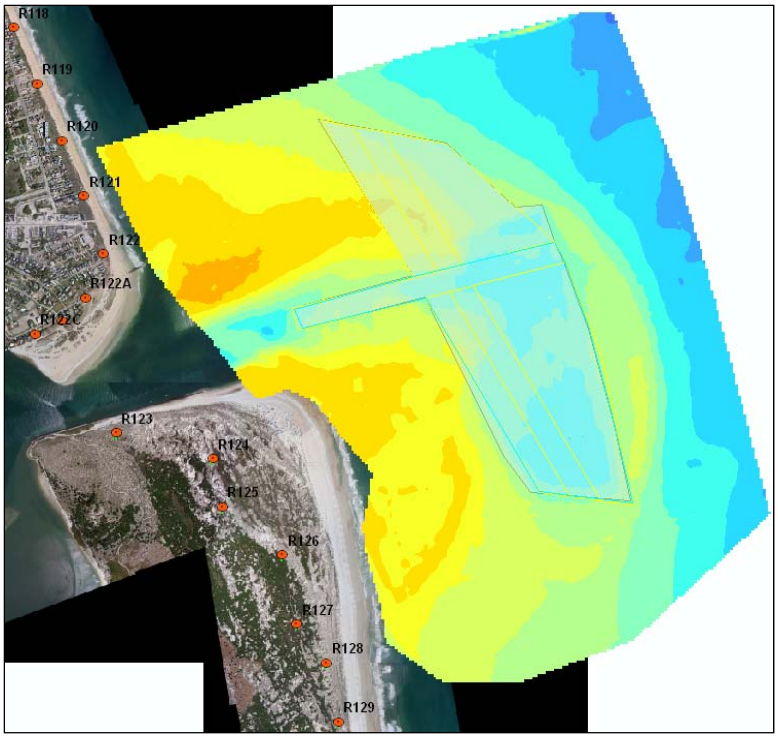


Figure 19. 2007 aerial of St. Augustine Inlet; 2007 bathymetry of ebb shoal (NAVD 88); authorized borrow site depicted in light blue.

4 Quantitative Analyses

4.1 Beach profile volumetric change

Beach profiles were imported into the Regional Morphology Analysis Program (RMAP) and were used to assemble and archive data for each region. Beach profile volumes were computed within RMAP for datasets between and including 1986 to 2010. Of note, the 2008 beach profile surveys exceed the industry/FDEP accepted temporal gap for topographic and hydrographic portions of the survey. The data exhibited unacceptable vertical gaps at the topographic and hydrographic interface owing to the passage of wave event(s) between collection of the topographic and hydrographic surveys, and were not considered further in this study.

Volumes within each profile were calculated by integrating under the profile offshore to a depth of closure that has been used in previous studies for this region, 20 ft NAVD88. It is likely that the actual depth of closure is slightly deeper than this value. Closure depth, h_c, can be calculated for quartz-sand beaches from Hallermeier (1981) as,

$$h_c = 2.28H_e - 68.5\left(H_e^2 \big/ gT_e^2 \right) \tag{1}$$

where H_e is the nearshore storm-wave height that is exceeded only 12 hours per year in meters, T_e is the associated wave period in seconds, and g is the gravitational acceleration equal to 9.81 m/sec^2. H_e was determined using the near CDIP Buoy 132 at Fernandina Beach. Wave heights exceeded by only 12 hours per year were determined for the three years (2006 to 2008) that the buoy was in service. Depth of closure was determined to be 25.22 ft as shown in Table 5. As discussed, the depth of closure applied herein was 20 ft NAVD for exact comparison with previous monitoring reports (see Taylor Engineering 2003, 2005, 2006, 2007, 2008).

Table 5. Depth of closure calculation (Equation 1). Depth of closure = 25.22 ft (2008 values for H_e and T_e).

Year	Month	Day	Hour	H_e, m	T_e, sec
2008	8	22	6	3.83	9.9
2007	10	30	3	3.0	7.0
2006	11	21	5	2.4	7.0

Profile volume change per foot of linear beach was calculated for sequential time periods. Nourishment volumes were removed using measured placement volumes (see Taylor Eng, Inc. reports 2003, 2005). Volume rate of change for the time periods between 1986 to 1999, 1999 to 2007 and 1999 to 2010 without nourishment volumes are shown in Figure 20.

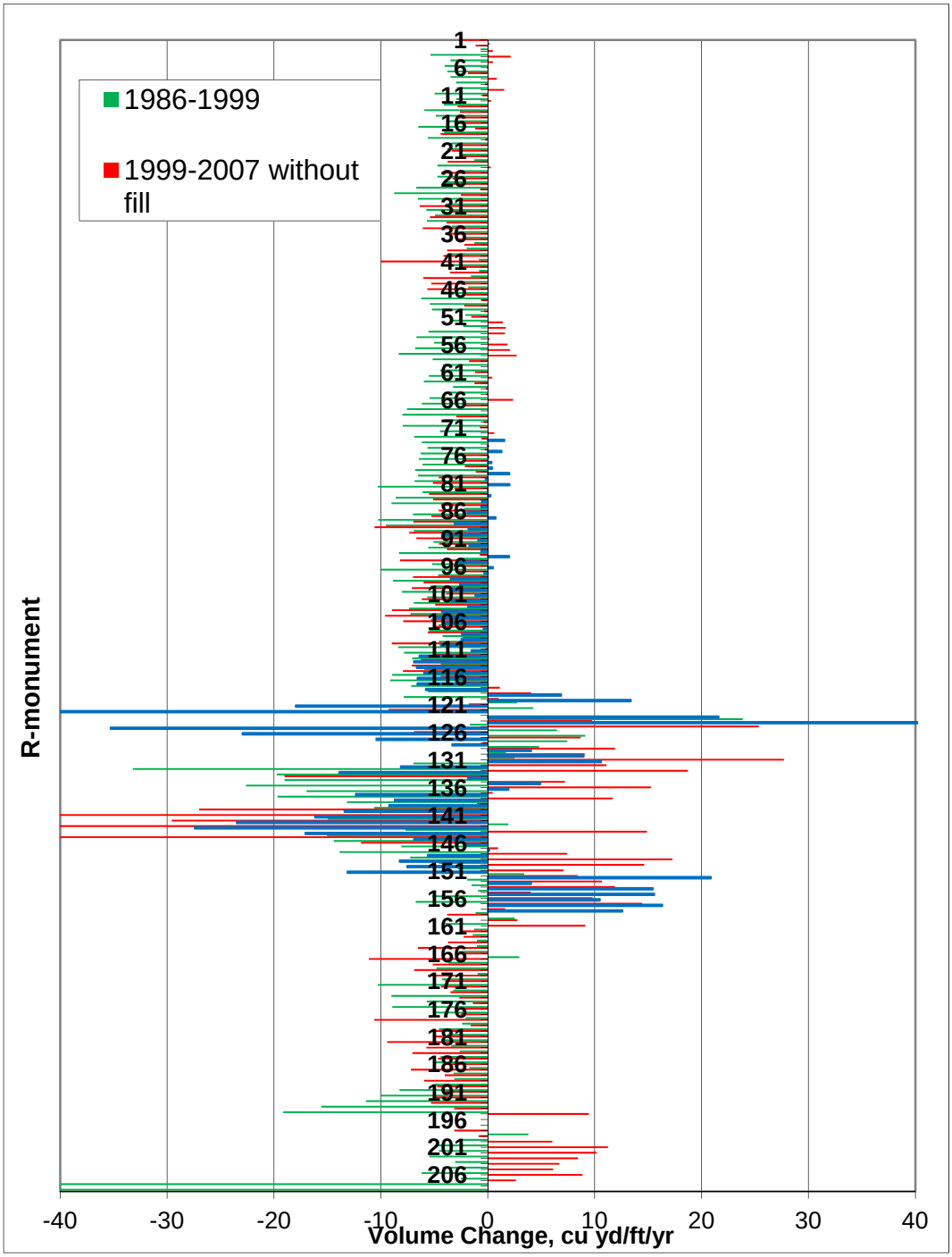


Figure 20. Beach profile volume rate of change, 1986 to 1999, 1999 to 2007, and 1999 to 2010. Nourishment volumes were removed from 2007 and 2010 surveys.

The rate of beach profile volume change north of the inlet is similar for all three time periods, except for the region at Guana River State Park, between R-46 and R-67 which shows a decrease in erosion for the 1999 to 2007 time period. The rate of erosion also decreased (and/or the rate of accretion increased) for the 1999 to 2010 period between R-73 and the inlet at R-122.

South of the inlet some commonalities as well as differences can be observed. With beach nourishment volumes removed, directly south from R-122 to R-123, the beach has been generally erosive for all time periods, followed by accretion from R-123 to R-125, and mixed erosion and accretion through R-128. All time periods show accretion from R-129 to R-131 followed by general erosion to R-151. The St. Augustine Beach Pier located at R-142 is within the high erosion area between R-138 and R-146. There is one more generally accretive region from R-152 to R-159, followed by general erosion from R-160 southward to the next inlet, Matanzas, at rates of approximately 5 cu yd/ft/yr.

4.2 Integrated beach volumes

Profile volumes were integrated alongshore to obtain total volumes between beach profiles. The average end-area formula for finding the approximate volume of a prismoid was used to determine the volume between each beach profile as:

$$V = \left(\frac{A_1 + A_2}{2} \right) \cdot l \tag{2}$$

where

V = volume
A_1 = area of one base
A_2 = area of the other base
l = the perpendicular distance between bases (See Taylor Eng Monitoring Reports, FDEP data)

Data coverage is listed in Table 6.

Profile reach volumes were summed over approximately a 5000-ft alongshore distance (five R-Monuments) to examine average annual volume change per 5000 linear alongshore feet for the time period from 1986 to

Table 6. Data coverage per time interval.

Interval	Cell Reach					
	R1 – R103	R103 – R110	R110 – R122	R124 – R127	R128 – R157	R157 – R194
1986 – 1999	X	X	X	X	X	X
1999 – 2003	X	X	X	X	X	X
2003 – 2005Pre			X	X	X	
2005Pre – 2005Post			X	X	X	
2005Post - 2007			X	X	X	
1999 – 2007	X	X	X	X	X	X
1999-2010		X	X	X	X	

1999, (prior to ebb shoal mining) and for 1999 to 2007 and 1999 to 2010 (post-dredging) (Figure 21). For the time period from 1999 to 2007, illustrated by the green bars in Figure 21, an observable decrease in average annual reach volume change exists from the inlet to R-70, which may be singularly attributed to the effect of the inlet; however, it must be noted that Guana State Park extends between monuments R-46 to R-67 and has changed little over the 1999 – 2007 period (Figure 21). The observed trend is most likely a combination of the inlet effect and the robust dune system at Guana State Park. Further, it is likely that the lack of development along this stretch of shoreline has not disrupted natural sediment processes which otherwise would likely cause erosion of the sand dunes (Van Der Meulen and Salman 1996). The net transport on the southern beaches is toward the south; however, a node (transport reversal) is present at R-132 and a strong erosional signal is present at R-142, the location of St. Augustine Beach Pier. Over the 1999 to 2007 period, the northern portion of Anastasia State Park (R-123 to R-135) experienced significant accretion where the region directly to the south, at St. Augustine Beach Pier experienced significant erosion. Similar trends are observed for the 1999-2010 period, with general erosion north of the inlet, accretion on the northern portion of Anastasia Island and erosion near the Pier at R-142, and accretion for the available data south of R-150.

Average annual reach volume change for data from 1999 to 2003 and 2003 to 2007 were calculated to highlight a strong oscillatory signal that was present (Figure 22). This type of oscillatory signal was observed throughout the entire county.

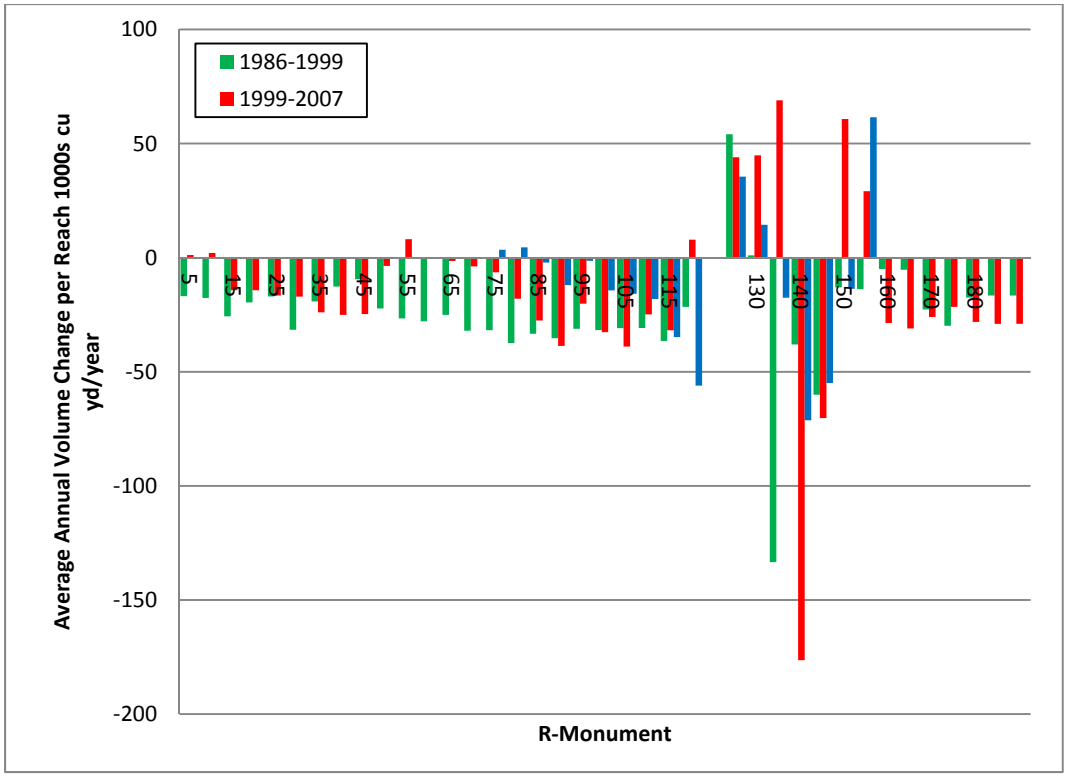


Figure 21. Average annual reach volume change 1986 to 1999, 1999 to 2007 (fill removed), and 1999 to 2010 (fill removed). Reaches are approximately 5000 ft in the alongshore.

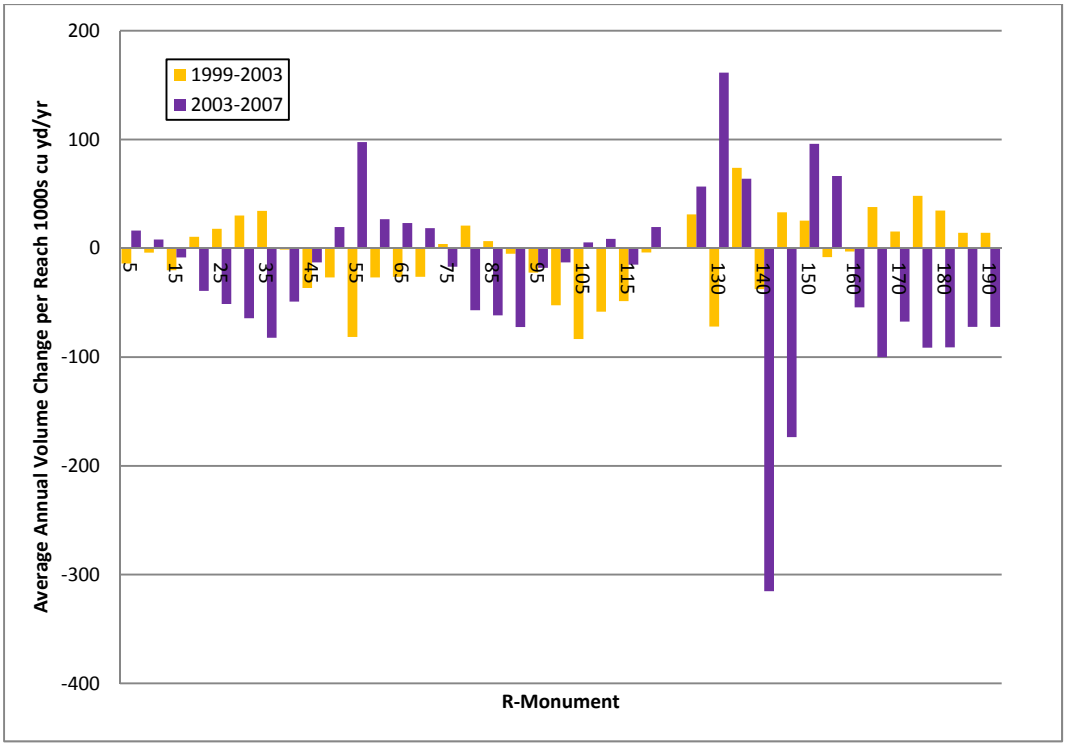


Figure 22. Average annual reach volume change from 1999 to 2003 and 2003 to 2007 illustrating the oscillatory nature of gains and losses along the beach during this period, particularly evident north of the inlet. Reaches are approximately 5000 ft in the alongshore.

4.3 Bathymetric analysis

Analysis of the ebb tidal shoal volume change between surveys was made within a GIS framework using an area mask (Figure 23) to ensure that exactly the same regions were compared among all surveys. In addition, caution was taken to ensure that elevations above depth of closure that were captured in the beach profile lines directly adjacent to the inlet were not duplicated within the ebb shoal mask. GIS was used to analyze and compute area elevation changes and volumes gained or lost, as well as observe trends in morphologic patterns.

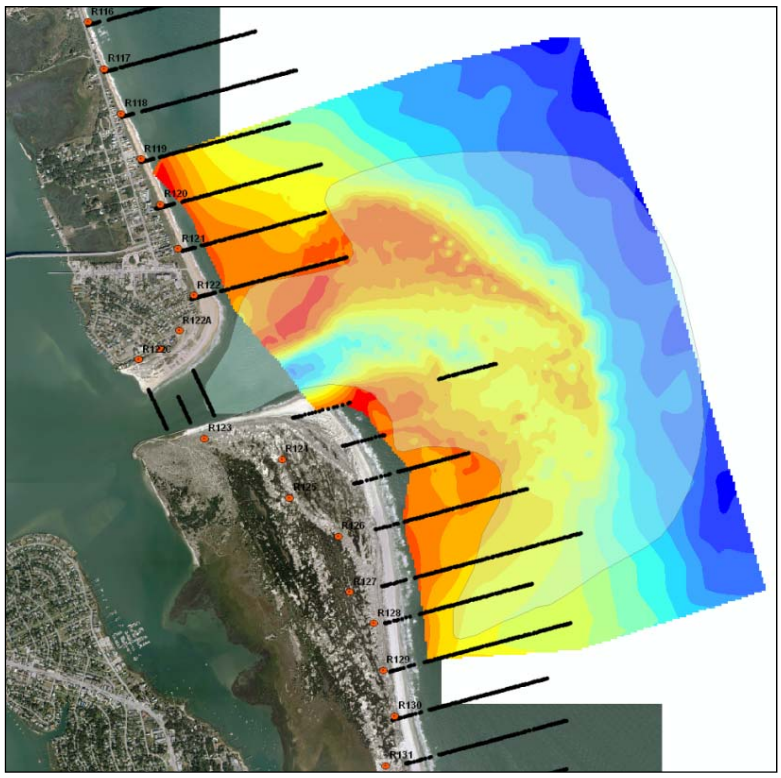


Figure 23. Surface raster of 1998 bathymetry of Ebb Shoal (NAVD 88); beach profile line survey points; ebb shoal mask (denoted by polygon over the bathymetry); elevations in ft NAVD88

The area elevation changes were calculated by differencing rasters (Figure 24) to determine the elevation change between surveys. Surface volume changes were computed within each survey mask for differenced rasters above and below a reference plane (in this case, the zero NAVD88 plane). Table 7 shows how the 1998 ebb shoal volume varied depending on which contour was defined as the offshore boundary of the polygon. Herein, the ebb shoal volume was calculated to 23 ft and 30 ft, the approximate depth at which the ebb shoal has been mined in previous years.

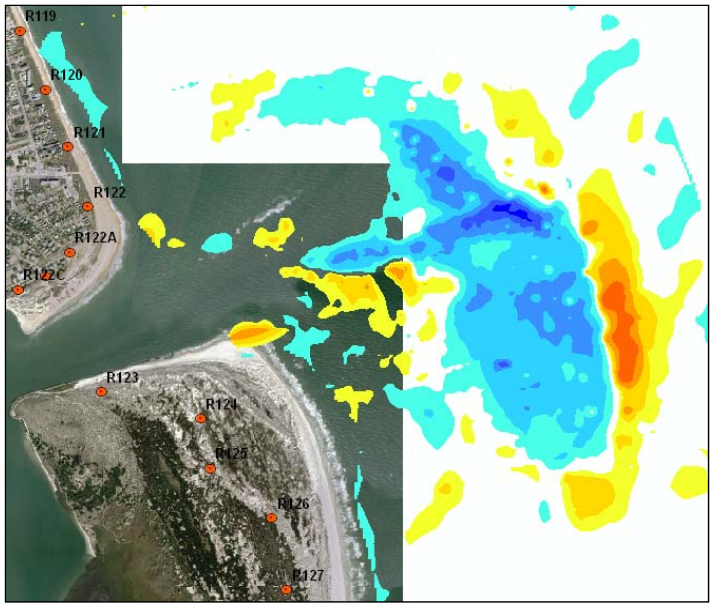


Figure 24. Difference in ebb shoal elevation from 1998 to 2003 (post construction); Cool colors depict erosion or mining, warm colors depict accretion

Table 7. 1998 ebb shoal volume, cu yd.

23 ft Contour	26 ft Contour	30 ft Contour
20,272,227	27,926,463	35,580,699

Table 8 contains the changes in the volume of the ebb shoal by summing changes within the ebb shoal mask used where mask limits described the shoal extent (NAD 83 ft Federal Information Processing Standard ZONE (FIPSZONE) 901) to the north at (all in feet) 569,373E, 2,032,445N, to the east at 575,770E, 2,029,062N, to the south at 57,356E, 2,022,246N to the west 564,666E, and 2,026,701N.

Table 9 contains the changes in the volume of the ebb shoal borrow site only.

4.4 Shoreline change at northern Anastasia Island

Anastasia Island, in particular the region north of R-127, is closely linked to the morphology of the ebb tidal shoal. The relationship between the shoreline north of R-127 and the position of ebb shoal features including the navigation channel were examined using existing bathymetric and topographic surveys to establish whether shoreline position is correlated with ebb shoal and channel features. For the time period between 1974 and 1999, rapid and significant changes in the ebb shoal configuration, channel orientation, and shoreline progression occurred. In 1974, the ebb shoal was still

Table 8. Change in ebb shoal volume (Updated from Taylor Eng Monitoring Report Inlet Management Plan Phase 2, 1996).

Change in Ebb Shoal Volume		Change in Ebb Shoal Volume Accounting for Sand Mining		
Interval	ΔV Ebb Shoal, cu yd	Interval	ΔV Ebb Shoal, cu yd	ΔV cu yd/yr
1986 – 1998	5,071,250	1986 - 1998	5,071,250	390,096
1998 – 2003post	-3,434,151	1998 - 2003	1,065,849	266,462
2003post - 2005pre	525,976	2003 - 2005pre	525,976	262,988
2005pre - 2005post	-3,449,089	2005pre - 2005post	-449,089	-449,089
2005post - 2007	790,051	2005post - 2007	790,051	526,701
2007 – 2008	633,712	2007 – 2008	633,712	633,712
2003 - 2007	-2,133,062	2003 - 2007	866,938	216,735
1998 - 2007	-5,567,213	1998 - 2007	1,932,787	241,598
1998 - 2010	-4,566,726	1998 - 2009	2,733,274	248,480

Table 9. Change in ebb shoal borrow site volume.

Change in Borrow Site Volume		Change in Borrow Site Volume Accounting for Nourishment		
Interval	ΔV Borrow Site, cu yd	Interval	ΔV Borrow Site, cu yd	ΔV cu yd/yr
1998 – 2003post	-4,353,696	1998 - 2003	146,304	36,576
2003post - 2005pre	356,842	2003 - 2005pre	356,842	178,421
2005pre - 2005post	-2,983,335	2005pre - 2005post	16,665	16,665
2005post - 2007	975,553	2005post - 2007	975,553	650,369
2007 – 2008	636,397	2007 – 2008	636,397	636,397
2003post -2007	-1,650,940	2003 -2007	1,349,060	337,265
1998 - 2007	-6,004,636	1998 - 2007	1,495,364	186,921
1998 - 2010	-4,035,678	1998-2009	3,264,332	296,757

evolving (Figure 25) due to the re-location of the inlet in the 1940s (Inlet Management Plan, Part 2, Taylor Engineering Inc. 1996). At that time, the location of the channel was at the centerline of the inlet (Figure 25). By 1995, the navigation channel had migrated to the south, against the south jetty at the inlet. At the same time, the northern tip of Anastasia had accreted and maintained a convex, seaward protruding shoreline due to the on-shore movement of swash bars from the ebb shoal (Figure 26).

In 1999, the navigation channel was still located against the south-jetty and the entrance was oriented toward the south east, continuing its departure from the earlier 1974 configuration which was shore-perpendicular and was at the centerline of the inlet. The shoreline north of R-127 maintained its convex orientation (Figure 27).

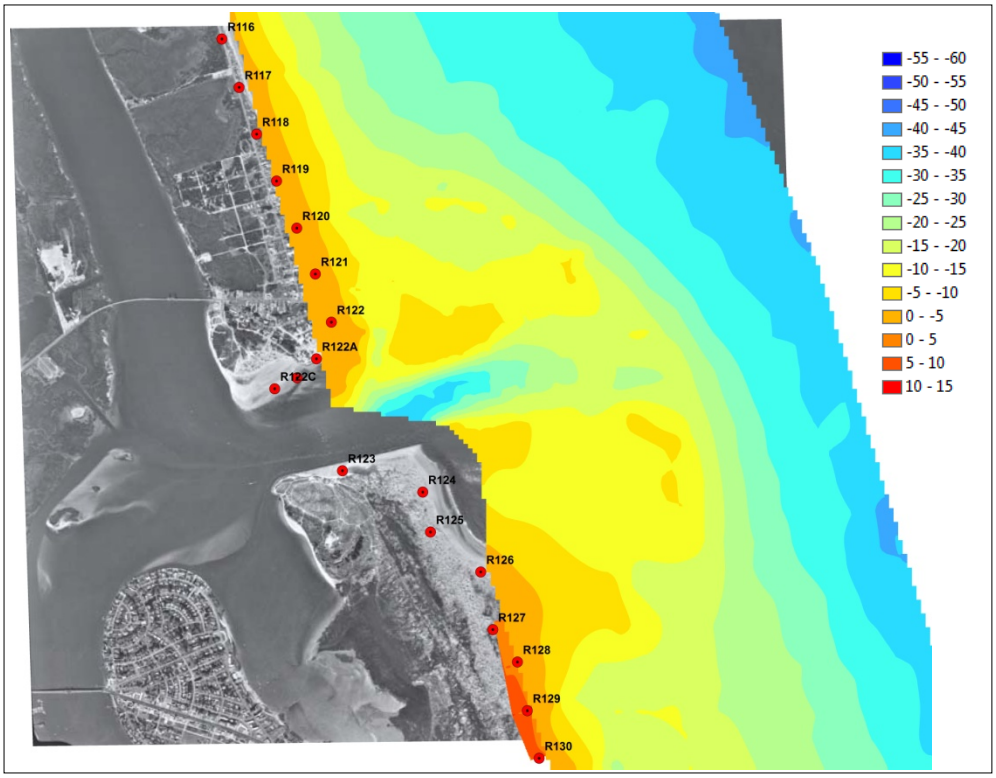


Figure 25. Anastasia 1974; aerial (1974) and bathymetry (1974).

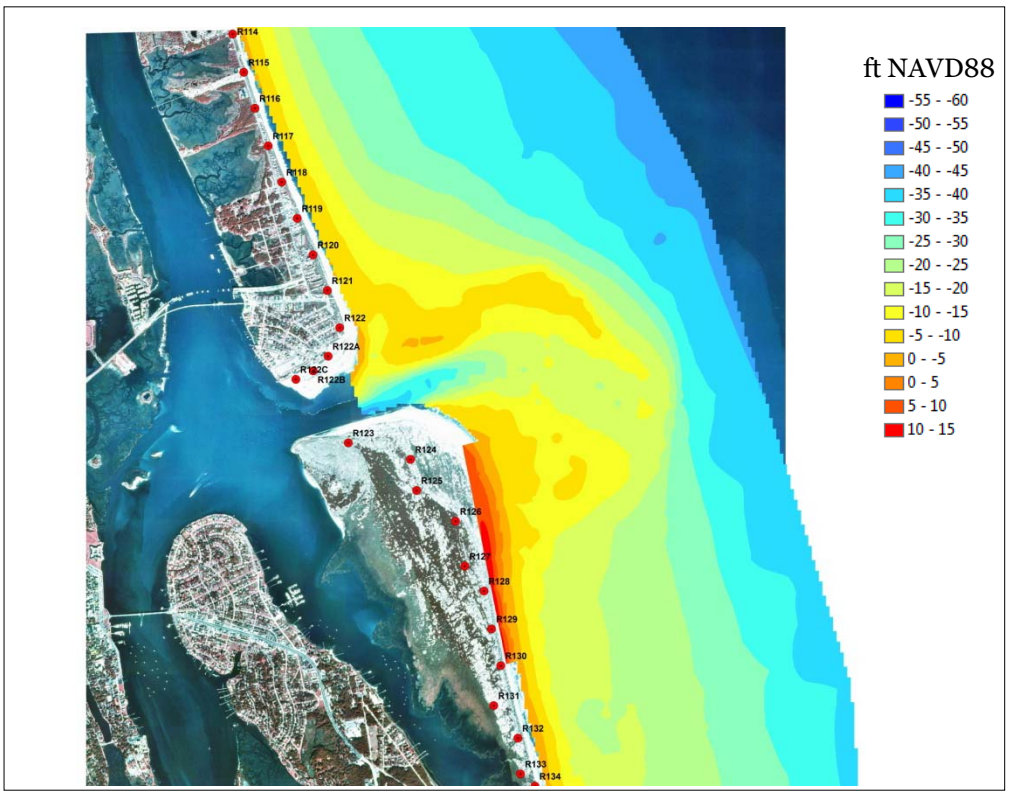


Figure 26. Anastasia 1994/95; aerial (1994) and bathymetry (1995).

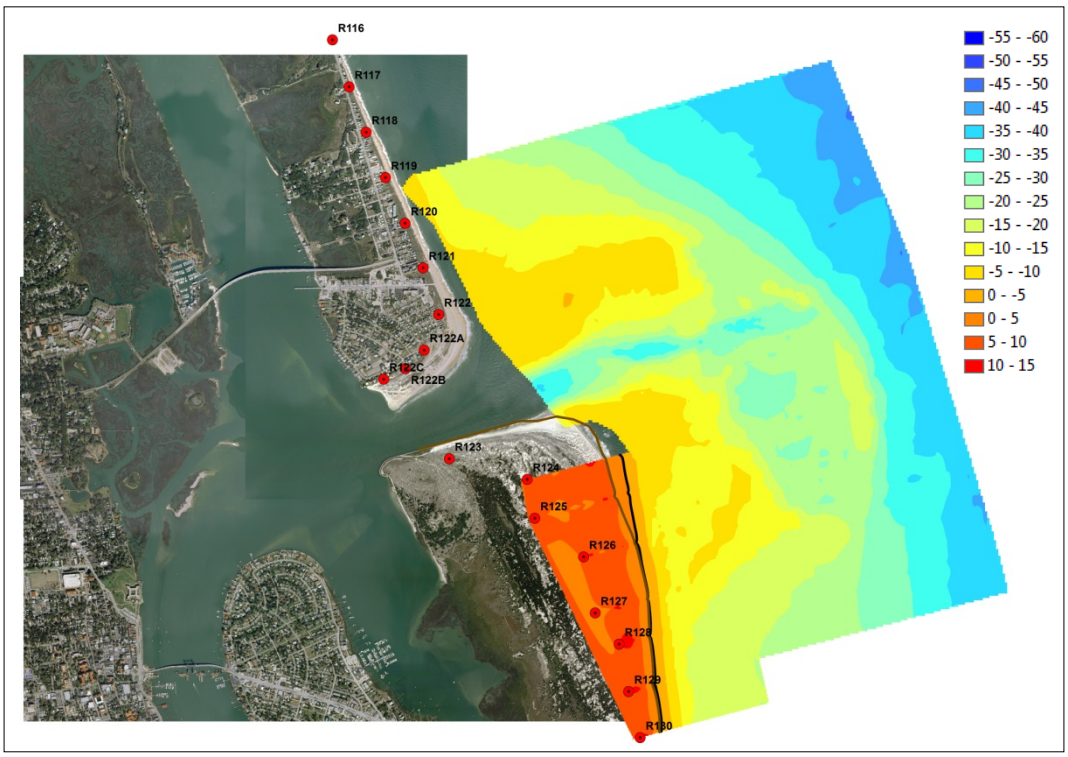


Figure 27. Anastasia 1999, 2003, and 2005 shoreline contours and 2003 bathymetry.

Although data are limited for the time period between 1974 and 1999, it appears that if the channel migrates to the north, and/or if the cross-shore width of the south lobe is expanded, erosion of the northern shoreline may occur. On the other hand, if the width of the south lobe is constrained by the channel entrance and bypassing bar, and if the channel is aligned with the south jetty, there is onshore migration of ebb swash bars and the shoreline at the north tip of Anastasia Park accretes.

Despite significant changes in the ebb shoal in the region of the borrow site because of nourishment projects in 2001 to 2003 and 2005, the shoreline location north of R-127 was relatively constant for the time period between 2003 and 2007 (Figures 28, 29, and 30).

In all, over the duration of the two nourishment projects, the region of Anastasia State Park between R-124 and R-129 eroded by approximately -58,000 cu yd. Over the same period, the ebb shoal directly offshore of R-124 to R-129 eroded by approximately -913,000 cu yd.

By May of 2007, the revetment at St. Augustine Beach Pier at R-142 became exposed and was impeding northerly sediment transport (Figure 31). In late 2007, the shoreline north of R-127 began eroding and by 2008 (Figure 32), the shoreline had eroded close to its 1999 location (Figure 33).

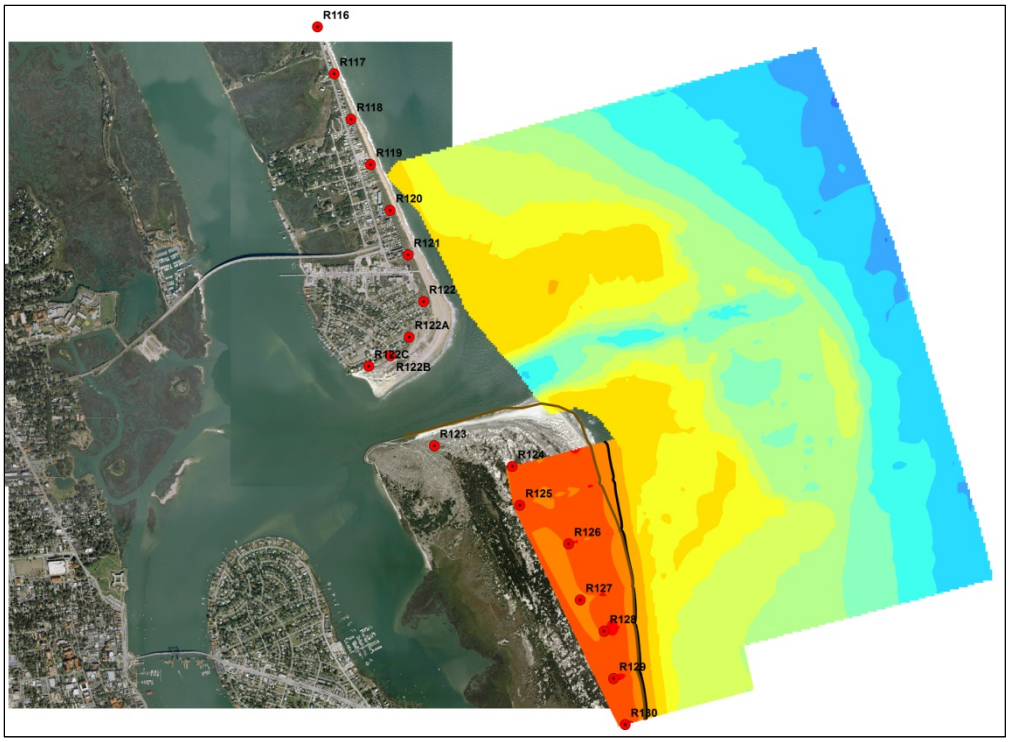


Figure 28. Anastasia 1999, 2003, and 2005 shoreline contours and 2003 bathymetry.

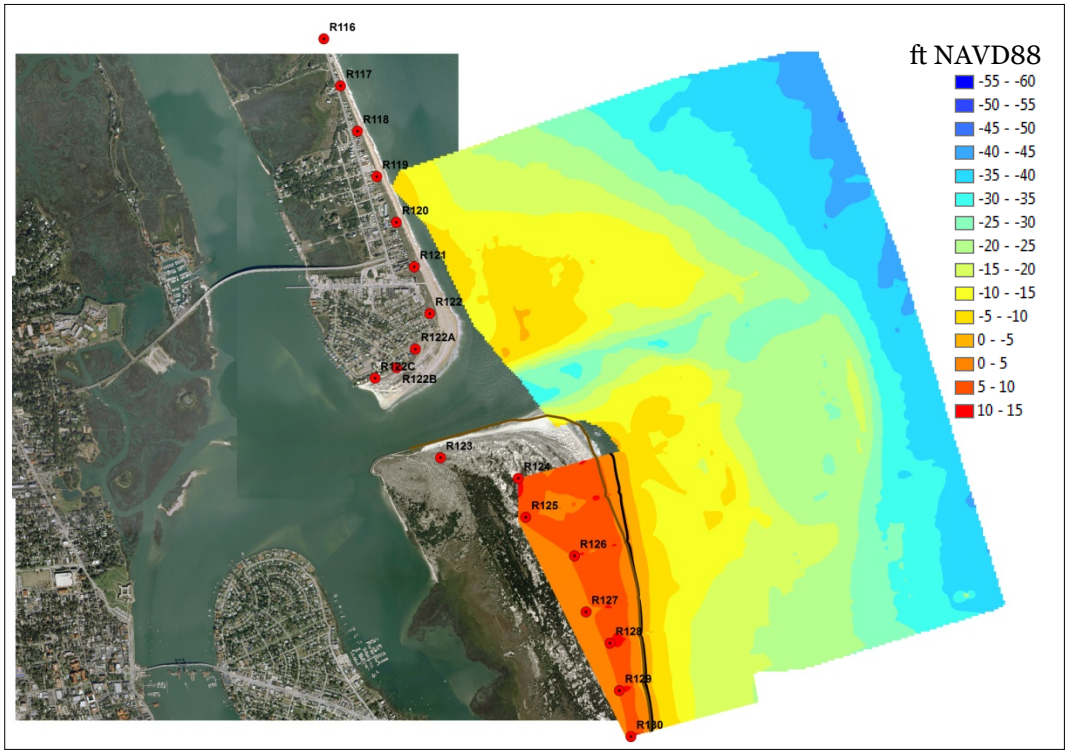


Figure 29. Anastasia 1999, 2003, and 2005 shoreline contours and 2005 bathymetry.

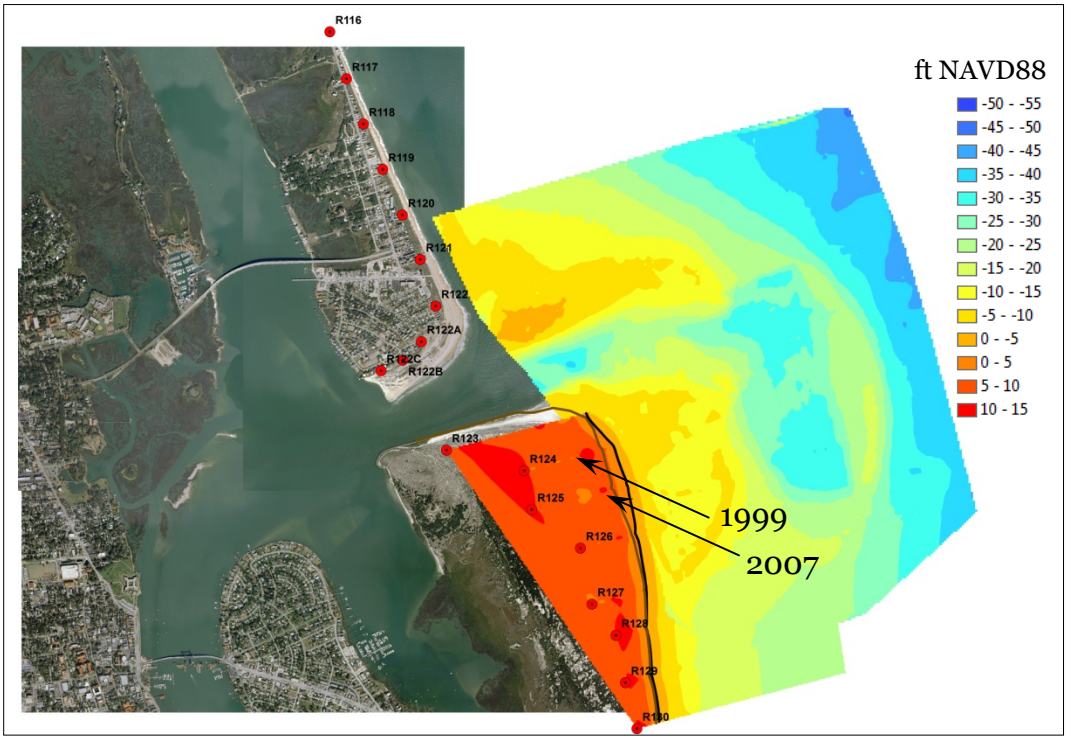


Figure 30. Anastasia 1999 and 2007 shoreline contours and 2007 bathymetry.

Figure 31. St. Augustine Beach Pier: January 2006 and May 2007.

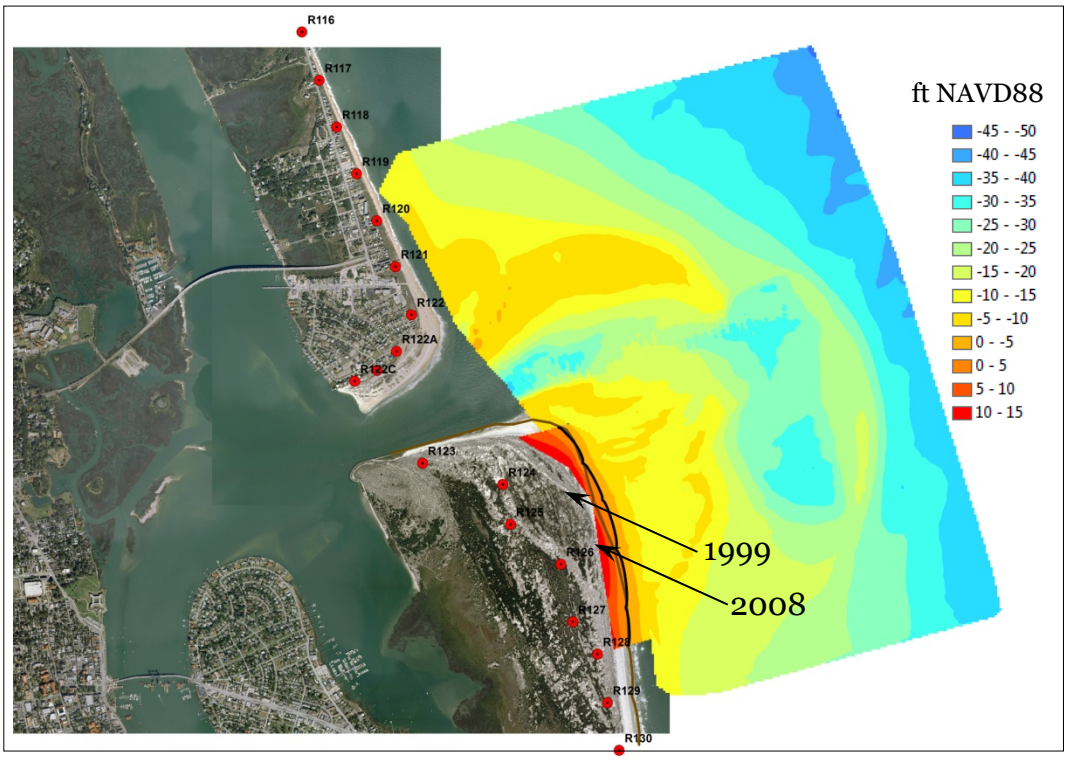


Figure 32. Anastasia 1999 and 2008 shoreline contours and 2008 bathymetry.

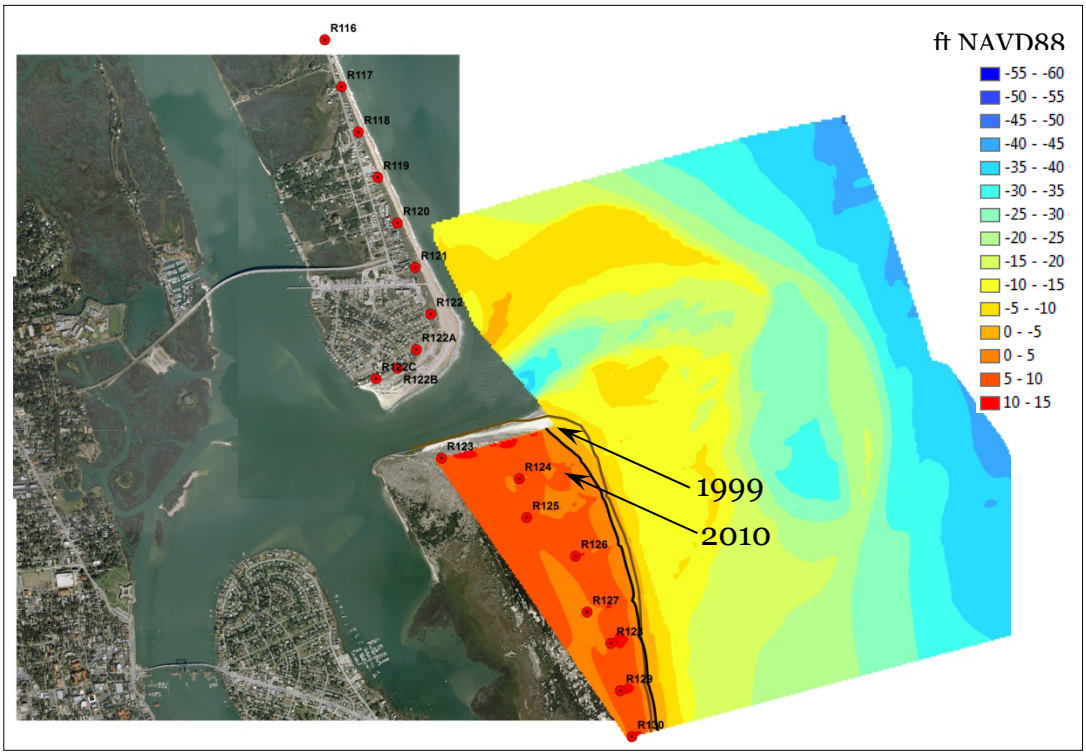


Figure 33. Anastasia 1999 and 2010 shoreline contours and 2010 bathymetry.

Because of the exposure of the revetment at St. Augustine Beach Pier in mid-2007, and the lack of northerly sediment transport to Anastasia Park, it appears that the coupling between the ebb shoal/inlet complex and the shoreline was again present in 2008. It is clearly observed in 2010 as the channel has migrated toward the north and the cross-shore width of the south lobe has increased (Figure 33) offshore of R-125.

Interestingly, over the time period between 2003 and 2007, despite rather extensive engineering work at the ebb and a corresponding change in the configuration of the shoal (mainly localized to the dredge location), the shoreline is remarkably stable over this time period. It is as if the shoreline had been decoupled from changes in the channel and ebb shoal configuration over this time period. The foremost difference in the littoral system over this period was the addition of 7-mil cu yd to beaches to the south. Approximately 1.6-mil cu yd, a substantial portion of which was derived from the nourishment projects, advected north of R-136 between 1998 and 2007 (Taylor Engineering Inc. 2008). It is hypothesized here that the shoreline at the northern tip of Anastasia Park extended seaward and remained stable between 2003 and 2007 because of a constant sediment supply from the south. The shoreline held steadfast despite significant changes to the borrow site at the ebb shoal in 2005.

Because monitoring data between 1999 and 2010 have borne out that the shoreline north of R-127 was stable over the time period between mid-2003 and late 2007 when an abundance of sediment was present in the system after nourishment it could be surmised that additional nourishment would once again "decouple" the shoreline from the ebb shoal/inlet complex and stabilize the northern tip of Anastasia Park. By 2010 the constant sediment supply from the south had ceased, the navigation channel had relocated to the north and the cross-shore width of the south lobe had increased. The 2010 shoreline eroded (Figure 35) resulting in a similar tendency as the 1974 shoreline, that is, an apparent association of shoreline position with the location of the navigation channel and the cross-shore width of the southern lobe. It appears that the processes at the shoreline at Anastasia and the ebb shoal are once again linked.

4.5 Alongshore region of influence of the inlet

Five methods are described in the Coastal Engineering Manual (USACE 2008; CEM EM 110-2-1100 Part V) to estimate the alongshore extent of inlet influence. They are as follows: (1) examination of historical shoreline

(or volumetric) changes; (2) even-odd analysis; (3) alongshore variations in beach morphology; (4) wave refraction analysis; (5) examination of inlet's net sink effect. Of these, Methods 2, 3 and 4 typically yield only estimates of direct inlet effect, whereas Methods 1 and 5 potentially yield estimates of both direct and indirect (near field and far field) inlet effects. The CEM goes on to state that Method 5, the inlet's sink effect, may be the most powerful approach because it first assesses the inlet's littoral impact within the inlet, and then attempts to identify the adjacent shoreline length along which the inlet's volumetric impact is manifest. In practice, some combination of methods is typically necessary to assess the volumetric and lineal extent of an inlet's effect upon the adjacent shores. For this study, Methods 1 and 5 were used to determine the volumetric and lineal extent of the influence of St. Augustine Inlet on adjacent shorelines for both sediment budget time periods.

Method 1: Examination of historical shoreline changes (or volumetric changes). In this method, temporal fluctuations in shoreline location adjacent to an inlet are quantified by comparing profile surveys. Specifically, the cross-shore location of a specific beach elevation (mean high water, etc.) is identified at constant locations along the coast for each time at which data are available. The rates of shoreline change at each location, and between consecutive data sets, are then computed. Alternatively, the change in beach volume above a certain elevation can be quantified at each location for each data set. This alternative (change in beach volume above -20ft NAVD) was selected for this study. Using these methods, Fenster and Dolan (1996) describe four criteria to identify the spatial extent of inlet processes on adjacent shorelines:

- The cessation of abrupt changes in the rates of change alongshore, and/or the reduction in variability of these rates alongshore;
- The slope of a regression line drawn through a subset of along-the-shore values (neglecting transects nearest the inlet) most closely equals zero;
- Changes in the sign of the rate value from erosion to accretion (or vice versa); a change from less erosional to more erosional (or vice versa); or, from less accretionary to more accretionary (or vice versa);
- A change in slope of the cumulative shoreline change or volume change computed along the shoreline.

Fenster and Dolan (1996) found that the first criterion revealed the greatest lineal extent of inlet-related shoreline impact. The second

criterion generally yielded the next greatest degree of impact, and the third criterion yielded the most conservative zone. They concluded that there are zones in which inlet-related processes dominate shoreline trends (estimated from the third criterion), and where inlet-related processes influence shoreline trends (estimated from the first criterion).

The fourth criterion is a potentially useful synthesis of the first three, particularly where shoreline change data are noisy. In this approach, the shoreline change [or more meaningfully, the local volume change (volume per unit alongshore beach width)], is integrated along the shoreline, starting at the inlet (x=0) and continuing to the updrift and downdrift beaches. The process of integration smoothes fluctuations between adjacent profiles. This allows improved visualization of large-scale trends and easier discrimination of the data points that are dominating the data set. Integrating away from the inlet (and for a positive valued shoreline axis), positive slopes in the cumulative curve represent shoreline accretion while negative slopes represent erosion.

Method 5: Examination of the inlet's net sink effect. Whereas Method 1 will discern an inlet's effect through examination of shoreline change, this method relies primarily upon volumetric changes measured at and within the inlet. Additionally, the assessment of the inlet's impacts is not *a priori* biased by the length of shoreline selected for examination.

- An inlet's net sink effect is defined as the quantity of material that the inlet has captured from the littoral system. In most cases, natural and stabilized inlets remove sand from the littoral system through accretion of adjacent shores, shoaling in channels, and accretion of ebb- and flood-tidal shoals. However, inlets with riverine input may be the source of littoral material for the coast (e.g., Columbia River, Washington/Oregon).
- The net sink effect, or volumetric impact, is first computed by adding: The volume (or rate) of impoundment adjacent to the inlet entrance; the volume (or rate) of net sand accumulation within the inlet's channels and shoals; the volume (or rate) of sand removed from the littoral system by dredging and offshore (or out-of-system) disposal. If dredged material is placed on the adjacent beaches, it remains within the adjacent littoral system and thus is not added to the total.
- Then, the following is subtracted from this total: The volume (or rate) of riverine (or other upland) sedimentary input; the volume (or rate) of

barrier removed due to creation (through dredging or breach) of the inlet (if this event is within the time period of consideration).

- The resulting value is the volume (or rate) of sand which has been removed from the adjacent shores' littoral systems over the period of examination. Inlet-adjacent volume changes are then examined to discern the minimum distance away from the inlet along which this volumetric impact is manifest.

For this study, the inlet's sink effect was computed using the bathymetric change analysis described in Section 4.3. The resulting volume (or rate) of sand which was removed from the adjacent shores' littoral systems is listed in Table 8.

Inlet-adjacent volume changes were then examined to discern the minimum distance away from the inlet along which this volumetric impact was manifest by using Method 1 in conjunction with Method 5. Figure 34 is an illustration of the use of Method 1 in conjunction with Method 5 to determine the alongshore region of the influence of the St. Augustine Inlet. To apply the method, it is necessary to determine the most northerly and southerly locations at which a change in slope occurs (see arrows). The change in slope indicates that, up until this location, the beaches have significant connectivity (sediment exchange) and balance the volume that was captured by the inlet complex during the time of consideration.

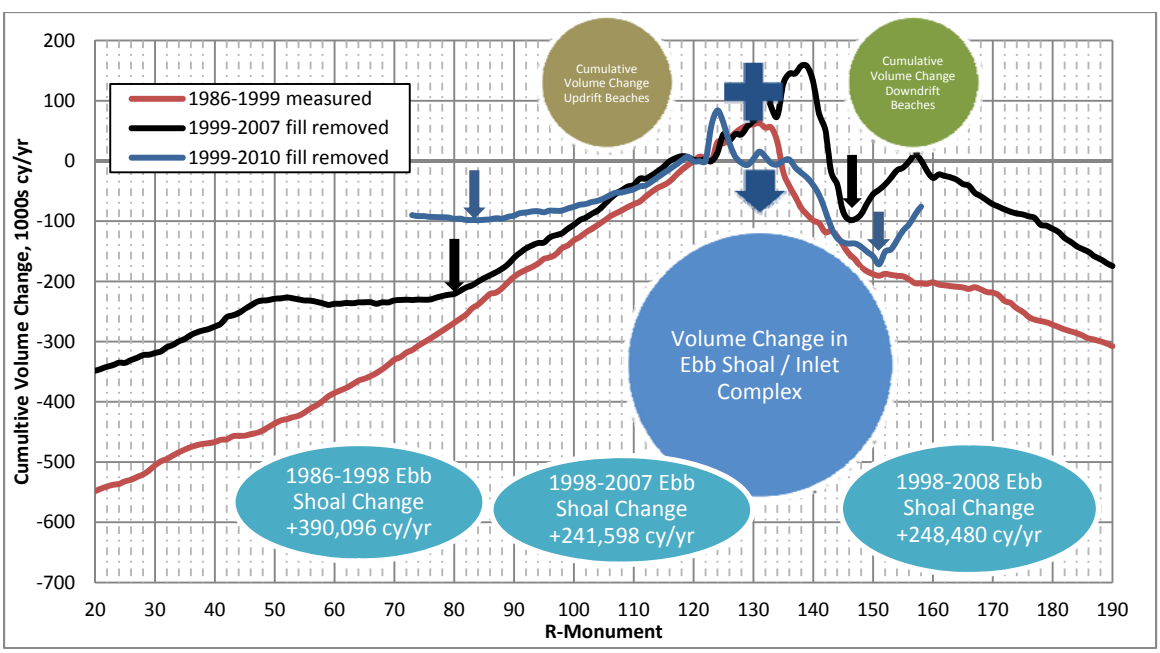


Figure 34. Determination of the extent of inlet influence; lines show the cumulative beach profile volume change for the updrift and downdrift beaches, and the blue circles show the volumetric change of the ebb tidal shoal complex for each time period.

Average annual cumulative volume change for the updrift (north) and downdrift (south) shorelines was calculated, starting at zero at the inlet and summing cumulatively at each R-monument both updrift and downdrift of the inlet. Downdrift volume change was calculated with and without the inclusion of beach nourishment volumes (Figures 35 and 36). Nourishment volumes were removed from each profile reach based upon measured post-nourishment surveys (Taylor Engineering Inc. 2003, 2005).

The 1999 to 2010 cumulative volume change is presented in Figure 36.

Following Method 1 outlined in the CEM Part V-6 (USACE 2008), the alongshore reach of shoreline strongly influenced by the inlet was determined through examination of the alongshore location where a change in slope of the cumulative shoreline change or volume change exists when computed along the shoreline. Cumulative beach profile change computed updrift and downdrift of the inlet (Figures 35-36) was inspected to discern a change in slope of the plotted data (neglecting transects nearest the inlet) (see CEM EM 1110-2-1100 (V-6-30); USACE 2008). For the 1999 to 2003 period, change in slope for northerly and southerly beaches occurs at R-90 and R-160, respectively. For the 2003 to 2007 period, change in slope for northerly and southerly beaches occurs at R-72 and R-147, respectively

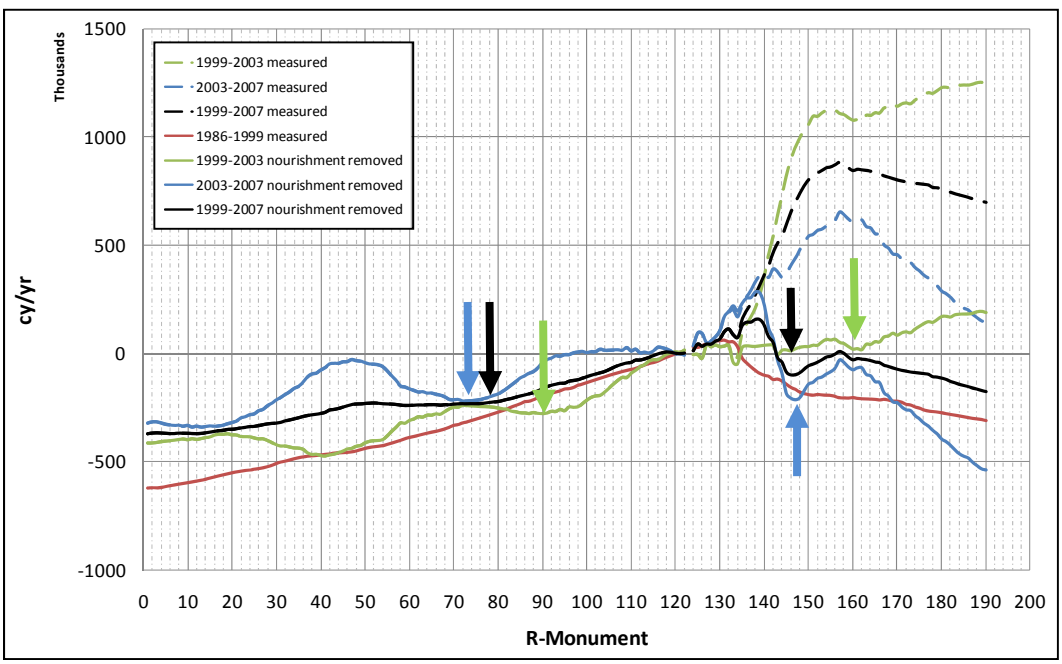


Figure 35. Cumulative beach profile volume change with and without beach nourishment, 1993-2007; arrows show the change in slope of the cumulative volume curves indicating the limit of inlet influence for each time period.

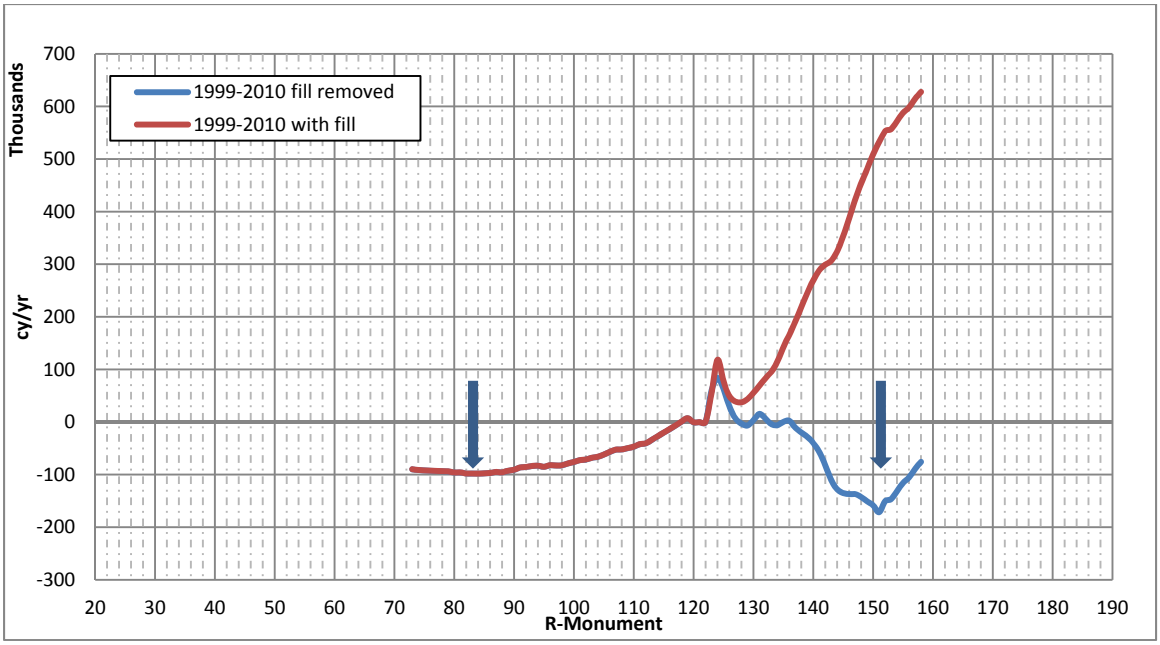


Figure 36. Cumulative volume change from 1999-2010; arrows show the change in slope of the cumulative volume curves indicating the limit of inlet influence for this period.

(Figure 34). For 1999 to 2007, a southern change in slope can be observed at R-146; and a change at R-78 for the northern beaches. For 1986-1999, it wasn't possible to observe changes in slopes for the north or south beaches (Figures 35-36). For the 1999 to 2010 period, a maximum erosion of -98,800 cu yd/year and a slight change in slope of the curve occur at R-83, north of the inlet. South of the inlet, the change in slope at R-151 is much easier to see, totaling -179,300 cu yd/year. Table 10 summarizes the analysis for each time period. These data can be applied to estimate the total rate at which the inlet has removed sand from the littoral system. For example, for the 1999 to 2010 data, the analysis implies that the total "sink" effect of the inlet should be approximately -98,800+ -179,300 cu yd/year, or, ~-278,100 cu yd/year. When applying Method 5, we would expect that the total volume captured by the inlet complex should balance the rate of adjacent beach volumetric change.

Table 10. Alongshore extent of inlet influence and associated cumulative volume change.

Time Period	R-monument and Volume, 1000s cu yd/yr		Total, 1000s cu yd/yr
	North	South	
1986-1999	Not discernible	Not discernible	n/a
1999-2003	R-90, -277.7	R-160, +17.9	-259.8
2003-2007	R-72, -221.2	R-147, -215.4	-436.6
1999-2007	R-78, -220.9	R-146, -97.6	-318.5
1999-2010	R-83, -98.8	R-151, -179.3	-278.1

4.6 Inlet's net sink effect

In conjunction with Method 1, Method 5, "Examination of the inlet's net sink effect" from the CEM (see CEM EM 1110-2-1100, p. V-6-29-50; USACE 2008) was used to strengthen the analysis discussed in the previous section. The method is advantageous because the impacts from the inlet are not biased *a priori* by the length of shoreline selected for examination. Using results from Method 1 as guidance for Method 5, we examined the inlet's sink effect for the 1999 to 2010 period in the alongshore region spanning R-83 to R-151. For this study, the inlet's net sink effect was computed using the bathymetric change analysis described in Section 3.2 which calculates the volume (or rate) of net sand accumulation within the inlet's channels and shoals. Inlet-adjacent volume changes were then examined to discern the minimum distance away from the inlet along which this volumetric impact is manifest, using results from Method 1 as guidance.

The method outlined in Example Problem V-6-8 from the CEM (see CEM EM 1110-2-1100, p. V-6-29-51; USACE 2008) was used to determine the alongshore distance both updrift and downdrift of the inlet where the volumetric impact of the net sand accumulation within the inlet's channels and shoals is manifest.

Integrated volumes were calculated for the reaches listed in Table 10 for updrift and downdrift beaches, respectively, for each time period. The change in beach volume was compared with the volume change in the inlet's ebb shoal complex over the same time duration. Results are listed in Table 11. Volume losses at the updrift and downdrift beaches compared well with volume gains at the ebb shoal (Figure 37; Table 11) and residuals (losses updrift + losses downdrift + gains ebb shoal complex = residual) were <10,000 cy/yr over the 1986 to 1999, 1999 to 2007, and 1999 to 2010 time periods. Good agreement indicates that the inlet effect is indeed realized in the region bordering R-80 to the north and R-151 to the south. At different time periods, the specific location of the north and south boundary changes slightly, but in general, and over the long-term, R-80 and R-151 appear to be the bounds of the inlet effect. Note that the 1999 to 2010 period is also included in Table 11 and on Figure 37, but the analysis was slightly different because of the lack of flood tidal shoal bathymetric data as discussed next.

Table 11. Summary volume change (cy) for ebb shoal, north beaches and south beaches accounting for nourishment.

Time Period	R-monument and Volume, 1000s cu yd/yr		Ebb Shoal Volume, 1000s cu yd/yr	Total, 1000s cu yd/yr	Residual, 1000s cu yd/yr
	North	South			
1986-1999	R-82, -261.5	R-144, -125.4	390.1	-386.9	3.2
1999-2003	R-90, -277.7	R-160, +17.9	266.5	-259.8	6.7
2003-2007	R-72, -221.2	R-147, -215.4	216.7	-436.6	-219.9
1999-2007	R-78, -220.9	R-146, -97.6	241.6	-318.5	-76.9
1999-2010	R-83, -98.8	R-151, -179.3	278.1	-278.1	0.0

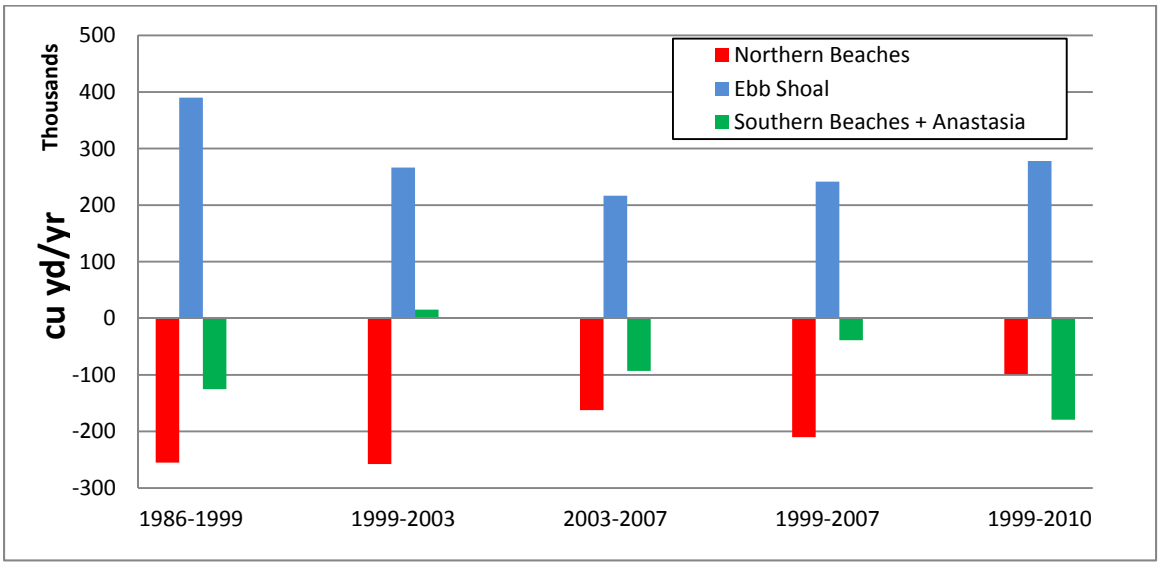
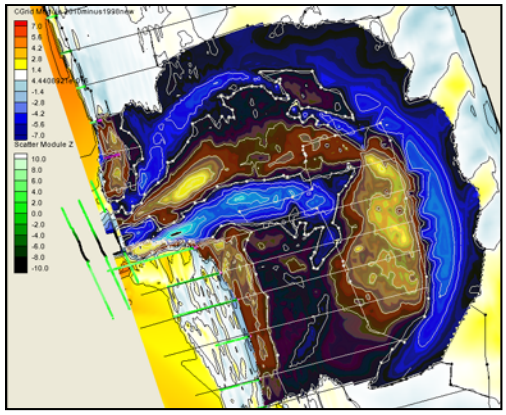


Figure 37. Volume change north beaches, ebb shoal, Anastasia and south beaches.

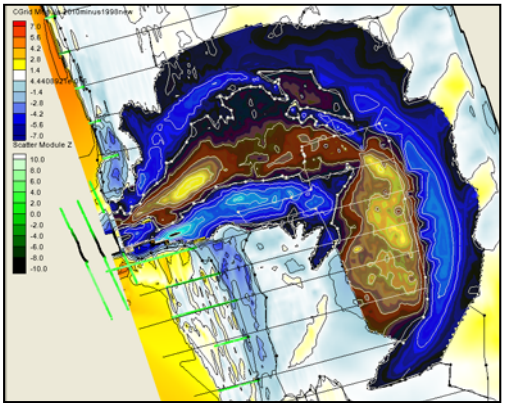
For 1999 to 2010, three alternatives were applied to evaluate the inlet sink, with two options each to represent volumetric change for the Flood Tidal Shoals + Channels (FTS&C). Figure 38 illustrates the regions used in each of the alternatives, Figure 39 shows the numbering of these regions, and Table 12 summarizes the calculated sink for each alternative. For the FTS&C, values were tested with the infilling rate as documented by Srinivas and Taylor (1998) (110,500 cu yd/year) and a value of zero, then evaluated against the maximum cumulative volumetric change shown in Figure 36.

The difference between Alternatives A and C is based upon the definition of the submerged platform fronting Anastasia State Park (Morphologic Zone 7 in Figure 39) which can either be considered part of:

- a continuous beach system fronting the Park (adjacent beach); or
- The nearshore platform of the ebb shoal (inlet sink).



a.



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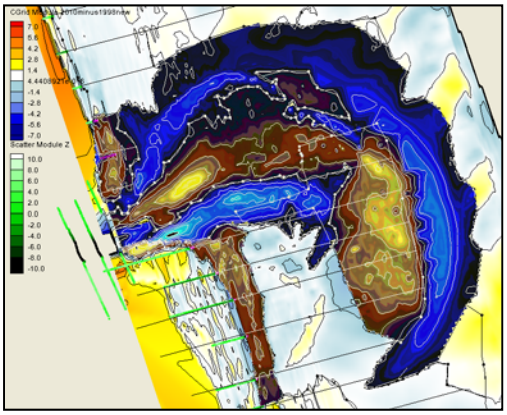

c.

Figure 38. Regions of St. Augustine Inlet used to evaluate the 1999 to 2010 inlet sink: a. all nine morphologic zones; b. morphologic zones 2-5, 9; c. morphologic zones 1-6, 9.

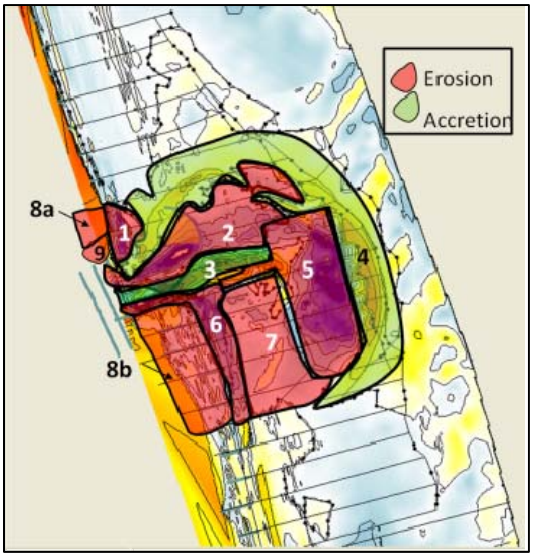

Figure 39. Numbering of regions within St. Augustine Inlet used to evaluate the 1999 to 2010 inlet sink.

Table 12. Inlet sink analysis for 1999 to 2010.

Option and Morphologic Zones	Volumetric Rate (cu yd/yr)	Borrow (cu yd/yr)	Flood Tidal Shoals and Channels (cu yd/yr)	Inlet Sink (cu yd/yr)	Adjacent Beaches (cu yd/yr)		Imbalance (cu yd/yr)
					R83-R122	R123-R151	
A: 1-7, 9	-385,236	634,783	1) 110,500 2) 0 3) 28,545	A1) 360,046 A2) 249,546 A3) 278,091	-98,824	-179,266	A1) 81,955 A2) -28,545 A3) 0
B: 2-5, 9	-147,142			B1) 598,140 B2) 287,640 B3) 516,185	Add Morph Zone 1: -138,870	Add Morph Zones 6+7: -377,315	B1) 81,955 B2) -28,545 B3) 0
C: 1-6, 9	-309,084			C1) 436,198 C2) 325,698 C3) 354,243	-98,824	Add Morph Zone 7: -255,419	C1) 81,955 C2) -28,545 C3) 0
A3) Used for Sediment Budget	-385,236	634,783	28,545	278,091	-98,824	-179,266	0

From a geomorphologic standpoint, cells 1- 7 (Figure 39) collectively are a part of the ebb shoal proper. Typically the morphology of the ebb shoal inlet complex is studied using either aerial photographs, satellite imagery, or measured topography and bathymetry. With the aid of these tools, the identification and the location of the inlet and shoal components, such as the main channel, flood marginal channels, outer shield and nearshore

platform, becomes rather straightforward. However, from the point of view from the beach itself, it is difficult to discern exactly which features represent the submerged beach and those that represent the ebb shoal.

For the sink analysis, if a portion of the volume change was not assigned to the "inlet sink," it was assigned by R-monument to the "adjacent beaches." Each alternative for the inlet sink was independently evaluated against the associated adjacent beach cumulative change. Table 12 summarizes the associated adjacent beach cumulative rate of change for each alternative.

The "Imbalance" column in Table 12 shows the degree to which the rate of Inlet Sink is realized on the adjacent beaches. All options have identical results and, to balance the cumulative adjacent beach change, indicate that the flood tidal shoals and interior channels would need to accrete at a rate of 28,545 cu yd/year or erode at a rate of 81,955 cu yd/year (see last column in Table 12). Because flood tidal shoals are typically sinks for sand (accretive), and in the absence of measurements for the FTS&C for the 1999 to 2010 period, a volumetric change rate for the FTS&C equal to +28,545 cu yd/year was adopted. Given the ranges of net and gross transport rates in the area, Option A3 was selected as the most likely option for consideration in the sediment budget, shown in the last row of Table 12. Thus, the total inlet sink for use in the sediment budget formulation was 278,091 cu yd/year, which is balanced by alongshore erosion equal to -98,824 cu yd/year north of St. Augustine Inlet and -179,266 cu yd/year south of the inlet.

5 Regional Sediment Budgets

A regional sediment budget for St. Augustine Inlet and St. Johns County, Florida, was developed for the 1999 to 2010 period. Development of the sediment budget had three main objectives: characterize the transport pathways and magnitudes for the 1999 to 2010 period, compare to an earlier sediment budget for 1974 to 1995 (Srinivas and Taylor 1998), and provide input to numerical modeling of the region (Reports 2 and 3, Beck and Legault 2012a, b).

5.1 Methodology

For development of the 1999 to 2010 sediment budget, the Bodge Method (Bodge 1999; Coastal Engineering Manual Part V-6) was applied. This method uses the volumetric change rate of the inlet sink and the updrift and downdrift beaches as calculated in the previous chapter, and evaluates these against a range of viable net and gross transport rates for the region. The method also assigns a likely range in values for bypassing, inlet-induced erosion, and impoundment at jetties (if any) for both updrift and downdrift beaches. The resulting calculations that balance the known volumetric changes represent a “Family of Solutions” in that each represents a viable budget. These results can be narrowed to better represent the more likely conditions during the period of the budget.

As presented in the previous section, the total inlet sink for 1999 to 2010 was approximately 278,091 cu yd/year, which is manifest by erosion equal to -98,824 cu yd/year north of St. Augustine Inlet and -179,266 cu yd/year south of the inlet.

The system of equations developed for the sediment budget applies values for left and right beaches from the perspective of a seaward-looking observer (Figure 40).

The equations solved are as follows (Bodge 1999):

$$\Delta V_L = L_1 - p_2 L_2 - m_1 R_1 \tag{3}$$

$$\Delta V_{shoal} = R_1 - p_1 R_1 + m_1 R_1 - L_2 + p_2 L_2 - m_2 L_2 \tag{4}$$

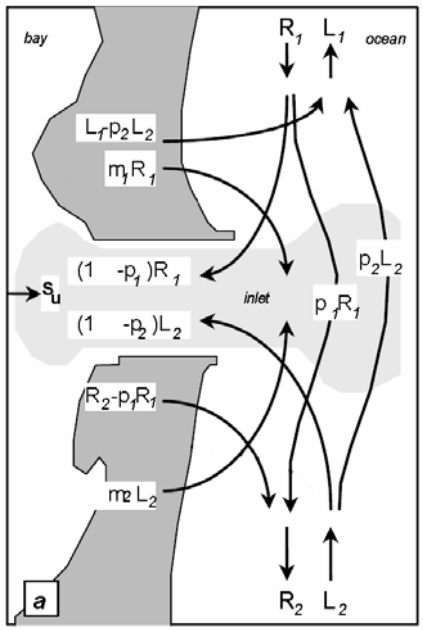

Figure 40. Definition of variables for sediment budget (from CEM IV-6; USACE 2008).

$$\Delta V_R = -R_2 + p_1 R_1 + m_2 L_2 \tag{5}$$

Values applied in the 1999-2010 calculation were as follows:

Gross volume of sand entering the inlet =

ΔV_{shoal}=278,091 cu yd/year

Volume change rate to the left (north) shoreline =

ΔV_L=-98,824 cu yd/year

Volume change rate to the right (south) shoreline =

ΔV_R=-179,266 cu yd/year

To develop the Family of Solutions, the parameters p_1, p_2, m_1, and m_2 ranged from 0 to 1:

p_1, p_2 = fraction of incident transport (R or L) naturally bypassed across the inlet (p_1 = from the left, p_2 = from the right; 0.0 = no bypassing; 1.0 = perfect bypassing);

m_1 = local inlet-induced transport from the left shoreline into the inlet (expressed as a fraction or multiple of the right-directed incident transport, R_1)

m_2 = local inlet-induced transport from the right shoreline into the inlet (expressed as a fraction or multiple of the left-directed incident transport, L_2);

A range of right-directed and left-directed transport rates were applied:

R, L = rightward- and leftward-directed incident transport values at the study area's boundaries

$$R_1=R_2=100{,}000 \text{ to } 400{,}000 \text{ cu yd/year}$$

$$L_1=L_2=-100{,}000 \text{ to } -400{,}000 \text{ cu yd/year}$$

A matlab code was applied with the values as discussed above.

5.2 Family of Solutions

The resulting Family of Solutions is shown in Figure 41.

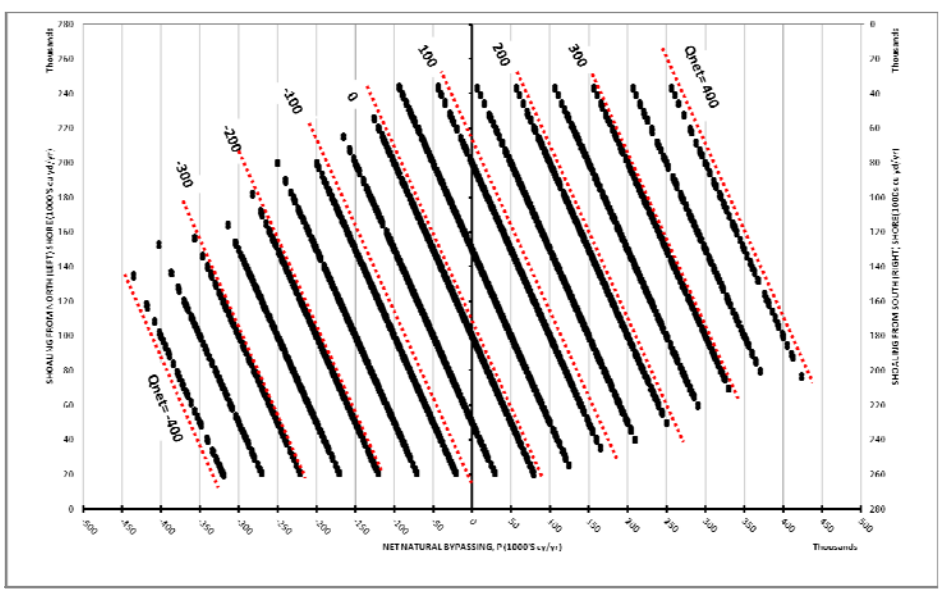

Figure 41. Sediment Budget Family of Solutions for St. Augustine Inlet, 1999 to 2010

To narrow the solutions, the most likely solutions were reduced as follows:

Shoaling from Vilano (north) > Shoaling from Anastasia (south)

Bypassing from the north < 70 percent net transport from north

Shoaling from Anastasia >33 percent ΔV_{shoal}

These narrowed solutions are shown in Figure 42 with red symbols. Two possible solutions are identified: the modal solution, which is the most frequently-occurring solution, and the centroid of the area represented by all the viable solutions. For each of these solutions, it is important to note that the family of solutions only specifies the net longshore sediment transport rate, Q; these solutions do not completely constrain the gross transport rate at the study boundary.

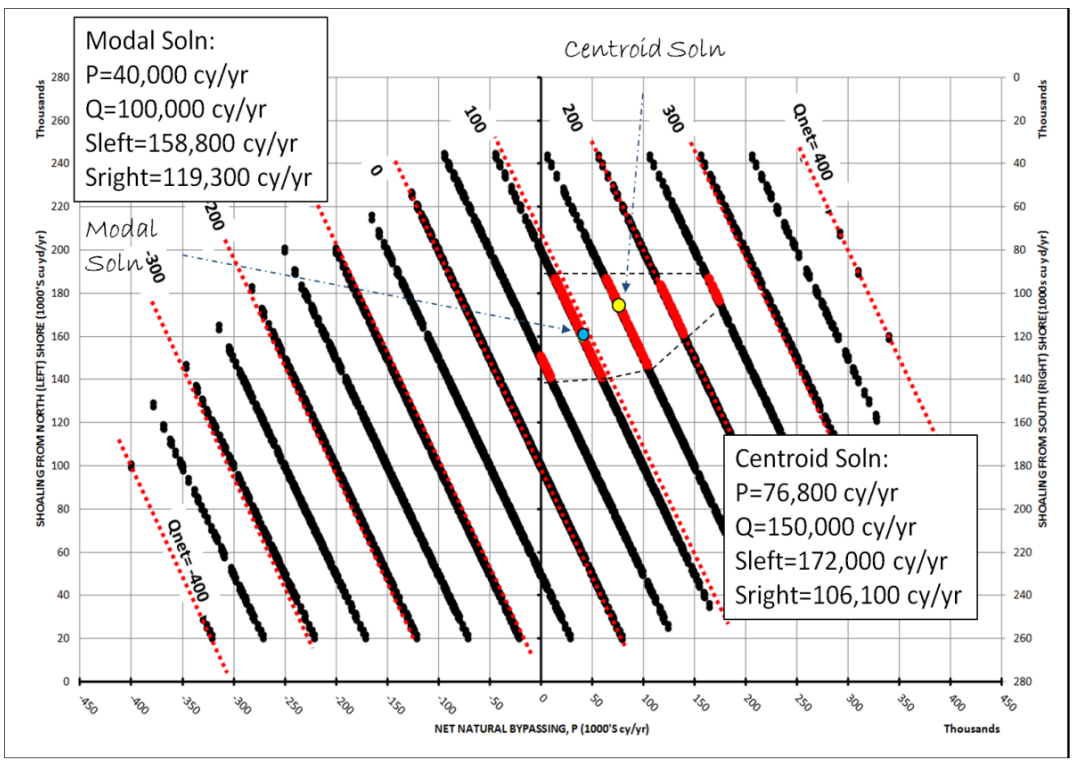

Figure 42. Narrowed Family of Solutions; blue and yellow dots indicate the modal and centroid solutions, respectively, within the Family of Solutions.

The centroid solution, shown in Figure 43, has a net longshore sand transport at the northern boundary of the study area (R-83) of approximately 150,000 cu yd/year, with approximately 77,000 cu yd/year bypassing the inlet. Shoaling from the north into the inlet complex was ~ 172,000 cu yd/year (82,353 + 89,634 cu yd/year), and shoaling from the south into the inlet was ~106,000 cu yd/year (89,633 + 16,471 cu yd/year). At the southern boundary of the study area (R-151), the net longshore sand transport was to the south, approximately 150,000 cu yd/year.

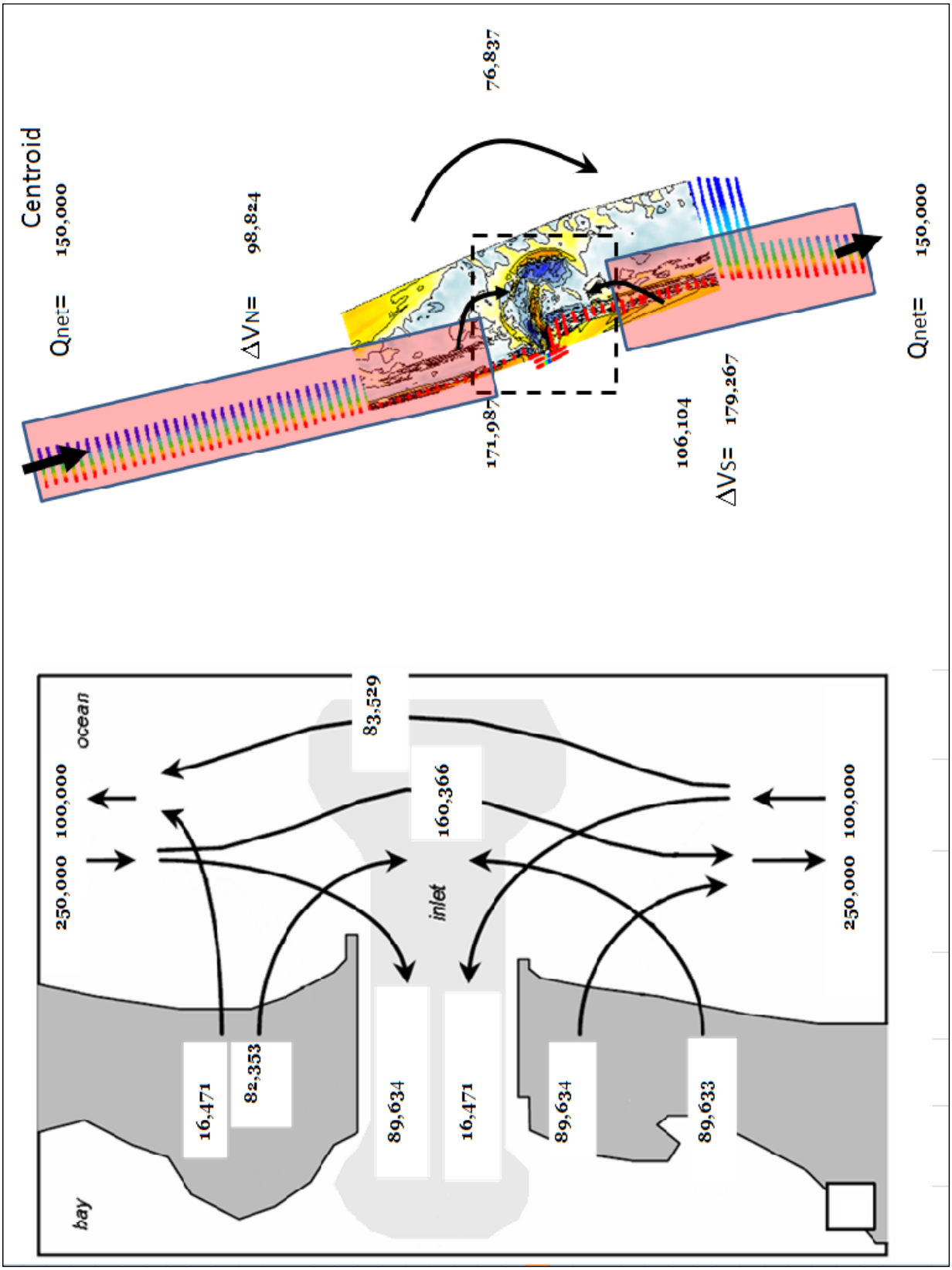

Figure 43. Centroid solution to the regional sediment budget 1999 to 2010, representing the centroid of the viable solutions in Figure 42.

The modal solution, shown in Figure 44, indicates a net longshore sand transport entering the study area from the north at R-83 was 100,000 cu yd/year, of which 40,000 cu yd/year was bypassed and ~159,000 cu yd/year (69,166+89,634 cu yd/year) shoaled into the inlet from the north. Beaches south of the inlet received the net bypassing around the inlet (40,000 cu yd/year) but transported ~119,000 cu yd/year (89,633+29,647 cu yd/year) north to the inlet. At the southern boundary of the study area (R-151), transport was towards the south at approximately 100,000 cu yd/year.

5.3 Sediment budgets 1974 to 1995 & 1999 to 2010

For comparison, the sediment budget from Srinivas and Taylor (1998) for the 1974 to 1995 time period is shown in Figure 45; the centroid solution for 1999 to 2010 is compared in Figure 46.

There are several commonalities and differences between the two budgets. Both budgets show general agreement: net longshore sand transport is from north to south, a persistent reversal to the north exists directly south of the inlet, beaches adjacent to the inlet were erosional, and the ebb tidal shoal complex and the flood shoals were accretional. However, the magnitudes of the transport rates and volume changes were nearly doubled for the earlier period, and the extent of inlet influence for the 1974 to 1995 period was only 3.6 miles on the north beach as compared to 7.4 miles for the 1999 to 2010 budget. The inlet influence to the south in the earlier budget, 5.7 miles, is comparable to that in the later budget (5.5 miles).

There are many possibilities for differences between the budgets. It may be that the inlet ebb tidal shoal complex is coming to more of quasi-equilibrium in the 2000s and not capturing as much sand as in the earlier period. The 21-year period covered by the first period may have included more storms as compared to the latter 11-year period. The longshore sand transport rates for the 1974 to 1995 budget represent potential rates calculated from Wave Information Study (WIS) hindcast data, and therefore represent the capacity of the waves to move sand, if sufficient sand is available in the system. It is possible that this earlier period had more sand available for transport as compared to the 1999 to 2010 period; or that the latter period represents a more quiescent period.

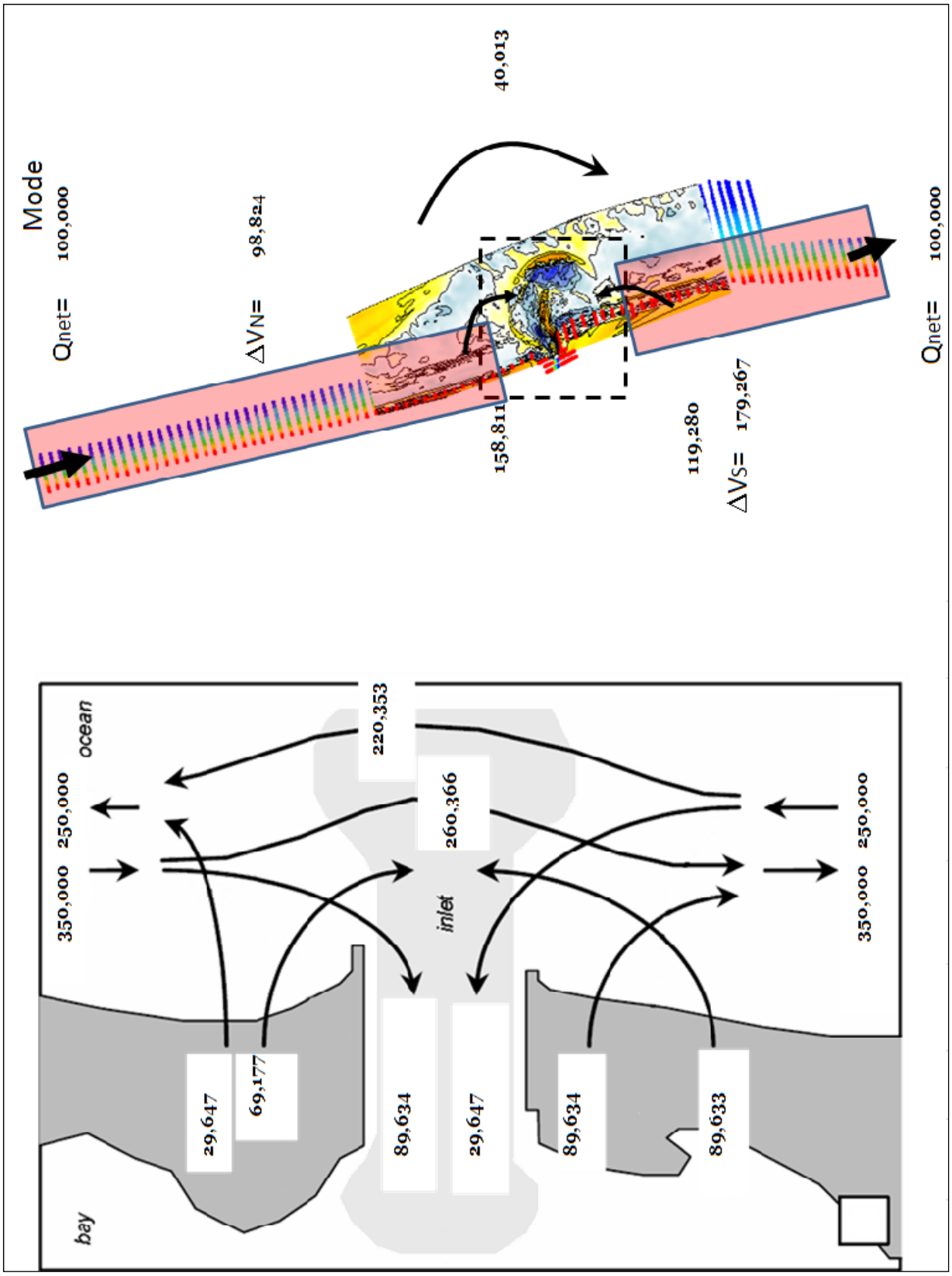

Figure 44. Modal solution to the regional sediment budget 1999-2010, representing the mode of the viable solutions in Figure 42.

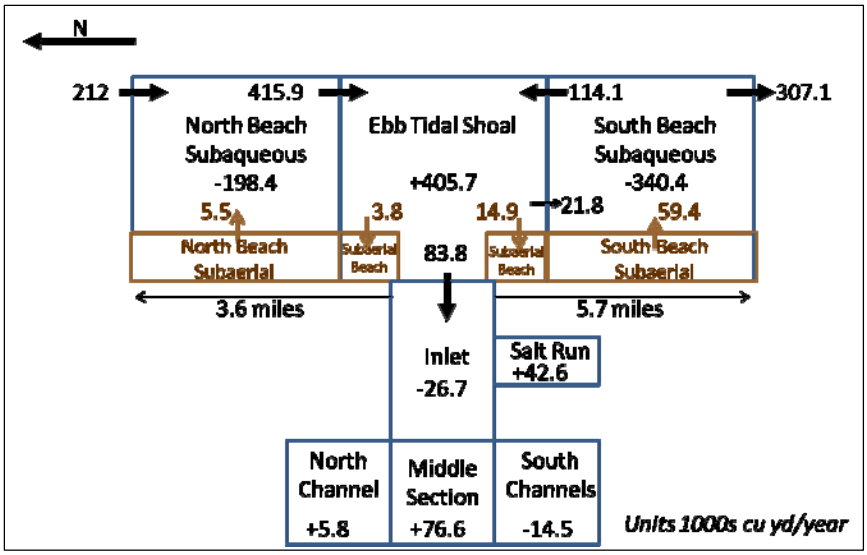

Figure 45. Sediment budget for 1974 to 1995 period (adapted from Srinivas and Taylor 1998)

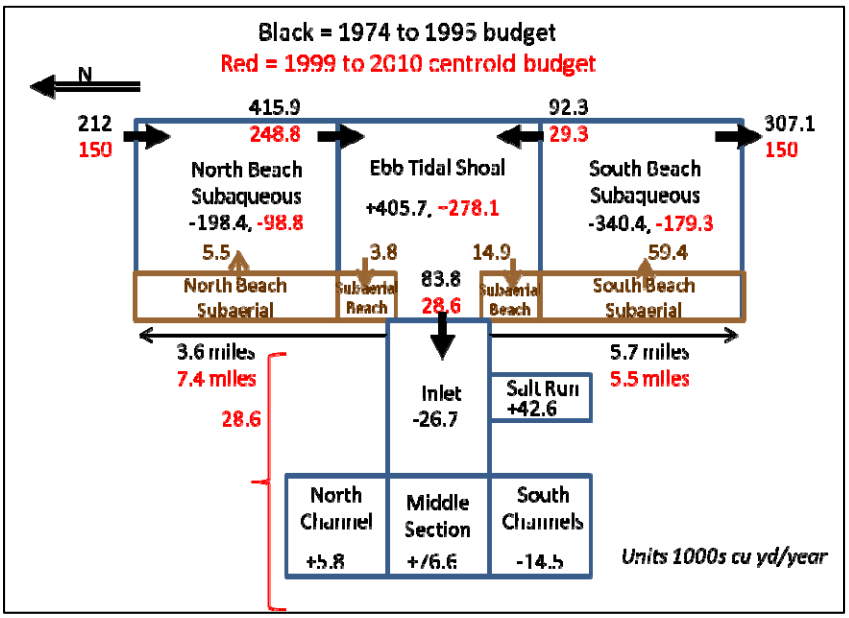

Figure 46. Comparison of budgets, 1974 to 1995 (black) and 1999 to 2010 centroid solution (red)

Of primary importance for this study was whether the behavior of the beach and/or inlet changed fundamentally following either the 2003 or 2005 dredging events. Volume change was presented for two time periods, 1974 to 1995, which corresponds to pre-ebb shoal dredging, and 1999 to 2010 which represent the post-dredging periods. All volumes were adjusted to account for the 2003 and 2005 ebb shoal dredging and beach placement. Before 1999, the north beaches eroded at a rate of -198,400 cu yd/yr; after 1999 these beaches eroded at a slightly slower rate of -98,800 cu yd/yr. The

ebb shoal itself gained sand at a rate of +405,700 cu yd/yr before 1999; and grew at a slower rate of +278,100 cu yd/yr after 1999. The south beaches lost sand at a rate of -340,400 cu yd/yr prior to 1999, and eroded at a rate of -179,300 cu yd/yr after 1999. All of these values indicate that the inlet trapped less sediment in the latter, post-dredge time period than it had before dredging. While the processes governing exactly why the inlet might have trapped less are still an active topic of speculation, it is evident that the inlet borrow area did not cause an overall increase in sediment trapping at the inlet.

Figure 47 illustrates the location of the 30-ft contour in 1974, 1995, and 2010. The location of the 30-ft contour shows the growth of the ebb tidal shoal seaward between 1974 and 2010, and also depicts the slight migration of this contour landward north and south of the inlet.

The measured rates of change for each time period were (from the Inlet Management Plan, Taylor Engineering Inc. 1996) used to calculate the total ebb shoal volume based on the assumption that the initial ebb shoal volume in 1940 was zero following inlet relocation (Table 13). Calculations are compared to measured volumes in Table 14. For example, the measured and calculated ebb shoal volumes for 1998 were 27,926,463 cu yd and 27,424,000 cu yd, respectively.

Volume estimates from Table 14 were plotted in Figure 48 and a second order polynomial was fit to the calculated total volumes over time using a least-squares fit (solid line in Figure 48). Differentiation with respect to time yielded an equation to estimate the time rate of change of the ebb shoal volume (dashed line in Figure 48). Through examination of the time rate of change, it is observed that for each individual year, the ebb shoal is estimated to gain at a slower rate each year, approximately 5,000 cu yd/yr lower than the previous year.

For example, between 1940 and 1941, the ebb shoal gained approximately 600,000 cu yd, whereas between 2009 and 2010, the ebb shoal gained 280,000 cu yd (Figure 48). The rate of growth has decreased by 320,000 cu yd/yr over the 70 years examined. The 1999 to 2010 sediment budget was also affected by the allocation of morphologic zones to define either the “adjacent beaches” or to the “inlet sink”. For example, considering that the offshore submerged platform fronting Anastasia State Park is a part of the beach system (Morphologic Zone 7 in Figure 39), the resulting

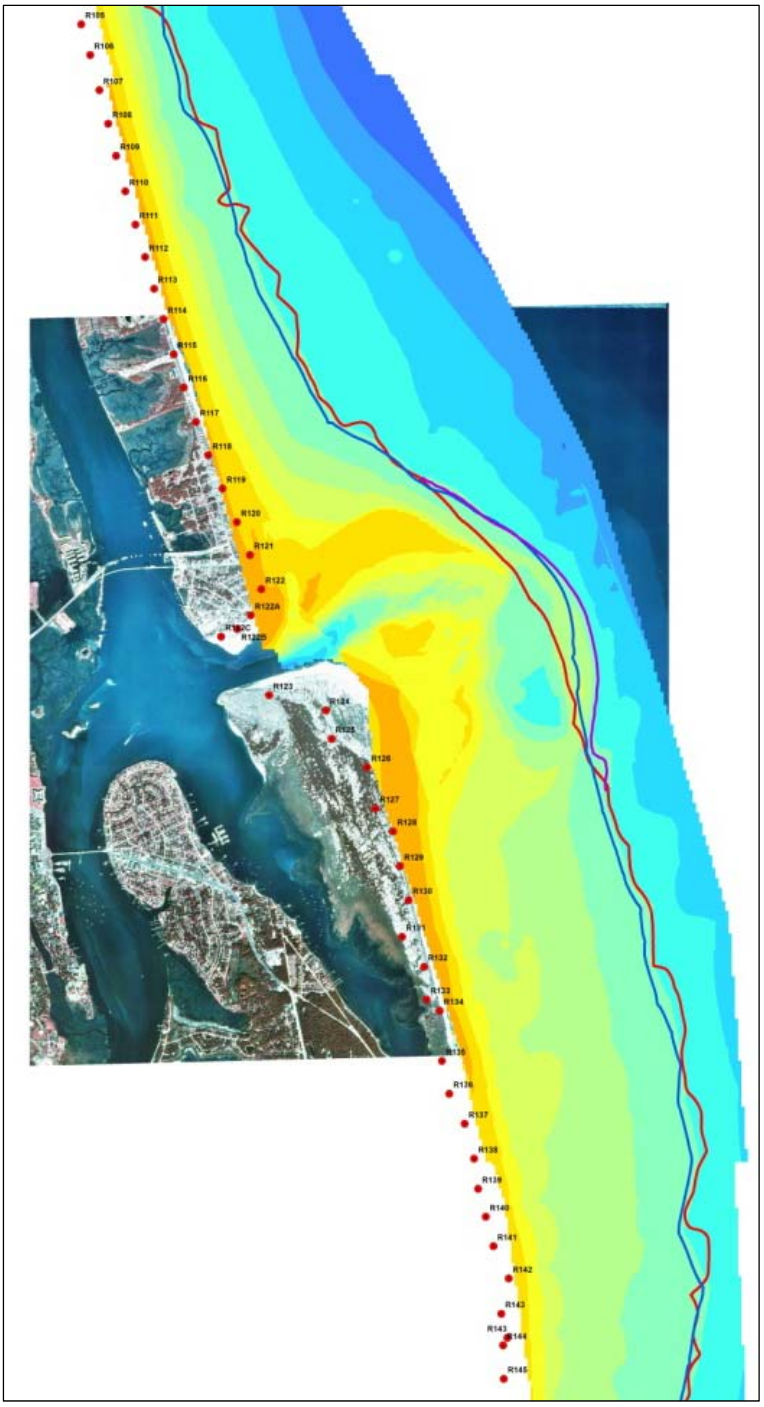

Figure 47. Bathymetry illustrating the -30 ft contour in 1974 (red), 1995 (blue) and 2010 (purple).

Table 13. Volume change in ebb tidal shoal.

Dates	Volume Change, 1000s cu yd/year			
	Ebb Shoal		Anastasia Island	Cumulative ebb shoal
	Inner	Outer		
1937-1974	259	45	216	520
1974-1995	233	173		406
1999-2010	278			278

Table 14. Measured and calculated total ebb shoal volume

Measured Volumes, cy				
1940 ** (t=0)	1974 (t=34)	1995 (t=55)	1998 (t=58)	2010 (t=70)
0 (assumed)	n/a	n/a	27,926,463	31,262,463
Calculated* Total Ebb Shoal Volume (cy)				
1940 ** (t=0)	1974 (t=34)	1995 (t=55)	1998 (t=58)	2010 (t=70)
0 (assumed)	17,680,000	26,206,000	27,424,000	30,760,000

* V (cu yd) = $-2{,}303t^2 + 602{,}600t$, where t=years since 1940

** Ebb Shoal Volume was assumed 0 in 1940

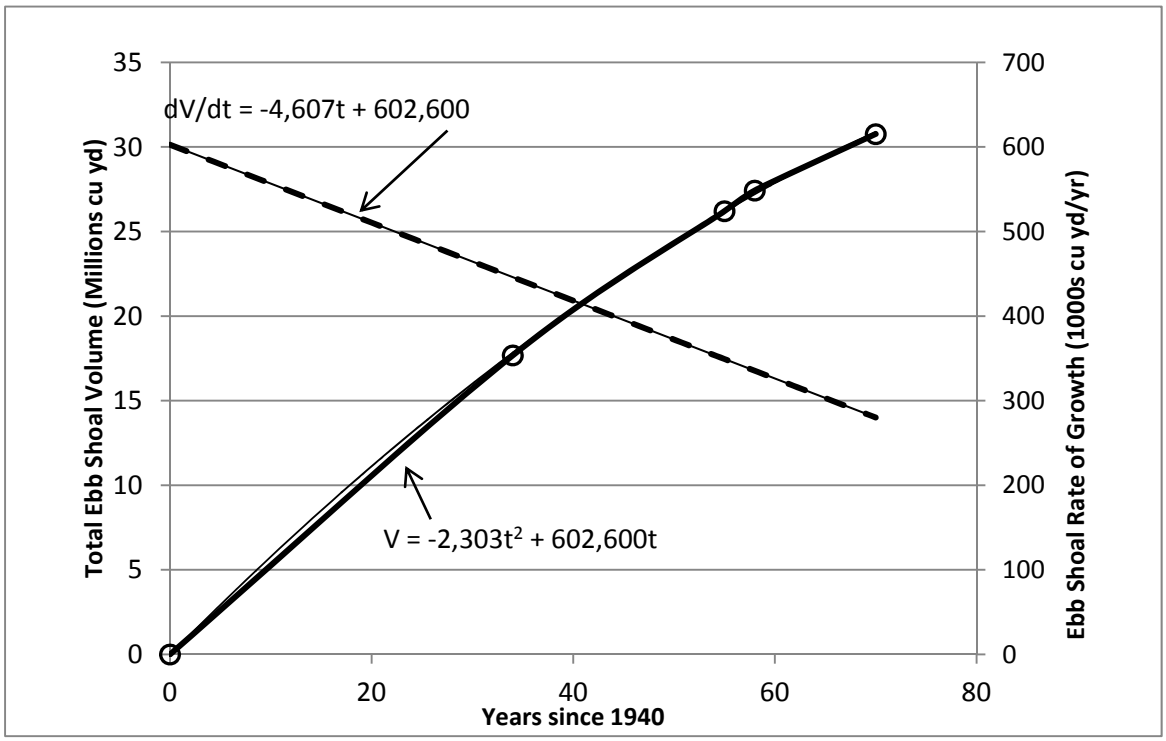

Figure 48. Polynomial relating the total ebb shoal volume (solid line) and volume change (dashed line) as a function of years since 1940 (ebb shoal volume measured to the 26-ft contour).

sediment budget indicates 355,000 cu yd/yr of accretion in the ebb shoal (Morphologic Zones 1-6 and 9, Table 12) and 255,000 cu yd/yr of erosion on the adjacent beaches to the south. Erosion on the beaches to the north remained constant at 99,000 cu yd/year. Whereas these values are closer to the sediment budget from 1974 to 1995 than the centroidal solution presented in Figure 43, the centroidal solution is one which is more in line with a geomorphologic perspective for ebb tidal shoals and agrees with the strict definition of the ebb shoal proper. Using a strict definition of the ebb shoal yields a more conservative (lower) estimate for growth of the ebb shoal between 1999 and 2010, and consequently a conservative estimate of what could be mined from the ebb tidal shoal on an average annual basis.

6 Summary and Conclusions

This study evaluated beach profile, bathymetric, and dredging and placement data from St. Johns County and St. Augustine Inlet, FL to understand the effects of sand mining from the ebb tidal shoal and placement of this sand on the adjacent beaches, and to update the regional sediment budget. The time periods of focus were from 1990 to 1998, which was prior to mining of the St. Augustine Inlet ebb tidal shoal, and 1998 to 2010, which included two mining and beach placement activities with a total volume of 7 mil cu yd placed on adjacent beaches. The updated sediment budget from 1999 to 2010 was compared to the earlier sediment budget from 1974 to 1995 (Srinivas and Taylor 1998). Specific analyses conducted in this study were:

- Define the extent of inlet influence north and south of St. Augustine Inlet for the 1999 to 2010 period;
- Determine the total inlet sink, the quantity (or volumetric rate) captured by the inlet over the period of interest;
- Develop an updated sediment budget for the 1999 to 2010 period and compare to the previous sediment budget for 1974 to 1995.

The previous sediment budget from 1974 to 1995 (Srinivas and Taylor 1998) found the inlet influence to extend 19,000 ft (3.6 mi) north and 30,000 ft (5.7 mi) south of the inlet based on shoreline and beach volumetric analyses. In the budget developed herein, the distances of influence were found to be 7.4 miles north and 5.5 miles south. Profile data analyzed from 1999 to 2003, 2003 to 2007, and the combined period 1999 to 2007 indicate distances north equal to 9.1, 6.1, and 8.0 miles, respectively, reinforcing the longer impact distance north of the inlet. For the same periods of time, southern impact distances were 7.0, 4.5, and 4.5 miles, respectively, agreeing with the 1974 to 1995 budget and the updated 1999 to 2010 budget introduced in this report.

The differences found between the previous and the updated sediment budget can, to a large extent, be attributed to the difference in analysis methods. For the former time period of 1974 to 1995, even/odd analysis was used to describe the region of inlet influence for the beaches to the north. The strongest signal from the analysis was recognized as a function of wave

sheltering from the ebb shoal. The impact of this particular physical interaction between the inlet/ebb shoal complex and adjacent beaches is limited in alongshore extent to the shadow zone of wave sheltering. The latter sediment budget determined the region of influence based upon the conservation of mass of sediments among the inlet/ebb shoal complex and the adjacent beaches. This type of analysis implicitly encompasses all physical forcing that controls sediment exchange between the ebb shoal and adjacent beaches. The presence of the seawall to the south of the inlet resulted in a strong signal for the former and latter sediment budget methodologies. Consequently, that distance, strongly controlled by the presence of the seawall, was determined to be the same for both time periods.

The total inlet sink for the previous sediment budget can be approximated as the sum of the inlet ebb shoal, inlet-subaerial beaches, and interior inlet-channel rates of volume change, or 508,200 cu yd/year for the 1974 to 1995 period. The more recent sediment budget for 1999 to 2010 has a total inlet sink of 278,091 cu yd/year, or approximately 55 percent of the earlier value. As discussed in the previous chapter, there could be many reasons for this difference. The foremost reason for this difference is the continued evolution of the ebb shoal. Figures 25 and 26 show the difference in ebb shoal configuration from 1974 to 1995. In 1974, the offshore contours were relatively straight and parallel away from the ebb shoal and the -30ft contour was about 4,000 ft offshore for the north beach and about 7,200 ft offshore for the south beach. For the 1995 contours, the ebb shoal is further developed, is compact and has a better defined outer (bar) shield than in 1974. The outer shield of the ebb shoal extends an additional 1,000 ft offshore. By 2010, the outer shield extended an additional 600 ft offshore (Figure 33). Second, as discussed previously, the very definition of the extent of ebb shoal itself can change the relative adjacent beach volume accretion rate.

In other comparisons of the two budgets, several differences were observed as discussed in the previous chapter. The most significant of these was the differences in magnitudes of the longshore sand transport rates north and south of the inlet and how this is manifest in volume changes within the inlet system. As noted previously, the longshore sand transport rates for the 1974 to 1995 budget represent potential rates calculated from Wave Information Study (WIS) hindcast data, and therefore represent the capacity of the waves to move sand, if sufficient

sand is available in the system. It is possible that this earlier period had more sand available for transport as compared to the 1999 to 2010 period; or that the latter period represents a more quiescent period.

Through examination of the time rate of change for the ebb shoal, it was observed that for each individual year, the ebb shoal accreted at a slower rate each year between 1940 and 2010. The rate of growth for the shoal had decreased by 320,000 cu yd/yr over the 70 years examined. Further, the 1999 to 2010 sediment budget was also affected by the allocation of morphologic zones to define either the "adjacent beaches" or to the "inlet sink". For example, considering that the offshore submerged platform fronting Anastasia State Park is a part of the beach system would lead to a sediment budget where the ebb shoal would be accreting by 355,000 cu yd/yr and the adjacent beaches to the south would erode by 255,000 cu yd/yr. Whereas these values are closer to the sediment budget from 1974 to 1995, the centroidal solution present here is one which is more in line with a geomorphologic perspective for ebb tidal shoals and agrees with the strict definition of the ebb shoal proper.

In summary, St. Augustine Inlet is a valuable sand resource for the beaches of St. Johns County, Florida. If managed properly, the mining site can be dredged at a maximum of 278,000 cu yd/year and will naturally replenish itself without adverse erosion on the adjacent beaches. Mining exceeding this rate may cause unstable evolution of the inlet morphology and/or erosion on the adjacent beaches. This rate of mining and placement on the adjacent beaches will partially offset the adjacent beach erosion as observed since 1974 in the region. These analyses, morphologic modeling (Beck and Legault 2012a) as well as monitoring of the adjacent beaches and ebb shoal evolution should continue to ensure the sustainability of future sand management practices at the Inlet.

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14. ABSTRACT

This report is the first in a series documenting analyses for St. Augustine Inlet and adjacent beaches within St. Johns County, Florida. The study quantified beach and inlet volumetric change to evaluate the historical and future impacts of the ebb shoal mining and adjacent beach nourishment. The majority of the analyses applied volume change from 1999 to 2010 determined from adjacent beach profiles and bathymetric surveys of the inlet. The total rate at which the inlet removed sand from the littoral system, the "total inlet sink," was balanced by volume change north and south of the inlet. A system of equations was developed to use these measurements and ranges in viable net and gross transport rates to develop a "Family of Solutions" representing viable sediment budgets for the region. The centroid of a narrowed set of solutions was formulated into a representative 1999 to 2010 sediment budget. Findings indicated that the alongshore extent of inlet impact south of the inlet for the 1999 to 2010 period were similar to a previous budget from 1974 to 1995, but extended further north during the later period. The rate at which the inlet removed sand from the littoral system was less in the latter 1999 to 2010 period relative to the former 1974 t0 1995 period, indicating the ebb shoal continues to decrease the rate of accretion. Through examination of the time rate of change for the ebb shoal from 1940 to 2010, the accretion rate has decreased by 320,000 cu yd/yr over the 70 years examined. The study also evaluated whether the behavior of the beach and/or inlet changed fundamentally following either 2003 or 2005 mining of the ebb shoal. All of the analyses indicated that the inlet trapped less sediment in the post-dredge time period than it had before dredging. While the processes governing why the inlet might have trapped less is still an active topic of speculation, it is evident that the inlet borrow area did not cause an overall increase in sediment trapping at the inlet.

15. SUBJECT TERMS

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Beach nourishment	Ebb-shoal mining	Sediment sink method
	Regional sediment management	Sediment transport

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