HOW EFFICIENT IS MOTHER NATURE AT OREGON INLET, NORTH CAROLINA?

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Abstract: The stability and processes at Oregon Inlet, located on the Outer Banks of North Carolina, have direct implications for the local community and surrounding shoreline. With one of the highest wave climates on the East Coast, longshore energy flux mobilizes large amounts of sediment, which if not bypassed can cause erosion downdrift. Budgeting considerations for the increasing expenses associated with the required annual dredging have dictated a need to understand the bypassing efficiency at the inlet. Using historic aerial photography and recent survey data collected by the US Army Corps of Engineers' Field Research Facility, various depositional "sinks" have been identified and monitored to examine their storage potential in an effort to determine: 1) how much sand bypasses or moves into the inlet, and 2) the effect of bypassing efficiency on the surrounding coastline. A direct link between the gross potential sediment transport and the natural bypassing efficiency was found. Data for 1989-2001 show that during energetic years, up to 71 percent of the sediment was bypassed, while during years of lower wave energy the bypassing was as low as 19 percent. The ebb-shoal complex of this 156-year-old inlet was found to be at equilibrium volume and it serves as the primary sediment pathway. Removal of sediment by dredging, deposition on the flood shoal, and spit evolution were identified as important sinks for sediment. Signatures of bypassing inefficiency were observed as shoreline erosion on the downdrift sides, usually to the south, but at times to the north.

INTRODUCTION

Oregon Inlet (OI), located on the Outer Banks of North Carolina, Figure 1, connects the Atlantic Ocean with the second-largest estuarine system in the United States. The only inlet along a 170 km stretch of coastline, the stability of OI is significant for both environmental and economic concerns. Millions of visitors enjoy the surrounding beaches of the Cape Hatteras National Seashore each year and the inlet supports important commercial and recreational fishing fleets. Navigation through the inlet is often difficult due to shoaling within the channel. Annual dredging is required to maintain the channel and the site is under continued consideration for dual jetty stabilization.

It has long been understood that tidal inlets act as significant depositional sinks for littoral sediments moving along the coast, often depriving surrounding shorelines of a regular sediment supply. In response, shoreline losses are sometimes mitigated by mechanically bypassing dredge material from the inlet channel. FitzGerald (1982) suggests that the degree to which natural sediment bypassing occurs is the primary factor

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that determines adjacent shoreline erosion and accretion trends and also affects the navigation and stability of the inlet channel.

This report describes an exploratory investigation that attempts to examine the various mechanisms by which sediment is deposited and bypassed around OI in an effort to better understand natural sediment bypassing and its impact on surrounding shorelines. Through the use of analytical models, unique measurements, and computations that examine volume changes in key morphologic features, annual sediment bypass efficiencies have been computed for OI from 1989 to 2001.

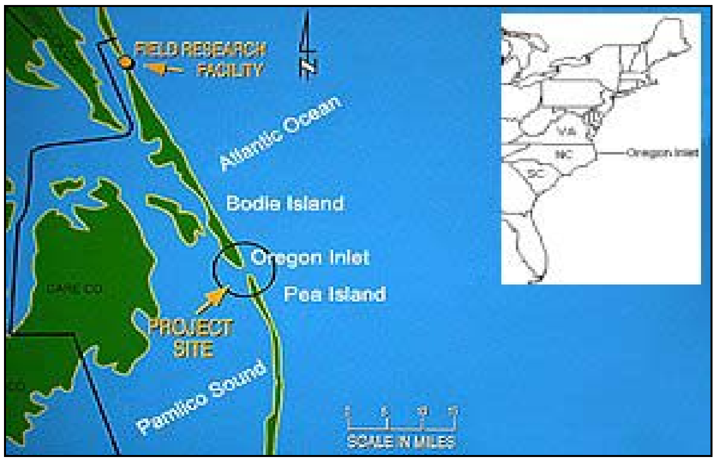

Figure 1. Project location. FRF is 48 km north of OI.

BACKGROUND

Since opening in 1846, OI has migrated south at an average rate exceeding 2 km per century. By 1989 this southerly migration threatened to sever the southern abutment of the bridge that provides the only land route to the communities south of the inlet. In 1990, NC Department of Transportation constructed a 953-m-long rubble mound terminal groin to stabilize the south shoulder of the inlet. The terminal groin was designed to create a fillet in its lee and return the shoreline to the pre-1986 position. Starting during construction, the US Army Corps of Engineers (USACE), Engineering Research and Development Center, Coastal and Hydraulic Laboratory's, Field Research Facility (FRF), in cooperation with the USACE District in Wilmington (USACEDW), has been conducting an ongoing monitoring program to assess the performance of the terminal groin. Miller et al, (1996) reported that the terminal groin has operated as designed.

The Outer Banks experience one of the highest wave climates on the east coast, with over 20 storms per year in which the significant wave heights exceed 2 m (Leffler, et al, 1996). Potential sediment transport computations for 1956-1990 by USACEDW (2001) indicate a net annual southerly transport, consistent with the migration of the inlet, the formation of the north spit, and the morphology of the ebb shoal complex, Figure 2. Previous studies (Jarrett 1978; Inman and Dolan 1989; USACEDW 1995) indicate that annual potential transport rates were on the order of 1.0 million m^3 to the south and 0.5 million m^3 to the north, for a gross annual transport of

1.5 million m^3. The open coast tide range is 1 m. OI has an average historical cross-sectional area of 4700 m^2 and an average spring-tidal prism of 7.96×10^7 m^3 USACEDW (2001).

Figure 2. OI during the "Halloween Storm" on October 31, 1991. Note the symmetry of the ebb shoal complex as outlined by the breaking waves.

The NC Division of Coastal Management (CAMA) has established long-term average annual shoreline erosion rates for north and south of OI at approximately 2 m and 4 m, respectively. As a condition for the permit granted by CAMA to construct the terminal groin, Figure 3, an ongoing shoreline-monitoring program that extends 10 km south of OI has been conducted by the North Carolina State University, (see report series Overton and Fisher, 1990-present). The study established historic shoreline erosion rates based on aerial photographs between 1984 and 1989 at approximately 4 m/yr.

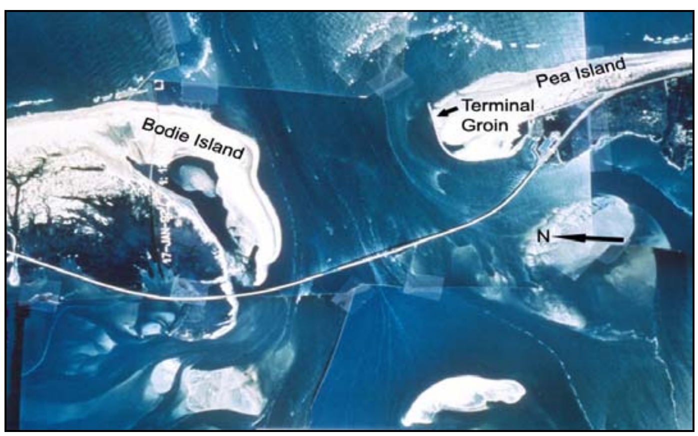

Figure 3. OI, January 17, 1991. Note the re-curved spit on the north, Bodie Island side (left in photo). The terminal groin and Pea Island are visible on the south side of the inlet. Photo coverage is 2 km N/S.

Inman and Dolan (1989) suggest that the normal process of inlet migration involves the accretion of sand on the updrift side of the inlet accompanied by equal erosion of the downdrift side. At OI this has manifested itself in terms of spit accretion on Bodie Island (north) and erosion of Pea Island (south); however, the construction of the terminal groin has fixed the southern shoulder of the inlet since 1991, halting the southerly migration of the inlet and erosion at least within the first 2 km. By 1997

Overton and Fisher had established an average accretion rate of 0.6 m/yr over the first 2 km and erosion of 2 m/yr over the next 3 km. The erosion rate over the last 5 km fluctuated around the historical average of 4 m/yr.

MONITORING PROGRAM

This report builds on the FRF's monitoring program, which conducted semi-annual sled surveys of the adjacent beaches from 1991-1997. The surveys extended from 6 km north to 6 km south of the inlet, with survey lines spaced at 300 m intervals and extending offshore to the 9 m depth contour. Miller (1991) outlines the sled survey system. Surveys of the inlet region in May of 1999 and 2001 were conducted by the FRF using their amphibious LARC survey system. With the combination of a Real-Time Kinematic - Global Positioning System (RTK-GPS) and a digital fathometer, the LARC survey system generates accurate (+/- 5 cm) location and elevation data by filtering out noise from wave action. Speed of sound variability was accounted for by CTD (Conductivity, Temperature, Depth) profiles taken during the surveys. Additional survey lines were added to extend the coverage to 10 km north and south of the inlet and they were extended offshore to the 11 m depth contour. These most recent surveys, for the first time, included the inlet channel, ebb shoal, and a portion of the flood shoal. The FRF's amphibious survey system provides a unique look at the region by allowing surveying across the surf zone, over the shoals, and on the beach. For more information link to: http://www.frf.usace.army.mil/larc/larcsystem.stm.

METHODOLOGY

This report attempts to quantify the efficiency of natural sediment bypassing at OI by comparing volume changes in key morphologic features surrounding the inlet to the total amount of sediment brought to the inlet each year. Sediment that is deposited in the various sinks around the inlet represents an interruption in the longshore transport process, while sediment not accounted for in these areas is assumed to be bypassed. Four fundamental questions were posed:

1) What is the bypassing efficiency of Oregon Inlet and how does it vary?
2) Where are the primary depositional zones?
3) Can we explain the range and year-to-year efficiency variation?
4) What is the effect of bypassing efficiency on the surrounding coastline?

The first step in answering these questions was to determine how much sediment was brought to OI on an annual basis. Gross potential longshore transport rates from 1989-2001 were taken as a baseline to serve as the sediment source for the depositional sinks. Potential longshore transport volumes were computed using the energy flux method (sometimes called the 'CERC formula') described in detail in the USACE Coastal Engineering Manual, Part III, (Rosati, et al, 2002). Input wave height, period, and direction parameters (associated with the spectral peak) were obtained from the FRF's directional wave array. Linear wave theory, as governed by Snell's law and the conservation of wave energy flux, was used to refract and shoal the incident waves to breaking. Although for brief periods during the past decade there have been wave and water level gauges at OI, and even at times a directional gauge, the FRF site was chosen because of the continuous data record. Use of the FRF data was based on the following:

1) we were primarily interested in potential gross transport rates, (as opposed to net), since sediment moving in any direction along the coastline can be forced into the inlet either by wave-induced or tidal currents,

2) comparisons of directional wave information during brief times when gauges were located at both OI and the FRF show that the wave climate summaries from the FRF are representative of the wave climate at OI, and

3) the shoreline orientations are generally similar.

Any assessment of potential transport rates along this coast is sensitive to the bearing chosen to distinguish northward and southward transport. At OI this is complicated by the fact that the bearings are different from one side of the inlet to the other, the bearing varies with distance from the inlet, and it has changed over the years. A general orientation of the shoreline measured from 10 km north to 7 km south would indicate that a bearing of 70 deg would be appropriate. Within 4 km of the inlet, however, segments of the shoreline are rotated and the angles vary by approximately $\pm$6 deg. At OI we chose a shore normal bearing of 72 deg (ref. true north). This is consistent with the established value at the FRF where the wave gauge was located. To determine the sensitivity of our computations, potential transport rates were computed based on angles both larger and smaller than 72 deg and it was determined that for every 3 deg change in the choice of shore perpendicular, the annual net transport rate varied by approximately 15 percent. The annual gross transport rate varied much less, averaging just 2 percent.

Table 1. Potential Transport Rates (1,000 m^3), 1989-2001, Oregon Inlet, NC*

Year	North	South	Net	Gross
1989	-930	840	-90	1,770
1990	-730	810	80	1,540
1991	-830	620	-210	1,450
1992	-1,160	680	-480	1,840
1993	-650	440	-210	1,090
1994	-780	850	70	1,630
1995	-670	750	80	1,420
1996	-770	610	-160	1,380
1997	-390	680	290	1,070
1998	-780	730	-50	1,510
1999	-970	750	-220	1,720
2000	-570	600	30	1,170
2001	-630	630	0	1,260
Average:	-760	690	-70	1,450

* Computations based on wave data at the FRF with shore normal = 72 deg (negative indicates northward).

From the calculations given in Table 1, annual longshore rates from 1989-2001 average 760,000 m^3 northward and 690,000 m^3 southward, for a gross of 1.45 million m^3 and a net of 70,000 m^3 to the north. The gross agrees well with historic estimates. The northward and southward transport values, however, are more closely balanced than found in previous studies. Some prior investigators, using the same potential transport formulation, chose bearings between 64 and 69 deg, and some varied them on the north and south sides of the inlet USACEDW, (2001). Computations using similar angles were conducted as part of the present study to compare results to previous statistics, and an increased magnitude of northerly-directed transport was found, a result that deviated even further from historic estimates. We believe that the nearshore directional wave measurements provide accurate results and can only surmise that this discrepancy is related to some climatological change that we did not investigate.

The next step in quantifying the efficiency of natural sediment bypassing was to examine volume changes in key morphologic features surrounding the inlet. Using bathymetry from the 1999 and 2001 LARC surveys, volume changes in various components of the shoals and spit system were computed. Aerial photography and contour plots for 1999 and 2001 were used to identify the components of the system, Figure 4. All absolute and relative volume change computations were done using Golden Software's Surfer 8 mapping software. XYZ (easting, northing, elevation) data files from the surveys were gridded on a 40 m x 40 m grid using a Kriging search algorithm appropriate for the 300 m spacing of the survey track lines. Relative volume change was computed using a cut-fill method by calculating the volume between the two surfaces defined by the 1999 and 2001 surveys using isolated grids for each given region, (north spit, flood shoal, ebb shoal, etc).

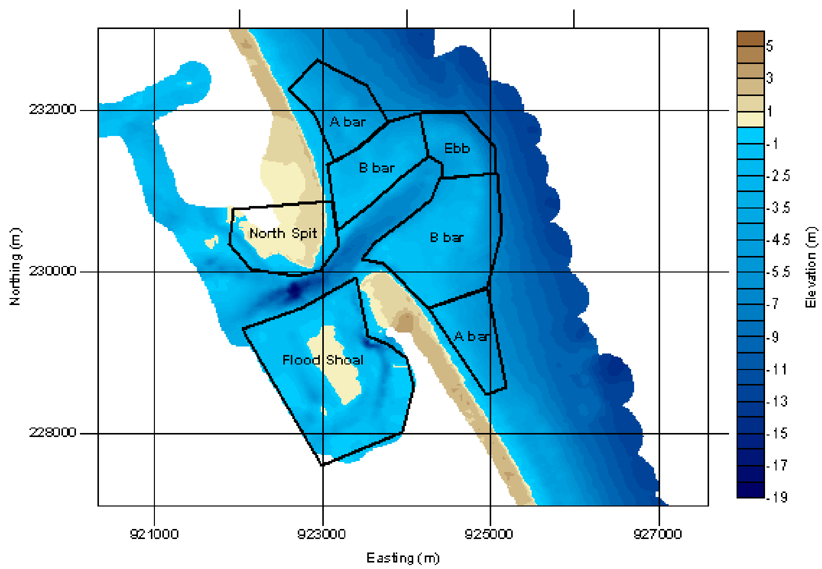

Figure 4. Oregon Inlet May, 2001. The ebb shoal complex (with 'A' attachment and 'B' bypass bars), flood shoal, and north spit were examined for volume changes.

Based on the survey data from 1999 and 2001, an accretion rate of 150,000 m^3/yr was determined for the flood shoal. This is assumed to be an underestimate of the actual accretion rate since the survey covered only 30-40 percent of the area west of the inlet that, based on aerial photographs, appears to be gaining sediment. This value is used in calculating the bypassing efficiencies but it is likely a conservative value as Everts, et al (1983) estimated an accretion rate of 300,000 m^3/year for the flood shoals in the OI estuary.

Volume change computations for Bodie Island, (north spit, Figure 4), indicate an accretion rate of 460,000 m^3/yr from May 1999 to May 2001. Annual assessment of Bodie Island spit migration by USACEDW (2002) show that the tip of Bodie Island advanced south 266 m during this time period. From this data, it was inferred that 1 m of spit migration corresponded to approximately 3400 m^3 of additional volume. USACEDW (2002) determined that the spit migration generally accelerated during the study period. Using this relationship between spit migration and volume accumulation, it was determined that the volume accumulation rate was 130,000 m^3/yr, 1989-1993; 320,000 m^3/yr, 1994-1998; and 460,000 m^3/yr, 1999-2001.

Another major morphologic feature at OI is the ebb shoal complex. The "Reservoir Model," an analytical model of ebb shoal development presented by Kraus (2000), suggests that given the extended age of OI, the ebb shoal complex should be at equilibrium volume. This leads to the assumption that none of the ebb shoal components are accumulating sediment. If the ebb shoal complex is not in equilibrium, the bypassing efficiency will be low until the 'reservoirs' fill up. Because surveys of the ebb shoal complex were conducted only in 1999 and 2001, it was critical to confirm ebb shoal equilibrium in order to extend this assumption to previous years.

Figure 5. Aerial photographs of Oregon Inlet from 1998 (left) and 2001 (right) reveal the changing shape of the ebb-shoal complex in response to changing hydrodynamics as the inlet narrowed.

Kraus (2000) describes the various components of the ebb shoal complex as the ebb shoal, bypass bars, and attachment bars. Volume changes were computed between 1999 and 2001 for all of the components and an accretion rate of 150,000 m^3/yr was determined for the ebb shoal complex. This accretion can be attributed to the changing hydrodynamics of the inlet. Aerial photography throughout the study period provides a clue as to what happened. Figure 5 shows the recent reorientation of the ebb-shoal complex. As the inlet narrowed, the ebb velocity increased, extending the ebb shoal farther off shore. This generated more area for accumulation of sediment eroded by the channel. Since aerial photographs show that this ebb shoal complex reorientation took place only recently, we believe deposition on the ebb shoal complex was much lower during the earlier years and can be disregarded. Future surveys would be expected to confirm that it has re-established equilibrium. Again, this assumption is a conservative one, suggesting that more sediment was bypassed than may actually have occurred.

As an additional check, an estimate of the "absolute" ebb shoal volume was also computed by comparing survey data to an idealized "no-inlet" profile. The procedure for calculating outer bar volumes is outlined by Walton and Adams (1976) and is based on the assumption that parallel contour lines updrift and downdrift of an inlet are outside the influence of the inlet, and are therefore representative of the natural topography were the inlet not present. Therefore, a no-inlet surface can be defined by projecting contour lines along the slope of the shore face. By selecting three points outside the inlet region the equation of a plane was defined as a lower surface and used to calculate the volume of sediment contained within the ebb shoal. Calculations from 1999 and 2001 agree remarkably well with the estimated 20.8 x 10^6 m^3 of outer bar volume at OI found by Walton and Adams (1976). This suggests that the ebb shoal complex has been at an equilibrium volume for at least the past 25 years. Given the age of the inlet (over 150 years) this result is not entirely surprising and is in agreement with the Reservoir Model of ebb-tidal shoal evolution and sand bypassing presented by Kraus (2000).

The final component of the Oregon Inlet depositional environment examined as a sink was material removed from the area through dredging. Bruun and Gerritsen (1959) show that since sediment pathways follow the trace of the ebb shoal in bar bypassing, any channel dredged through the offshore bar will be subjected to deposition of sediment derived from the longshore drift. At OI, annual dredging is required to maintain the integrity of the navigation channel, and can therefore be treated as a sink. Because frequent dredging is required, it is believed that bar bypassing is reasonably efficient at OI and is the primary bypassing mechanism. This is consistent with the idea that the ebb shoal has reached its equilibrium volume, as it bypasses much of the sediment that arrives on the shoal. However, the removal of sediment by dredging results in shoaling and filling in of the dredged channel relatively quickly due to the efficiency of bypassing on the ebb shoal. Bruun and Gerritsen (1959) suggest that in order to obtain efficient bar bypassing considerable wave energy must be present. Walton and Adams (1976) use a wave energy parameter ($height^2$ x $period^2$) to distinguish wave exposure. At OI the calculations give a value of 872 ft^2s^2, placing it in the "highly exposed" category, so it is not surprising that dredged channels would fill in quickly.

RESULTS

Once the primary depositional sinks were established, the next step was to compile the data required to calculate bypassing efficiencies. The results are given in Table 2. Annual natural bypassing efficiencies ranged from a high of 71 percent to a low of 19 percent, with an annual average of 49 percent. A literature search produced only one similar study, *Natural Bypassing of Sand at Coastal Inlets*, by Brunn and Gerritsen (1959). They summarize a University of Florida study in the 1950s based on repetitive surveys of Fort Pierce Inlet (Florida). This was a jettied inlet with a natural reef as part of the ebb shoal complex with potential transport rates on the order of 200,000 m^3 /yr. They provided an efficiency range of between 40 and 60 percent, comparable to the results found for OI in this study.

Table 2. Summary of bypassing efficiencies (volumes in 1000 m^3), Oregon Inlet, NC 1989-2001

Year	Gross	North Spit	Flood Shoal	Dredging	Bypassed	Efficiency	Calculated
1989	1,760	-130	-150	-320	1,160	66%	66%
1990	1,550	-130	-150	-220	1,050	68%	56%
1991	1,450	-130	-150	-530	640	44%	51%
1992	1,840	-130	-150	-820	740	40%	69%
1993	1,090	-130	-150	-330	480	44%	34%
1994	1,630	-320	-150	0	1,160	71%	59%
1995	1,420	-320	-150	-50	900	63%	50%
1996	1,390	-320	-150	-340	580	42%	48%
1997	1,070	-320	-150	-210	390	36%	33%
1998	1,520	-320	-150	-200	850	56%	54%
1999	1,720	-460	-150	-250	860	50%	64%
2000	1,170	-460	-150	-190	370	32%	38%
2001	1,260	-460	-150	-390	240	19%	42%
					Average	49%	51%
					St. Dev	15%	12%

The highest efficiencies tend to occur during years with the highest gross potential sediment transport. The highest efficiencies were in 1989-'90, '94-'95, and '98-'99, and averaged 62 percent. Gross potential transport rates averaged 1.6 million m^3 during those years. In the other years, the efficiencies did not exceed 44 percent (averaged 37 percent) and the gross transport averaged 1.2 million m^3. The one exception was 1992 when the potential transport was high and the efficiency was low. This may have been due to the exceptionally large quantity of material dredged from the navigation span at the bridge. Although this was considered a loss of material in this single year, it in all probability, had built up at that location over many annual cycles.

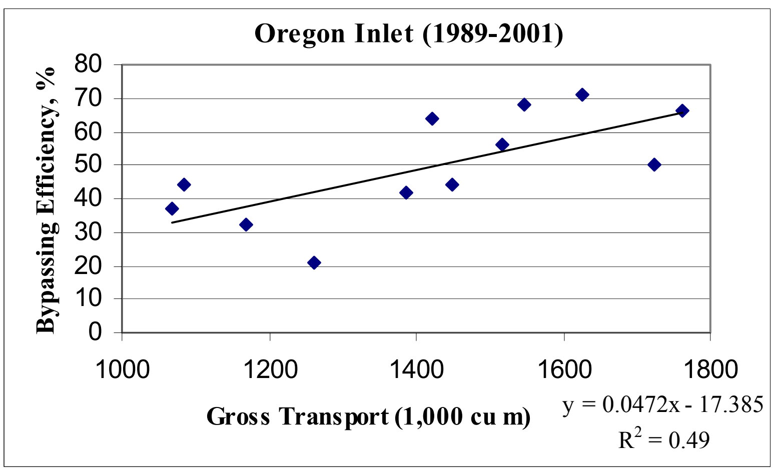

Figure 6. Bypassing efficiencies as a function of gross transport.

With 1992 removed, the correlation coefficient between the gross transport and bypassing efficiency was 0.70 (including 1992 it was 0.53). A linear regression was applied to the data to predict bypassing rates based on gross transport. Again, the 1992 value was discarded due to the abnormally high dredging for this year. The calculated values are shown in Table 2 and a scatter plot showing bypassing efficiencies is shown in Figure 6. It is also interesting to note that following years with major storms, such as 1991 (Halloween Storm) and 1999 (Hurricane Dennis), transport tended to be inefficient for the following 2 years. This may be related to where the sediment is deposited in OI.

Since annual flood shoal volume increase was considered constant, ebb shoal volume change was assumed to be negligible; and dredging did not show a pattern with efficiency changes, attention was directed to the spit volume changes. Typical spit evolution, as described by the analytical model of Kraus (1999), consists of the development of a submerged platform, followed by deposition (eventually the spit becomes sub-aerial and visible), and, in some cases as at OI, re-curvature. Using aerial photography, (see http://frf.usace.army.mil/oregoninlet) it was evident that a major spit evolution sequence started in 1987. Another sequence (superimposed on the prior) started in 1991 and a third sometime prior to 1996. Hurricane Dennis also created a spit platform in 1999. During subsequent years, sediment was deposited on the platform and the spit re-curved, aligning itself with the channel. This is evident in Figure 7, which shows a shift of the channel to the south and accretion of sediment on the re-curved spit to the north. The spit development created a major sink for sediment transported into the inlet. Evidently, sediment was being transported onto the spit through enhanced flood margin channels through the attachment bars. It is not clear why the rate that sediment accreted on the spit increased in 1994 and again in 1999, Table 2. Recall the volumes were estimated from corresponding rates of shoreline advance toward the south based on annual assessments. We do see that these rate changes were roughly associated with the start of the multi-year storm and high efficiency cycle, followed by low efficiency during 1994-1997 and 1998-2001.

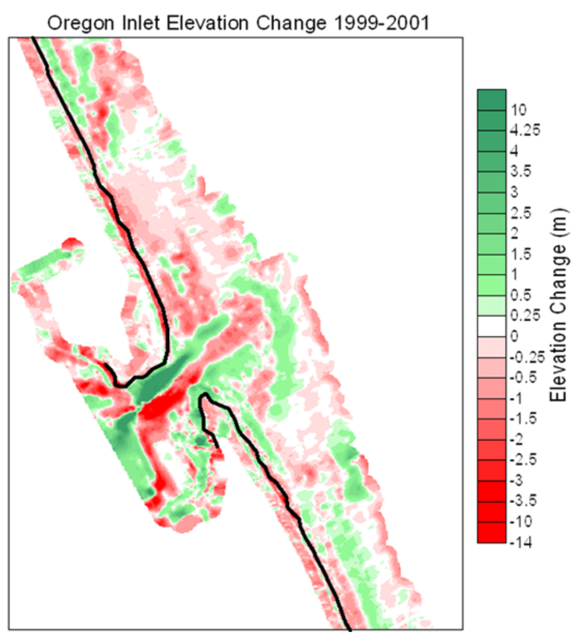

Figure 7. Elevation changes at Oregon Inlet from May 1999 to May 2001. The 1999 shoreline is drawn in black for reference. The alongshore distance is approximately 9 km.

Having established that the efficiencies varied in response to varying gross annual transport rates, storms, and spit evolution, it was important to determine what effect that would have on the shoreline. One would expect to find shoreline erosion and retreat on the downdrift beaches of OI following years with low bypassing efficiencies. Although dredged material, often placed on Pea Island to the south, would in part mitigate low natural bypassing efficiencies, an attempt was made to identify shoreline response that could be attributed to the efficiency level. Pea Island has historically been downdrift of the inlet. However, during some years such as 1991-1993, the net transport suggests that the north side (Bodie Island) would be downdrift.

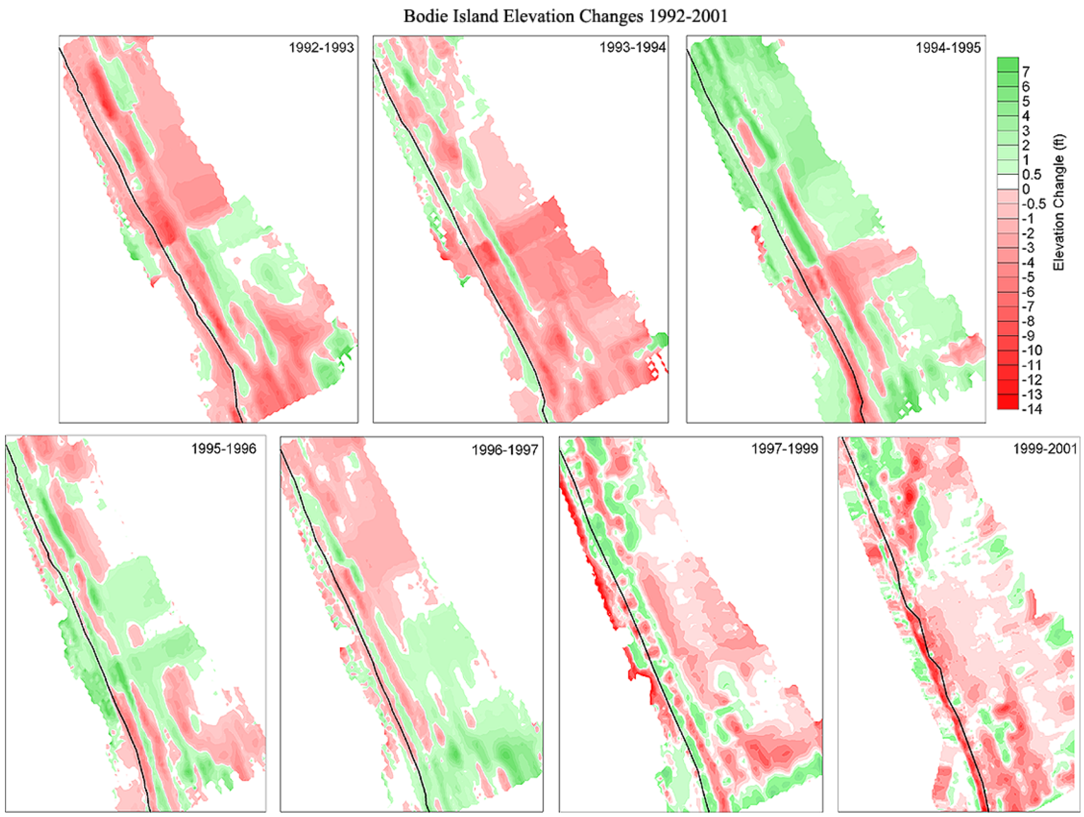

Figure 8. Elevation changes along 5 km of Bodie Island (north side) from 1992 to 2001. Red shows areas of erosion and green areas of accretion. Black line is the shoreline.

Miller, et al (1996) discusses the shoreline response from 1991-1996. Their results examine the changes that occurred from the winter of 1991 to the winter of 1994, and from the winter of 1994 to the winter of 1996. This time period was divided into two intervals to represent the different conditions present when the transport is predominately south to north, 1991-1993, and when it is north to south, 1994-1995. When Bodie Island was the downdrift side of the inlet, erosion is prevalent as can be seen in changes during 1992-1993 and 1993–1994 in Figure 8. There is erosion on the downdrift bypass and attachment bars, and there is little sediment fed to the north beaches. From 1994-1995, as the wave climate returned to more historic conditions, there is accretion on Bodie Island beaches and the ebb shoal complex rebuilds. One feature that can be seen is the significant erosion of the beaches along the shoreline, (black line in Figure), just north of the inlet, from 1994-1996 and 1999-2001. It is believed that this sediment was transported into the inlet and deposited on the north spit. From 1997-1999, these beaches show signs of recovery.

The shoreline response on the south side of the inlet was much different, Figure 9. From 1991-1993, there is evidence of shoreline accretion. In 1992 the bypass and attachment bars are accreting as the ebb shoal complex re-orients itself. A source of some of this material must have been the 1.05 million m^3 of sediment that was dredged from the channel and placed on the beaches south of the inlet. It is also believed that the south to north longshore transport helped feed sand to the Pea Island shoreline. Erosion is prevalent from 1995-1996, as the net longshore transport returned to a southerly direction. Shoreline monitoring completed by Overton and Fisher (1990-present) also provides insight into depositional trends on Pea Island, especially near the terminal groin. From 1991-1992, there was considerable accretion of the shoreline, as the northern tip of Pea Island built out to fill in the area behind the terminal groin. This accretionary trend continued up through the summer of 1993, consistent with the south to north longshore transport. Beginning in 1994 and continuing through 1997, however, shoreline erosion became more evident all along Pea Island as the net transport shifted back to the south.

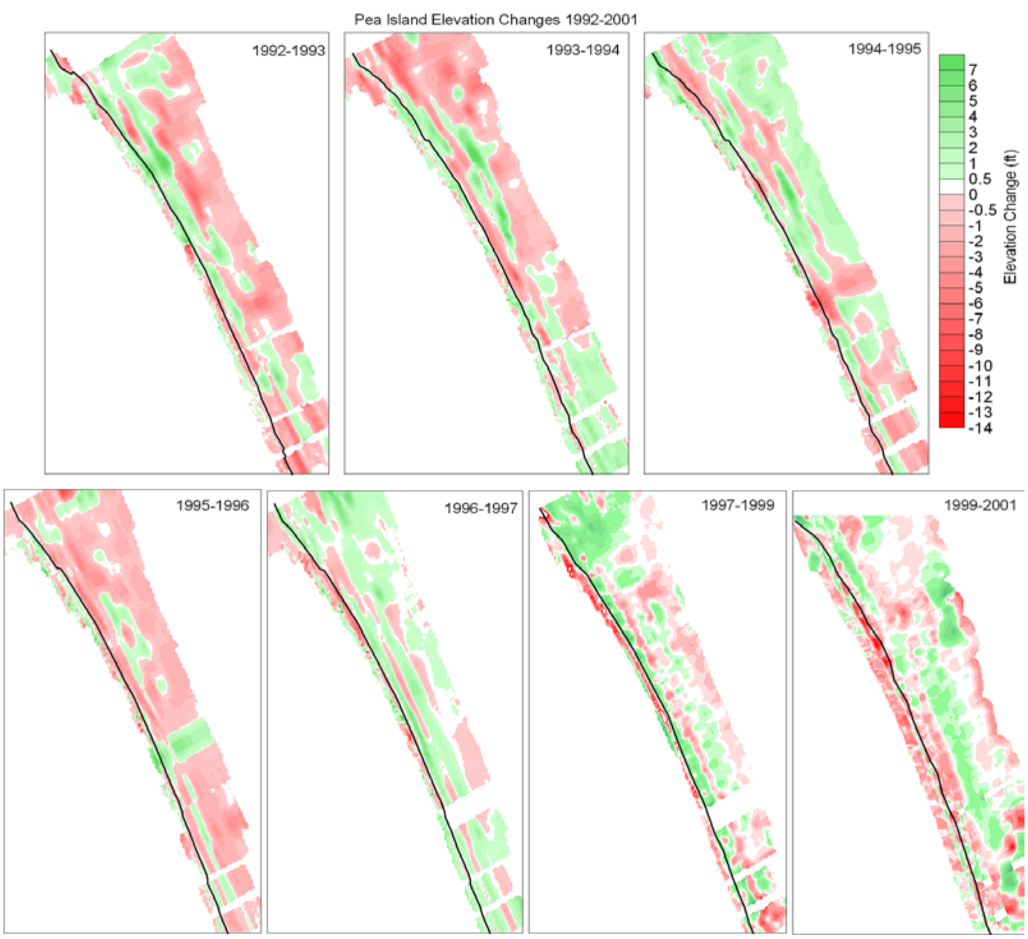

Figure 9. Pea Island (south side) elevation changes from 1992 to 2001. Red shows areas of erosion and green shows areas of accretion. Black line is the shoreline.

These results show a direct link between the gross potential transport and natural bypassing efficiency at OI. The efficiency is reasonably well correlated to years with high potential transport, yet low efficiency was observed in the years that followed due to spit growth and evolution. A signature of the effect that this efficiency has on the beaches can be seen as erosion of the downdrift shoreline.

CONCLUSIONS

An exploratory investigation was conducted to determine natural annual bypassing efficiencies at OI from 1989 to 2001. The bypassing efficiency at OI varied from 71 to 19 percent with an annual average of 49 percent. The highest efficiencies corresponded to years with the highest gross potential sediment transport. The correlation coefficient between gross transport and bypassing efficiency was 0.70. The relationship was:

$$\textit{Bypassing Efficiency}[\%] = 0.0472 \times \textit{Gross Transport}[Km^3] - 17.4[\%] \qquad (1)$$

where gross transport is in 1000 m^3 and efficiency is given as percent bypassed. This ignored 1992 when high gross transport was offset by the highest annual dredging volume experienced during the investigation. Including 1992, the correlation was 0.53.

Year to year variation was found to be primarily controlled by both wave climate and spit evolution. Inefficient years followed years with major storms apparently responsible for initiating spit evolution, which was a major depositional zone that accounted for up to 460,000 m^3 of sediment annually. An unexplained increase in the rate of accumulation on the spit was observed in 1994 and again in 1999. Sediment deposition on the flood shoal, Bodie Island spit, and in the channel during times of low bypassing efficiency resulted in shoreline erosion on the downdrift beaches, which at OI can at times be either side of the inlet.

The study identified the need for repetitive surveys of the entire inlet, including the ebb shoal, the entire active flood shoals, the shoreline up and down coast (a minimum of 5 km in this case), and the inlet channel. The study would have benefited from nearshore directional wave measurements both up and down coast. A future investigation should include a rigorous wave study to assess potential transport levels and minimize the sensitivity of net transport on the selection of the shore-normal bearing.

These results provide the engineer a planning tool that could be used to anticipate future dredging requirements based simply on the recent past wave climate information.

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