

Linking Inlet Hydrodynamics and Morphologic Response at Oregon Inlet, NC

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ABSTRACT

A series of recent bathymetric and topographic surveys (1999, 2001, 2003) conducted at Oregon Inlet provides a unique opportunity to investigate sediment transport and morphologic trends in the area. The surveys, conducted by the U.S. Army Corps of Engineers, Coastal and Hydraulics Lab, Field Research Facility in Duck, NC, aid in understanding how sediment moves around the inlet because the amphibious survey system gives complete survey coverage on the beach, through the surf zone, and across shoals. By comparing year-to-year variations in morphology, this study attempted to correlate erosional and depositional patterns to wave climate and inlet hydrodynamics over the past four years. Results indicate significant ebb shoal deposition from 2001 to 2003 on the order of 900,000 m³. It is believed that the observed changes in the morphology of the ebb shoal are a result of the approximately 175,000 m³ of sediment that accumulated on the north spit during the study period. As the north spit encroached into the inlet at a rate of 14 m/yr, the channel curved around the tip of the spit and deflected approximately 35° to the south. The corresponding channel migration was 28 m/yr. In response to the initial decrease in width, the channel scoured approximately 2 m deeper to compensate for the loss in cross sectional area. From 2001 to 2003, the cross sectional area of the inlet actually increased, contrary to the period from 1999 to 2001, when the inlet experienced its greatest drop in area since the 1930s. This recovery may suggest that the inlet is approaching an equilibrium cross sectional area.

LINKING INLET HYDRODYNAMICS AND MORPHOLOGIC RESPONSE AT OREGON INLET, NC

1 INTRODUCTION

The following study examines survey data collected by the U.S. Army Corps of Engineers in 1999, 2001, and 2003 at Oregon Inlet, NC in an attempt to link changes in **morphology**¹ to inlet hydrodynamics. The investigation documents shoreline change, identifies areas of **erosion** and **deposition**, and quantifies migration and sediment **accretion** rates.

1.1 BACKGROUND

Tidal inlets are relatively narrow strips of water that connect larger bodies of water such as oceans to smaller bodies of water such as bays or lagoons (Kraus, 2001). These complex systems are environmentally significant in that they regularly exchange water and mix nutrients between open ocean and inter-tidal bay environments (CIRP website). The stability of these inlets relies on the careful balance of depositional and erosional forces. Wave-induced currents, as opposed to tidal or wind-driven currents, dominate sediment deposition around inlet regions. However, without significant tidal energy to prevent infilling of channel pathways, tidal inlets may tend toward closure. The interaction between tidal and wave-induced currents can often lead to complex transport patterns and can change the **littoral** drift pattern entirely (Bruun, 1959), making it difficult to determine the fate of sediment moving in and around tidal inlets. **Bathymetric** and topographic surveys can aid in determining areas of deposition and erosion by quantifying **spit** growth, **ebb** and **food** shoal accretion, and shoreline variability.

It is important to understand sediment transport at inlets in terms of the impact on the regional sediment budget. Tidal inlets are inherently inefficient at **bypassing** sediment and act as traps for sediment moving down the coastline. The process by which sand is transported from the **updrift** side of an inlet to the **downdrift** shoreline is referred to as inlet sediment bypassing (FitzGerald, 1982). The efficiency of sediment bypassing is important for tidal inlets because it controls the rate of sand nourishment to the downdrift beaches.

Bruun (1959) identifies two primary mechanisms by which sediment bypasses tidal inlets: (1) bar bypassing, in which sediment is transported along the ocean bar from wave energy, and (2) tidal flow bypassing, in which sediment is transported by currents associated with incoming and outgoing tides. Due to the significant energy required to mobilize sediment, bypassing cannot occur without considerable wave action and tidal energy, and Bruun (1959) argues that most cases of bypassing represent some combination of these two mechanisms. As sediment moves along these pathways, energy

¹ Bold-faced words are technical terms that are defined in the glossary at the end of the report.

losses and other inefficiencies result in sediment deposition within the inlet, where it is taken out of the alongshore transport.

1.2 SITE DESCRIPTION

Oregon Inlet, located on the Outer Banks in North Carolina, is one of four inlets that drain Pamlico Sound, the nation's second largest estuarine complex. Access through the inlet channel has significant economic implications for local fisherman, as Oregon Inlet supports one the largest fishing fleets on the east coast. The North Carolina coast is a dynamic region, and experiences one of the highest wave climates on the Atlantic coast, with average annual significant wave height and period of 1 meter and 9 seconds, respectively (Leffler et al, 1996). High longshore energy flux mobilizes large quantities of sediment (1,000,000-2,000,000 m³/yr) from surrounding beaches into suspension, especially during storms (Inman and Dolan, 1989). This mobilization of sediment in the inlet region results in significant deposition and infilling. In response, the U.S. Army Corps of Engineers removes approximately 200,00-500,000 m³ of sediment each year from the navigation channel (Vandever and Miller, 2003). The dynamic nature of this area must be considered for any engineering modifications such as **dredging**, mechanical sediment bypassing, jetty construction, or ground transportation, as altering one aspect of the system can affect the whole.

Bonner Bridge, which spans the inlet, provides an important link to the Pea Island Wildlife Refuge and provides the only ground transportation to communities south of the inlet (Figure 1). In 1990, the North Carolina Department of Transportation constructed a 953 m rubble mound **terminal groin** to halt erosion at the south tie in of the bridge (Miller et al, 1996). The current bridge has significant problems with **scour** under the bridge's foundation, and significant measures have been taken to stabilize the structure. Construction of a new bridge is scheduled to begin in 2006 at a cost of \$120 million (Outer Banks Sentinel, 2002). The new construction will relocate the bridge farther west

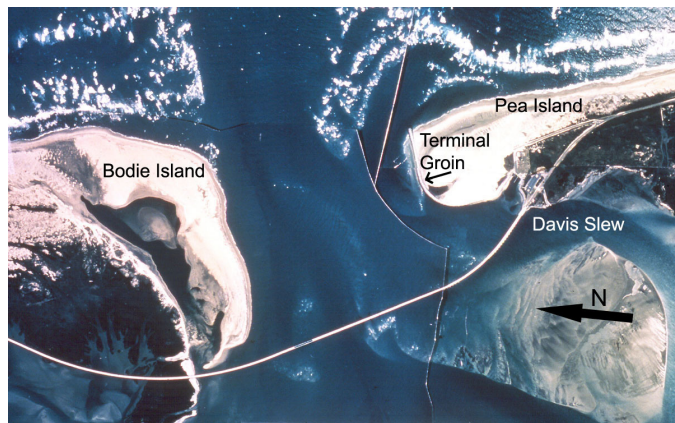


Figure 1. Oregon Inlet, January 17, 1991. The terminal groin and Pea Island are visible on the south side of the inlet. Bonner Bridge crosses on the west side of the inlet. (Photo courtesy of USACE)

of the inlet to protect it from strong tidal currents and to allow for more flexibility in the location of the navigation channel.

1.3 PROBLEM STATEMENT

A series of recent bathymetric and topographic surveys (1999, 2001, 2003) conducted at Oregon Inlet provides a unique opportunity to investigate sediment transport and morphologic trends in the area. Because of the inlet's economic and political significance, it is necessary to identify key erosional and depositional zones, which are important in maintaining the dredged channel through the inlet outer bar and ensuring the stability of the bridge.

The surveys, conducted by the U.S. Army Corps of Engineers, Coastal and Hydraulics Lab, Field Research Facility in Duck, NC, aid in understanding how sediment moves around the inlet because the amphibious survey system gives complete survey coverage on the beach, through the surf zone, and across shoals. By comparing year-to-year variations in morphology, this study will attempt to correlate erosional and depositional patterns to wave climate and inlet hydrodynamics over the past four years. The effect of the inlet on the surrounding shoreline will also be examined.

The study is a continuation of the analysis presented by Vandever and Miller (2003), which examined bypassing and shoreline response at Oregon Inlet by comparing the 1999 and 2001 bathymetric surveys, and extrapolating the results to previous years. This report has two primary objectives: (1) to use the 2003 survey data to verify previous results by Vandever and Miller (2003) and (2) to link the observed morphologic changes to the hydrodynamic forcings during this period. The incorporation of new currents and **tidal prism** data collected by the Virginia Institute of Marine Science in 2002 and 2003 will aid in the second task. The new investigation will verify hypotheses and predictive equations developed in the earlier analysis. In addition to documenting the morphologic changes at the inlet, the study will address the following questions:

1. What is the bypassing efficiency at Oregon Inlet from 2001 to 2003?
2. How valid is the ebb shoal equilibrium volume assumption and are the observed changes statistically significant?
3. How efficient is flow through Davis Slough?
4. What is the rate of channel migration and how does it relate to spit growth?
5. Does the shoreline-volume relationship for Bodie Island developed for 1999-2001 hold for the 2003 survey?

2 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, 2001, and 2003 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>.

3 METHODOLOGY

The first step in quantifying the morphologic changes during the study period was to examine volume changes in key morphologic features surrounding the inlet. Using bathymetry from the 1999, 2001, and 2003 LARC surveys, volume changes in various components of the shoals and spit system were computed. Aerial photography and contour plots for each of the three survey years were used to identify the components of the system. 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. Two separate gridding algorithms were employed for the ocean and inlet sides of the survey region. This is an improvement from the algorithm used in Vandever and Miller (2003) because it groups similar regions together and is believed to provide a more accurate grid. For the ocean grid, the gridding algorithm weights points in the longshore compared to those in the cross shore, since these points have similar elevations. For the inlet grid, there is no trend in the contour lines so points in all directions are weighted equally.

Relative volume change was computed using a cut-fill method by calculating the volume between the two surfaces defined by the 2001 and 2003 surveys using isolated grids for each given region, (north spit, flood shoal, ebb shoal, etc). Absolute volume computations for the ebb shoal were conducted following the methodology in Vandever and Miller (2003) by defining a "no-inlet" surface and overlaying the bathymetry of a given survey. The results of these volume computations are discussed in the next section.

4 RESULTS

The results are presented in terms of qualitative and quantitative descriptions of the inlet response from 1999-2003. This will be followed by a discussion that places the response in the context of the inlet history. Significant changes in the morphology of the ebb shoal and inlet cross section occurred from May 2001 to July 2003. It is evident that the morphologic changes on the ebb shoal and north spit are closely coupled with the hydrodynamic forcings during the study period.

Sediment transport at Oregon Inlet is predominately southward, as indicated by the historic southerly migration of the system and spit growth into the channel. As a result, deposition on the north spit tends to control the response of the inlet. Before considering the changes from 2001 to 2003, it is instructive to review the response in previous years. From 1999 to 2001 the minimum width of the channel decreased from 810 m to 610 m. This was accompanied by a decrease in cross sectional area from 4334 m² to 3390 m² as the cross section changed from a broad U-shape to a narrow V-shape. Survey data and aerial photographs from 1999 to 2001 indicate that as sediment was deposited on the north spit at a rate of 460,000 m³/yr, the inlet channel deflected to the south. It should be noted that the terminal groin fixes the southern shoulder of the inlet and variations in cross sectional area have an intimate relationship with north spit deposition. As the width of the channel decreased, strong currents scoured sediment from the bottom, deepening the channel by 2 meters and improving flow efficiency (Figure 2).

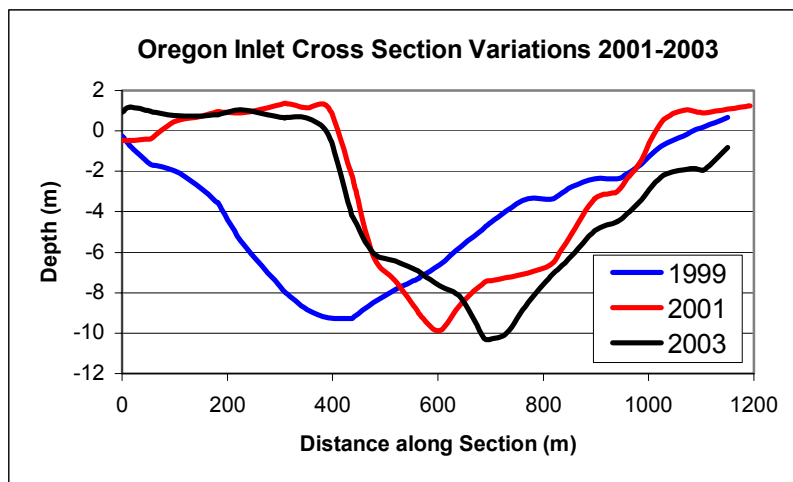


Figure 2. Cross section response at Oregon Inlet, NC from 1999-2003. Note the change in shape of the channel from a broad wide channel to a sharp v-shaped channel.

Similar to the response from 1999 to 2003, the changes observed in the system from 2001 to 2003 were set in motion by deposition on the north spit. During the study period, sediment was deposited on the north spit at a rate of 85,000 m³/yr. However this deposition was not accompanied by a decrease in minimum width or cross sectional area, which increased from 610 m to 655 m and 3390 m² to 3620 m², respectively. Possible explanations for this response are discussed later. As the north spit encroached into the channel at a rate of 14 m/yr, the channel curved around the tip of the spit and deflected approximately 35° to the south farther offshore. The corresponding channel migration was 28 m/yr. The deposition was characterized by filling in the sides of the advancing spit tip, which initially built out into the inlet from 1999 to 2001 (see Figures 3 and 4).



Figure 3. Aerial photography at Oregon Inlet, NC in 1999, 2001, and 2003. Note the changing shape of the ebb shoal as the inlet narrows and ebb currents become more dominant.

As the channel deflected to the south, approximately $900,000 \text{ m}^3$ of sediment was scoured from the channel and deposited on the ebb shoal. This deposition is a result of strong ebb currents in the channel caused by the encroachment of the north spit into the channel. Figure 4 shows the elevation changes from 2001 to 2003. Scour in the inlet channel itself and in the Davis Slough flood channel account for much of this sediment.

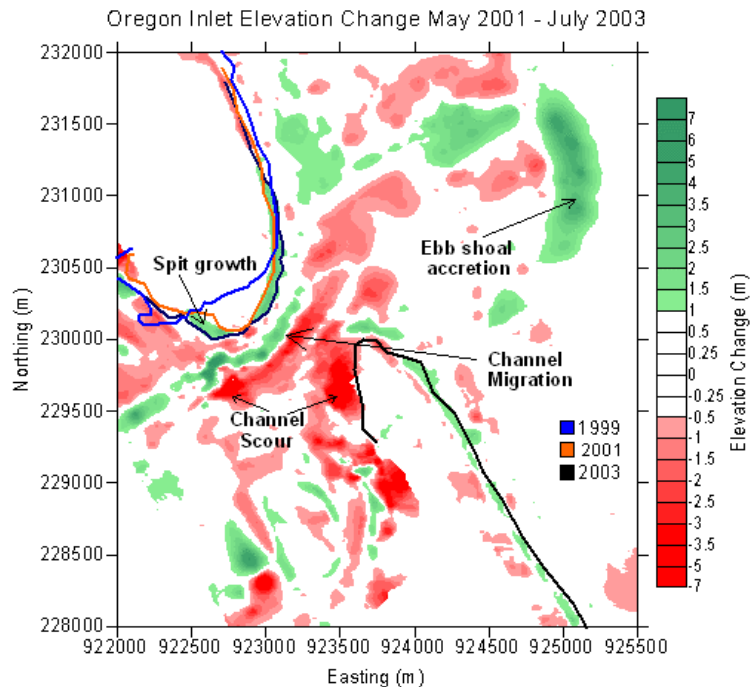


Figure 4. Elevation change from 2001-2003 at Oregon Inlet, NC. Green areas indicate accretion and red areas indicate erosion. The 1999, 2001, and 2003 shorelines are shown for reference.

An important assumption in the bypassing analysis presented by Vandever and Miller (2003) was that the ebb shoal had reached an equilibrium volume and that no new deposition was occurring on the outer bar. Furthermore, sediment that arrives at the updrift side of the ebb shoal is assumed to bypass along the shoal to the downdrift side,

and the absolute volume of the ebb shoal is assumed constant. This was a necessary assumption in computing bypassing efficiencies from 1990-1998 due to the lack of survey coverage during this period. At first glance, the ebb shoal equilibrium assumption appears to be invalid for the period from 2001 to 2003 because of the observed ebb shoal accretion. However, it should be noted that this is not sediment derived from the longshore drift, and is actually sediment from within the inlet system. It can therefore be concluded that the ebb shoal does not act as a sink for sediment moving down the coastline.

A volume balance of erosional and depositional quantities shows that sediment eroded from the new channel and Davis Slough partially balances deposition on the ebb shoal and infilling of the old channel. Furthermore, erosion and deposition of the updrift bypassing bar is due only to a translation of the bar in response to the shifting channel, and does not represent deposition derived from the longshore transport. The fact that much of the erosional and depositional trends can be attributed to sediment movement within the inlet system indicates that the ebb shoal equilibrium assumption still remains valid for Oregon Inlet.

Table 1. Summary of results from 1999-2003.

	Area (m²)	Shoreline Change (m/yr)	Channel Migration (m/yr)	Volume Change (1000 m³/yr)	Volume-Shoreline Relationship (m³/m)
1999	4335	-	-	-	-
2001	3390	128	114	435	3400
2003	3620	14	28	37	2600

Vandever and Miller (2003) proposed a shoreline-volume relationship to estimate volume changes on the north spit given the subaerial shoreline change. This value was calculated to be 3400 m³ of volume deposition per meter of shoreline change and gave reasonable estimates of volume change from 1990-1998. A value of 2600 m³/m was calculated from 2001-2003, given the 73,000 m³ of deposition and 28 m of shoreline change over that period (Table 1). These volume and shoreline values correspond to the approach taken by Vandever and Miller (2003), relating total spit deposition and subaerial spit tip migration. The purpose of that analysis was to determine volume deposition for years when only shoreline positions existed. While this value compares reasonably well to the previous value, more comprehensive surveys would further validate the shoreline-volume claim presented in that discussion.

An alternate approach for the spit volume-shoreline relationship is to look at individual depositional zones and compare sediment deposition to shoreline response for specific regions on the spit. This analysis produces values in the range of 725 m³/m and 975 m³/m from 2001-2003 for the west (sound) and east (ocean) sides of the spit, respectively, ignoring regions where erosion occurred. It is believed that the values for the period from 2001 to 2003 are lower than those found from 1999-2001 because much of the recent deposition occurred on the shallow spit platform created during the 1999

hurricane season. This would result in increased subaerial migration with less total deposition. This relationship will have to be explored further with subsequent studies.

As previously discussed, from 2001 to 2003, the cross sectional area of the inlet increased, contrary to the response exhibited from 1999 to 2001 when the inlet experienced its greatest drop in area since the 1930s. During this period there was a distinct change in morphology of the inlet channel as it assumed a more efficient V-shape. The cross sectional areas for 2001 and 2003 are the lowest since the 1930s and are approximately 25 percent below the average for the past 75 years. The recovery exhibited by the inlet relative to the 1999-2001 response may suggest that it is approaching a minimum or equilibrium cross sectional area. In this state of equilibrium, the scouring effect of the tidal currents would tend to balance the depositional effect of the wave-induced sediment transport. It is interesting to note that while the inlet showed signs of recovery from 2001 to 2003, the channel continued to migrate southward and scour significant quantities of sediment from the channel. The recovery in minimum width and cross sectional area can be seen in Figure 5. Another possible explanation is that sediment deposition and spit growth at Oregon Inlet are driven by extreme events such as hurricanes and nor'easters. While the 1999 hurricane season had two significant events in Hurricanes Dennis and Floyd, no major hurricanes affected the North Carolina coast from May 2001 to July 2003.

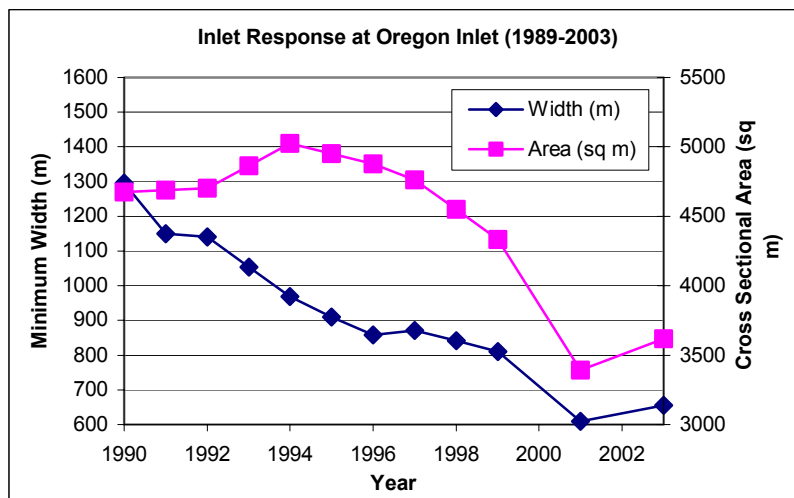


Figure 5. Cross sectional area response at Oregon Inlet, NC. Data points indicate dates of surveys and may indicate an average of multiple surveys in a given year.

Joyner (1997) analyzed the response of the inlet following the construction of the terminal groin in 1990, and examines the concept of an equilibrium condition at Oregon Inlet, citing the stabilization of changes in minimum width from 1996 to 1997. However, as can be seen in Figure 5, it is possible for Oregon Inlet to exhibit opposite trends with respect to minimum width and cross sectional area (note 1992-1994 response). Joyner also notes the decreasing trend in inlet width since the completion of the terminal groin in 1990. Furthermore, Joyner demonstrated the extreme variability shown in cross sectional area at Oregon Inlet, and while attempts were made to correlate these changes with such

parameters as storm frequency, no significant relationships were determined. As a result, it is very difficult to predict the response of the inlet based on what is known at present.

5 CONCLUSIONS

The study documents the morphologic response of Oregon Inlet from 1999-2003. Furthermore, it shows the difficulties associated with drawing together multiple data sets to provide a comprehensive investigation of hydrodynamics and morphology. While the study benefited from the high spatial resolution of the LARC survey data, the higher temporal resolution obtained by more frequent surveys would greatly aid in resolving small time-scale changes that occur in response to individual storms as well as seasonal variations.

A main objective of the study was to link hydrodynamic forcings and morphologic response at the inlet. While quantitative evidence of morphologic evolution, such as volume changes and migration rates have been documented, little data are available for hydrodynamic parameters such as tidal currents and tidal prism. The Virginia Institute of Marine Science (VIMS) conducted tidal prism surveys in 2002 and 2003; however, they are not similar enough to be compared easily. This is because the prism was approximately 19% larger in July 2003 than April 2002 due to sustained southwest winds across Pamlico Sound, as is typical during the summer months (Jesse McNinch, personal communication, November 11, 2003). This means that the flow of water out of the inlet was substantially higher in 2003 due to the wind forcing, so it is difficult to make a direct comparison of currents for the two surveys. However, the 2003 survey did include an estimate of the flow through Davis slough. It was found that approximately 27% of the total volume exchange through the inlet flows through Davis Slough (McNinch, unpublished data). While the 2002 survey did not include an estimate of this flow, subsequent surveys will allow for the comparison of these values, and estimates of the flow efficiency through Davis Slough can be obtained.

While the study set out to examine sediment bypassing at Oregon Inlet, there was more than enough work to be done documenting the morphologic evolution and inlet response during the time period. Due to difficulties obtaining potential sediment transport data from the Field Research Facility, bypassing rates were not calculated. This is partially because total values for 2003 have not been computed and also due to errors in the processing of the wave data. However, these quantitative values are simply numerical representations of the response described in the results section of this report. Based on the values obtained from volume change computations, it is believed that the bypassing rates are significantly higher than in previous years, and may be on the order of 80-90%. This is because of the relatively small volumetric deposition on the north spit from 2001-2003 (approximately 85% lower than 1999-2001). Furthermore, while the 1999 and 2001 surveys showed significant flood shoal accretion during that time, the period from 2001-2003 was characterized by scour and erosion in the flood shoal region. Additionally, little or no dredging occurred from 2001-2003. As a result, there were very few depositional zones for sediment from the littoral drift and much of the sediment bypassed

the inlet. This further supports the argument that the inlet is approaching an equilibrium state, because as north spit deposition decreases, little or no sediment from the longshore drift will be deposited in the inlet, and bypassing efficiency will increase.

The study clearly documents the complex nature of the system and illustrates the significance of deposition on the north spit as a determining factor for inlet response. While the study looked at the inlet response in two separate periods, from 1999-2001 and from 2001-2003, perhaps a more instructive approach is to examine the response during the entire study period. As an example, the 900,000 m³ of sediment that was scoured from the inlet channel from 2001-2003 and deposited on the ebb shoal was believed to be a result of the relatively insignificant deposition on the north spit during that same time period. Similarly, it would be expected that the much more significant deposition of 920,000 m³ of sediment on the north spit from 1999-2001 would have resulted in a much larger scouring effect and deposition on the ebb shoal than actually occurred. This may suggest that the scouring from 2001-2003 represented the large-scale time response of the inlet to the 1999-2001 spit growth.

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GLOSSARY

accretion – the gaining or deposition of sediment

bathymetry – a survey or measurement of water depth (bathymetric survey)

bypassing – the process by which sediment is transported from the updrift to downdrift side of an inlet

depositional – refers to processes or zones related to sediment deposition

downdrift – the region in the lee of the inlet with respect to the dominant direction of sediment transport. At Oregon Inlet this is to the south.

dredging – the mechanical removal of sediment from navigation channels

ebb (shoal) – ebb refers to the phase of the tidal cycle when the tide is “going out.” This is accompanied by strong tidal currents flowing out to sea, or west to east at Oregon Inlet. The ebb shoal is the shoal that is formed when sediment transported by ebb currents settles out of suspension on the ocean side of the inlet.

erosional – refers to processes or zones related to erosion or natural removal of sediment

fathometer – a digital echosounder that uses acoustic signals to determine water depth

flood (shoal) – flood refers to the phase of the tidal cycle when the tide is “coming in.” This is accompanied by strong tidal currents flowing into the inlet, or east to west at Oregon Inlet. The flood shoal is the shoal that is formed when sediment transported by flood currents settles out of suspension on the bay side of the inlet.

littoral (drift) – refers to sediment transport parallel or along the shoreline (longshore transport)

morphology – refers to the shape or evolution in the shape of the beach profile or inlet cross section

scour – the hydraulic removal of sediment, especially from around or underneath a structure such as a bridge support

shoal – a large flat sandbar in shallow water, typical a hazard to navigation

spit – a narrow point of land extending into the water. Spit growth refers to the elongation and curvature of these features.

terminal groin – a small jetty extending from a shore to protect a beach against erosion or to trap shifting sands. The terminal groin at Oregon Inlet secures the south side of the inlet.

tidal prism - volume of water that flows into a tidal channel and out again during a complete tide.

updrift – the region of shoreline in the direction opposite the dominant sediment transport direction. At Oregon Inlet, this is to the north.

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