POST-STABILIZATION MORPHOLOGY OF OREGON INLET, NC

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Abstract

The behavior of Oregon Inlet, located north of Cape Hatteras, North Carolina, on the Pamlico Sound estuary, and its commercial, ecological, and recreational importance have been the subject of much study and controversy. The construction of a terminal groin on the southern shoulder of the inlet in 1990 served to heighten this interest. Both the U.S. Army Corps of Engineers (USACE) and the NC Department of Transportation (NCDOT) have maintained monitoring programs since that time to study the impact of the terminal groin on the morphology of the inlet and the adjacent shorelines. This paper utilizes data from the USACE and NCDOT programs to examine the relationship between the growth of the Bodie Island spit and the resulting bathymetric changes in the inlet. Data collected are compared with results from the literature.

The morphology of Oregon Inlet exhibited changes expected with the stabilization of a single shoulder of a tidal inlet. In contrast, the cross-sectional area of the channel at the minimum inlet width changed little. When analyzed in light of empirical equilibrium conditions reported in the literature, the results supported the conclusion that the inlet had achieved a new equilibrium configuration due to the presence of the terminal groin.

1. Introduction and Location of Study Area

Since the construction of a terminal groin at Oregon Inlet, NC, both the U.S. Army Corps of Engineers (USACE) and the NC Department of Transportation (NCDOT) have maintained programs to monitor the morphology of the inlet and the adjacent shorelines. This paper utilizes data from the USACE and NCDOT programs to examine changes in inlet width and orientation due to migration of the non-stabilized northern inlet shoulder (Bodie Island); also discussed are associated changes in the bathymetric configuration of the inlet. The results of the measurements are analyzed for consistency with empirical equilibrium indicators reported in previous studies of inlet behavior.

Oregon Inlet is located on the Outer Banks of North Carolina, just south of Nags Head and north of Cape Hatteras. It is the only inlet in the Outer Banks between Cape Hatteras and Cape Henry, VA, providing an exchange for Pamlico, Currituck, and Albemarle

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Sounds with the Atlantic Ocean. Figure 1 shows the location of the inlet in relation to the United States and, on a smaller scale, to the North Carolina coastline and coastal waters. The inlet is the site of the only bridge currently spanning a major inlet in North Carolina, the Herbert C. Bonner Bridge, completed in 1964.

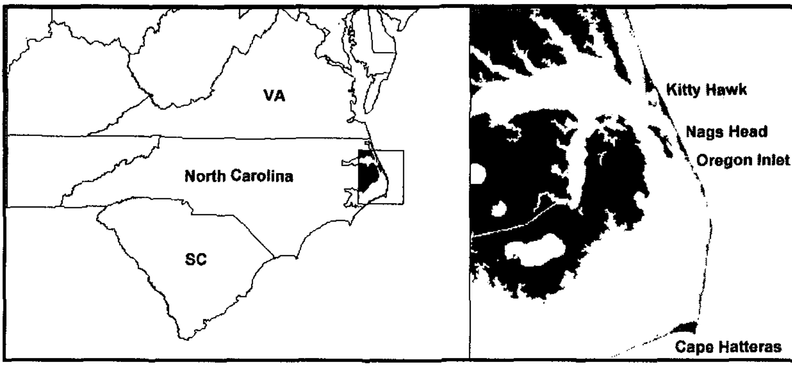

Figure 1. Location of study area, Oregon Inlet, NC.

The mean ocean tidal range at Oregon Inlet is 2.0 ft, with a spring range of 2.4 ft (Moffatt and Nichol, 1990). The average significant wave height at Oregon Inlet is approximately 3 ft, with an extreme height of approximately 10 ft (Moffatt and Nichol, 1990). Wind effects on tidal flow at Oregon Inlet may be very dramatic, especially in cases of rapid wind reversals over Pamlico Sound (Inman and Dolan, 1989). Winds from severe storms have caused differences in water levels in excess of 9 ft across the inlet (Moffatt and Nichol, 1990). Gross longshore sediment transport has been estimated to be 5.8 x 10^7 ft^3/yr in the vicinity of Oregon Inlet (Inman and Dolan, 1989). Hollyfield, et al. (Inman and Dolan, 1989) and Dennis (1997) have reported values for the tidal prism of Oregon Inlet of 3 x 10^9 ft^3 and 2.3 x 10^9 ft^3, respectively. The tidal prism values were both determined from pre-terminal groin measurements and will be used in later sections of this paper.

At Oregon Inlet, the net longshore sediment drift is in a southerly direction, resulting in a predominant southward inlet migration. Between 1846 and 1989, Oregon Inlet migrated approximately 2.2 miles southward and 2,070 feet landward. By the late 1980s, the southern approach to the Bonner Bridge had become endangered by inlet migration, and the NCDOT sponsored construction of a terminal groin to stabilize the southern (Pea Island) shoulder. Construction was begun in October 1989 and was completed early in 1991. The present study considered data gathered from October 1989 until April 1997.

2. Data and Methods

The purpose of the present research was to characterize the migration and equilibrium condition of Oregon Inlet since the terminal groin was constructed. The study was accomplished using time series of shoreline positions and bathymetric data taken between October 1989 to April 1997. Using these data, changes in inlet geometry were analyzed in light of empirical equilibrium indicators reported in the literature, specifically in studies by O'Brien (1931, 1969) and Jarrett (1976).

The primary sources of data for this study included a database of shoreline positions and hydrographic surveys of the inlet area. The shoreline database was generated as part of a shoreline erosion monitoring project conducted by the NCSU-Kenan Natural Hazards Mapping Program at North Carolina State University (Overton and Fisher, 1997), in conjunction with the NCDOT. The shoreline positions were digitized by the NCDOT from rectified aerial photographs, taken at a bimonthly frequency beginning in October 1989.

Morphological parameters observed from the shoreline database include minimum inlet width, planimetric accretion and erosion of the Bodie Island shoulder, and location and orientation of the minimum width section. The majority of definitions for this study are consistent with work done by Vincent and Corson on inlet geometry (1981); detailed definitions for the parameters follow this section.

The hydrographic surveys were obtained from the U.S. Army Corps of Engineers, Wilmington district (USACE, 1990a, 1990b, 1994, 1995, 1996, 1997). The dates of the surveys and the related shoreline positions are listed in Table 1. Three full-inlet, bank-to-bank surveys were available; the remaining surveys covered only the channel section through the inlet. The data were processed to create contours, grids, and profiles of the submerged inlet area from which subsequent measurements were made. Parameters measured included cross-sectional area, maximum channel depths, and ebb delta area.

Table 1. Summary of hydrographic surveys analyzed

Survey date	Related shoreline date	Extent of survey
Jan. 17, 1990	Feb. 14, 1990	Full inlet, bank-to-bank
Dec. 12, 1990	Dec. 6, 1990	Full inlet, bank-to-bank
Aug. 25, 1994	Aug. 9, 1994	Partial channel
Apr. 20, 1995	Apr. 5, 1995	Partial channel
Dec. 4, 1996	Jan. 3, 1997	Full inlet, bank-to-bank
Apr. 30, 1997	Apr. 8, 1997	Full channel

Data were collected from the shoreline positions and hydrographic data sets by the measurement of several geometric parameters of inlet configuration. All measurements were made using the MicroStation CADD software in conjunction with Intergraph's Terrain Analyst software for profile creation and contouring of the bathymetric data. The contours were used to determine channel position, which was digitized by following the deepest contiguous contours through the inlet. An example of channel delineation is shown in Figure 2. Unless otherwise noted, all measurements of depth were taken from Mean Sea Level 1929 (referred to hereafter as "mean sea level"). The following is a list of the parameters and the working definitions:

1. Minimum inlet width (W) is defined as the narrowest point between the inlet shoulders, as shown by the shoreline data set. The location of the minimum width section was determined by constructing the minimum distance line between the digital shoreline shoulders using the CADD software. An example of width delineation is displayed in Figure 2. The section of minimum width may also be referred to as the gorge or throat section.

2. Maximum channel depth (d_m) is defined as the maximum depth occurring at the section of minimum inlet width. Maximum depth and all other bathymetric measurements were determined from computer-generated digital profile plots of the bathymetric data. Figure 3 graphically portrays gorge profile definitions.

3. Cross-sectional area (A_C) was taken at minimum width by digitally measuring the area bounded by the profile, the water surface at 0.0 ft on the plot (mean sea level), and the vertical axes of the plot. The vertical axes represent the locations of the Bodie and Pea Island shoulders of the inlet; see Figure 3.

4. Ebb tidal delta area (A_E) was defined, again following Vincent and Corson (1980), as the area of the region bounded by the inlet shoulders, the minimum width line, the contour of controlling depth, and a set of boundary lines marking the point on either side of the inlet where the controlling depth contour became approximately shore-parallel (Figure 2). The area was measured by an application of the CADD software.

3. Graphical Presentation of Data and Discussion of Results

This section documents the results of the analysis of the shoreline and bathymetric time series. The results are presented in three parts. First, the observed trends in planimetric inlet morphology are discussed, followed by a description of changes observed in the bathymetric configuration of the inlet. Finally, Table 2 summarizes the results of the measurements of inlet minimum width, maximum depth, cross-sectional area, and ebb tidal delta area.

Planimetric inlet morphology

While the construction of the terminal groin has effectively halted the migration of the southern (Pea Island) shoulder of the inlet, the northern (Bodie Island) shoulder exhibited both alongshore and cross-shore migration over the study period. Inlet migration has resulted in changes in inlet width and orientation.

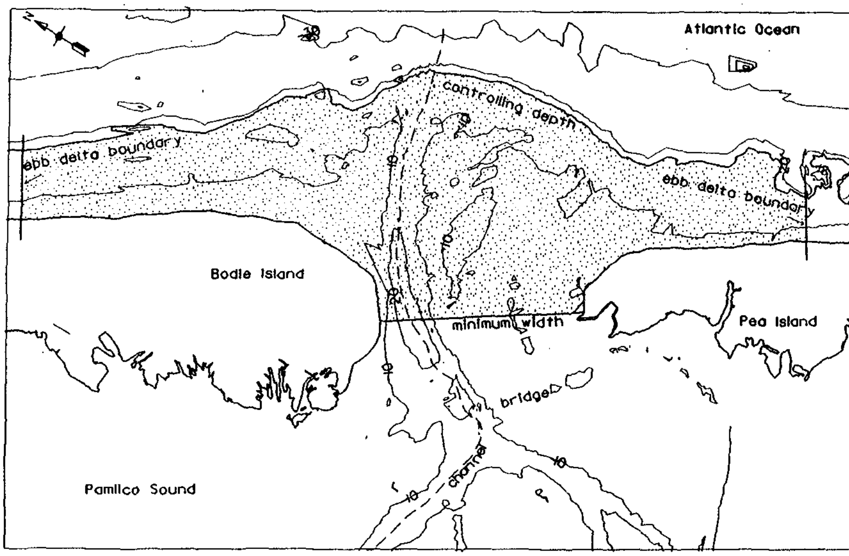

Figure 2. Parameter definition sketch, planimetric view.

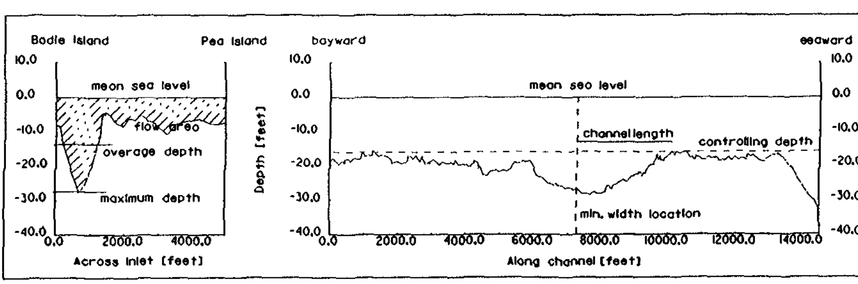

Figure 3. Parameter definition sketch, bathymetric view.

A progression of semi-annual shoreline positions is shown in Figure 4, beginning with April 1990 and ending with April 1997. The October 1989 position is included in each frame to provide a reference from which changes may be observed. In each frame, the dated shoreline position is marked by a dotted pattern fill. The solid lines crossing the inlet mark the gorge section for both the October 1989 and the designated positions; the most bayward solid line marks the location of the highway and bridge over the inlet.

The Bodie Island spit accreted bayward over the study period, reaching and crossing the location of the bridge. The beginning of this movement is noticeable from the figure as early as April 1991. This date marks the approximate completion of the terminal groin, which becomes a permanent reference point in the remaining frames. The spit continued to accrete bayward, with some migration into the inlet, until October 1993. At this point, the spit began to show more dramatic accretion toward Pea Island. From this date through the end of the study period, the spit continued to migrate toward Pea Island, with accretion taking place at the northern portion of the bridge as the end of the spit widened.

Trends in inlet width may be observed from Figure 5, a plot of minimum inlet width vs. time since construction of the terminal groin. The narrowing between the April 1990 and October 1990 positions was due primarily to the encroachment of the terminal groin into the inlet. After this date, the terminal groin stabilized and defined the location of the southern shoulder, and changes in width were due to the migration of the Bodie Island spit. Following the initial decrease in width, the inlet continued to show a slighter narrowing trend, with short-lived minor widenings observed. The inlet reached its narrowest width of the present study period, 2,732 ft, on February 11, 1996. Since that time, the data showed a relatively short but distinct trend toward widening, with the latest measured value at 3,017 ft in April 1997.

Accretion of the spit was also responsible for a change in location and orientation of the gorge section. The shifting of the gorge became most noticeable beginning in April 1995, which coincided with the beginning of significant widening of the spit at the bridge. The shift of the gorgc bayward required a rotation of the section, since the terminal groin remained as the southern extent of the inlet. The gorge continued to move bayward and orient itsclf in a more northerly direction through the remainder of the study period.

Bathymetric inlct morphology

Changes in the inlet's bathymetric configuration were observed coincident with the changes in inlet width and orientation. Using data from the hydrographic surveys, profiles were created to measure changes in channel location and shape. The profiles, shown in Figure 6, were taken across the gorge section, using the minimum width line as a transect. The plots are aligned using the axis representing Pea Island as a reference point. This alignment was chosen because the terminal groin has stabilized this shoulder of the inlet, so that its position is constant. The plots show the bottom elevations, relative to mean sea level, of the gorge section from Bodie Island to Pea Island (left to right).

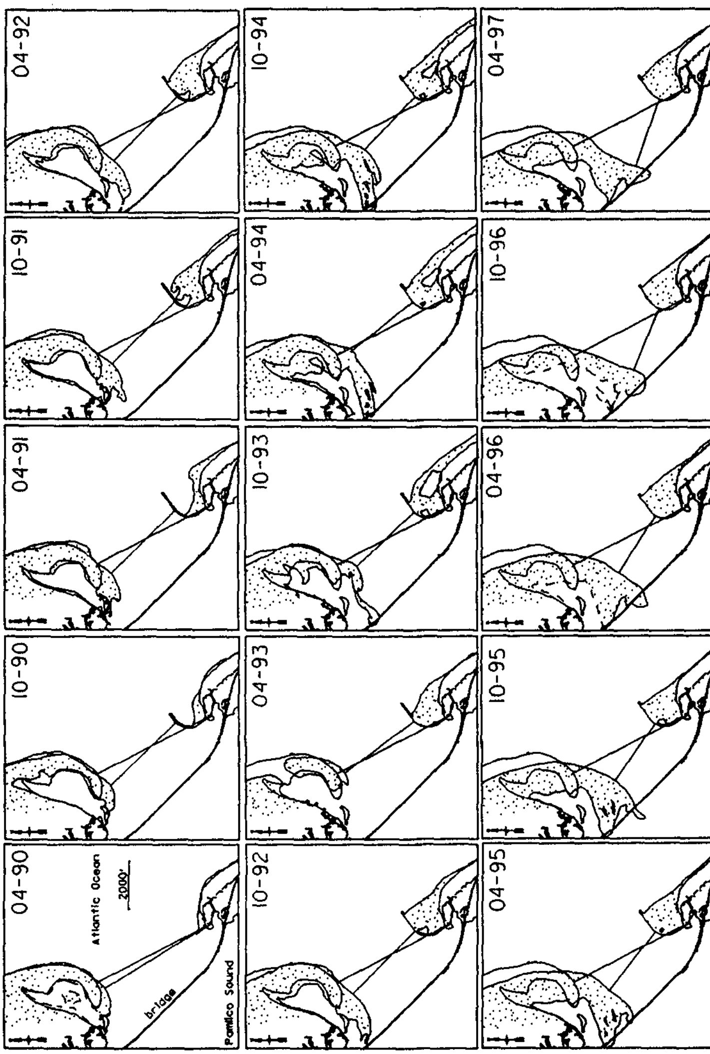

Figure 4. Inlet migration, October 1989 to April 1997.

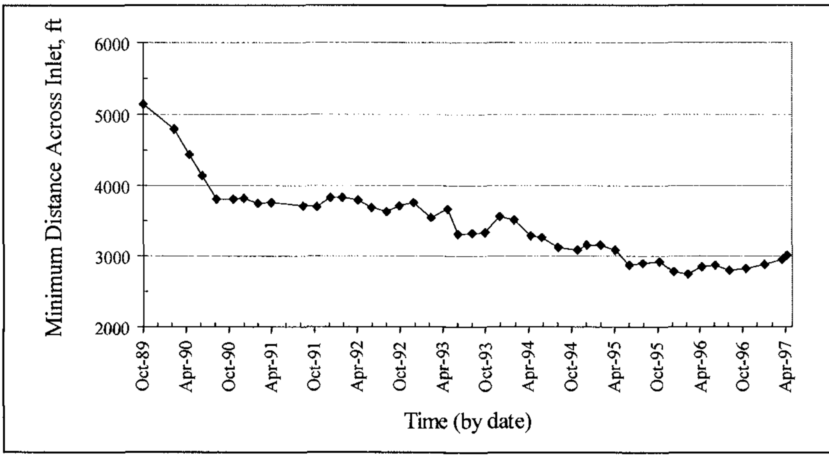

Figure 5. Oregon Inlet minimum width, October 1989 to April 1997.

The channel at the gorge section showed lateral migration toward the terminal groin (Pea Island). This is evident between the January 1990 and December 1990 profiles. A more visible migration was noticed between December 1990 and December 1996, as the channel shifted 2,160 ft toward Pea Island. In contrast, the position of the channel relative to the Bodie Island axis has remained relatively constant, at a distance of 700 to 900 ft.

Along with its lateral migration, the channel deepened, with maximum depths increasing from approximately 27 feet below mean sea level in January 1990 to 50 feet in December 1996, then slightly decreasing to 46 feet in April 1997. The deepening trend was dominant over the study period, except for the April 1995 survey, which showed a maximum channel depth of only 26 feet.

A second set of profiles was constructed along the lines marking the channel locations from bayward of the bridge to seaward of the ebb delta. The profiles are displayed in Figure 7, and show the bottom elevations along the channel from the sound toward the ocean entrance (left to right). The bridge location was chosen as an alignment reference point for these profiles; its position is marked on the figure by a solid vertical line. The dashed vertical lines mark the location of the minimum inlet width.

As the inlet width decreased through December 1996, the maximum depth of the channel at the gorge increased. While these changes took place, the cross-sectional area of the gorge remained relatively constant, hovering around 50,000 ft^2. A constant cross-sectional area suggests that a state of equilibrium exists, as do the changes in depth coincident with changes in width. From inspection of the profiles in Figure 6, the

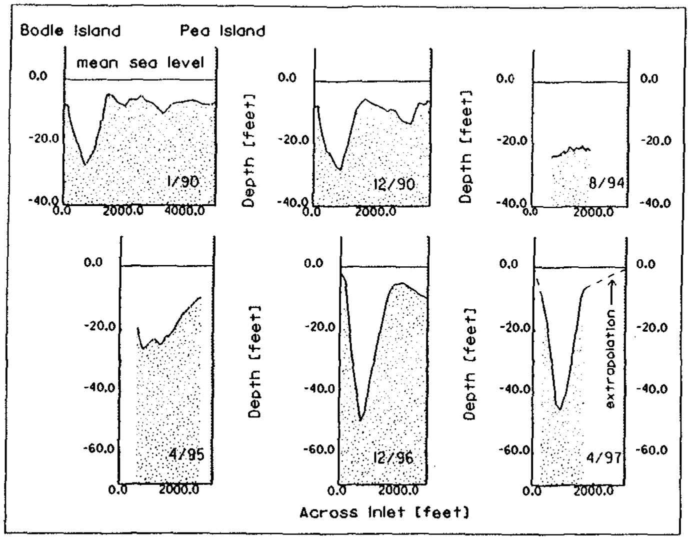

Figure 6. Gorge cross-section bathymetric profiles.

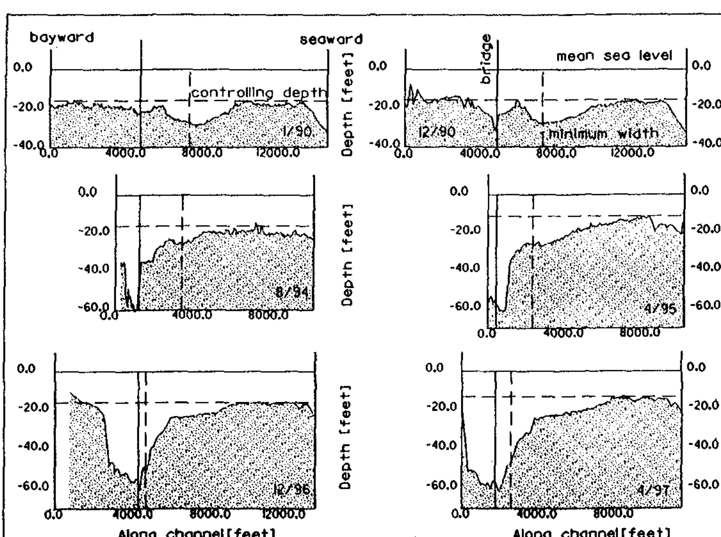

Figure 7. Channel lengthwise bathymetic profiles

channel itself became narrower as the inlet width decreased. In order to maintain a constant cross-sectional area, a narrowing inlet must become deeper to accommodate the same discharge volume, or tidal prism. The data show that this has been the case at Oregon Inlet since the terminal groin was constructed.

Summary of results

A summary of observed planimetric and bathymetric parameter measurements is displayed in Table 2. Measurements of bathymetric parameters were taken from the channel profile plots previously described. The three bank-to-bank surveys contained sufficient data for the measurement of all parameters under study; at least one parameter was not measurable for the remaining profiles, due to insufficient data. All vertical measurements were made relative to mean sea level.

Table 2. Summary of data measured from shoreline positions and hydrographic surveys.

Date	W, ft	A_C, ft^2	d_m, ft	A_E, mi^2
Jan. 17, 1990	4,968	50,235	-27.4	2.17
Dec. 12, 1990	3,819	48,687	-28.5	1.92
Aug. 25, 1994	3,122	I/D*	-23.0	I/D*
Apr. 20, 1995	3,081	I/D*	-25.0	I/D*
Dec. 4, 1996	2,878	51,192	-50.0	2.07
Apr. 30, 1997	3,017	46,335	-46.0	I/D*

*I/D denotes insufficient data for measurement.

A note should be made about the measurement of A_C for the April 1997 data. As can be seen from the profile in Figure 6, the survey did not span the entire inlet, so that the area could not be measured exactly as defined. However, it was judged that enough information was present to allow the reasonable measurement of cross-sectional area by extending the profile on either side of the channel to the vertical axes. It is believed that, though the measurement is not as exact as those for the bank-to-bank surveys, the area determined in this way is reasonably close to what would actually be measured from a full survey, if it existed. Any error in the measurement from the actual value should be an underestimate, since most of the profiles showed some deepening on either side of the channel banks which would not be accounted for in the profile extrapolation. This method of measuring cross-sectional area was considered for the August 1994 and April 1995 surveys, but it was judged that insufficient information existed for any reasonable extrapolation to the vertical axes of the plots.

A second aspect of the analysis that deserves comment is the fact that the shoreline position dates do not exactly coincide with the dates of the hydrographic surveys. Since inlet parameters may adjust themselves rapidly to existing wave and tidal current conditions, the difference in time between a hydrographic survey and its corresponding shoreline position may be a significant source of error. Unfortunately, it is a source of error that could not be quantified or known for certain. However, since most of the survey/shoreline position sets were collected within two to three weeks of each other, it was assumed for the sake of the study that the shoreline data was representative of the actual shoreline position at the times of the surveys.

The changes in inlet width became smaller in magnitude, or "slower" in rate, as the study period progressed. Small changes from a certain state were described by van de Kreeke (1992) as an indication of inlet equilibrium. Though it was not clear whether the inlet would continue to widen or remain more constant in width, the data suggested that the hydraulic forcing factors at Oregon Inlet are currently sufficient to maintain an inlet width greater than 2,732 feet. The inlet has been narrower, at 2,100 feet in 1975 (Moffatt & Nichol, 1990), so that the narrowing was no indication in itself of progression toward inlet closure due to the presence of the terminal groin. Conversely, the combination of small changes in inlet width and small variance in cross-sectional area supported the hypothesis that the inlet had reached equilibrium since terminal groin construction. An analysis of the data using empirical results from previous researchers on equilibrium inlet geometry was conducted to further test the hypothesis; Section 4 of this paper describes the comparative analysis.

4. Comparison of results with reported empirical equations

The relationship between tidal prism and cross-sectional gorge area is a commonly studied and used empirical description of inlet equilibrium (Escoffier, 1940; van de Kreeke, 1992; O'Brien, 1931, 1969; Jarrett, 1976). Since the results of this study showed small variance in cross-sectional area, it was believed that the data would fit one of the classic tidal prism-flow area relationships. This section documents the results of a comparison of empirical equations from studies by O'Brien (1931, 1969) and Jarrett (1976) with the measured cross-sectional area data and reported tidal prism values for Oregon Inlet.

The empirical equations describing the equilibrium relationship between tidal prism and cross-sectional area take the form $A_C = C \times P^n$, where A_C is cross-sectional area in ft^2 and P is tidal prism in ft^3, and C and n are empirically determined constants. Table 3 lists the specific equations of this form considered for the present study, along with the geographic locations and stabilization status of the inlets considered in the development of each equation.

Table 3. Tidal prism-flow area relationships.

Researcher and Date	Inlet Source Data Types	Equation
O'Brien (1931)	Mostly Pacific coast, with and without jetties	$A_C = 4.69x10^{-4} P^{0.85}$ (1)
O'Brien (1969)	Atlantic, Pacific, and Gulf coasts, without jetties	$A_C = 2.0x10^{-5} P$ (2)
Jarrett (1976)	Atlantic, Pacific, Gulf coasts, single or no jetty	$A_C = 1.04x10^{-5} P^{1.03}$ (3)
	Atlantic coast, all inlets	$A_C = 7.75x10^{-6} P^{1.05}$ (4)
	Atlantic coast, single or no jetty	$A_C = 5.37x10^{-6} P^{1.07}$ (5)
	Atlantic coast, two jetties	$A_C = 5.77x10^{-5} P^{0.95}$ (6)
	Pacific coast, two jetties	$A_C = 5.28x10^{-4} P^{0.85}$ (7)

The cross-sectional areas measured by this study were compared with calculated results from Equations (1) through (6). Equation (7) was not included in this analysis, because it was intended to describe Pacific coast, dual-jettied inlets, and it agrees closely with Equation (1) from O'Brien (1931). For the analysis, tidal prisms were calculated using Equations (1) through (6) with the measured values of A_C. The results are reported in Table 4. The calculated tidal prisms were compared with values reported for Oregon Inlet by Hollyfield, et al. (Inman and Dolan, 1989) and Dennis (1997), also included in Table 4. The reported values for Oregon Inlet's tidal prism fell within 95% confidence limits determined by Jarrett for reliability of his equations.

Table 4. Calculated values vs. reported values for tidal prism at Oregon Inlet.

Equation	Calculated tidal prism ($x10^9$ ft^3)				Reported tidal prism (ft^3)
	1/17/90	12/12/90	12/4/96	4/97	
(1)	0.939	0.882	0.904	0.752	Hollyfield, et al: $3 x10^9$
(2)	2.80	2.65	2.71	2.32	
(3)	3.43	3.25	3.32	2.85	
(4)	3.40	3.24	3.30	2.84	Dennis: 2.30×10^9
(5)	3.62	3.45	3.51	3.04	
(6)	2.00	1.90	1.94	1.64	

The best prediction of Oregon Inlet's tidal prism was obtained using Equation (2), O'Brien's 1969 result for inlets without jetties. Equation (1) consistently underestimated tidal prism values, as did Equation (6). Equations (3), (4), and (5) tended to overestimate. Since the reported tidal prisms fall within the confidence limits of Jarrett's data, it is reasonable to believe that Equations (3), (4), (5) and (6) may be used to generally describe Oregon Inlet's behavior. From this analysis it appears that the relationship between post-groin cross-sectional gorge areas and tidal prism at Oregon Inlet is similar to those determined by O'Brien and Jarrett. This information supports the hypothesis that the inlet has exhibited an equilibrium condition over the study period.

The values reported for Oregon Inlet's tidal prism were calculated using pre-terminal groin data. To the author's knowledge, post-terminal groin data for calculation of the tidal prism were not available, though the data would be helpful in accurately understanding changes that have occurred since the construction of the terminal groin.

5. Conclusions

This report documented a study of morphological changes observed at Oregon Inlet, NC. The study period was from October 1989 to April 1997, the time since the construction of a terminal groin on the downdrift shoulder of the inlet. It was hypothesized that the hydraulic and sedimentary environment of the inlet had approached or reached a state of equilibrium since the construction of the terminal groin, and that the groin had not negatively affected the stability of the inlet. To test the hypothesis, shoreline position and bathymetric data were analyzed to examine changes in inlet geometry. The results of the analyses supported the hypothesis.

Further study of the morphology and hydraulic and sedimentary conditions of Oregon Inlet is necessary to more fully understand its behavior, particularly as it relates to future engineering works for transportation safety and reliability. Specifically, an accurate hydraulic model of the inlet and adjacent waters it affects would be helpful in determining a post-groin tidal prism as well as predicting effects of winds, waves, and engineering efforts on flows through the inlet. Furthermore, the application of a sediment transport model with a hydraulic model of the inlet would provide means for determining the effects of influencing factors on inlet morphology and stability.

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