Interaction of Tidal Inlets in a Multi-inlet Bay System: A Case Study Along the Central Gulf Coast of Florida

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ABSTRACT


Changes in the morphology of individual tidal inlets on sandy coasts are influenced by tides, waves, winds and longshore currents. In a multi-inlet bay system, however, a change in the configuration of one inlet can affect hydraulics throughout the bay and can influence the stability of adjacent inlets. This study presents a means of quantifying the degree of interaction between multiple inlets on a low-energy, microtidal coast by applying a two-dimensional hydrodynamic model to the inlet-bay system. The study area was Boca Ciega Bay along the Gulf coast of Florida. The investigation assessed the interaction between John’s Pass and Blind Pass.

The study consists of analysis of the morphological history of the study area, a field investigation, construction of a numerical hydraulic model, and analysis of historical and predictive simulations. A two-dimensional hydraulic model was constructed and calibrated to spring and neap tidal conditions and verified for post-dredging conditions two years later. The bay tidal prism and portion serviced by each inlet was determined from model output and field data. Predictive and historical simulations were made to investigate how changes in bay or inlet morphology affect the hydraulic environment of the system.

Results indicate traditional stability analyses alone may be inadequate for characterizing the behavior of multi-inlet bay systems because the morphological development of an inlet is influenced by factors that affect the tidal-prism distribution of the bay. The change in prism fed by each inlet and the subsequent hydraulic response of the pass may be quantified through model analysis.

ADDITIONAL INDEX WORDS: inlet stability, shoreline configuration, geomorphology, tidal prism.

INTRODUCTION

Tidal inlets provide tidal conveyance from open bodies of water to more sheltered lagoons, estuaries, or bays. Because passes are influenced by a variety of forcing mechanisms including winds, tides, longshore currents and waves, inlets are in a constant state of flux. As a result of coastal development, the problem of characterizing the dynamic behavior of inlets has been of interest to scientists, coastal planners, and engineers. Excessive deposition may require dredging of an inlet in order for navigable passages to be maintained. Severe scour of an inlet’s gorge could threaten the stability of structures embedded in or adjacent to the channel.

Studies attempting to characterize the behavior of inlets on sandy shores in consideration of hydraulic characteristics are extensive (e.g. ESCOFFIER, 1940, 1977; O’BRIEN, 1976; BRUUN and GERRITSEN, 1960; JARRETT, 1976; O’BRIEN and DEAN, 1972). Based on the assumption that bay and inlet act as a single isolated system, these methods consider how tidal-prism volumes, littoral-drift quantities, or current velocities influence the geometry of a pass. Although these factors must be considered in assessing inlet stability, many bays are fed by multiple inlets, and dredging or development at one inlet can influence flow conditions throughout the bay and, consequently, the behavior of other connected inlets. In analysis of inlet stability, factors affecting not only one inlet, but the hydraulic system as a whole, must be considered.

This paper provides a link between traditional empirical stability analysis and modern hydrodynamic modeling methods. It illustrates the use of two-dimensional model analysis to explain the geomorphological development of a multi-inlet system. The authors discuss the use of the hydrodynamic model to evaluate the extent to which variations in the size and shape of one pass may lead to changes in scour and depositional trends at adjacent inlets. By applying the model method to a system where long-term scour at one pass has threatened the stability of the inlet’s bridge, the paper provides an example of how modern modeling techniques serve as a useful tool in assessing inlet management alternatives in a complex hydraulic environment.

The study area was Boca Ciega Bay, located along the cen-
The central Gulf coast of Florida is characterized by a chain of barrier islands separated by tidal inlets. The region represents a low-energy, microtidal environment with semi-diurnal, mixed tides (Davis and Gibeaut, 1990). Beach and bottom sediments consist mostly of fine to very fine quartz sand. The coast may be characterized as a littoral-drift shore. Shoreline configurations are influenced largely by the distribution and availability of sediment as well as tidal and wave action (Bruun, 1978).

The Boca Ciega Bay region includes inlets with distinct differences in size and flow characteristics. Blind Pass is a wave-dominated pass (Davis and Gibeaut, 1990). The action of wave-induced, littoral-drift transport significantly influences the inlet’s configuration. As a result of sand deposition, the updrift side of Blind Pass extends seaward and in front of its downdrift shoreline (Bruun, 1978). Because of a historical reduction in tidal flow that caused sediment deposits to migrate toward shore, the inlet has no substantial ebb-tidal shoal (CPE, 1992).

John’s Pass, in contrast, is a tide-dominated inlet. It has a well-defined channel and carries a sizeable tidal prism (Davis and Gibeaut, 1990). An extensive, lobe-shaped outer shoal, created largely as a result of sediment deposition by ebb-tidal currents, extends approximately 5400 feet (1600 m) offshore (CTC, 1993).

The co-dependency of Blind Pass and John’s Pass appears to be reflected in the history of their cross-sectional areas. While Blind Pass has historically been closing due to shoaling, John’s Pass has been increasing in size (CPE, 1992). As a result, severe bed erosion has occurred at John’s Pass (Vincent and Ross, 1992).

**Evolution of Boca Ciega Bay**

Although the general configuration of Boca Ciega Bay has not significantly changed since the 1970’s (NOAA, 1977, 1997), an earlier history of human activity and natural events has helped the system develop its present morphologic and hydraulic characteristics. In the late 1800’s, when nautical charts of Boca Ciega Bay were first published by the United States Coast and Geodetic Survey (USCGS), the bay was in its natural condition. During this period, Blind Pass was a mixed-energy inlet (Davis and Gibeaut, 1990). The cross-sectional area was approximately 5800 ft² (540 m²), slightly larger than John’s Pass. Both inlets had a tendency to migrate toward the south (Mehta et al., 1976). Although several inlets linked the Gulf and bay, three of these passes—Indian Pass at the Narrows (Figure 1) and two relatively unstable openings between John’s Pass and Blind Pass—were closed.
by the 1930’s and have remained closed since then. In 1916, sand was pumped into the inlet just north of Blind Pass, but the action of storm events opened and closed it again several times until 1935, when it permanently closed. By the end of the 1920’s, the United States Army Corps of Engineers filled Indian Pass to help prevent further shoaling of the Intracoastal Waterway at the Narrows (Mehta et al., 1976).

By the 1920’s, the original bridges across John’s Pass and Blind Pass were constructed, and they altered the natural condition of the inlets for the first time (CTC, 1993). In the following decades, development continued to impact inlet and bay hydraulics; for example, the causeway connecting mainland Pinellas County to Treasure Island was constructed from 1935 through 1937. Dredge-and-fill islands south of the causeway followed. As a result, the tidal prism through Blind Pass was substantially reduced and, it is believed, was primarily captured by John’s Pass (CPE, 1992). Resultant lower current velocities at Blind Pass may be linked to that development and to an increase in channel length between 1873 and 1939 (Mehta et al., 1976). Those lower velocities, it was suggested, resulted in shoaling at Blind Pass and a reduction in its cross-sectional area (Mehta et al., 1976).

During the 1940’s and 1950’s, extensive dredge-and-fill operations continued throughout much of Boca Ciega Bay (CTC, 1993). As the cross-sectional area of Blind Pass decreased during this period, the size of John’s Pass increased. This trend continued through the 1970’s. In 1974, the area of John’s Pass had reached 9500 ft² (880 m²) at the throat, nearly twenty times that of Blind Pass. The combined area of the two passes at this time was approximately the same as it was in the 1870’s (Mehta et al., 1976).

After the completion of dredge-and-fill development and the construction of the Pinellas Bayway, the surface-area configuration of Boca Ciega Bay, broadly viewed, had been relatively well established (NOAA, 1977, 1997). The effects of local and federal dredging projects and beach nourishment efforts as well as the position of jetties, seawalls, and bridges influenced physical characteristics of the inlets.

John’s Pass

John’s Pass was created in 1848 when a major hurricane cut through the Boca Ciega barrier island. The inlet is currently approximately 2100 feet (640m) long and 600 feet (180 m) wide (Vincent and Ross, 1992). A tide-dominated inlet, it has extensive ebb- and flood-tidal deltas (Davis and Gibbaut, 1990) and a federally maintained navigation channel. Much of the inlet’s shoreline has been hardened by seawalls. A revetment helps stabilize the southern channel, and a fully impounded, terminal groin extends along its northern shoreline. Only the southwest shore remains unhardened (CTC, 1993).

As a result of historical increases in tidal prism and cross-sectional area, bed erosion has occurred at John’s Pass. Beginning in 1976, severe scour near bridge pilings had been noted. Several years later, three bridge pilings had become exposed while those remaining were within a few feet of exposure (Vincent and Ross, 1992). Although crutch bents, which extend into the bed of the channel, were added in 1981 to help support the bridge, continued channel lowering led to “scour critical” conditions (PH&A, 1997). Dredging operations, beach nourishment projects, construction of coastal structures, and storm events have influenced the flow regime of John’s Pass throughout the history of this pass.

Blind Pass

Blind Pass, approximately 500 feet (150 m) wide at its entrance (FDC, 1997), separates Treasure Island from Long Key. The evolution of this inlet has been strongly influenced by human activity. In 1937, a jetty was built on the south side of the inlet to prevent migration of the pass. The structure now extends to a distance of approximately 260 feet (80 m) perpendicular to the shore. In addition, a breakwater, angled toward the south, was also added in 1986 (CPE, 1992).

A jetty was constructed on the northern shore of Blind Pass in 1962. The jetty was extended and raised in the 1970’s, and, in the 1980’s, it was lengthened to reach a distance of 520 feet (160 m) into the Gulf (CPE, 1992).

A mixed-energy inlet in the late 1800’s, Blind Pass has been shoaling throughout much of its known history. It is now classified as wave-dominated (Davis and Gibbaut, 1990). The decrease in throat area has been linked to the building of Treasure Island Causeway as well as to dredge-and-fill operations; the construction of Paradise Island at the bay side of the channel is believed to have restricted flow (Mehta et al., 1976). Consequently, the cross-sectional area of Blind Pass decreased from 2,450 ft² (228 m²) to 442 ft² (41 m²) following dredge-and-fill development. More recent changes in the size of Blind Pass are a result of periodic dredging and shoaling of the inlet’s channel (CPE, 1992).

METHODS

A two-dimensional, numerical hydraulic model was used to simulate flow through Boca Ciega Bay, John’s Pass, and Blind Pass (Ross et al., 1999). The work consisted of two parts: 1. collection of field data in Boca Ciega Bay, Blind Pass, and John’s Pass; and 2. construction and calibration of the model.

Field Study for Calibration Data

A field survey of the study area was conducted between April 25, 1998 and May 8, 1998. The period included both spring- and flood-tide conditions. Data collected during the study included tidal heights at four locations along the boundary of the model domain, velocities at 21 stations throughout the bay and inlets, and bathymetry at various locations within the study area.

Tide Heights

Stilling-well tide gauges were installed on April 25, 1998 in the vicinity of John’s Pass, Pass-A-Grille inlet, Indian Key southwest of Maximo Point, and at the Narrows Intracoastal Waterway. Tide heights were recorded at 10-minute intervals. Gauges remained in place through May 8, 1998. The location of each of the four gauges is shown in Figure 2.
Velocities

The 21 velocity stations were located at bridge locations throughout Boca Ciega Bay, including at John’s Pass, Blind Pass, and the Narrows Intracoastal Waterway (Figure 3). Data were collected during two periods, April 28-29, 1998 and May 6-7, 1998, for spring- and neap-tide conditions, respectively.

Current speeds and directions were measured on the upstream sides of main channels. Typically, velocities were measured at depths of 0.6 times the water depth at relatively shallow channels and at 0.8 and 0.2 times the water depth at deeper channels. Current speeds and directions at John’s Pass were measured at locations along the lateral extent of the cross-section.

Bathymetric Transects

A recording fathometer was used to determine depths throughout the study area. Fathometer traces were recorded at bridge locations and at areas shown in Figure 2.

Computer Model

A two-dimensional hydraulic model was used to simulate flow throughout Boca Ciega Bay, Blind Pass, and John’s Pass. The model uses the vertically-integrated equations of motion and continuity to solve for depth-integrated trans-
flow, or constricted channels where flow cross-sections are not represented by average bathymetry (Ross et al., 1999). Each "gate" represents a cell side and consists of a main channel, a secondary channel, and a barrier section (Figure 5). Barrier heights may be positive (land) or negative (submerged regions). Values for depths and widths for main channels, secondary channels, and barrier sections were assigned based on fathometer traces and hydrographic surveys of the study region.

The cross-section of John's Pass consisted of five "gates," which represented the inlet's channel and adjacent bottom topography. Depths at the throat section were determined from bathymetric transects recorded during the field study. Bathymetry in areas directly adjacent to the inlet were obtained from a USACOE (1998) survey of John's Pass. Similarly, nine "gates" were defined at the entrance of Blind Pass. Bathymetric data collected during the field study and a hydrographic survey of Blind Pass (FDC, 1997) were used to determine the dimensions of the inlet's cross-section.

**Boca Ciega Bay Model Calibration**

The Boca Ciega Bay model was calibrated for the two measurement periods. Output included velocities and tidal heights corresponding to the 21 velocity stations. The measured velocities were used for calibration. Output was reported in 15-minute intervals. The model was run for 72 hours of simulation for spring- and neap-tide periods. The initial 24 hours were used to remove transients. Velocities and tidal heights from the final 48 hours of simulation were used for calibration (Becker and Ross, 1999).

Accurate characterization of water depth, channel dimensions, and obstructions to flow throughout the bay were the basis of the calibration process. In order to more precisely describe frictional characteristics of the inlet-bay system, additional "gates" representing shoals, boat docks, or other features unique to the study area were added based on hydrographic surveys, aerial photographs, and bathymetric spot checks of the bay and inlets. For the Boca Ciega Bay model domain, a total of 192 sub-grid features were defined in the data set in order to represent constrictions to flow throughout the bay and inlets.

**Tides**

Measured tidal heights at the Pass-A-Grille inlet tide station were used as the driving function of the model. Leads, lags, and amplitude adjustments for tides at each open-water segment were then calculated relative to the Pass-A-Grille inlet tide function.

**Flow Simulation of Boca Ciega Bay**

The calibrated model was used to simulate flow for the 11-day period, representing conditions between April 27, 1998 and May 7, 1998. The first four days of the simulation cor-
responded to spring tidal ranges; the last three days represented neap conditions.

RESULTS OF CALIBRATION

The velocities and tidal heights at John’s Pass and Blind Pass that resulted from the calibrated model are shown in Figures 6 and 7. Root mean squared errors for each of the 21 velocity stations are shown in Table 1.

Results determined from output of the 11-day simulation were: peak flood and ebb velocities at John’s Pass and Blind Pass; discharge through each inlet and through channels along the boundary of the model domain; tidal prism of Boca Ciega Bay and the percentage carried by each inlet and boundary channel; and net flow directions through each inlet and boundary channel.

Peak Velocities

Simulated velocities at John’s Pass and Blind Pass are shown in Table 2. Maximum flood and ebb velocities in the main and secondary channels were determined by averaging peak velocities during four days of spring tides (principally diurnal) and three days of neap tides (semi-diurnal).

Discharge and Cumulative Volumes

Discharge across the throat cross-section of each channel can be calculated using a simple continuity relation between volume, area, and velocity. The volume of water that passes a cross-section in a given amount of time may be expressed as:

\[ \forall = A \cdot v(t) \Delta t \]  

where \( \forall \) = volume of water, \( A \) = the cross-sectional area, \( v \) = velocity across the section and \( t \) = time. Flow rates calculated from model output at John’s Pass, Blind Pass, and Boca Ciega Bay are shown in Figure 8. Cumulative volumes computed from equation 1 and from velocities and tidal heights generated by the model are also displayed. A linear-fit regression line indicates net flow directions at each pass.

Tidal prism volumes are shown for spring, neap, and 11-
Table 1. Root mean squared errors for spring-tide, neap-tide, and verification simulations.

<table>
<thead>
<tr>
<th>Velocity Station</th>
<th>Root Mean Squared Error (ft/sec)</th>
<th>Spring Calibration</th>
<th>Neap Calibration</th>
<th>Spring Verification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Narrows</td>
<td>1.53</td>
<td>0.68</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>N. Madeira Bch. E (Welch Cswy.)</td>
<td>0.46</td>
<td>0.34</td>
<td>0.33</td>
<td></td>
</tr>
<tr>
<td>Long Bayou South</td>
<td>0.38</td>
<td>0.37</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>John's Pass</td>
<td>0.58</td>
<td>0.64</td>
<td>0.42</td>
<td></td>
</tr>
<tr>
<td>S. Sunshine Beach A</td>
<td>1.35</td>
<td>0.83</td>
<td>1.75</td>
<td></td>
</tr>
<tr>
<td>S. Sunshine Beach B</td>
<td>0.69</td>
<td>0.42</td>
<td>0.45</td>
<td></td>
</tr>
<tr>
<td>Treasure Island Causeway</td>
<td>0.29</td>
<td>0.26</td>
<td>0.20</td>
<td></td>
</tr>
<tr>
<td>Paradise Island E.</td>
<td>0.48</td>
<td>0.14</td>
<td>0.70</td>
<td></td>
</tr>
<tr>
<td>S. Causeway Island E.</td>
<td>0.87</td>
<td>0.23</td>
<td>1.49</td>
<td></td>
</tr>
<tr>
<td>Blind Pass Bridge</td>
<td>0.24</td>
<td>0.16</td>
<td>0.22</td>
<td></td>
</tr>
<tr>
<td>Corey Causeway A</td>
<td>0.87</td>
<td>0.25</td>
<td>0.69</td>
<td></td>
</tr>
<tr>
<td>Corey Causeway B</td>
<td>0.90</td>
<td>0.33</td>
<td>1.06</td>
<td></td>
</tr>
<tr>
<td>Corey Causeway C</td>
<td>0.48</td>
<td>0.22</td>
<td>0.28</td>
<td></td>
</tr>
<tr>
<td>Vina del Mar E.</td>
<td>0.50</td>
<td>0.26</td>
<td>0.85</td>
<td></td>
</tr>
<tr>
<td>Vina del Mar W.</td>
<td>0.77</td>
<td>0.26</td>
<td>0.96</td>
<td></td>
</tr>
<tr>
<td>Isla del Sol</td>
<td>1.12</td>
<td>1.40</td>
<td>2.16</td>
<td></td>
</tr>
<tr>
<td>Cat's Point</td>
<td>1.08</td>
<td>0.82</td>
<td>1.83</td>
<td></td>
</tr>
<tr>
<td>Crystal Island C</td>
<td>0.32</td>
<td>0.37</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>S. Causeway Island S.</td>
<td>1.19</td>
<td>0.41</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>Pasadena Isle</td>
<td>0.69</td>
<td>0.58</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>Boca Ciega Isle</td>
<td>N/A</td>
<td>0.03</td>
<td>N/A</td>
<td></td>
</tr>
</tbody>
</table>

Table 2. Peak channel velocities at Johns’ Pass and Blind Pass.

<table>
<thead>
<tr>
<th>Inlet Channel</th>
<th>Peak Spring Velocity (ft/sec)</th>
<th>Peak Neap Velocity (ft/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>John's Pass</td>
<td>3.3</td>
<td>2.3</td>
</tr>
<tr>
<td>John's Pass (Secondary)</td>
<td>3.1</td>
<td>2.1</td>
</tr>
<tr>
<td>Blind Pass</td>
<td>2.4</td>
<td>1.6</td>
</tr>
<tr>
<td>Blind Pass (Secondary)</td>
<td>0.8</td>
<td>0.6</td>
</tr>
</tbody>
</table>

In order to gain confidence in the ability of the model to simulate actual conditions and, ultimately, to be used in a predictive capacity, verification runs of the Boca Ciega Bay model were performed for the spring tidal period of July 30 through July 31, 2000. More than two years elapsed between the original model calibration period (April, May 1998) and the verification period (July, 2000). In that time, approximately 9.2 million cubic feet (260,000 m³) of sediment were dredged from Blind Pass from its entrance at the Gulf of Mexico to approximately 4000 feet (1200 m) south of the bridge. Dredging was completed in May, 2000. At John’s Pass, maintenance dredging of the navigation channel seaward of the bridge was conducted beginning February 20, 2000 and continued through the beginning of August, 2000 (USACOE, 2000). In order to accurately determine changes in inlet bathymetry since the original calibration field survey, post-dredge surveys for Blind Pass and John’s Pass were obtained (USACOE, 2000). In addition, as described in the following section, a recording fathometer was used to measure the cross-sectional area at various velocity-collection locations.

Field Data for Verification Runs

Stilling well tide gauges were installed on July 29, 2000 at Pass-A-Grille-Inlet and Boca Ciega South locations (Figure 2). Gauges remained in place through August 1, 2000. Bathymetry at John’s Pass, Blind Pass, and Vina del Mar East velocity-collection locations (Figure 3) were measured using a recording fathometer. Current speeds and directions were measured on July 31, 2000 at various velocity stations (Table 1) corresponding to locations of the original field study.

Input Data

As in the calibrated model, measured tidal heights at the Pass-A-Grille tide station were used as the driving function of the model. Similarly, wind speed and direction measure-
Table 3. Tidal prism of channels serving Boca Ciega Bay.

<table>
<thead>
<tr>
<th>Inlet or Channel</th>
<th>Avg. 11-Day Prism (ft³)</th>
<th>% of Bay</th>
<th>Avg. Spring ¹ Prism (ft³)</th>
<th>% of Bay</th>
<th>Max. Spring Prism (ft³)</th>
<th>% of Bay</th>
<th>Avg. Neap Prism (ft³)</th>
<th>% of Bay</th>
</tr>
</thead>
<tbody>
<tr>
<td>John's Pass</td>
<td>3.5E+08</td>
<td>40</td>
<td>7.0E+08</td>
<td>40</td>
<td>7.3E+08</td>
<td>37</td>
<td>3.1E+08</td>
<td>39</td>
</tr>
<tr>
<td>Vina del Mar E.</td>
<td>2.7E+08</td>
<td>30</td>
<td>5.5E+08</td>
<td>31</td>
<td>6.5E+08</td>
<td>33</td>
<td>2.4E+08</td>
<td>30</td>
</tr>
<tr>
<td>Vina del Mar W.</td>
<td>3.1E+07</td>
<td>3</td>
<td>6.1E+07</td>
<td>4</td>
<td>6.2E+07</td>
<td>3</td>
<td>2.6E+07</td>
<td>3</td>
</tr>
<tr>
<td>Cat's Point</td>
<td>1.2E+08</td>
<td>13</td>
<td>2.0E+08</td>
<td>11</td>
<td>2.5E+08</td>
<td>12</td>
<td>1.1E+08</td>
<td>13</td>
</tr>
<tr>
<td>Isla del Sol</td>
<td>6.5E+07</td>
<td>7</td>
<td>1.2E+08</td>
<td>7</td>
<td>1.7E+08</td>
<td>9</td>
<td>5.9E+07</td>
<td>8</td>
</tr>
<tr>
<td>Blind Pass (throat)</td>
<td>4.3E+07</td>
<td>5</td>
<td>7.9E+07</td>
<td>5</td>
<td>8.1E+07</td>
<td>4</td>
<td>3.7E+07</td>
<td>5</td>
</tr>
<tr>
<td>Narrows</td>
<td>1.7E+07</td>
<td>2</td>
<td>4.0E+07</td>
<td>2</td>
<td>4.1E+07</td>
<td>2</td>
<td>1.4E+07</td>
<td>2</td>
</tr>
<tr>
<td>Boca Ciega Bay</td>
<td>9.0E+08</td>
<td>100</td>
<td>1.7E+09</td>
<td>100</td>
<td>2.0E+09</td>
<td>100</td>
<td>7.8E+08</td>
<td>100</td>
</tr>
</tbody>
</table>

¹ Average of predominant diurnal tide.

ments at Azalea Park were obtained from the Pinellas County Department of Environmental Management, Air Quality Division, for the verification period. Cell sides and cell depths representing the dredged channels of Blind Pass and John's Pass were modified to reflect post-dredge bathymetry (USA-COE, 2000). The model was then run with pre- and post-dredge inlet dimensions. “Gates” representing channel depths at velocity-station locations were not altered because bathymetric transects showed little change in cross-sectional areas at station locations. All other input values remained the same as during the original model calibration.

Results of Verification

The Boca Ciega Bay model was run for 48 hours of simulation. The first 24 hours were used to remove transients. Velocities and tidal heights from the final 24 hours of simulation were then compared to velocities measured on July 31, 2000.

Results of post-dredge verification runs indicate that simulated velocities agree closely with measured values (Figure 9). Root mean square errors at velocity stations are listed in Table 1. For the purpose of stability analysis and assessment of the interaction of the two tidal inlets, calibration and verification results suggest the model serves as a useful and relatively reliable tool within the realm of error demonstrated. A comparison of pre- and post-dredge output suggests dredging had a negligible effect on velocities at station locations measured and consequently on the hydraulics of the overall bay system.

Comparatively high differences between observed and simulated velocities in the southeast portion of the model domain are believed to be related to storm activity and the hydraulic effects of Tampa Bay. Field observations indicate that current velocities at the southern end of the model domain are influenced by the exchange of water between Tampa Bay and Boca Ciega Bay. During a tidal cycle, analysis of observed velocities suggests that when water flows out of Tampa Bay, water enters Cat's Point and Isla del Sol channels and then exits through the Vina del Mar East channel (Figure 3). This system appears to be relatively isolated from Blind Pass and John's Pass. In order to more accurately depict hydraulic conditions of the southeast section of Boca Ciega Bay, more detailed study of this interaction with Tampa Bay may be developed through further model and/or field analysis.

STABILITY OF THE PASSES

Empirical Relationships

According to results of JARRETT'S (1976) regression analysis, the relationship between tidal prism and cross-sectional area may be described by power functions in the form:
\[ A = CP^n, \]  

where \( A \) = cross-sectional area (ft\(^2\)), \( P \) = spring or diurnal tidal prism (ft\(^3\)), and \( C \) and \( n \) are regression constants which are considered to vary with local conditions. Jarrett (1976) developed the following equation to describe the relationship between tidal prism and cross-sectional area for all Gulf coast inlets:

\[ A = 5.02 \times 10^{-4} P^{0.84}. \]  

Results of the calibrated model were used to evaluate the relationship between tidal prism and area of John’s Pass and Blind Pass. The cross-sectional area of Blind Pass during the study of Boca Ciega Bay was approximately 2500 ft\(^2\) (230 m\(^2\)); the corresponding spring tidal prism was 7.9 \times 10^7 ft\(^3\) (2.2 \times 10^6 m\(^3\)). At John’s Pass, the measured cross-sectional area was approximately 10,200 ft\(^2\) (950 m\(^2\)). A spring tidal prism of 7.0 \times 10^6 ft\(^3\) (2.0 \times 10^6 m\(^3\)) was determined from model data. Tidal prism versus area values plotted against results of Jarrett’s (1976) original regression analysis (equation 3) are shown in Figure 10.

Plots of prism versus area for John’s Pass and Blind Pass show that values for each of the inlets lie close to Jarrett’s (1976) regression line (Figure 10). Such empirical relationships, however, do not account for variability in grain-size, net longshore transport rates, or sediment transport characteristics (O’Brien, 1976), which can vary significantly from one inlet to the next. Values for John’s Pass and Blind Pass show little deviation from the original regression line even though hydraulic characteristics of each inlet differ significantly. Although values suggest both inlets are in equilibrium, scour at John’s Pass and deposition at Blind Pass suggest neither inlet is stable. Thus, Jarrett’s analysis, by itself, is not necessarily sufficient in evaluating inlet stability.

### Ratios of Tidal Prism to Littoral Drift

Bruun’s (1978) stability index (Table 4) characterizes inlets from the ratio of tidal prism to gross littoral-drift quantities that reach the inlet’s channel. Because it is difficult to accurately quantify the amount of sediment that actually interferes with an inlet’s channel, net littoral drift estimates at John’s Pass and Blind Pass were obtained to provide order-of-magnitude approximations. It should be noted, however, that predominant littoral drift quantities used in calculations may be considerably smaller than gross drift quantities. As a result, computed index values for this study may be greater than accurate gross littoral-drift values would reflect.

Net littoral-drift estimates for John’s Pass ranged from 8.1 \times 10^4 to 1.35 \times 10^5 ft\(^3\)/year (2.3 \times 10^4 to 3.82 \times 10^4 m\(^3\)/year) toward the south (CTC, 1993). The spring tidal prism of John’s Pass that resulted from the Boca Ciega Bay model was 7.0 \times 10^6 ft\(^3\) (2.0 \times 10^6 m\(^3\)). Based on a littoral-drift quantity of 1.35 \times 10^5 ft\(^3\)/year (3.82 \times 10^4 m\(^3\)/year), the ratio of tidal prism to littoral drift, based on a longshore transport average of 2.31 \times 10^6 ft\(^3\)/year (6.5 \times 10^4 m\(^3\)/year) at the entrance of the inlet, is 34. The ability of Blind Pass to naturally maintain a channel may be rated as “poor” (Table 4).

The predominant direction of longshore transport at Blind Pass varies seasonally. In spring and summer, sand is primarily carried to the north, in fall and winter to the south. Longshore-transport estimates in the vicinity of Blind Pass were 1.97 \times 10^6 ft\(^3\)/year (5.6 \times 10^4 m\(^3\)/year) toward the north and 2.65 \times 10^6 ft\(^3\)/year (7.5 \times 10^4 m\(^3\)/year) toward the south (CPE, 1992). The spring tidal prism computed from output of the model was 7.9 \times 10^6 ft\(^3\) (2.2 \times 10^6 m\(^3\)). The ratio of tidal prism to littoral drift, based on a longshore transport average of 2.31 \times 10^6 ft\(^3\)/year (6.5 \times 10^4 m\(^3\)/year) at the entrance of the inlet, is 34. The ability of Blind Pass to naturally maintain a channel may be rated as “poor” (Table 4).

It should be noted that littoral-drift quantities used to assess stability at John’s Pass and Blind Pass represent theoretical values obtained from shoreline orientations and wave data (CTC, 1993, CPE, 1992) and were not based on data measured at the inlets. The reliability of the method is difficult to assess, and littoral-drift values should only be re-

<table>
<thead>
<tr>
<th>Stability Rating</th>
<th>Inlet Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Good</td>
<td>Relatively few bars, well flushed channels</td>
</tr>
<tr>
<td>Fair</td>
<td>More prominent offshore bar formation</td>
</tr>
<tr>
<td>Fair to Poor</td>
<td>Large offshore bar, often with a channel through it</td>
</tr>
<tr>
<td>Poor</td>
<td>Unpredictable channels, unstable openings</td>
</tr>
</tbody>
</table>

Table 4. Stability index proposed by Bruun (1978).
Stability Diagrams from Predictive Simulations

The tendency of a tidal inlet to scour or deposit sediment may be characterized by relating the maximum velocity to the cross-sectional area of the inlet (Escoffier, 1940, 1977). The cross-sectional area of Blind Pass during the approximate time of the study was 2500 ft² (230 m²) at the throat. Maximum spring velocities in the main channel averaged 2.7 ft/sec (0.82 m/sec). Peak spring velocities, weighted by area across the width of the cross-section, averaged 1.8 ft/sec (0.55 m/sec). Results of successive computer runs in which the main and secondary channel depths at the Blind Pass throat section were increased and then decreased in 10-percent increments produced maximum spring velocities as shown in Figure 11. As a result of the hydraulic interaction between John's Pass and Blind Pass and their relative size difference, changes in the cross-sectional area of Blind Pass only very slightly affect the velocities at John's Pass (Figure 11b). The tidal prisms of the inlets and Boca Ciega Bay as a function of the cross-sectional area of Blind Pass are shown in Figure 12.

The cross-sectional area of John's Pass was measured to be 10,200 ft² (950 m²). Maximum spring velocities in the main channel averaged 3.6 ft/sec (1.1 m/sec) and 3.4 ft/sec (1.0 m/sec), averaged across the cross-section. Results of computer simulations in which the channel dimensions representing the inlet were increased and then decreased are shown in Figure 13. Changes in the tidal prisms of each of the inlets and Boca Ciega Bay are shown in Figure 14.

Stability diagrams may be used to predict how an inlet responds to deposition or erosion of its channel. An inlet may be classified as "stable" or "unstable" against a tendency to close based on how maximum velocity changes as the cross-sectional area of the inlet is reduced (O'Brien and Dean, 1972). The stability diagram for Blind Pass indicates that the "critical area" for the inlet was approximately 1000 square feet (90 m²). The associated spring velocity, averaged across the width of the inlet, was 2.8 feet per second (0.85 m/s). For
cross-sectional areas larger than the "critical area" but less than the equilibrium (measured) cross-sectional area, the inlet may be classified as scouring or "stable." Tidal currents would tend to flush the inlet of sediments as a result of an increase in velocity (O'BRIEN and DEAN, 1972). Consequently, the channel cross-sectional area may be maintained. An "unstable" condition may occur if the cross-sectional area of Blind Pass were less than approximately 1000 square feet (90 m²). Model results show a sharp drop in the tidal prism of Blind Pass associated with such a reduction in the area of the inlet (Figure 12a). It should be noted, however, that when the cross-sectional area of Blind Pass is greater than approximately 2000 ft² (186 m²), velocities fall below 2 ft/sec (0.6 m/sec) (Figure 11a), and the ability of the current to move sediment will diminish.

The "critical area" for John's Pass was approximately 6100 ft² (570 m²) with an associated, weighted velocity of 4.2 ft/sec (1.3 m/sec) (Figure 13a). The decrease in velocity at the "critical area" is linked to a significant reduction in the tidal prism of John's Pass (Figure 14a).

Stability diagrams are based on the concept that maximum velocities resulting from changes in the cross-sectional area of a channel may be used to determine erosional or depositional tendencies of an inlet. They do not account for littoral drift, which may impede flow through a channel, or for changes in the distribution of sediment which may occur as a result of variations in the flow regime of the bay and inlets. Because flow through John's Pass accounts for 40% of the tidal prism of Boca Ciega Bay (Table 3), a hypothetical scenario in which the cross-sectional area falls below 6100 ft² (570 m²) would result in a sharp drop in the tidal prism of the entire bay (Figure 14c).

Evaluating the Degree of Inlet Interaction

Stability and tidal-prism diagrams based on results of the computer model provide a means of quantifying how a change in the size and configuration of one inlet influences the hydraulic environment of an inlet-bay system. For example, if...
the area of Blind Pass were reduced but remained greater than approximately 1000 ft² (90 m²), the tidal prism of the inlet would change very little (Figure 12a); the response of the inlet would be an increase in velocity (Figure 11a). If the size of Blind Pass fell below 1000 ft² (90 m²), results indicate the tidal prism of the inlet would drop markedly and, consequently, velocities would fall. Because of the relative size of Blind Pass, changes in the morphology of the inlet only very slightly affect the hydraulic environment of John’s Pass (Figures 11b and 12b) and do not substantially change the tidal prism of the bay (Figure 12c).

At John’s Pass, model results show that as the area of the inlet is reduced, the tidal prism of John’s Pass (Figure 14a) is not significantly affected until the inlet reaches an area of approximately 6100 ft² (570 m²). Because flow through John’s Pass accounts for approximately 40% of the tidal prism of Boca Ciega Bay, a relatively large reduction in the area of the inlet would be required to affect the tidal prism of the bay (Figure 14c) as well as velocities at Blind Pass (Figure 13b).

Stability and tidal-prism diagrams may be used to determine under what conditions the interaction of inlets in a particular coastal region substantially affects the morphology of the passes. In the case of Boca Ciega Bay, John’s Pass and Blind Pass act as relatively independent hydraulic units, unless the area of John’s Pass is reduced by more than 40% of its current size.

Flow Regime of Boca Ciega Bay

John’s Pass, approximately four times the size of Blind Pass, carries more than eight times the tidal prism of Blind Pass and approximately forty percent of the tidal prism of Boca Ciega Bay. A history of the cross-sectional areas of the two inlets indicates that John’s Pass has increased in size as the area of Blind Pass declined. Results of the Boca Ciega Bay model show to what extent the two inlets are currently hydraulically inter-dependent. Because only approximately 5% of the bay tidal prism is fed through Blind Pass (Table 3), changes in the area of the inlet do not significantly affect hydraulics at John’s Pass (Figure 11b). Substantial reductions in the area of John’s Pass, however, affect the tidal prism of the inlets as well as Boca Ciega Bay. As a result, a change in the velocity at Blind Pass would occur if the area of John’s Pass were greatly reduced (Figure 13b). An increase in the size of John’s Pass, however, does not significantly affect hydraulics at Blind Pass.

Stability of John’s Pass

Current speeds generated by the Boca Ciega Bay model indicate that maximum spring velocities, weighted across the width of the inlet, reached an average of 3.4 ft/sec (1.0 m/sec). A tidal-prism-to-littoral-drift ratio of 522 indicates that the inlet is hydraulically capable of flushing sediments from its channels (Table 4) so that its relatively high current speeds may be maintained. Stability diagrams which depict maximum velocities as a function of the inlet’s cross-sectional area also indicate that John’s Pass is capable of maintaining its channel (Figure 13a).

Stability of Blind Pass

At Blind Pass, peak velocities, weighted across the width of the channel, averaged 1.8 ft/sec (0.55 m/sec). Although stability diagrams for Blind Pass (Figure 11a) indicate that current speeds would increase in response to inlet shoaling, relatively large quantities of littoral-drift material can prevent adequate scour of the pass. A tidal-prism-to-littoral-drift ratio of 34 (Table 4) suggests that sand interferes with the inlet channel and impedes flow. As a result of increased shoaling at an inlet, a gradually lengthening of an inlet’s channel will typically occur. Because of the increase in channel length, current velocities as well as transport capabilities decline. Consequently, the cross-sectional area of a shoaling inlet gradually decreases with time (Van de Kreeke, 1985). At Blind Pass, model results indicate that a gradual decrease in tidal prism occurs as the inlet’s area is significantly reduced (Figure 12). As a result of a decline in the transport capacity of Blind Pass, the inlet is unable to naturally maintain its channel and periodic dredging is required.

HYDRAULIC EVOLUTION OF BOCA CIEGA BAY

The morphology of Blind Pass indicates that the inlet was transformed from a mixed-energy pass to one dominated by deposition from wave-induced longshore transport. At the same time, a history of the cross-sectional area of John’s Pass shows the pass has increased in size throughout most of its history. This increase is believed to have been caused by a decrease in the tidal prism of Blind Pass as well as the closure of Indian Pass in the 1920’s (Mehta et al., 1976).

A simulation of the Boca Ciega Bay model in which the configuration of the bay and the cross-sectional areas of inlets broadly corresponding to 1926 dimensions was run in order to assess the hydraulic environment during the period. The cross-sectional area of John’s Pass in 1926 was reportedly 5780 ft² (537 m²); the area of Blind Pass was 2280 ft² (212 m²) (CPE, 1992). The entrance of Blind Pass was approximately 4000 feet (1000 m) north of its present location. Indian Pass was closed by this time. Dredge-and-fill islands had not yet been developed (Mehta et al., 1976). Although survey data from the early 1900’s is limited and its accuracy is difficult to assess, a nautical chart of the region shows the general configuration of the bay before dredge-and-fill activities (US&GS, 1885).

According to the model simulation of flow conditions in 1926 assuming offshore tidal phase conditions of today, maximum spring velocities were 6.8 ft/sec (2.1 m/sec) at John’s Pass. The spring tidal prism at the inlet reached 7.9 × 10⁶ ft³ (2.2 × 10⁸ m³), approximately 13% greater than in 1998. Relatively high velocities and the sizeable tidal prism carried by John’s Pass suggest the inlet had a greater potential to scour in 1926 than after the development of dredge-and-fill islands. A computer simulation of a scenario in which the islands occupied the bay while the cross-sectional areas of Blind Pass and John’s Pass corresponded to 1926 dimensions shows the result of development of the islands was a drop in the velocities to 5.9 ft/sec (1.8 m/sec) at John’s Pass and a concurrent decrease in tidal prism. The model shows a de-
crease in scour potential at John's Pass as a result of the development of dredge-and-fill islands.

At Blind Pass, maximum spring velocities generated by the model representing 1926 conditions were 3.1 ft/sec (0.94 m/sec). The tidal prism was $1.5 \times 10^8$ ft$^3$ ($4.2 \times 10^6$ m$^3$), approximately 90% greater than the 1998 tidal-prism volume. According to the model, Blind Pass had a significantly greater ability to scour in the early 1900's than in its recent history.

The computer simulation of the scenario in which the islands occupied the bay while the cross-sectional areas corresponded to 1926 dimensions indicates that maximum velocities at Blind Pass dropped to approximately 1.9 ft/sec (0.58 m/sec). According to the model, the placement of dredge-and-fill islands reduced the tidal prism of Blind Pass. Lower current velocities prevented adequate scour of the channel.

Because survey data of the study area in the early 1900's is very limited and tide heights and phase lags of today were used for the historical model run, current speeds produced by the historical computer simulations should be interpreted as estimates used only to consider how changes in the configuration of the bay may have affected depositional or erosional trends at inlets. Results suggest the development of dredge-and-fill islands decreased the tidal prism of Blind Pass and, consequently, the ability to flush its channels. Although a portion of this prism would have been captured by John's Pass, an overall decrease in the tidal prism of John's Pass suggests the ability of the inlet to scour its channel also lessened.

**CONCLUSIONS**

The results of the model study demonstrate for a bay fed by multiple inlets:

1. The numerical hydraulic model serves as a tool to link traditional stability analysis to modern techniques used to characterize flow conditions within an estuary or bay system. Stability diagrams developed from model output at each inlet may be used together, but not independently, to assess the degree of interaction between multiple inlets serving a particular embayment.

2. Changes in the morphology of an inlet can affect the hydraulic environment of the bay, and vice versa. A change in area of one inlet can change the tidal-prism distribution of the bay and, consequently, can influence the morphology of other inlets. For example, a relatively small percentage of the Boca Ciega Bay tidal prism is fed through Blind Pass; therefore, the influence of the inlet on scour tendencies at John's Pass is very minor. Considerable reductions in the size of John's Pass, however, would result in a decrease in the tidal prism of the bay and, thereby, would affect velocities at Blind Pass.

3. The degree of interaction between tidal passes is a significant factor in assessing the stability of an inlet. The interconnectedness of a bay system influences the hydraulic inter-dependency of the passes. Through model simulation, the degree of interaction between inlets in a particular study area may be quantified by determining how the tidal prism and current velocities of one inlet change in response to opening or closing an adjacent pass. For example, results of the Boca Ciega Bay model indicate that John's Pass is relatively isolated from Blind Pass unless the cross-sectional area of John's Pass is reduced by more than 40%.

4. The historical evolution of a bay system will have long-term consequences on the morphological evolution of a tidal inlet. The inlet response period may be many years or decades. Historical model simulations indicate how changes in the bay configuration (e.g. dredge-and-fill activities and the construction of causeways or bridges) can influence the hydraulic environment of the system and, consequently, the stability of tidal inlets. Although inconclusive, historical simulations of the Boca Ciega Bay model suggest there is no evidence that the deepening of John's Pass is a consequence of the deposition and closure tendency of Blind Pass. However, the tendency of Blind Pass to close is very likely the result of a decrease in tidal prism and an increase in friction as a result of dredge-and-fill development of Boca Ciega Bay in the 1940's and 1950's.

5. In order to evaluate the stability of inlets in a bay with more than one opening, the hydraulic environment of the system as a whole must be characterized. By developing a numerical hydraulic model which simulates flow throughout the study region and quantifying the degree of interaction between tidal passes within the system, the hydraulic response of each inlet may be more effectively assessed. Although extensive-collection efforts may be required, the application of the numerical model has become less costly and increasingly widespread.

6. The calibration and verification of the hydraulic model used in this analysis was cursory but sufficient to address the degree of interaction of inlets for a characteristic spring and neap period. Flow-field refinement (increased discretization) and residual circulation implications would be useful to help understand and characterize, in detail, the morphology of the particular inlets.

7. This study helps support the premise that simple methodologies used to assess inlet stability, while useful, do not by themselves provide a sufficient means of evaluating depositional and erosional tendencies of inlets in a multi-inlet bay system.

**LITERATURE CITED**


