

GENERAL METHODOLOGY FOR INLET RESERVOIR MODEL ANALYSIS OF SAND MANAGEMENT NEAR TIDAL INLETS

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Abstract: This paper introduces a general methodology for applying the Inlet Reservoir Model in regional sand management at inlets. The procedure is based on numerical modeling and data analysis for various spatial and time scales to evaluate the inlet evolution, existing condition, and alternatives for a proposed design. The methodology is discussed through a case study for Hurricane Pass, on Florida gulf coast. The case study addresses potential consequences of proposed dredging of the Hurricane Pass ebb shoal for restoration of the beach on Honeymoon Island State Park. The analysis is based on observed inlet evolution, and modeling of regional hydrodynamics, waves, and sediment transport at various times marking main stages of the inlet system evolution. Modeling results serve as input to the Inlet Reservoir Model to quantify volumetric change and bypassing rates between the different morphologic features that comprise the inlet shoal system. The model is then applied to assess the long-term consequences of proposed dredging on the adjacent beaches and recovery rate of the borrow area.

INTRODUCTION

Tidal inlet morphologic features such as ebb shoals and flood shoals are part of an interactive sand-sharing system that evolves toward and around dynamic equilibrium under sediment transport produced by waves and tidal currents. These shoals offer attractive potential sources of sediment for beach nourishment because of their close proximity to shore and probable compatibility of sediment grain size and color with those of the neighboring beaches. However, removal of sediment by mining will interrupt the natural sediment bypassing of the integrated sediment-sharing system. Until recently, the consequences of mining inlets were difficult to estimate due to complexity of coastal processes at inlets and lack of guidelines and tools to quantify the various responses of the system to mining of inlet shoals and channel dredging. Timeframes for such responses are a central

factor because, in dealing with large sand shoals, adjustment in bypassing and morphology may take many years. Mehta, et al. (1996) reviewed the acting processes, listed inlets in Florida where ebb shoals have been mined and identified needs for predictive technology to assess the consequences of ebb-shoal mining. Cialone and Stauble (1998) reviewed eight ebb-shoal mining projects on the Atlantic and Gulf of Mexico coasts. Their analysis indicates varying responses ranging from beneficial to detrimental. The main detrimental impact was chronic downdrift beach erosion at some sites. Mixed outcomes of previous projects and lack of tools to assess consequences make potential for adverse consequences of ebb-shoal mining a concern to permitting agencies. As a result, regulatory agencies may be cautious and resist or reject proposed use of inlet shoals as sand sources.

The Inlet Reservoir Model (Kraus 2000a, 2000b) is a new technology that can estimate alterations in growth of inlet morphologic features and changes in the bypassing rate in response to mining of ebb- and flood-tidal shoals. The model provides estimates of ebb-shoal evolution and natural bypassing rates at inlets. It also predicts the time response of the bypassing rate and shoal recovery rate as a consequence of ebb-shoal mining (and flood-shoal mining). The model has been applied to address engineering issues at several sites, including Ocean City Inlet, Maryland (Kraus 2000a, 2000b), Shinnecock Inlet, New York, (Militello and Kraus 2001), Fire Island Inlet, New York (Kraus et al. 2003), and Sebastian Inlet, Florida (Zarillo, et al. 2003).

Dabees and Kraus (2004) present a general methodology for examining the response of a complex inlet system, Capri Pass, Florida, to proposed sediment mining to nourish the downdrift Hideaway Beach. The methodology incorporates bathymetric data and aerial photography, operation of wave and tidal circulation numerical models, and application of the Inlet Reservoir Model. The methodology was implemented at three inlet systems spaced within approximately 300 km along southwest Florida gulf coast; Hurricane Pass, Venice Inlet, and Capri Pass. The studies for Hurricane Pass and Capri Pass were performed to evaluate the use of inlet ebb shoals as sand sources for re-nourishment of downdrift beaches. The Venice Inlet study evaluated the flood shoal as an alternate to offshore borrow areas for re-nourishment of Venice Beach and navigation enhancement. The case studies emphasize the general methodology to determine sediment pathways, identify multiple sand sources within an inlet system, optimize location and time of dredging, and assess cumulative consequences.

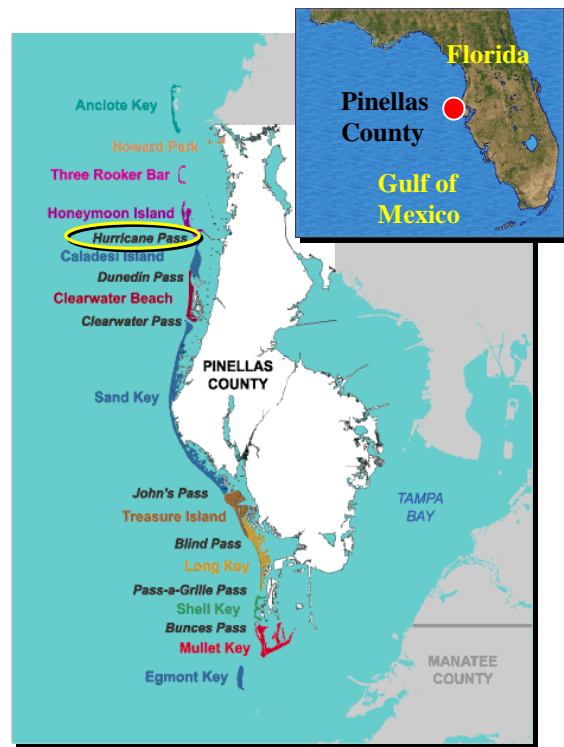


Fig. 1. Hurricane Pass location within Pinellas County barrier island system

Through such a methodology, alternatives for the location of mining and acceptable amount of volume to be taken can be evaluated and compared quantitatively, as well as time scales of shoal recovery and interruption of natural sand bypassing. This paper discusses this methodology through the Hurricane Pass case study.

HURRICANE PASS CASE STUDY

Honeymoon Island and Hurricane Pass are part of a system of barrier islands and tidal inlets along the Gulf of Mexico coastline in Pinellas County, Florida. Figure 1 shows the location of Hurricane Pass. The pass was opened by a storm in 1921, separating Hog Island into Honeymoon Island to the north and Caladesi Island south. After Hurricane Pass was formed in 1921, the inlet and adjacent shorelines evolution were influenced by regional natural and anthropogenic changes. Of importance are the development of Honeymoon Island in the 1960s and closure of Dunedin Pass, the next inlet south of Hurricane Pass, in 1988. The 1960s development of Honeymoon Island included construction of the Dunedin Causeway in 1962, which connected Honeymoon Island to the mainland, and a 1969 landfill of the west side of Honeymoon Island. Construction of the causeway severed the bay system, reducing the tidal prism that probably contributed to the closure of Dunedin Inlet in 1988. The 1969 landfill included placement of 870,000 m³ of dredged sediment along the Honeymoon Island shoreline. The fill was dredged from a borrow area directly offshore of the fill area. Figure 2 shows 1957 aerial photographs, representing conditions prior to the changes that occurred during the 1960s and in 2000 – representative of present condition.

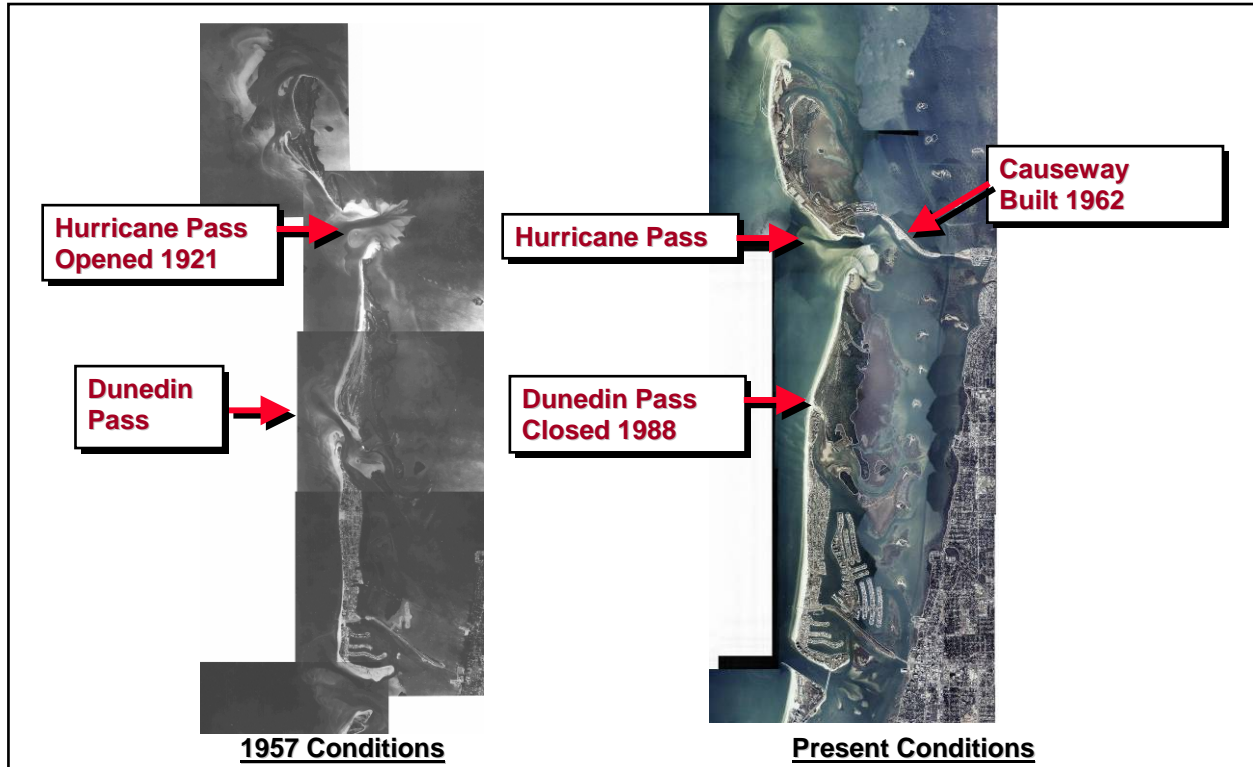


Fig. 2. Aerial photographs of 1957 and 2000 representing conditions prior to 1960s developments, and present condition

Inlet evolution

Previous studies documented the inlet evolution, inlet dynamics, morphologic and geotechnical features of Hurricane Pass (USACE 1984; Dean and O'Brien 1987; Cuffe 1991; Davis et al 2003). The present study compiled present and historic surveys, aerial photographs, and other data to quantify morphologic change throughout the inlet evolution and provide input for numerical models.

Figures 3 to 5 illustrate the major evolution stages of Honeymoon Island and Hurricane Pass. Figure 3 shows morphologic change from the inception of Hurricane Pass in 1921 until 1957, prior to the 1960s development. During that period, natural physical processes of wave, sediment transport, and tidal flow controlled inlet evolution. The figure shows formation of the ebb shoal, flood shoal, main channel, and marginal flood channels. The ebb tidal delta was growing southward as a result of the dominant southward sediment transport near the inlet.

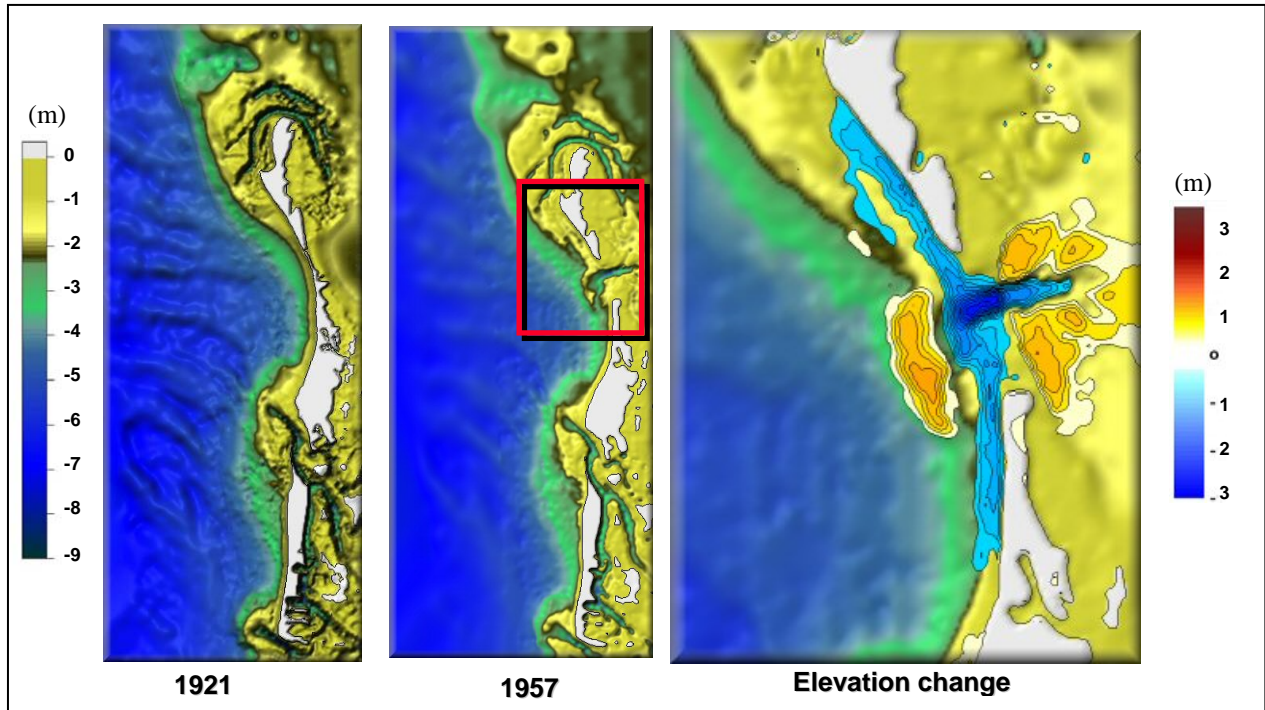


Fig. 3. Regional bathymetry and morphological change from 1921 to 1957

Figure 4 shows the immediate impacts of the 1960s commercial and residential developments on the evolution of the inlet system. The figure represents morphologic change from 1957 until 1974, during which the construction of the Dunedin Causeway and Honeymoon Island landfill took place. Morphologic changes are seen as a response to causeway construction that reduced the tidal prism through Hurricane Pass. Those changes include migration of the inlet shoal system landward as the channel width decreased in adjusting to the smaller tidal prism and the growth of the sand spits at both ends of the inlet. The figure also illustrates the elevation change from the landfill along the south part of Honeymoon Island and the offshore depression created by the dredging of the borrow area.

The borrow area was dredged below the elevation of limestone bedrock, producing fill material that included sand and coarse lime stone aggregates. The landfill was constructed at a shoreline angle that was not parallel to the original shoreline, as shown in Figure 4. The artificial shoreline that was not in equilibrium with prevailing wave patterns and offshore depth contours produced large gradients of sediment transport that eroded the fine sand and left the rock aggregates forming an unstable headland similar to its present condition.

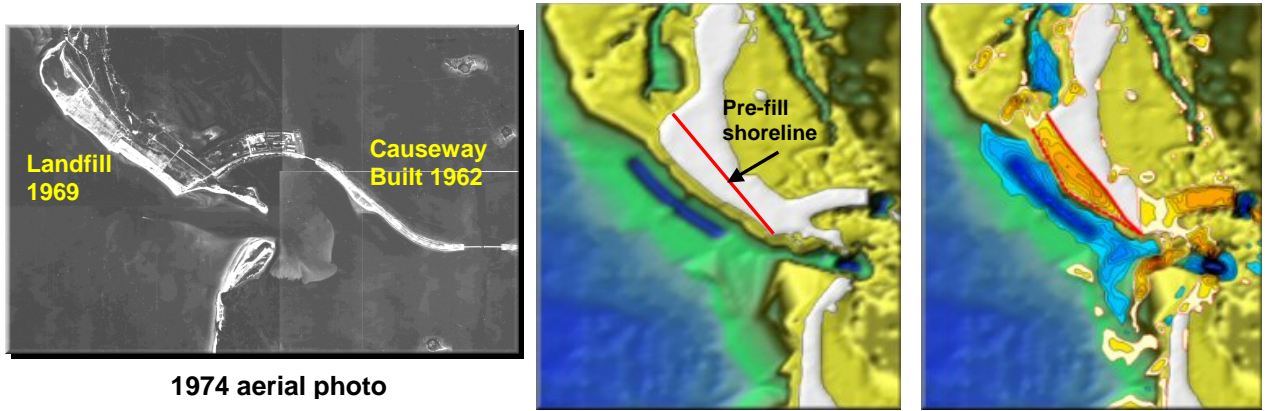


Fig. 4. Bathymetry and morphological change from 1957 to 1974

Figure 5 shows the present condition, based on hydrographic surveys of 2004, and the elevation change from the 1957 conditions. At the regional scale, comparison between the 1957 and present condition reveals closure of Dunedin Pass and the small inlet directly north of Honeymoon Island. The elevation change indicates erosion of large amounts of sand that were on the ebb shoals of those inlets. After the inlets closed, those shoals were no longer active and collapsed onshore, temporarily providing a sand supply to the Honeymoon Island and Caladesi Island beaches. Honeymoon Island growth was manifested in the form of a long sand spit that grew to the north of the island. Caladesi Island gained a supply of sand that helped maintain a supply of sand from the south to Hurricane Pass and growth of a spit at the north end of Caladesi Island.

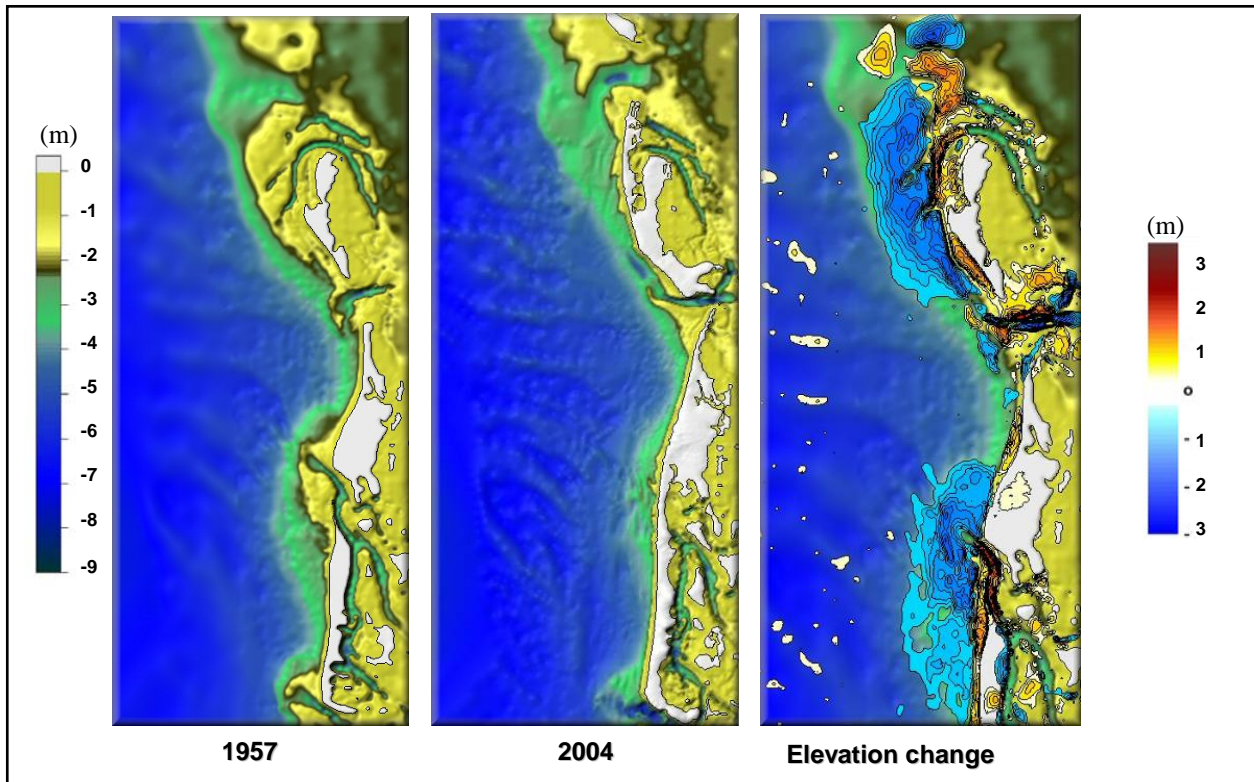


Fig. 5. Regional bathymetry and morphological change from 1921 to 1957

Wave and sediment transport modeling

Numerical modeling in this study covered regional simulation of waves, sediment transport, and hydrodynamics at various times that mark the main stages of the inlet system evolution. Wave and sediment transport modeling were performed for 1921, 1957, 1995, and 2004 conditions. Representative wave climate conditions served as input for detailed wave refraction modeling. The wave climate was based on the 20-year Wave Information Study (WIS) Station 258: 28.16° N, 83° W. Station 258 is located approximately 10 km offshore of Honeymoon Island, in water depth of approximately 12 m. The results of refraction modeling then allowed computation of potential longshore sediment transport for the adjacent shorelines of Honeymoon Island and Caladesi Island.

Wave-driven sediment transport potentials were computed from modeled breaking conditions for each representative wave condition. Sediment transport potentials were calculated based on the Kamphuis (1991) formula and probability of occurrence of each case. Results of all cases were grouped to calculate annual longshore sediment transport potentials as well as gross and net transport rates along the shorelines of Honeymoon and Caladesi Islands. Sediment transport computations for the 1957 and 2004 conditions were performed by calculating the sediment transport potentials at two layers. The first layer runs from the shoreline to a depth of 1.5 m, and the second layer from 1.5-m depth to the depth of closure (4.5m).

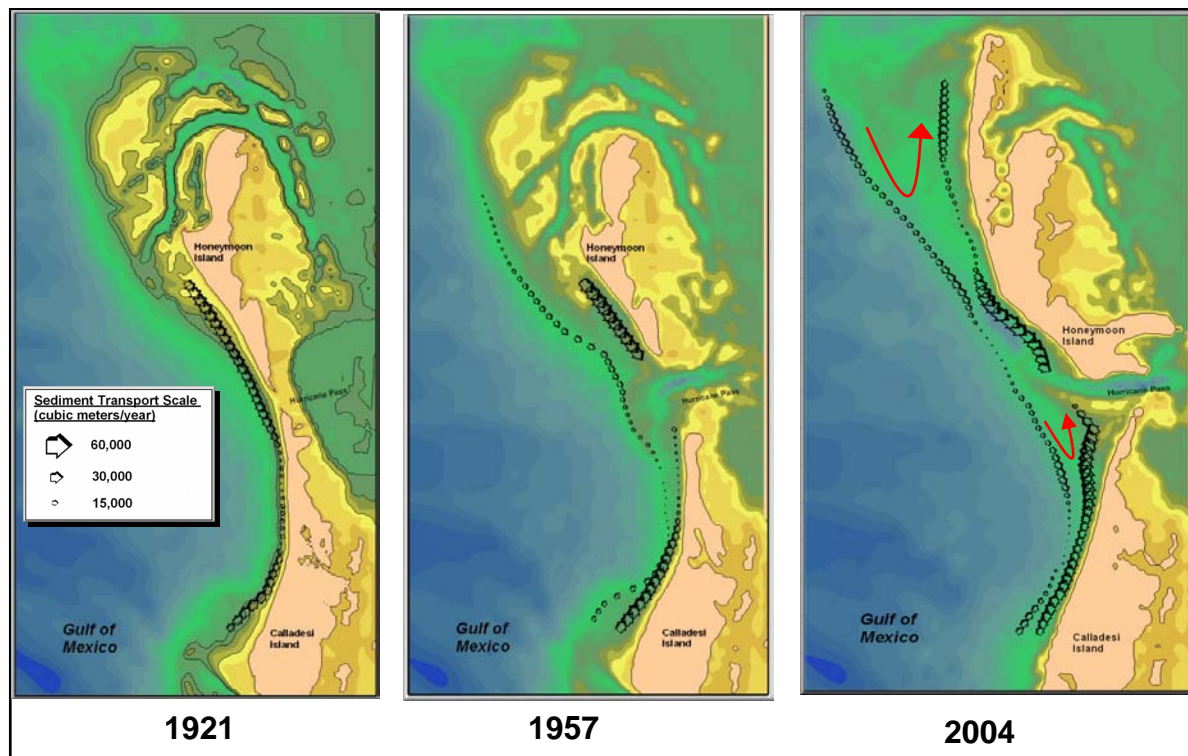


Fig. 6. Calculated regional sediment transport potentials for various conditions

Figure 6 shows the computed sediment transport potential for 1921, 1957, and 2004 conditions, for the shorelines of Honeymoon Island and Caladesi Island. The scaled vectors in the figure indicate the magnitude and direction of the sediment transport. The results indicate the variability of sediment transport at the three temporal stages. The 1921 conditions represented a wave-dominant

situation prior to the opening of Hurricane Pass. The sediment transport was predominantly south as the general regional trend. The 1957 conditions represented mixed inlet dynamics subject to wave and tidal currents. The sediment transport computation was done at two layers to provide more details of the sediment transport patterns near the inlet when the contours are not necessarily parallel to the shoreline. The 1957 results showed the influence of the ebb shoal of Hurricane Pass on sediment transport gradients and magnitudes. However, net sediment transport direction remained southward, as is evident from the shape of the ebb shoal.

The 2004 condition represent the mixed inlet dynamics and the impacts of anthropogenic changes. The present-condition sediment transport incorporates the response to closure of Dunedin Pass and the inlet north of Honeymoon Island on nearshore transport as shown in Figure 6. The net sediment transport along the offshore contours in general remained southward. However, the net sediment transport along the sand spit at the north part of Honeymoon Island is northward. This reversal indicates the sediment transport circulation associated with the collapse of the derelict shoal system and the growth of the sand spit to the north.

The south part of Honeymoon Island exhibits high potential sediment transport gradients increasing to the south, mainly due to the artificial shoreline orientation not in conformity with the natural contour orientation. Such large gradients eroded the fine sand and left coarse rock aggregates forming the artificial headland where the shoreline shows sharp transition in orientation. The change in orientation and sediment transport direction creates a divergent point that limits southward transport of sand. The offshore depression from the 1969 dredging created an offshore sink for some of southward sand transport, further limiting the southward sand supply towards the inlet.

On the south side of Hurricane Pass, reorientation of Caladesi Island in adjustment to the change in tidal prism and sand supply from the collapsing Dunedin Pass generated a general northward transport along Caladesi Island shoreline. This transport resulted in northward growth of Hurricane Pass Ebb shoal as discussed above. The results also show the sediment transport circulation at Hurricane Pass ebb shoal, which maintains sand within that morphologic feature.

Hydrodynamic regional modeling

The regional hydrodynamics of the northern Pinellas County Barrier Islands was simulated with the Advanced Circulation (ADCIRC) model (Luettich, et al. 1991). The modeling was performed to evaluate the change in tidal circulation and sediment transport patterns at the varying temporal stages of Hurricane Pass evolution. The model grid covered an area that extended from the middle of Sand Key to several kilometers north of Anclote Key, covering approximately 42 km alongshore by 22 km offshore. It was considered essential to include all inlets that connect the same bay area to the Gulf of Mexico in the regional coverage. Five regional models were prepared based on available survey data to represent the conditions of 1957, 1965, 1974, 1995, and 2004. The five temporal stages were needed to evaluate the variations in tidal prism and active morphologic features at different times.

The ADCIRC mesh for the present condition consisted of 27,149 nodes and 50,998 elements. The grid varied from lower resolution at the Gulf boundary to high resolution in the nearshore and inlet regions. Node spacing ranged from 1,000 m at the offshore boundary to 30 m for the high-resolution areas. The model driving forces were the Gulf of Mexico water level fluctuations resulting from astronomical tides. The water levels were computed based on tidal constituents (K1, O1, P1, Q1, M2, S2, N2, and K2) from ADCIRC Tidal Databases (Mukai, et al. 2002) developed by the USACE

Coastal Inlets Research Program for use as boundary conditions for local area circulation models. The simulation date was chosen to represent average and spring tide ranges and an 8-day run was simulated with a time step of 1 sec, and a total of 691,200 time steps per run. The model was calibrated with available measured water levels and magnitudes of velocities and tidal prism measurements cited in the USACE (1984) report.

Figure 7 displays sample results of the computed ebb current velocities for 1957 and present conditions. The figure summarizes responses to major changes that occurred between 1957 and present time that includes the causeway and landfill construction in the 1960s and the subsequent closure of adjacent inlets north and south of Hurricane Pass. Red-colored areas indicate velocities greater than the critical velocity for sediment movement. Littoral drift transported to red-colored areas is carried by the strong tidal current and deposited in areas where velocities are less than the critical velocity (areas between red and blue). The figure shows the change from 1957 to present time in ebb jet orientation, ebb current, and active shoal areas. ADCIRC results of active shoals and velocity patterns at each of the five temporal stages were analyzed to establish the Inlet Reservoir Model for Hurricane Pass. The ADCIRC model results also served to quantify the temporal change in tidal prism, input to the Inlet Reservoir Model through estimation of the ebb shoal volume.

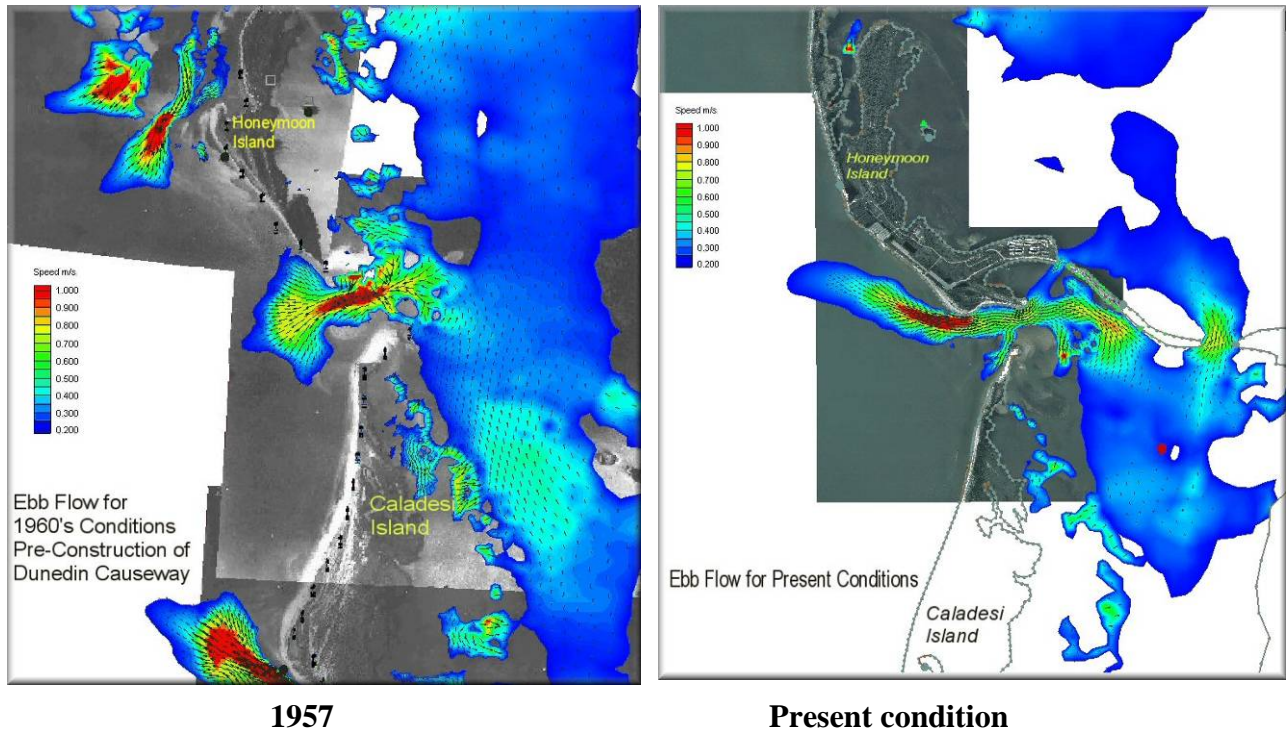


Fig. 7. ADCIRC simulations of Hurricane Pass Ebb flow for 1957 and present condition

INLET RESERVOIR MODEL ANALYSIS FOR HURRICANE PASS

The Inlet Reservoir Model calculates volume change of identified morphologic features and bypassing rates for an inlet, in the present application for the ebb-shoal complex. The first step is to identify sediment pathways across the ebb shoals and distinct morphologic features that form the ebb shoal complex. In a typical wave-dominated inlet, there would be three distinct ocean-side features: an ebb shoal, bypassing bar, and attachment bar. The concept of the Reservoir Model is based on the assumption that each feature has a maximum (equilibrium) sand-retention capacity that cannot be

exceeded. Once a feature has reached capacity, all additional sediment transport to that feature will bypass to the next feature(s), and so forth until sediment arrives at the downdrift side of the inlet or other location, such as the channel and flood shoal. If a morphologic feature is partially full, it still provides (partial) bypassing. The Inlet Reservoir Model calculates growth of the shoals as a function of the littoral drift and equilibrium volumes of the shoals, and it accounts for the naturally long timescales of large morphologic features and time delays in exchange of material among the features. Further information on the Inlet Reservoir Model can be found in Kraus (2000a, 2000b, 2002).

Inlet Reservoir Model setup

The Hurricane Pass ebb-shoal system is more complex than that of a typical inlet. The complexity owes to the change in tidal prism and resulting change in the equilibrium volume for the ebb shoal, whereas the Reservoir Model typically assumes a constant equilibrium volume. To overcome this limitation, the modeling was divided into three stages corresponding to different periods, each with a different constant tidal prism. The first stage, 1921-1962, is the period from the opening of the inlet until the construction of the Dunedin Causeway, which reduced the tidal prism to 75% of the tidal prism before causeway construction. The second stage, 1962-1988, is when Dunedin Pass closed, increase the tidal prism to 129% of that of 1962 or 97% of the tidal prism of 1957. The third stage, 1988- 2060, covers the present condition and provides future projections. The tidal prism change is based on the ADCIRC model runs of 1957, 1965 and 2004 conditions.

The wave, sediment transport, and tidal hydrodynamic modeling, in addition to the bathymetry data, were evaluated to define sediment pathways for each stage of Hurricane Pass evolution. Based on the modeling results and documented elevation change, the sediment pathways for predominant transport are represented as illustrated in the pathways column in Figure 8 for each of the three temporal stages. Sediment pathways for the other direction were also included in the model to accurately account for all sediment inputs to the inlet system.

The bathymetric data considered together with the modeling results defined the distinct morphologic features in the system. Throughout the three temporal stages of the inlet evolution to present time, the following features have been present: an ebb shoal, flood shoal, bypassing bars north and south of the inlet, and sand spits on each side of the inlet. For identification, the sand spits north and south of Hurricane Pass are called Honeymoon Spit and Caladesi Spit, respectively. The equilibrium volume of each feature was determined based on comparisons of available surveys and calculated volumes and rates of change for each feature. Figure 8 displays the morphologic features and sediment pathways for each of the three temporal stages. The features may have changed shape, location and size, but were distinct in all available surveys and aeriels. The input sediment transport rates were specified based on the sediment transport computations for each time period.

Results

The Inlet Reservoir Model analysis included three features: the ebb shoal containing the proposed borrow area, and the two spits representing the adjacent shorelines that may be subject to impacts from dredging the ebb shoal. The measured and calculated volumes for the Hurricane Pass ebb shoal and Honeymoon Spit are shown in Figures 9 and 10, respectively. Calculated and measured volumes match the observed and measured trends of change. The results indicate the variation in volumetric change in response to the change in tidal prism in 1962 and 1988. Figure 9 shows the

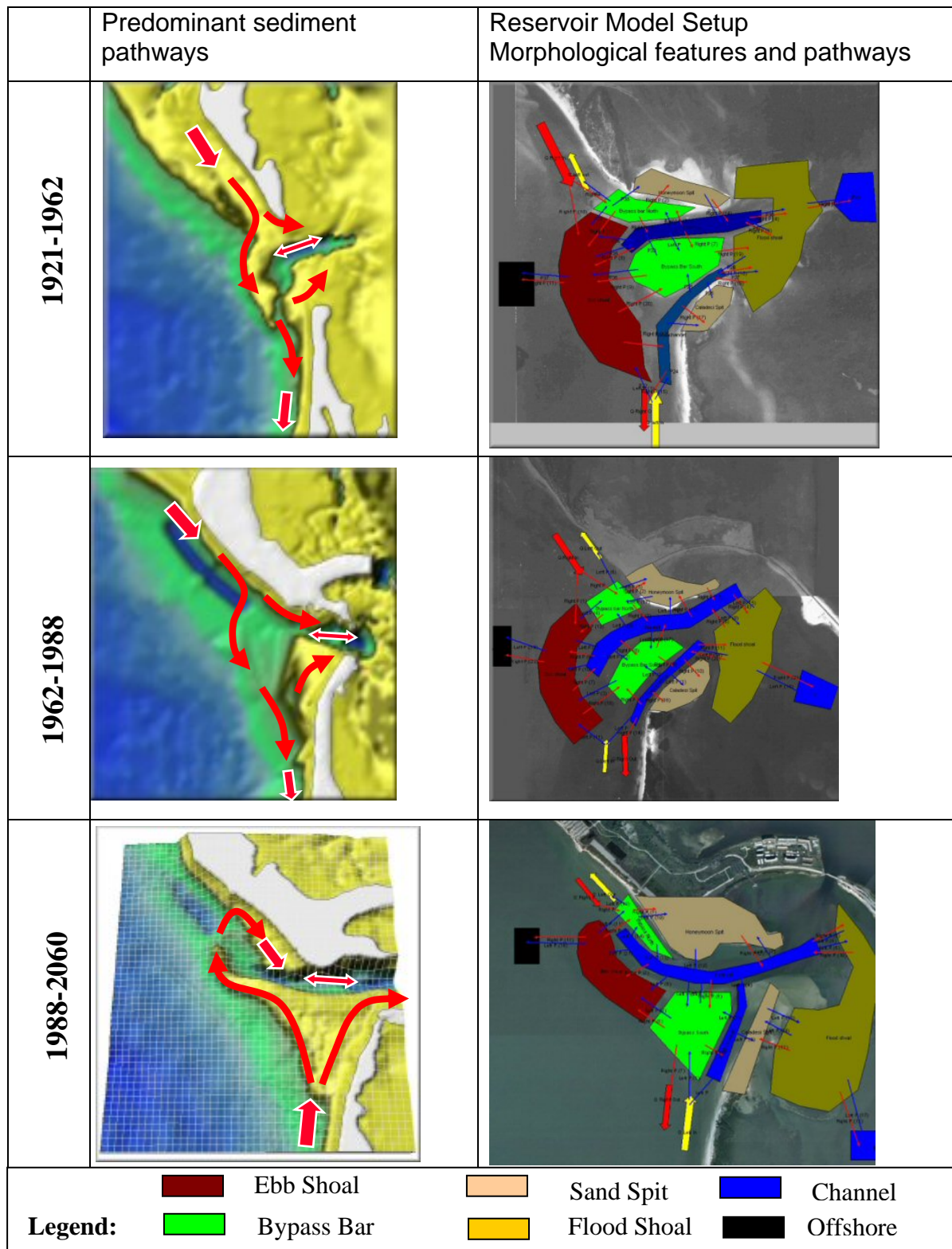


Fig. 8. Morphologic features and sediment pathways at each temporal stage

calculated ebb shoal volume growth to 320,000 m³ by 1957, compared to a measured volume of 316,000 m³, as it was growing towards an equilibrium volume of 400,000 m³. After the tidal prism decreased in 1962, the ebb tidal shoal migrated toward shore as the inlet adjusted to the reduced tidal prism. The model results show the ebb shoal excess volume decaying towards an equilibrium volume of 200,000 m³ for the reduced tidal prism. Figure 10 also shows the change in growth rates of Honeymoon Spit in response to the change in tidal prism. By 1988, when Dunedin Pass closed, the ebb shoal started to gain volume towards the present condition equilibrium of 250,000 m³.

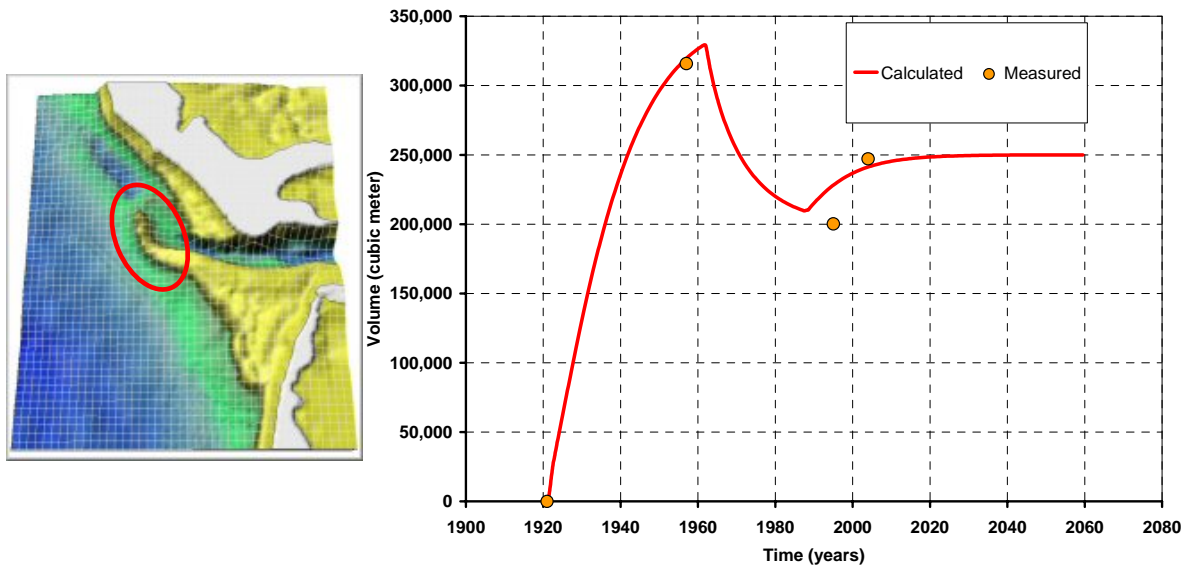


Fig. 9. Calculated and measured volumes for Hurricane Pass ebb shoal

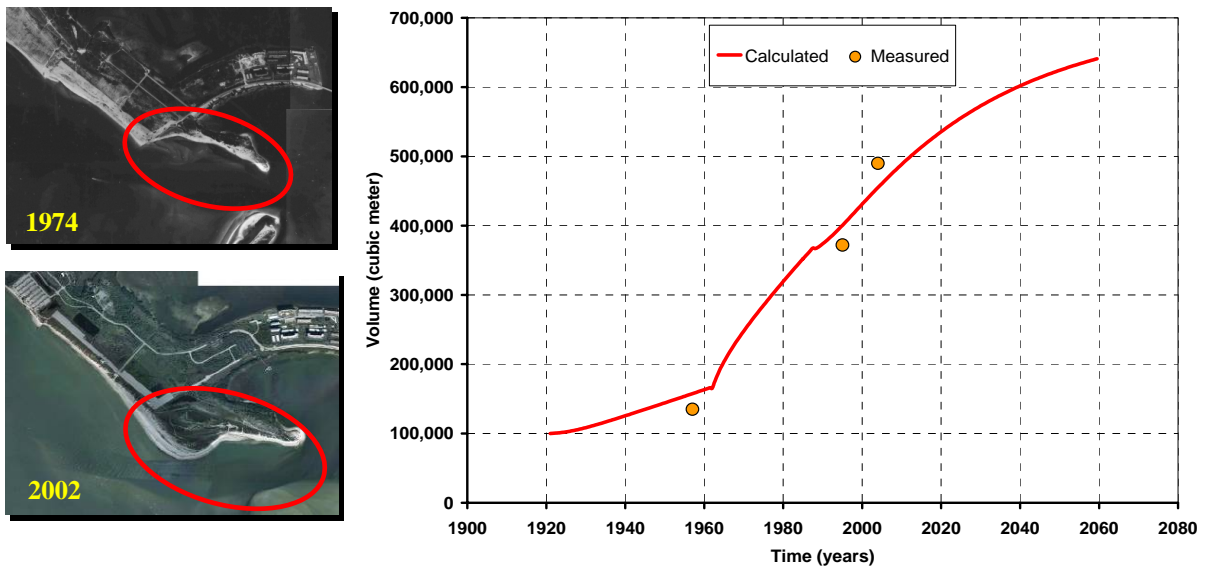


Fig. 10. Calculated and measured volumes for Honeymoon Spit

Effect of proposed dredging

The proposed dredging of 100,000 m³ is evaluated with the Inlet Reservoir Model. The dredged amount is applied for the year 2006, and the calculations for the ebb shoal and adjacent shoreline features were compared with the no-dredging condition. Two cases were considered for the post dredging conditions; one where only the dredging event was applied to the model, and the second by applying the dredging and fill placement that act as a feeder beach at the north boundary of the inlet system. Figure 11 displays the effects of the dredging with and without the fill effects on volumetric change to the ebb shoal. Figure 12 shows the expected recovery rates for the ebb shoal volume. The model indicates the effectiveness of the fill placement as a feeder beach in enhancing the recovery rates. The model indicates that the ebb shoal will recover 50 and 75% of the dredged amount in 5 and 10 years, respectively. Mining the ebb shoal is expected to reduce the efficiency of the ebb shoal to bypass sand to other features in the system. Figure 13 shows the change in bypassing rates of the ebb shoal, depicting the dredging and combined dredging plus fill effects. The model indicates that the fill will increase the bypassing rates during the first 3 years post nourishment, which will reduce the large offset in the bypassing rates during the initial recovery.

Figure 14 shows the effects of the dredging and fill placements on the volumetric change of Honeymoon Spit. The model indicates that the response of Honeymoon Spit to dredging will be compensated by the fill placement. The model did not indicate detectable impacts on Caladesi Island, because the main source of sand to Caladesi is from the south not through bypassing. Figure 15 shows the bypassing rates of Honeymoon Spit and the effects of the dredging on the sediment transport from this feature onto the inlet system. The calculations

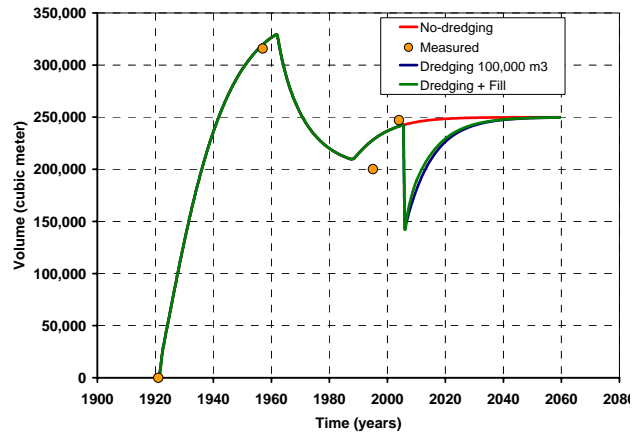


Fig. 11. Effects of the dredging on Hurricane Pass ebb shoal volume

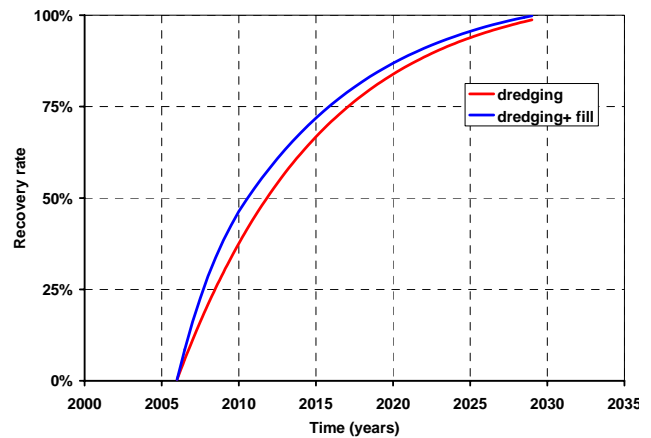


Fig. 12. Calculated recovery rate for Hurricane Pass ebb shoal dredging of 100,000 m³

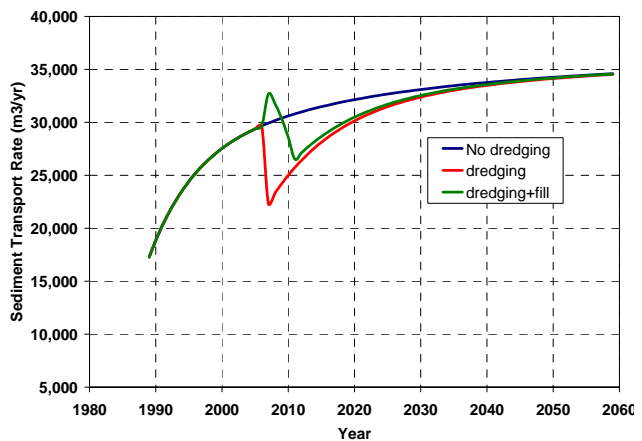


Fig. 13. Effects of dredging 100,000 m³ on the ebb shoal bypassing rates

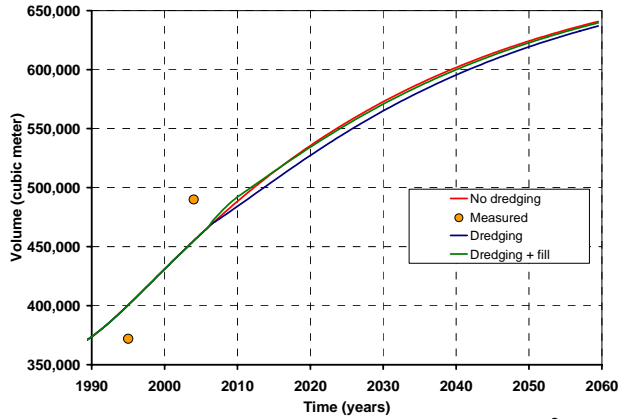


Fig. 14. Response to dredging 100,000 m³ of the ebb shoal on Honeymoon Spit volume

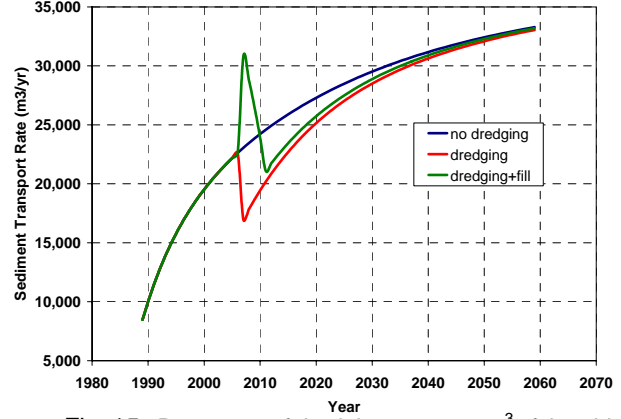


Fig. 15. Response of dredging 100,000 m³ of the ebb shoal on bypassing rates of Honeymoon Spit

indicate the effect of the fill placement as a sharp increase in the bypassing rates through the system over 3 years, a relatively short period of time. The short time is attributed mainly to the large sediment transport gradients along the south part of Honeymoon Island and limited sand supply. The Inlet Reservoir Model indicates that project performance will benefit greatly from reducing those large gradients by means of erosion-control structures. These would increase the lifetime of the project and provide a gradual feeder beach condition that will further offset the dredging bypassing deficit, increase the re-nourishment intervals to within the time frame for recovery of the borrow area.

CONCLUSIONS

A methodology was introduced for estimating the change in volume and sand bypassing rates in response to mining of ebb-tidal shoals. The methodology incorporates a regional approach that can account for multiple inlets sharing the same bay system and long-term changes in hydrodynamic forcing. Analysis of aerial photography and interpretation of morphologic features is also a part of the methodology. The methodology centers on the Inlet Reservoir Model that enables calculation of long-term evolution of inlets. Through availability of bathymetry data and aerial photographs to document beach and inlet morphology change, and numerical modeling to infer sediment pathway from waves and tidal currents, natural bypassing and sand mining consequences can be evaluated by means of the Inlet Reservoir Model. This paper has demonstrated the application of such a methodology to Hurricane Pass along the Florida gulf coast. The Inlet Reservoir Model provided a quantitative tool to assess long-term consequences of proposed dredging, including the expected recovery rates of the borrow area and response of other morphologic features in the inlet system to dredging of the ebb shoal. .

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